ELECTRICAL TESTER

DC DISTRIBUTION:
the swing towards more direct current flow in the grid

IEC 61850 and system security

STRAY CURRENTS IN WATER PIPES IN A REVERSE OSMOSIS PLANT

ISSUE 004 / 2022

Jill Duplessis
Editor

Letter from the Editor

Dear Readers,

Welcome to this fourth issue of Electrical Tester magazine! I think it's worth the wait and hope you will agree. I'm grateful for all our contributors and thank them for sharing their knowledge.

As the publication of each issue draws near, I reflect on the articles that have come together and can't help but notice that "like attracts like" as I ponder the themes that link these contributions. Indeed, while I am reminded of the quote from the writer Anaïs Nin ("We don't see things as they are; we see them as we are"), I nevertheless notice that the unifying themes of this issue seem to be 'the changes in complex systems through time' and 'helping'.

As part of this, our feature article highlights how DC power has ironically become such an integral factor in our evolving relationship with electricity and how it is helping us realise the next steps in our complex and ongoing journey with electrification. A pendulum swing towards increasing concentrations of DC in the world's power portfolio reminds me of the control systems courses I enjoyed so much in college. Whenever swings and shifts are involved in a system, I immediately think of stability. If the swings start becoming too extreme in either direction, the system becomes unstable and advances rapidly towards its demise. It's always comforting to me, therefore, to see something moving in a steady trajectory towards its centre.

Stability is one aspect of reliability. In protection systems, reliability is primarily spoken about in terms of dependability and security. Do you know the difference? I'm not speaking about cyber security, by the way. Andrea Bonetti, Hongliang Zhu, and Nikolay Ignatovski have produced a timely article that discusses this important topic and the need to achieve balance between these two distinct indicators of reliability.

In a blog post, Dave Pollard summarises the attributes of a complex system. One tell-tale characteristic is that "everything seems to connect to everything else and depends on something else having been done first". Indeed, as change occurs in a complex system, unforeseen ripples may emerge within connected aspects. The digitisation of the power grid, for example, raises interesting 'opportunities' in substation metering for billing that Rannveig Løken shares in her article. This IEC 61850 implementation work for energy meters in substations will pave the way for smart grid energy metering as well; with a solution in hand for substation metering, we will know how to do the same for smart grid metering in 'smaller substations'. Meanwhile, Stefan Larsson, Andrea Bonetti, and Lennart Schottenius address a prospective by-product of the Smart Grid – that is, the rapid scale proliferation of self-powered relays and the inherent challenges in testing them.

With increasing performance demands on our complex grid, particularly on asset reliability, testing must be managed with more intention than ever. Part of this requires expanding one's test portfolio when it makes sense. Dr Diego Robalino, Ken Petroff, and Vince Oppedisano write about a predictive insulation test, 1 Hz, that delivers exceptionally high value. Another way to manage testing with intention is to become as knowledgeable about test methods and their applications as possible. This issue is rich with articles that will *help* everyone do just that and I recommend them all.

And continuing with the theme of 'helping', well today it is more imperative than ever that we help each other. In that regard, I hope you appreciate Dr Stan Zurek's inductance article about the three students as much as I do, and I hope Rickard Jonsson's short article about reindeer and sustainability will move you. My right-hand assistant editor, Léonie, shares a great story about how a local community has managed to preserve Tesla's last remaining lab. As if to punctuate my conclusions about this issue, on my drive home from the dentist last week, I passed a building with a huge orange sign with white lettering. It read, "What do we live for, if it is not to make life less difficult for each other?"

Be well, my friends. Until next time!

Andrew Boughtwood

Group Director, Commercial, Sales & Marketing at Megger Group Limited

Letter from leadership

Dear ET Community,

Recent times have presented their fair share of challenges. Challenges to us as individuals, to us as a company, to our business partners, and to our customers around the world. Though the Covid tide appears to be turning for most nations, for which we thank our scientists and healthcare workers worldwide, different challenges now arise. The conflict in Ukraine, the rising cost of living, and the ever-present need for greater environmental protection and care are just some of these global issues.

Reflecting on such things brings to mind the various ways we approach challenges. It's the aspect of our resilience. Our ability on many levels to recognise and adapt to complex problems. Our sustained attention and efforts to make things better; better for ourselves, better for our companies, and, most importantly, better for our fellow human beings and our wonderful planet.

Resilience in ourselves is programmed into us; it's in our DNA, our mindset, and our belief systems. Similarly, resilience is a demonstrable strength of character in Megger. In recent decades, massive challenges have impacted the electrical supply industry, and these continue today. Among the biggest of these are the relentless demand for power generation and delivery through increasingly complex networks and the power network landscape changing to one where power generation is no longer obtained from a single source but is instead coming from multiple sources distributed around the grid. Indeed, many of you reading this article are likely to have your own domestic power sources, be that solar panels on your roofs, perhaps even wind turbines in your gardens, or intelligent access to your electric vehicle battery systems.

At Megger, we continue to adapt to these challenges and the subsequent needs of our customers; to remain important to them and to remain relevant to them.

In this issue of ET, our incredible team, under Jill's stewardship, once again bring you insights on various electrical supply and asset condition matters. To the many people in the wider Megger community who have contributed to creating another fantastic ET, I say well done and thank you.

To you, the reader, from us all at Megger, we thank you. Stay strong, nurture your resilience, and enjoy reading this issue!

Best wishes,

Andrew Boughtwood

ET

Contents

Electrical Tester team

Jill Duplessis
Editor

Jill Duplessis is Megger's Content Strategy Director. Her team is focused on customer UX; content processes, quality, and structure; and messaging, authoring, and knowledge management. Jill is the primary author of Megger's Transformer Life Management (TLM) bulletin series and is the author of many articles and papers, as well as a book titled Electrical Field Tests for the Life Management of Transformers.

Prior to working at Megger, Jill was Director of Power Programs for a start-up company in Washington D.C., where she was responsible for developing, testing, and deploying new applications of (intensity modulated) optical monitoring systems for transmission and distribution utilities. Before this, she gained over 17 years of experience in the condition assessment of substation assets, first as a Principal Engineer at Doble Engineering Company and following as a Primary Manager and Regional Application Specialist, Transformers, for OMICRON electronics USA.

She has prior electric utility work experience (with Florida Power Corporation, now part of Duke Energy, and Georgia Power Company), where she enjoyed an exposure to a wide breadth of engineering functions. Jill received a BSEE degree from Georgia Institute of Technology in 1991 and completed extensive master studies in electrical power engineering at Rensselaer Polytechnic Institute, Troy, NY..

Léonie Alvey
Assistant Editor

Prior to working as the Group Content Editor for Megger, Léonie graduated from Swansea University in 2010 with BA Hons in Egyptology and Classical Civilisations. Shortly after this time, she began a career writing, editing, and proofreading for PR agencies, magazines, web content, and sales content across a wide range of industries, both B2B and B2C. Since joining Megger in 2016, Léonie has concentrated on improving the quality of written work across all sectors of the business while also growing and maintaining Megger's global LinkedIn channel.

Editorial contributors

Isobel Fraser-Underhill
Visual Identity and Content Operations Manager

The Visual Identity and Content Operations Manager for Megger, Isobel graduated from the University of Kent in 2005 with BA Hons in Visual Design and Advertising. She has been working within the design industry for over 15 years in various B2B and B2C companies. Isobel joined Megger in July 2013, focusing on the company’s visual identity and creative operations.

Isobel has been the Designer and Assistant Editor of the Electrical Tester publication since 2013.

Keith Wilson
Technical Copywriter/Editorial Contributor

Keith is a qualified electrical engineer with experience in designing and commissioning control systems, principally for mechanical handling and process plant. He is a lifelong member of the Institution of Engineering and Technology and is now a well-known technical author.

Megger Limited
Archcliffe Road Dover
Kent CT17 9EN
T +44 (0)1304 502100
E electricaltester@megger.com
www.megger.com

DC distribution: the swing towards more direct current flow in the grid

Dr Ahmed El-Rasheed

Introduction

For over 100 years, electricity has almost exclusively been transmitted and distributed using Alternating Current (AC), but things are changing. Technological developments as well as economic, political, and environmental factors are now driving a move toward the adoption of Direct Current (DC) for transmission and distribution.

Electrical power is classified as AC or DC based on the direction of flow of the electricity. With AC power, the current changes direction at a defined frequency, while with DC power the current flows in one direction only. For many decades, it has been accepted that AC is best for transmission and distribution of electricity, while DC is best for powering electronic devices like televisions, computers, and mobile phones.

The electrical infrastructure in most countries is designed for AC transmission and distribution. An enormous amount of effort and investment will be necessary to change to DC so the justification for making this change must be compelling.

Over the next couple decades, however, there will be an exponential increase in the number of electrical loads that require DC power, like solid-state lighting (LED), business and consumer electronics, and electric vehicles. Parallel with this increase in the number of DC loads, there will be a similar increase in the number of power sources that supply DC. These include solar PV installations, and battery-based energy storage systems.

These trends will require dramatic changes in the way electricity is transmitted and distributed. It is important for everyone in the industry to understand the reasons for these changes and their potential impact. With this in mind, this article revisits the history of electrical transmission and distribution before examining recent developments in the field.

AC and DC power transmission

In the early days of electrical power, there was the technological battle of the age between Thomas Edison, who championed DC power, and Nikola Tesla who pioneered AC power.

For the victor, there was a great fortune to be made and a towering reputation to be built, so it was almost inevitable that the battle would turn ugly.

Initially, Nikola Tesla worked for Thomas Edison, but their differences drove Tesla to move to Edison’s principal competitor, Westinghouse. At Westinghouse, Tesla demonstrated that AC transmission and distribution were more efficient and economical than DC because it was so easy to increase AC voltage using a transformer. Of course, while it improves efficiency, increasing the voltage also increases the hazards associated with electricity. Edison was not slow to exploit this and to suggest that his lower voltage DC solution was far safer.

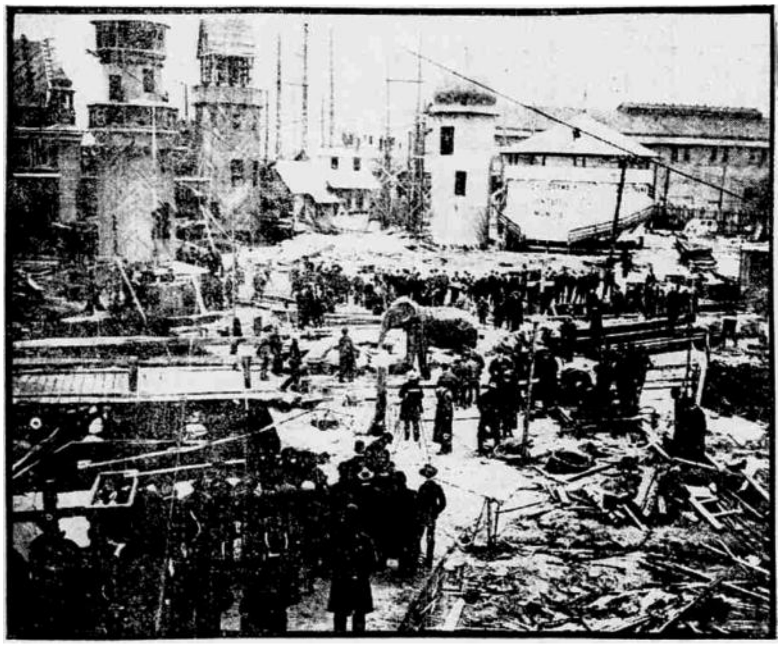


Figure 1: Ex-circus elephant, Topsy, electrocuted by Edison

To prove his point, Edison went to the cruel and unnecessary lengths of electrocuting ex-circus animals just to demonstrate the hazards presented by high AC voltages. This campaign against AC power culminated in the public execution of an unfortunate elephant, Topsy, an event which Edison even recorded for posterity using his newly invented movie camera.

Advantages of AC

At the present time, AC is used almost universally for power generation and for the electrical grid. When a consumer connects to a wall socket, it is AC power that they receive to feed a multitude of devices such as lights, refrigerators, and washing machines. As has already been mentioned, the main reason for the dominance of AC power is the availability of a cheap and reliable method of increasing and decreasing voltage – the transformer – which makes possible the inexpensive manipulation of voltage and current.

Tesla's genius insight was to exploit the properties of the transformer to step up the voltage of the AC power that came from the generating plant, prior to transmission. For a given amount of power delivered, stepping up the voltage decreases the current and, since losses in a cable are proportional to the square of the current, the savings are substantial.

For example, if a generator produces power at 25 kV it would need to deliver a current of 2 kA to supply a total load of 50 MW and the losses in a transmission line carrying such a current would be enormous. However, if a transformer is used to step the voltage up to 800 kV, the current falls to a mere 62 A and, if the same size cable were used, the losses at this current would be only 0.01 % of those at 25 kV.

In practice, of course, a much smaller cable would be used, but the savings would still be huge. So high-voltage transmission saves a lot of money for power companies and consumers. It also saves energy and reduces pollution because power plants do not need to make up the losses by using more fuel.

Another advantage of AC transmission and distribution is low maintenance costs compared with DC. Transformers and associated equipment are very reliable and last for decades in service. In addition, it is comparatively easy to interrupt AC current using devices like circuit breakers, since AC current passes through a zero point every half cycle, which is not the case with DC. In fact, a typical circuit breaker has an AC current interrupting capacity about 20 times greater than its DC current interrupting capacity.

Advantages of DC

Edison pushed for the adoption of DC, based on a system that would send power at 120 V DC through the cables connecting consumers to the generating plant. This idea is, however, deeply flawed as losses in the cables limit the maximum practical distance of transmission to just one or two kilometres. Unsurprisingly, Edison lost the technological battle in the early years of the twentieth century. But technology does not stand still, and it is now possible to easily increase and decrease the voltage of DC supplies. This has led to the growing adoption of high voltage DC (HVDC) transmission systems, and has made it possible to take advantage of the hitherto inaccessible advantages of DC transmission over AC.

Inductance and capacitance on transmission lines

A major benefit of DC transmission is that it does not suffer from losses due to capacitance or inductance. Every power line is equivalent to a series of resistors and inductors, shunted by stray capacitance to ground (see Figure 2). And the longer the transmission line, the greater the losses due to resistance, inductance, and capacitance. However, at DC, inductive reactance is zero and capacitive reactance is infinite, which means that DC suffers only resistive losses, whereas AC suffers losses due to all three components.

Therefore, once DC power is stepped up to a high voltage, the efficiency advantage is with DC rather than AC power. Largely for this reason, HVDC transmission is being adopted increasingly widely as, for example, in the undersea power lines between the United Kingdom and mainland Europe.

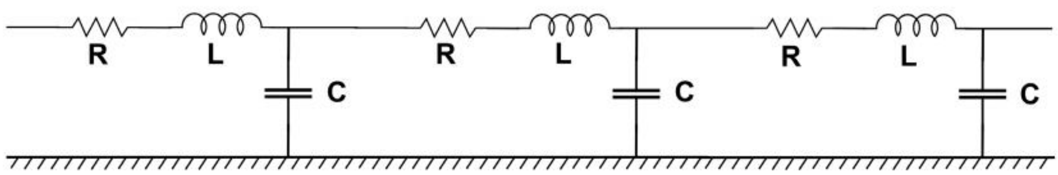


Figure 2: Equivalent circuit for a transmission line

Electric power is transmitted as AC throughout the UK and mainland Europe but, on each side of the English Channel (which separates the UK from Europe), there are two HVDC substations. At one end of the connection, which can transmit power in either direction, the substation takes AC power and converts it to HVDC for undersea transmission while at the other end, the substation takes HVDC power and converts it to AC for connection to either the UK or European grid, depending on the direction of the power flow.

This may seem like unnecessary complication and expense, raising the question of why HVDC transmission is used in this application. The answer goes back to the fact that the efficiency of DC transmission is unaffected

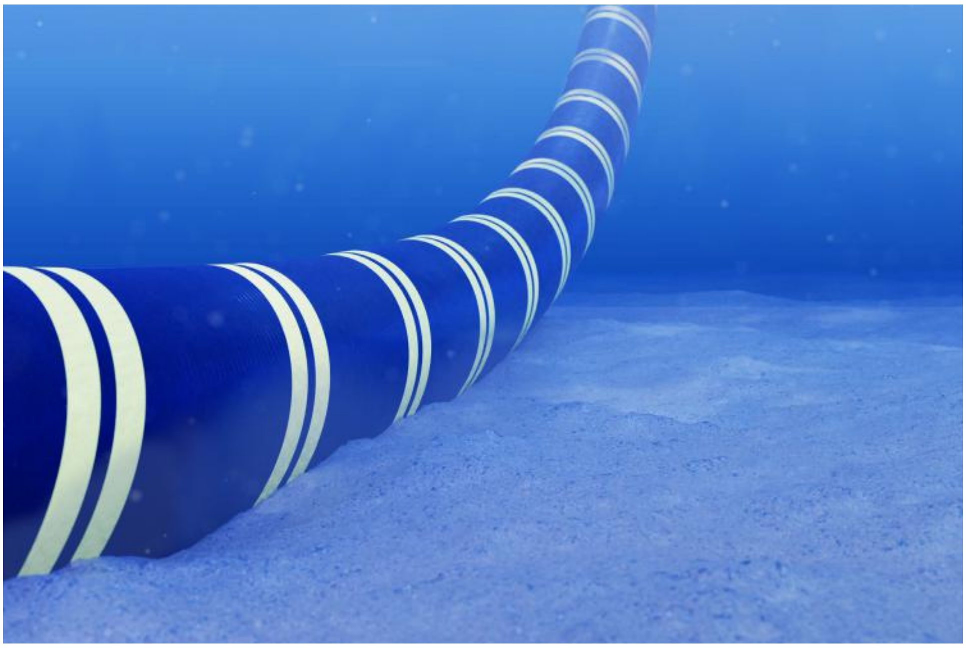


Figure 3: Subsea power cables during installation

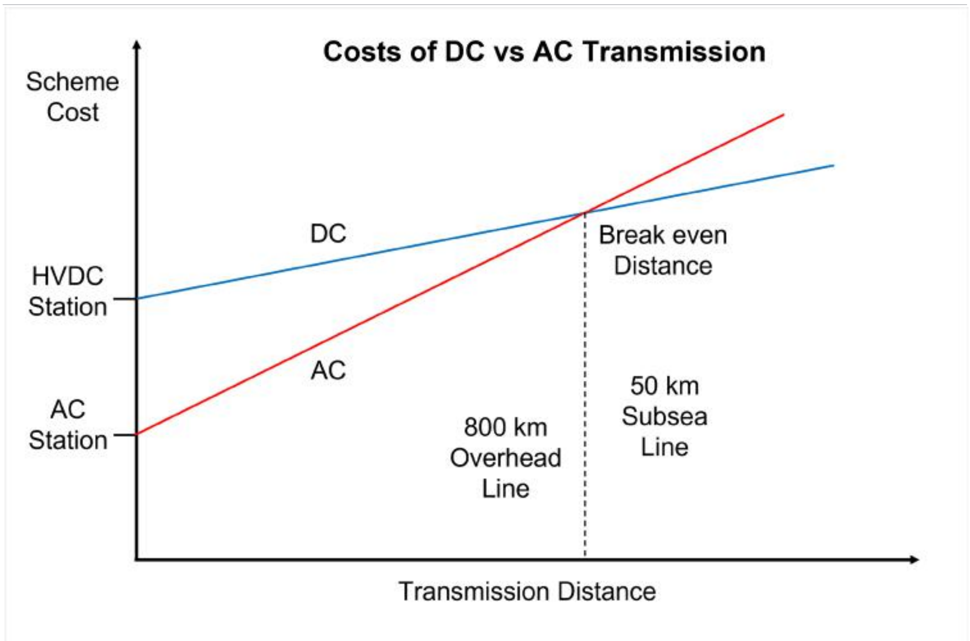


Figure 4: Current costs of DC and AC transmission over distance (km)

by the capacitance and inductance of the transmission line. In an undersea cable, stray capacitances in particular are much greater than in overhead transmission lines, and this makes transmission of AC power uneconomic for distances greater than about 50 km when total costs (power loss and equipment) are used to compare AC and DC systems (see Figure 4).

As technology continues to improve, the distance where DC becomes more efficient than AC will become smaller and ultimately it is likely that DC will be more efficient even over short distances.

No load power losses

Another advantage of DC transmission relates to active and reactive power. DC is concerned with active power only, while AC is concerned with both active and reactive power. The relationship between total (apparent) power and its components is given by this formula:

$$S = P + iQ$$

Where:

S is Apparent Power (VA)

P is Active Power (Watts)

i is the imaginary unit (√-1)

Q is Reactive Power (VAR)

Active power is the power that does useful work in electrical devices, while reactive power is consumed by inductances and capacitances without doing useful work. Transformers, AC motors, and capacitors consume reactive power. For example, a laptop charger has a small transformer inside it which will consume reactive power even when the laptop is not connected. This situation is repeated for every transformer connected to the supply; it will consume reactive power whether or not it is supplying a load. Likewise, AC motors consume reactive power irrespective of their loading. With DC, there is no reactive component of the power, which improves efficiency and reduces the load on the power source.

Skin effect

AC power transmission also suffers from the "skin effect", where the power density in cables is reduced because the AC current does not use the full cable cross section. The magnitude of the skin effect depends on the frequency of the alternating current. The higher the frequency, the more the electric current will be squeezed towards the outer edge (skin) of a cable. At 0 Hz (DC), the current flows through the whole cross section of a cable. This means that higher power can be transmitted through the same size cables when using DC rather than AC.

Reduced AC/DC conversion losses

Many devices, such as computers, televisions and other electronic devices, and even solid-state lighting, need to convert the AC supply into DC before using it. The process of AC to DC conversion introduces additional losses in the power system. On the other hand, DC to DC conversion is highly efficient when using the latest technology, such as on-chip buck-boost converters. A study by DOE (US Department of Energy) in 2014 calculated that supplying DC power to homes, thereby removing the need for AC to DC conversion, would provide an efficiency improvement of up to 5 %. This would represent a significant cost saving for consumers as well as for the power utilities.

Ease of interconnecting supplies

DC power has the advantage of simpler requirements for interconnecting multiple supplies. To feed a DC power line from two separate sources, it is only necessary to match the voltage level and the polarity of the sources. The amount of power available is increased by combining the two sources.

With AC power, the process is more complicated because the two sources must be arranged to have the same voltage level, the same frequency, the same phase angle, and the same impedance. This is a much more complex task, with a low tolerance for mismatching; if any of the parameters don't match, a potentially catastrophic fault will occur.

The modern power grid has multiple generation points, and they need to be safely and economically integrated. As power consumption continues to rise, the number of power generation sites will increase to meet this demand and, in the long run, DC power systems are likely to prove a better way of interconnecting these sites.

Renewable energy efficiency

There has been an exponential rise in renewable energy installations over the past 20 years, and this trend is expected to continue. There are environmental factors, as well as political and economic factors, that fuel this trend. Politically, most countries have pledged to reach net zero carbon emissions within the next few decades, which means that there is a lot of funding available for renewable energy projects. And, economically, solar and wind installations demand a relatively low investment of time and money, which makes them an attractive investment.

Solar photovoltaic (PV) installations

The potential for Solar PV is enormous. The US government has published a report stating: "PV panels on just 22 000 square miles of the nation's total land area – about the size of Lake Michigan – could supply enough electricity to power the entire United States." Additionally, the average cost of Solar PV panels has dropped by over 70 % since 2014, while their efficiency has also improved.

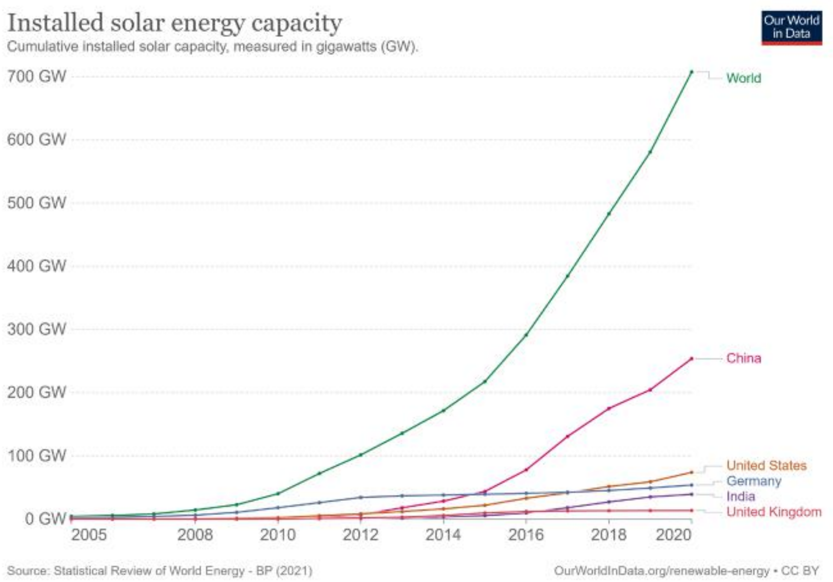


Figure 5: The current PV global installed base is over 700 GW and increasing rapidly

Solar PV panels produce DC power and, for connection to the present-day grid system, the power needs to be converted to AC. It is undeniably more efficient to provide the power as DC, especially in local generation and consumption sites, such as residential and office buildings.

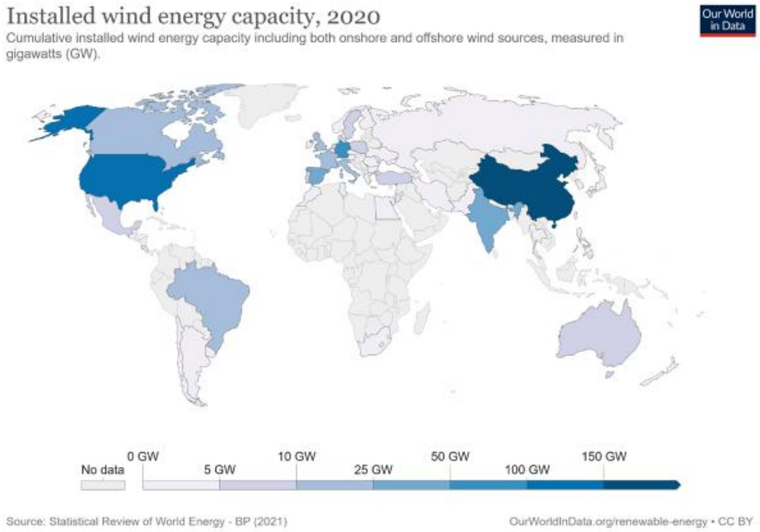


Figure 6: Installed wind energy base

As has already been mentioned, a growing range of devices operate on DC power and a rooftop PV panel can provide that power without redundant DC to AC conversion. The DC to DC voltage change needed is simpler and more efficient. All of which means that a modern home could have rooftop solar panels that power its electronics, solid-state lighting, and more efficient DC-motor-driven refrigerators, freezers, pumps, fans, and air conditioners.

Offshore wind

Another popular renewable energy source is offshore wind energy, which uses wind turbines on the sea. The sea is a desirable location for wind turbines because it is consistently windy, and it avoids the use of land which is often needed for other purposes. As a result, the global installed base of offshore wind energy is expected to exceed onshore within the next decade.

Although most wind turbines produce AC power, in offshore applications it is necessary to convert it to DC because the power cables run under the sea. As discussed earlier, undersea AC power connections are inefficient because of the increased stray capacitance from the proximity of the soil and salty seawater. Typically, offshore wind turbines are connected to an AC to DC converter that supplies DC to the undersea cables. In most instances, when the power reaches the shore, it is converted back to AC for connection to the grid. However, a DC infrastructure to distribute DC power would bring all the advantages of DC including improved efficiency

Battery energy storage

The increased adoption of renewable energy is a big benefit for the environment, but few renewable sources can be relied upon to supply energy consistently. Solar energy, for example, is only available during daylight hours, while the availability of wind energy increases and decreases with the wind. Therefore, energy storage becomes an important consideration. There are various options for this, including water reservoirs at altitude, compressed air tanks and batteries. The global trend is dominated by battery storage because of factors that include relative energy density, cost, and footprint. However, batteries provide DC power and are charged with DC power, which means a DC infrastructure is a much better fit for batteries.

Smart grid, electric vehicles, and the homes of tomorrow

At present, the electricity grid handles the flow of power from generating plants, through the transmission and distribution network, to the consumers who make use of that power. Soon, the grid will be ‘smart’, which means that intelligent devices will be installed throughout, providing a vast amount of information that will greatly improve the performance and capabilities of the system.

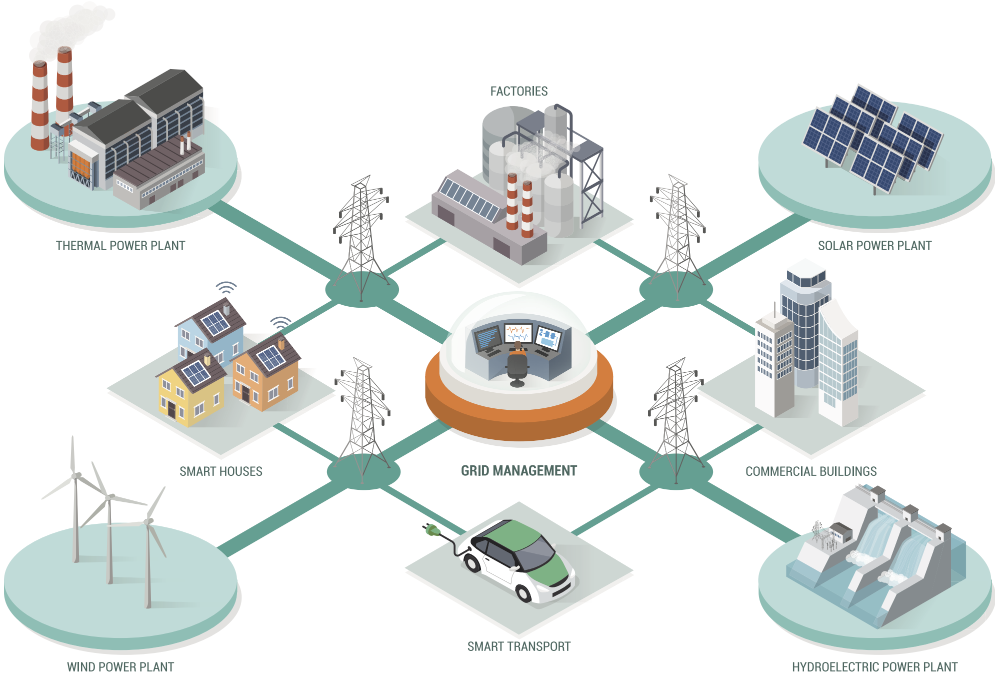


Figure 7: In future, power flow will be bidirectional

Bidirectional flow

One of the main features of the Smart Grid is bidirectional (two-way) flow of power and information. There will be micro-generation sites installed almost everywhere, like rooftop PV panels on houses. These micro-generation sites will feed power back into the grid. Therefore, a home will no longer be just a consumption point, instead it will be both a generation point and a consumption point. Interconnected smart devices will enable the efficient management of electrical power.

A location could, for example, be providing power for a couple hours and then consuming power for the next few hours. In some instances, power consuming and producing locations that are geographically close to each other will be interconnected to form a distributed energy resource (DER), which is, in turn, connected to the main grid. DERs may also include energy storage facilities such as batteries. Arrangements of this type use the same technology as the smart grid, and have the advantage that, in most circumstances, power is consumed close to the point where it is produced, which means that transmission and distribution losses are minimised. The grouping of power sources and consumers also makes management easier.

DERs, and the Smart Grid itself, require live information about supply and demand levels, combined with fast and efficient switching and combining of power sources. There can be little doubt that a DC distribution system with interconnected smart devices will make these requirements easier to achieve.

Electric vehicles

Electric vehicles are being adopted at a much faster rate than most economists had predicted. The growth rate is exponential, and even the COVID-19 pandemic has done nothing to slow it.

Many countries have announced plans to ban the sale of any new ICE (internal combustion engine) cars as early as 2030. This will force the full adoption of electric vehicles, but the current trend shows that in any case the market is already heading that way. Approximately 200 million cars are sold globally each year, and indications are that most of these sales will be electric vehicles by 2030.

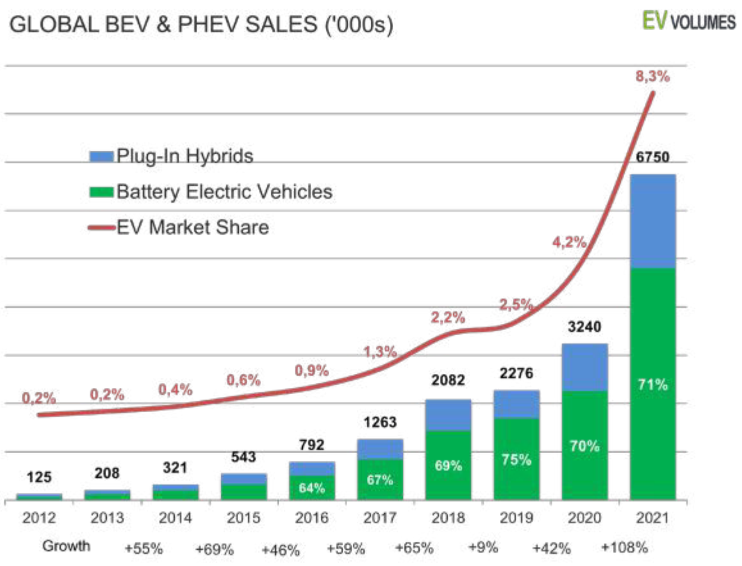


Figure 8: Global PHEV and BEV sales

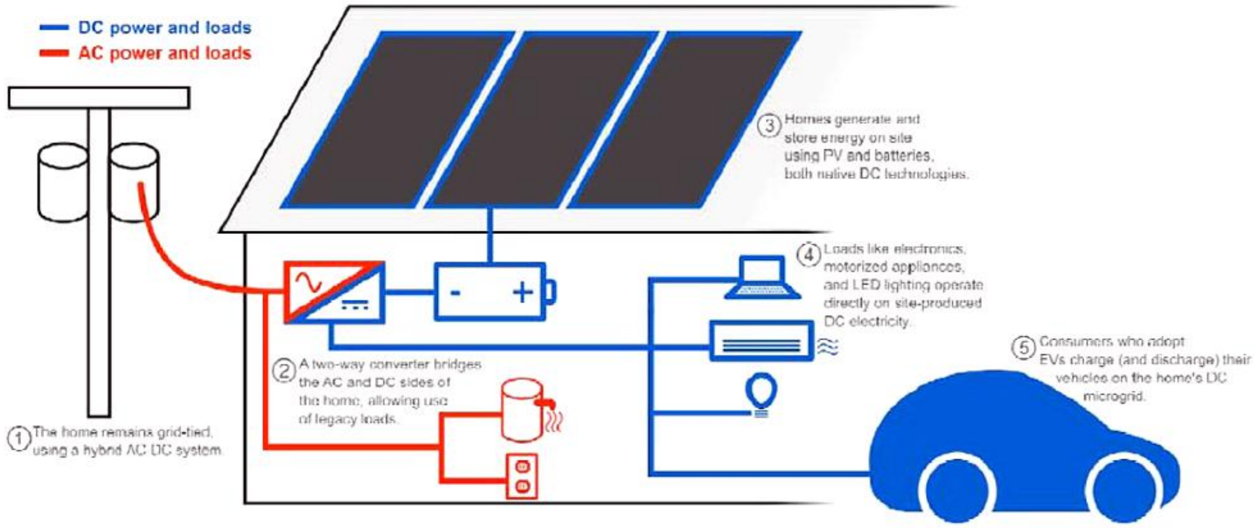


Figure 9: The hybrid DC home

This will lead to a large rise in demand for electric power and a huge installed base of batteries. In general, electric vehicles use batteries for their energy storage and as discussed, DC power is needed for charging. With AC charging points, conversion to DC is often carried out within the vehicle, but the fastest chargers are those that supply the vehicle directly with DC.

The challenges of integrating electric vehicles with the grid was dealt with in some detail in an article in Issue 1 of ET Magazine – which is still available on the Megger website – but a point from the article that is particularly notable is that multiple manufacturers have already made DCFCs (DC fast chargers) that will charge at a rate of 200 or even 400 kW. A 'gas' station with 10 of these chargers would present a load of 4 MW to the grid which would be difficult to handle with today's infrastructure. There's little doubt that the most efficient way to provide the power demanded would, once again, be to use DC power distribution.

Unfortunately, the infrastructure changes needed to move to DC distribution are too vast and too expensive to be practical in the short term. A more the likely scenario is the hybrid DC home where, for example, AC grid power is connected as well as DC power from locally installed PV panels. The native DC devices such as the EV and electronics would consume DC power directly, while devices that need AC will consume power from the grid. DC to AC conversion will be done to allow superfluous power to be sold back into the grid. And AC to DC conversion will be done to provide any DC power needed that is not available from the PV panels or the battery storage.

Conclusion

AC power is the dominant method for transmission and distribution of electric power, but advances in technology are making high voltage DC to DC conversion much more affordable. This has triggered a change and DC power systems are now being used in certain situations where they are more economical than their AC counterparts. In particular, DC power is favoured for very long transmission lines (over 800 km) and for undersea and underground power lines longer than 50 km. As the cost of DC to DC conversion falls even further, these distances will decrease.

On the consumption side, more and more modern devices are DC-native, such as solid-state lighting, electronics, electric vehicles, and many household appliances. DC power distribution will remove redundant AC to DC conversions in these devices and improve energy efficiency by at least 5 % and, according to some studies, by as much as 15 %.

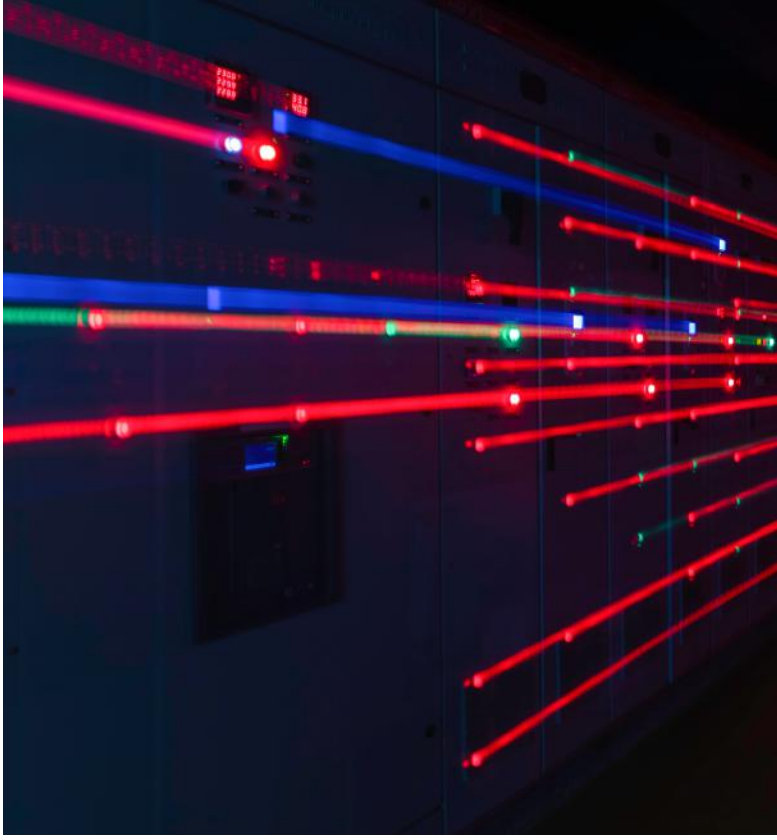
The move toward the Smart Grid also favours DC power distribution because it provides advantages in:

- Easily interconnecting multiple power sources
- Removing losses associated with AC power in no-load situations
- Providing higher energy density in cables by eliminating skin effect
- Removing redundant AC to DC conversions for DC-native devices

It is difficult to imagine the world changing from AC power to DC power distribution, and there will certainly be forces that will resist this change, not least the transformer manufacturers who face seeing their business decimated. Nevertheless, as we have seen, the advantages of DC distribution are clear and it's inevitable that change will happen although, for the most part, it will be gradual. Hybrid DC homes already exist, and they surely point the way to the future.

Self-powered relay testing challenges

Stefan Larsson, Andrea Bonetti, and Lennart Schottenius



When testing self-powered relays, many technicians ask why a current of 1 A injected by the relay test set is not registered as 1 A by the relay. Stefan Larson, Power Protection Product Manager at Megger Sweden, provides the answer and discusses other challenges associated with testing self-powered relays.

For the last 40 years, self-powered relays have been used in MV/LV substations in the secondary distribution network. Traditionally, MV/LV transformers larger than 800 kVA were protected by one of these devices, while protection for smaller transformers was provided by an MV fuse. In the last 15 years, however, power utilities have moved toward protecting transformers as small as 100 kVA with self-powered relays, which means they are now common in substations and secondary distribution network kiosks.

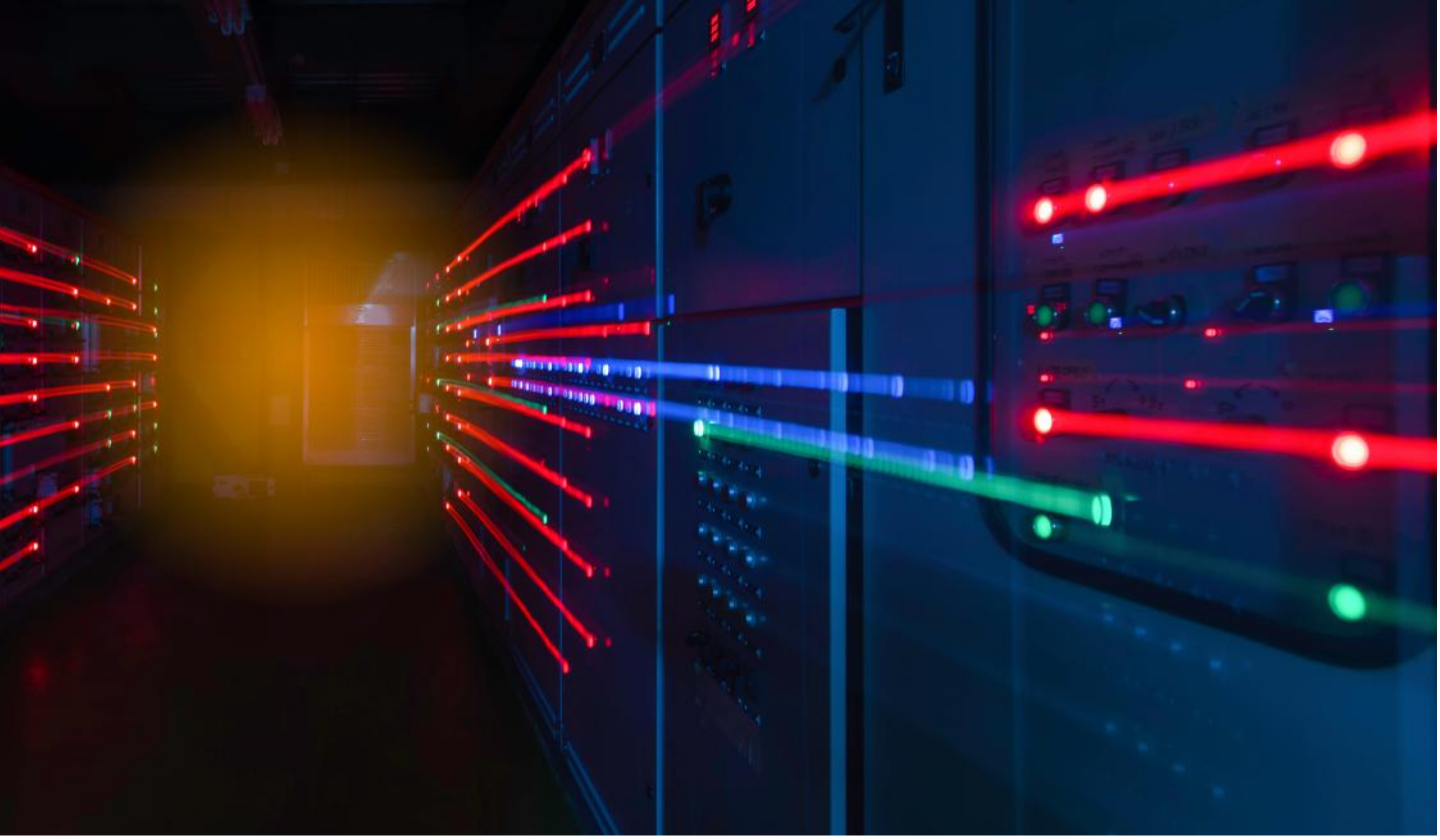
Self-powered relays take the energy they need to operate from the current delivered to the relay by the current transformer. This means that the load current – and, when present, the fault current – in the circuit being monitored provides the energy needed to power the relay. This arrangement has the big benefit that the need for an external power supply, which typically takes the form of a battery with its related DC network infrastructure, is minimised or, in many cases, completely eliminated. This simplifies the protection system and substantially reduces costs.

In the near future, these considerations are likely to become even more important, as the concept of the 'Smart Grid' becomes ever more pervasive. Solar panels are increasingly being installed on the roofs of ordinary domestic properties, electric vehicles are being charged at home and at some point, they will hopefully be able to deliver energy to the grid (V2G). In other words, the Smart Grid will penetrate electrical systems at all voltage levels.

A key factor that will influence the speed of this penetration is cost, and in particular the cost of providing adequate protection for the Smart Grid. In principle, there would be little problem in protecting the Smart Grid using the proven solutions that have been developed for protecting high-voltage power networks. In relation to the Smart Grid, however, these solutions are too complex and too expensive. Self-powered relays make an important contribution toward addressing these issues and it is therefore expected that their usage will increase significantly as more and more Smart Grid systems are implemented.

Despite their benefits, self-powered relays also present a number of challenges, particularly in relation to testing. Because of their integrated switch-mode power supplies, they present a very non-linear load to the test set. This means that a nominally sinusoidal 1 A current injected by the test set may be heavily distorted by the relay which, as a result, might measure a much higher or a much lower current.

Another issue is that of pre-fault conditions. As we have already discussed, the energy needed for the operation of a self-powered relay is derived from the current transformers. This means that if there is no load current



in the protected feeder, there is no energy to power the relay and, consequently, the relay is not active. If, under these conditions, a fault occurs, the fault current delivers energy to the relay which then starts up, detects the fault, and issues a trip command. The effective operate time, however, is the normal operate time of the relay plus the time that the relay takes to start up.

This situation is related to switching onto a fault condition: if the circuit breaker is closed onto a fault, there cannot be any pre-load into the protection relay before the breaker is closed. A similar situation can arise if the breaker is closed, but until a fault occurs, the load current is below the level necessary to provide enough energy to power the relay.

The issues associated with testing self-powered relays can be successfully addressed by using a test set such as Megger's SVERKER 900, which has been developed from the outset with self-powered relays in mind. The on-board current generators in the SVERKER 900, together with sophisticated adaptive real-time current generation algorithms, allow the reliable testing of protection relays of all kinds, including self-powered types.

Uniquely, the SVERKER 900 is compatible with the many different kinds of burden associated with various types of protection relays. It easily copes with electromechanical relays, static relays, sophisticated numerical relays, self-powered relays, and relays with current transformer operated trip release units. The pre-fault instrument can perform multiple timing tests, which is particularly useful when testing self-powered relays, as the pre-fault provides the load necessary to keep the relay turned on.

The SVERKER 900 is designed to manage current generation for self-powered relays, taking into account:

1. The harmonics generated by self-powered relays, which can disturb the control circuits in a relay test instrument

2. The non-linear load presented by self-powered relays, which requires high-performance real-time control loops to ensure that the test instrument generates the correct waveforms

3. The need for the test instrument to generate a relatively large amount of power in relation to the injected current to allow for the power needed to provide a supply for the relay

The spread of Smart Grids means that self-powered protection relays are likely to be widely used in future, even in smaller power systems. Testing these relays may at first seem challenging, but in reality the challenges can be readily overcome. The key is to use a test set, such as the SVERKER 900, which has been specifically designed for use with self-powered relays and to cater for their special requirements.

Metering challenges in IEC 61850 digital substations

Rannveig J. S. Løken

Statnett is the system operator of the Norwegian power system. The company owns and operates the transmission grid and balances consumption and production, thereby providing our customers with a reliable power supply at all times.

Metering and accreditation – today's solution

Figure 1 below shows a metering system for a transmission feeder which is typical of today's practice. Current and voltage measurements for the kWh meter are provided via dedicated copper cables connected to conventional voltage and current transformers. Technical requirements apply to the full metering chain, while accreditation control is only concerned with the kWh meter and its associated instrument transformers.

Grid settlements

Among the main tasks of the Grid Settlement Department in Statnett, the operator of the Norwegian power system, is the handling of gross cashflow related to grid tariffs, purchase of grid losses, cross-border revenues, and contracts for grid connection. The department also deals with standards and technical requirements for the measuring chain in the transmission grid. Grid tariffs are implemented, the meter values are checked, and the invoices to the customer for the grid tariffs are issued. In addition, the grid losses in the spot-market are forecast and purchased, and cross-border revenues are monitored. All of this is based on metered values, so it is important that these values are correct. In addition, contracts for grid connections with customers are maintained. These contracts refer to standards and technical requirement documents for the measuring chain in the transmission grid.

Standards and technical requirements

It is a requirement that meters shall be installed on all feeders in the transmission grid so that it is possible to make a complete station metering balance. A maximum discrepancy of 0.5 % is allowed on meters installed after 2016, and a maximum discrepancy of 0.8 % on meters installed before that date. Furthermore, the documents state that metering should be tested when new meters are installed, and that additional tests should be made every 4 or 8 years, depending on the exchange load. Several other technical requirements are specified for the metering chain, including time synchronisation and test methods for the meters. Changes to the standards and technical requirements documents have to be negotiated with the organisations that represent the users of Norway's central power grid.

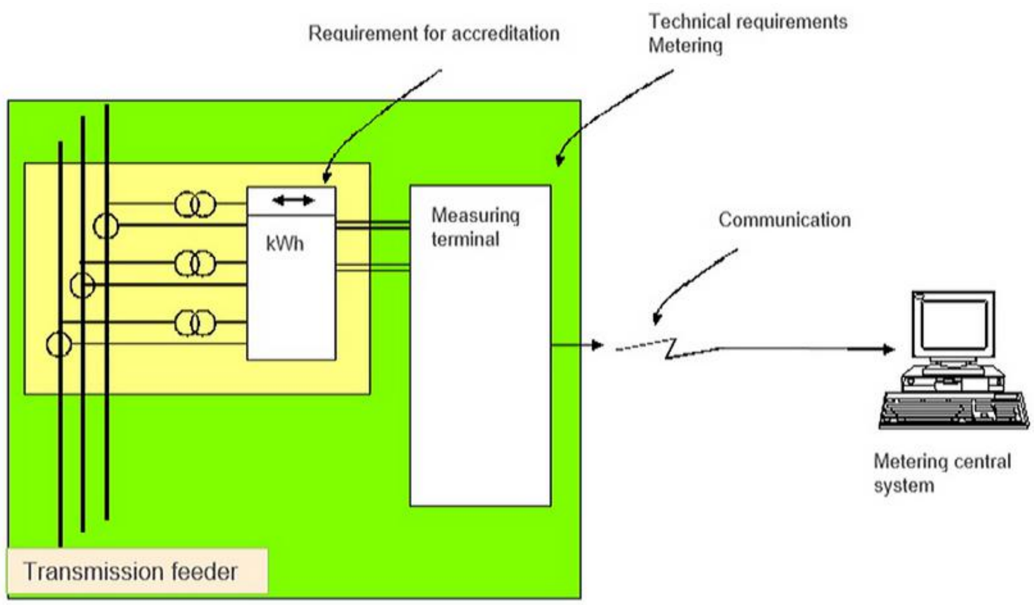


Figure 1: Metering system

Checking substation metering balance

Meter testing is carried out physically in the substations by trained experts. In addition, the Grid Settlement Department carries out further tests to verify metering values. There are about 1300 meters in the 220 substations that Statnett owns. Metering balance and completeness checking are performed for about 290 powerline balances. Figure 2 shows an overview of a substation with two power lines and two transformers connected to the busbar. The system that Statnett uses automatically shows balances, with losses on the right of the table. This example shows a good balance with a stable loss. A few values in this example have been manually changed because of incorrect measurements between times 9 and 12.

Checking losses on power lines

Figure 3 shows the power flow in a line from substation A to substation B. The losses should increase with the power flow, since Loss = I^2R. The system used automatically shows the highest losses on the power lines, and it checks that the losses correlate with the load on the lines.

Checking grid losses in a metering grid area

Grid losses in the metering grid area are checked. In Statnett, there are 16 metering grid areas. The first step is to perform a completeness check of all the meters. Thereafter, the losses of the power line are checked.

Manglende verdier

Rjukan Stasjon Avgang	T2	T1	ST1	Kvilldal	Sylling	Balanse
Kode	H1755	H1757	L1750	Q1752	Q1753	tap
Time	07.09.11	07.09.11	07.09.11	07.09.11	07.09.11	
Time 1	-103,000	-103,200	0,000	521,500	-316,000	-0,700
Time 2	-103,400	-103,400	0,000	473,000	-266,500	-0,300
Time 3	-102,600	-102,600	0,000	489,500	-284,500	-0,200
Time 4	-103,600	-103,800	0,100	485,000	-278,500	-0,800
Time 5	-105,200	-105,200	0,000	489,000	-279,500	-0,900
Time 6	-104,600	-104,800	0,000	469,500	-260,500	-0,400
Time 7	-143,800	-144,000	0,000	470,000	-183,000	-0,800
Time 8	-153,800	[illegible]	0,000	404,000	-97,000	[illegible]
Time 9	-152,600	-50,000	0,100	294,500	10,500	102,500
Time 10	-155,400		0,000	327,500	-17,000	155,100
Time 11	-157,000	-100,000	0,000	288,500	25,000	56,500
Time 12	-154,600	-154,600	0,000	247,000	62,000	-0,200
Time 13	-156,600	-156,800	0,000	242,000	70,500	-0,900
Time 14	-150,000	-150,400	0,100	329,000	-29,500	-0,800
Time 15	-149,400	-149,400	0,000	353,500	-55,000	-0,300
Time 16	-150,400	-150,800	0,000	345,500	-45,000	-0,700
Time 17	-151,000	-151,000	0,000	321,000	-20,000	-1,000
Time 18	-151,200	-151,400	0,100	370,500	-68,500	-0,600
Time 19	-154,400	-154,600	0,000	445,000	-136,500	-0,500
Time 20	-157,400	-157,600	0,000	456,000	-141,500	-0,500
Time 21	-157,000	-157,200	0,000	462,500	-149,500	-1,200
Time 22	-154,600	-154,800	0,000	405,000	-96,500	-0,900
Time 23	-145,400	-145,600	0,100	394,500	-104,000	-0,400
Time 24	-110,400	-110,400	0,000	425,000	-205,000	-0,800
				Gjennomsnitt		12,521

Stipulerte verdier basert på stasjonsbalanse

Avgang	T2	T1	ST1	Kvilldal	Sylling	Balanse
Kode	H1755	H1757	L1750	Q1752	Q1753	Tap
Time	07.09.11	07.09.11	07.09.11	07.09.11	07.09.11	
Time 1	-103,000	-103,200	0,000	521,500	-316,000	-0,700
Time 2	-103,400	-103,400	0,000	473,000	-266,500	-0,300
Time 3	-102,600	-102,600	0,000	489,500	-284,500	-0,200
Time 4	-103,600	-103,800	0,100	485,000	-278,500	-0,800
Time 5	-105,200	-105,200	0,000	489,000	-279,500	-0,900
Time 6	-104,600	-104,800	0,000	469,500	-260,500	-0,400
Time 7	-143,800	-144,000	0,000	470,000	-183,000	-0,800
Time 8	-153,800	-154,000	0,000	404,000	-97,000	-0,800
Time 9	-152,600	-153,100	0,100	294,500	10,500	-0,600
Time 10	-155,400	-155,700	0,000	327,500	-17,000	-0,600
Time 11	-157,000	-157,100	0,000	288,500	25,000	-0,600
Time 12	-154,600	-154,600	0,000	247,000	62,000	-0,200
Time 13	-156,600	-156,800	0,000	242,000	70,500	-0,900
Time 14	-150,000	-150,400	0,100	329,000	-29,500	-0,800
Time 15	-149,400	-149,400	0,000	353,500	-55,000	-0,300
Time 16	-150,400	-150,800	0,000	345,500	-45,000	-0,700
Time 17	-151,000	-151,000	0,000	321,000	-20,000	-1,000
Time 18	-151,200	-151,400	0,100	370,500	-68,500	-0,500
Time 19	-154,400	-154,600	0,000	445,000	-136,500	-0,500
Time 20	-157,400	-157,600	0,000	456,000	-141,500	-0,500
Time 21	-157,000	-157,200	0,000	462,500	-149,500	-1,200
Time 22	-154,600	-154,800	0,000	405,000	-96,500	-0,900
Time 23	-145,400	-145,600	0,100	394,500	-104,000	-0,400
Time 24	-110,400	-110,400	0,000	425,000	-205,000	-0,800
				Gjennomsnitt		-0,642

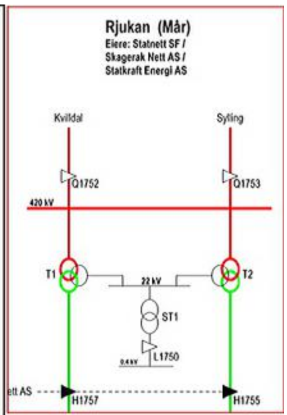
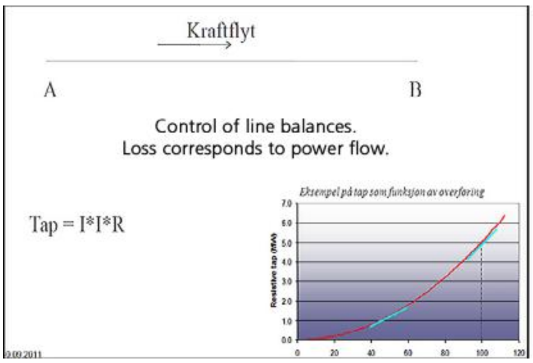


Figure 2: Substation metering balance



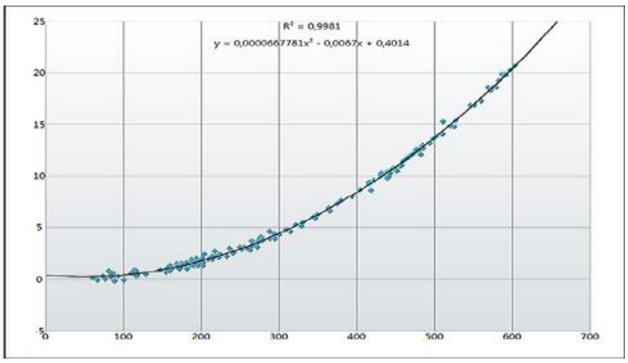


Figure 3: Power loss in power line

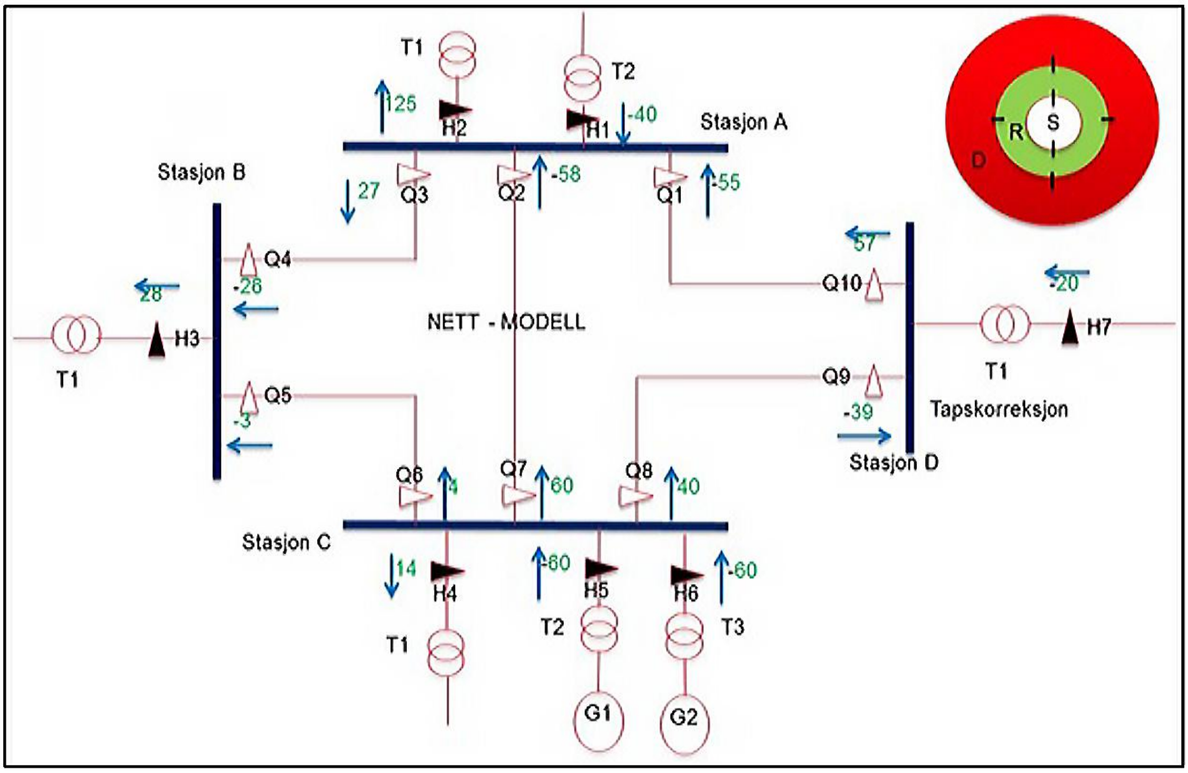


Figure 4: Grid loss in a metering area

Finally, the substation meter balance is checked in each area by comparing the total energy that has entered the grid with the total energy that has left the grid.

In Figure 4, the settlement meters are marked with H and the checking meters are marked with Q. Losses in this example = sum (H-meters) = -40+125+28+14-2*60-20 = 13 MWh

Further improvements?

There has been discussion about whether it is possible to detect minor discrepancies in substation metering balances with a high exchange load when there is a low load towards the customer metering point. One of the things that has been studied is the transformer metering balance. By providing an extra metering point it is possible to have a more accurate metering balance for the power transformer.

Statnett sees high exchange loads on power lines into the transmission grid at many of its 200 substations. Today's requirements states that they can have an error of 0.5 % so, if the exchange load is 400 MWh, an error of 2 MWh would still be considered acceptable. Minor discrepancies on one or even several of the meters on the power lines will not be easily detected in the power line balance check and will be included in the substation metering balance. The absolute loss might be higher than desired, and the substation metering balance is not always the best mechanism for detecting an error towards a customer metering point. Sometimes the load towards the customer is low and the load towards the transmission grid is high, as described in the next section.

Example of a metering balance today

Figure 5 shows a simplified substation. The average substation in Statnett has seven connections to the busbar. In this example, there are only two power line connections to the transmission grid. The power flow in power line 1 is 480 MWh but only 20 MWh goes through T1 to the customer, and only 0.1 MWh is used for the auxiliary supply for the control system of the substation. 458 MW is taken out from the busbar. The metered substation balance/loss in MWh is -480 + 458 + 20 + 0.1 = - 1.9 MWh.

Ideally, this balance should be closer to zero. The power flow from the transformer was 20 MWh, and the loss should have been lower. This discrepancy could be the result of one of the metering points on the power lines showing a minor error of 0.4 % which is within today's accepted deviation.

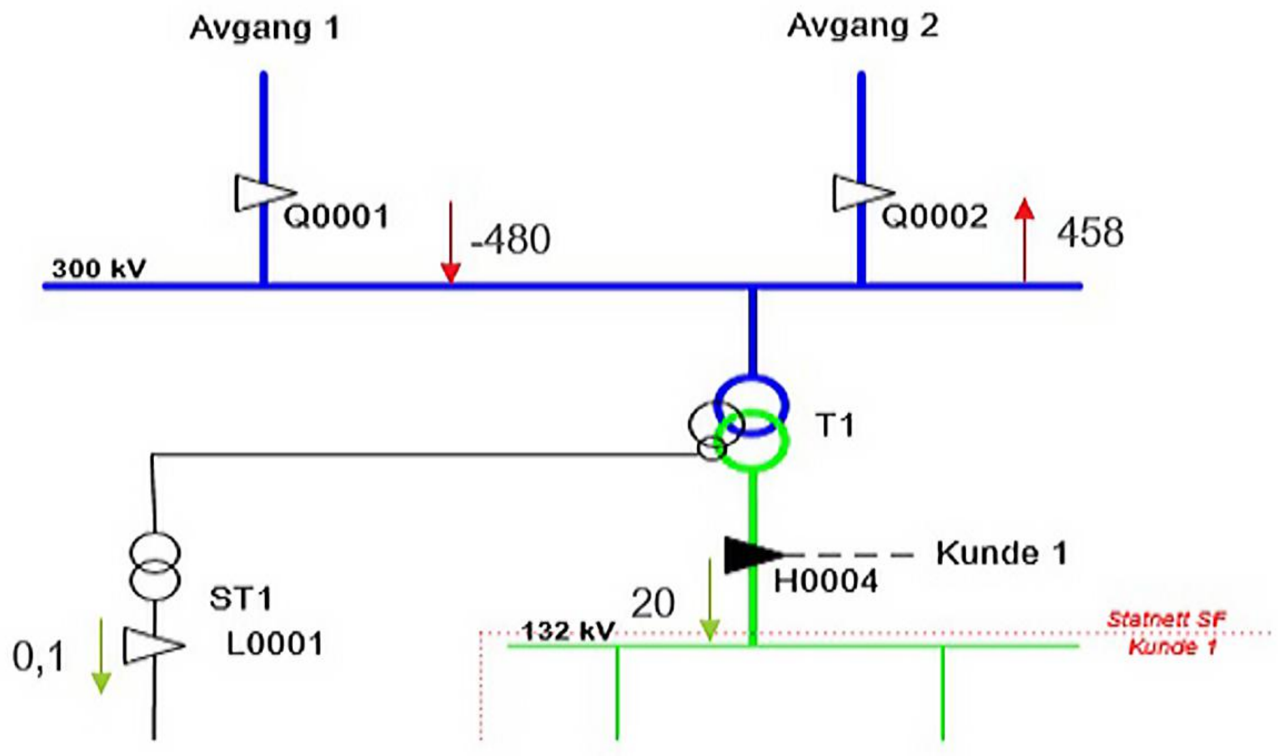


Figure 5: Metering balance example

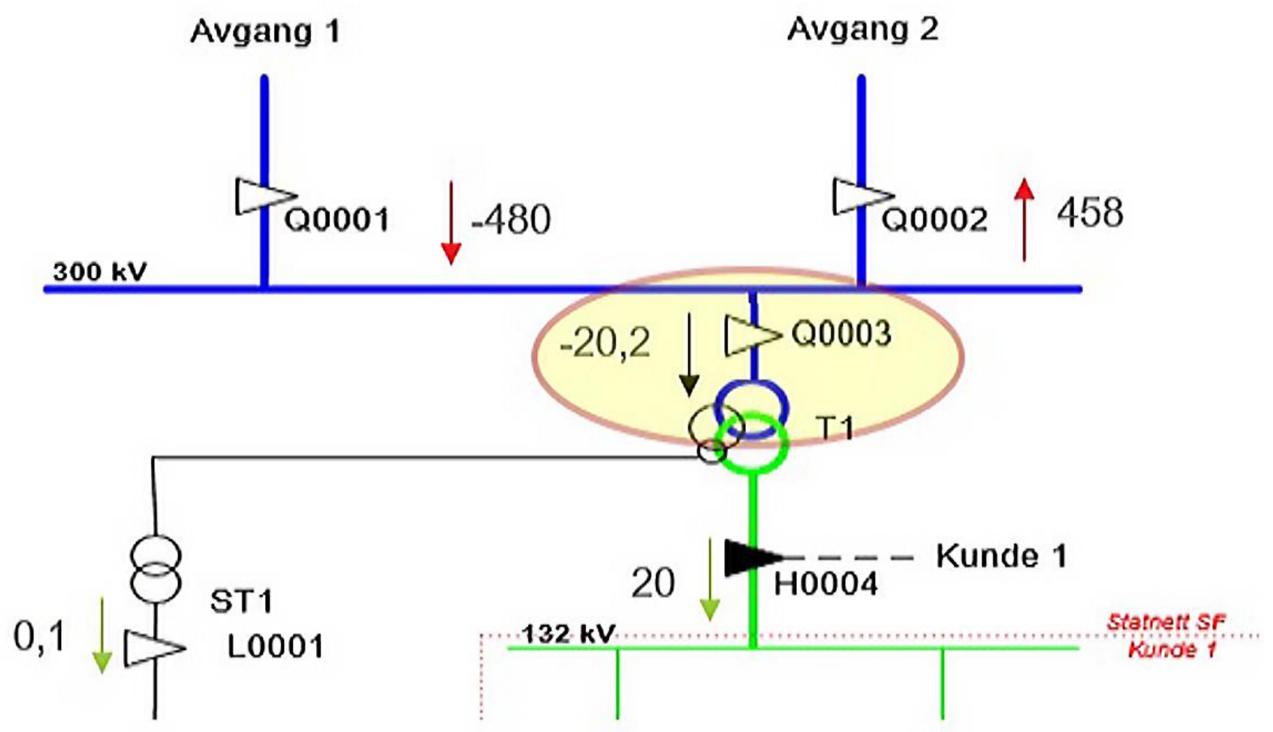


Figure 6: Improved metering balance example

Date\Time\Meter	Q0003	H0004	L0001	Loss/ Balance	Absolut Balance	Absolut value of the meters in the	Max accepted deviation of 0,4%	Margin between max accepted deviation and result of the test	
							=Absolut value*0,4%	Positiv result means that test was approved	
20.04.2020 01	-20,200	20,000	0,100	-0,100	0,100	40,3	0,16	0,06	0,06

It is accepted to use the average of margin metervalues for a day (24 hours).

Figure 7: Checking whether metering balance requirements are met

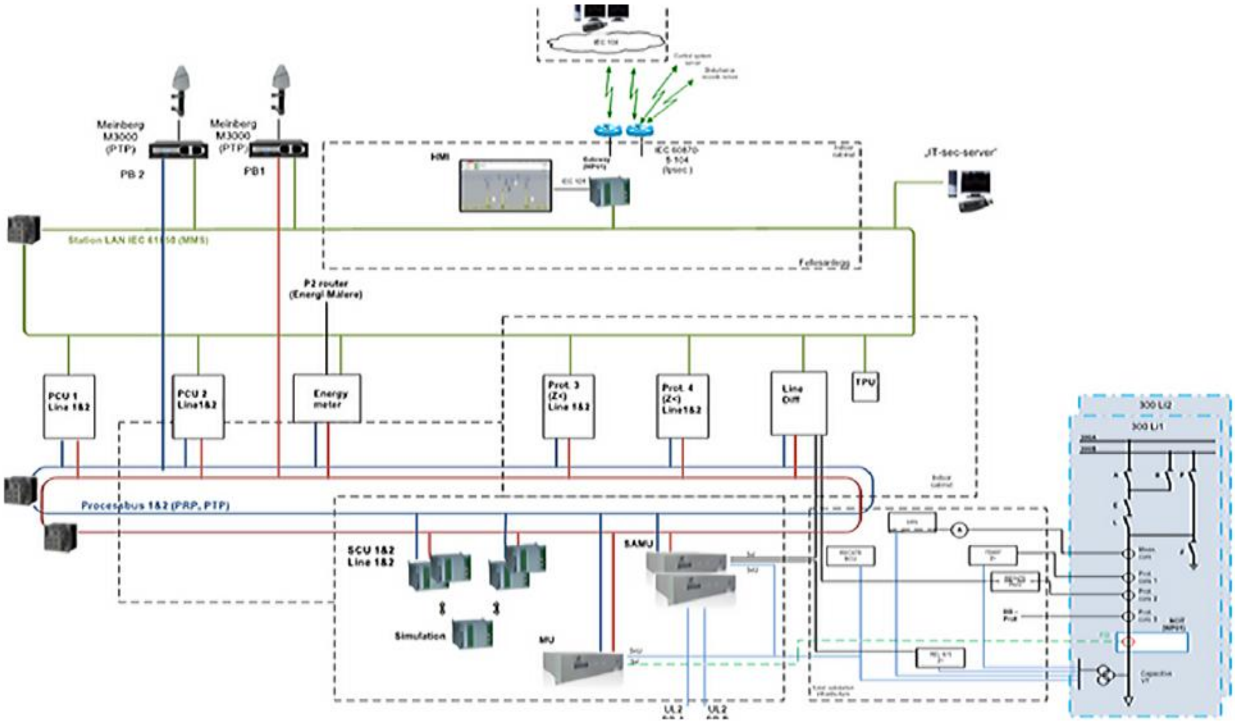


Figure 8: Configuration drawing for pilot project Furuset digital substation

Suggestion: Metering balance around the transformer in a digital substation

Figure 6 shows an improved metering balance system that requires one more metering point per transformer. There are metering points on both the primary and the secondary side of the transformer, which means that instrument transformers for current and voltage are needed on the primary and secondary side. In today's standard solution from Statnett, there is no instrument transformer for voltage on the primary side of the transformer.

The example in Figure 6 shows the following metering station balance/loss in MWh: -480 + 458 + 20 + 0.1 = -1.9 MWh. In addition, the balance around a transformer in MWh is: -20.2 + 20 + 0.1 = - 0.1 MWh

A suggested new requirement is that the maximum deviation for the whole metering balance should be within 0.4 % of the total absolute flow:

(Q0003+H0004+L0001) < (abs(Q0003) + abs(H0004) + abs(L0001)) *0.4%

This provides information about losses in the transformer and would be a stricter requirement than today's 0.5 % per metering point. At present, there are no set requirements for the station metering balance.

Example of checking whether requirements for metering balance are met

In Figure 7, the test requirement for metering balance is shown. It calculates the loss balance and absolute balance. In addition, it adds all the metering values to an absolute value of the meter in the substation. Based on

this value, the absolute maximum acceptable deviation is calculated along with the difference between maximum acceptable deviation and the actual test result. If the difference is positive – that is, if the maximum acceptable deviation is larger than the test result – the test was successful. In the example shown, the transformer metering balance must average a maximum of 0.16 MWh for a day for it to be acceptable. Today's substation metering balance (Figure 5) shows a loss of 1.9 MWh and is not that accurate. Transformer metering balance is more precise and can more easily detect discrepancies.

Transformer metering balance in digital substations

In Statnett, there have been discussions relating to the pilot project - Furuset digital substation - about how metering checking should be performed. In a digital substation, it is not possible to carry out the traditional checks in the substation because the hardwired connections to the meters have been replaced by optical fibres, and the metering values are based on Sampled Values instead of current and voltage measurements (see Figure 8 for a configuration drawing of the pilot project Furuset digital substation, where metering based on Sampled Values is implemented).

The IEC Committee 13, Working group 11 (IEC TC13 WG 11) has started discussions about an updated standard for metering that is applicable to digital substations where measurements are based on Sampled Values. This work will take some time to complete and Statnett would like to find an interim solution. A suggestion discussed in Statnett is using the substation metering balance to check the accuracy of the digital metering.

This idea will need to be thoroughly tested before it is implemented. Statnett will also have to consider future developments related to the calibration of digital metering chains. These solutions will make it possible to move into a new era and to update the technical requirements so that they accommodate substations where metering is based on Sampled Values from instrument transformers.

About the author

Rannveig S. J. Loken received her Bachelor of Science in Micro-electronics at Trondheim University College in 1990 and her Master of Science in Power Electric engineering from the Norwegian University of Science and Technology (NTNU) in 1992.

She works in Statnett, the TSO of Norway, and is the Project manager of the R&D Project Digital substation. She was the Head of Section for the Control and Protection system from 2007 until 2017.

She has been the Norwegian member for CIGRE SC B5 between 2008 and 2012, and has worked in several CIGRE working groups within SC B5. She was the secretary of CIGRE SC B5 from August 2012 until August 2018. In August 2018, she became the chair of CIGRE SC B5 Protection and Automation.

IEC 61850 GOOSE is fast, and it can help increase protection system security!

Andrea Bonetti,
Hongliang Zhu,
and Nikolay Ignatovski

E
T

Are protection relays fast enough when they receive GOOSE messages? And what about sending them? Are the Ethernet switches fast enough? Will GOOSE messages reach their destination? These are typical questions for which a large part of the protection community wants to have some answers before deciding to use the IEC 61850 standard for protection applications, instead of the sacred binary outputs and inputs. Answers to these questions have impact on the dependability of the protection system, which is its capability of clearing all power system faults. This is very important, because a failure to clear a power system fault often has a dangerous impact on the safety of people and of assets.

If there are many people still questioning the use of IEC 61850 for protection applications, however, there are many others that have simply gone and done it. Thanks to their experience, we have seen that GOOSE is fast enough, switches are fast enough, and faults are cleared as fast – or faster – than they were cleared with binary outputs and inputs. Isn't it time, therefore, to move on and start trying to do things better than before? Consider, for example, the effect that using GOOSE messages might have on the security of a protection system. Could GOOSE messages reduce the risk of unwanted trips? And looking beyond substations, thinking about a system of substations situated in different locations, we approach the concept of the Smart Grid with very interesting new applications of this simple concept, something that is not discussed nearly enough.

As we need to go through many concepts, some of which will be new to some readers, we have divided this article into three parts. The first part will provide the technical background for two important words in the power system protection community: dependability and security. The second part will explain a common problem of 'security' in relation to analogue protection systems (implemented with binary outputs and binary inputs). The third part will introduce the concept of IEC 61850 GOOSE messaging; it will provide a solution for the lack of security and will discuss several applications where similar solutions have been successfully implemented

Why are we writing this article?

Protection security is not a typical topic for technical articles or papers. When the authors started to discuss the need for writing such an article, the discussion quickly became lively! All the three authors have broad

> **...we have seen that GOOSE is fast enough, switches are fast enough, and faults are cleared as fast – or faster – than they were cleared with binary outputs and inputs.**

experience spanning many years in power system protection and have often faced the responsibility of explaining 'what has happened'. During the discussion about this article, this comment was made:

"Some weeks ago, a problem occurred in a substation which resulted in an unwanted trip. I ended up discussing precisely the situation we are talking about with my colleagues. Fortunately, unwanted trips don't happen very often, but when they do, the losses, the amount of undelivered power, and the number of consumers without electricity are significant. Unwanted trips lead to internal investigations, financial penalties, and many unpleasant discussions. I'm sure this is the case everywhere".

All the authors recognised the description as typical for these events, and the decision to write the article was made in the hope that it will avoid, or at least reduce, those unpleasant discussions. In addition, a peer-reviewed IEEE paper has recently been submitted [1].

The purpose of the protection system and the importance of its reliability

The purpose of the protection system, or more formally of the 'fault clearance system', is to [2]:

1) Detect power system faults and abnormalities
2) Identify the faulty section of the system
3) Interrupt the faulty electrical quantities, usually currents, as quickly as possible

Reliability is probably the most fundamental and important property of the protection system. It describes the capability (read probability) of the protection system

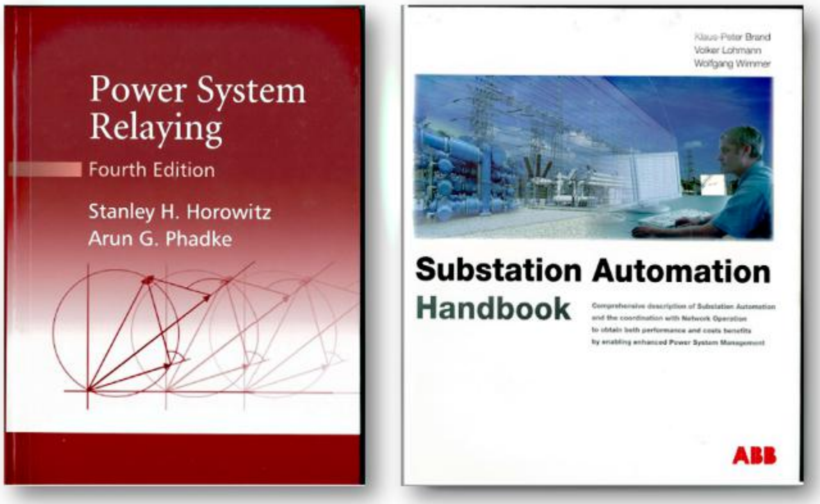


Figure 1: Two recommended books about power system protection that deal clearly with the concepts of protection dependability and security

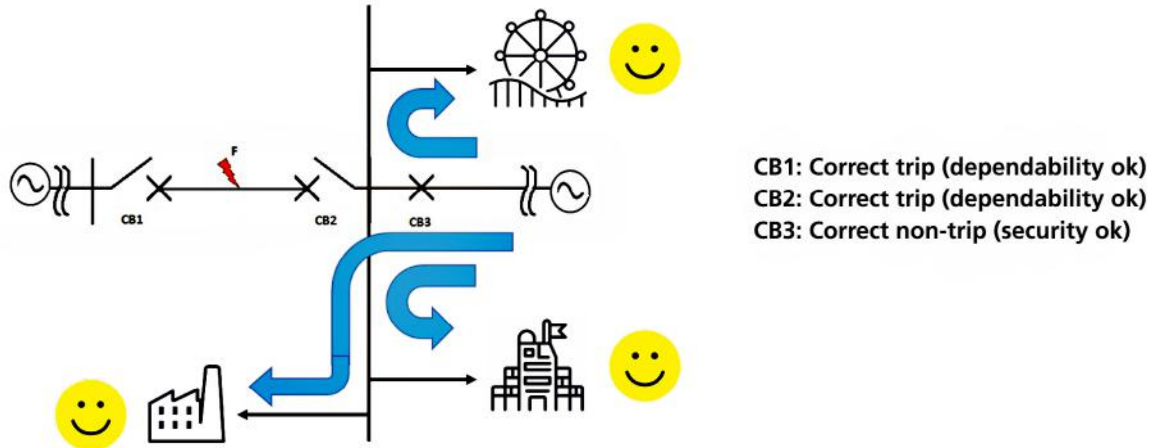


Figure 2: Correct selective elimination of a fault. Relays that were supposed to operate operated; relays that were not supposed to operate did not operate. Users connected to the busbar still received power from the right side of the power system

to perform its required function. It is the combined ability of not having a failure to operate and not having an unwanted operation. This last sentence may seem a bit odd, but it addresses the concepts of dependability and security of the protection system.

Protection dependability and protection security

Before going into further detail, it is necessary to have a clear understanding of two words that are used in a very specific way within the relay protection community: dependability and security. These two words are fundamental for a relay protection engineer. It has often been said that providing protection for a power system is the art of finding the best compromise between dependability and security.

These days, 'dependability' in relation to a protection system no longer generates confusion. It might seem to be a strange word but, once its meaning is understood, it doesn't generate misunderstandings. On the other hand, 'security' of a protection system is a source of many misunderstandings. This is mostly because it is today associated with 'cyber security', such as 'whether someone can tamper with the GOOSE message to change it', and questions like 'how secure is the GOOSE message?', meaning 'what is the probability that the GOOSE message will reach its destination?'. These are questions that concern the dependability of the protection system rather more than its security.

In addition, many books do not talk clearly about security and dependability of the protection system. They often talk about selectivity, which is actually a combination of security and dependability. The best books we've found that treat these concepts with a degree of formalism are Power System Relaying [2], which is an academic book, and Substation Automation Handbook [3], which takes a more industrial approach.

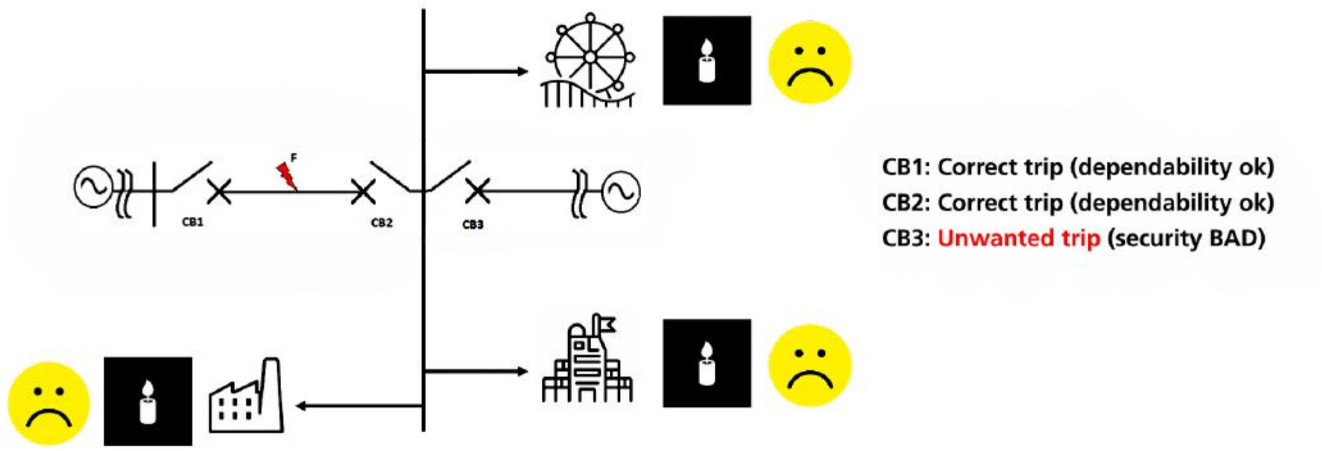


Figure 3: In this case, the fault has been cleared (correctly) by relays driving CB1 and CB2. The relays driving CB3 have misunderstood the situation and have tripped CB3. Users connected to the busbar between CB2 and CB3 have been blacked out by the unnecessary tripping of CB3.

> **Setting protection relays to provide a good global compromise between dependability and security is no easy task, and this is probably one of the main reasons for the large amount of respect the electrical community shows towards relay protection engineers.**

Formal definitions of these two words follow [3]:

- **Dependability** is the measure of certainty that the protection system will operate correctly for all the faults for which it is designed to operate
- **Security** is the measure of certainty that the protection system will not operate incorrectly for any fault

In power system protection, 'dependability' is the capability of a protection system to clear a power system fault if that fault is within its area of responsibility – the 'protected area'. Alternatively, dependability can be considered to refer to the probability of the protection system clearing such a fault. Lack of dependability can lead to a 'missed trip' or a 'delayed trip'. When this happens, a power transformer may burn or even explode – a situation that is likely to generate adverse publicity.

'Security' is the capability of the protection system to NOT operate if there is a power system fault that is NOT in the protected area. Security can also be seen as the probability of non-operation for such a fault. Additionally, security implies that the protection system will not operate if there is no power system fault at all. Lack of security can lead to an 'unwanted trip'. Often, lack of security means that power is disconnected in areas that are not affected by a fault. Once again, this is a situation that is likely to give rise to adverse publicity.

To become more familiar with these concepts, we will look at some simple schematic diagrams of power systems and examine how dependability and security are affected by the behaviour of the protection relays that control the circuit breakers. In Figure 2, we can see that there are three circuit breakers. The power line where the fault occurs is, by design, protected by CB1 and CB2. This means CB3 is protecting the part of the power system to the right of it.

The status of the circuit breakers after the fault indicate that the fault has been seen by CB1 (i.e., by the relays controlling CB1) as being within its area of responsibility. Similarly, CB2 (the relays controlling CB2) has recognised the fault as being within its area of responsibility. CB3 may or may not have seen the fault. If it has seen it, it has recognised that it is not in its area of responsibility and so has remained closed. The fault has been handled selectively: dependability for CB1 and CB2 was satisfactory; security for CB3 was satisfactory.

Not every situation is as well handled as this one. There are many reasons for this: errors in relay settings, errors in protection relays and, it must be admitted, the inherent impossibility of achieving perfect dependability and security at the same time. Protection relays do not have a full view of the situation, as most of their algorithms are based on local measurements of electrical quantities (voltages, currents, frequency etc). Information from local measurements alone is often not enough to allow perfect protection of a particular part of the power system, even if the measurements themselves are 100 % accurate. The result can look like what is shown in Figure 3.

Another common example of unwanted tripping is shown in Figure 4. Two parallel supply lines have been provided because it is very important that power flows

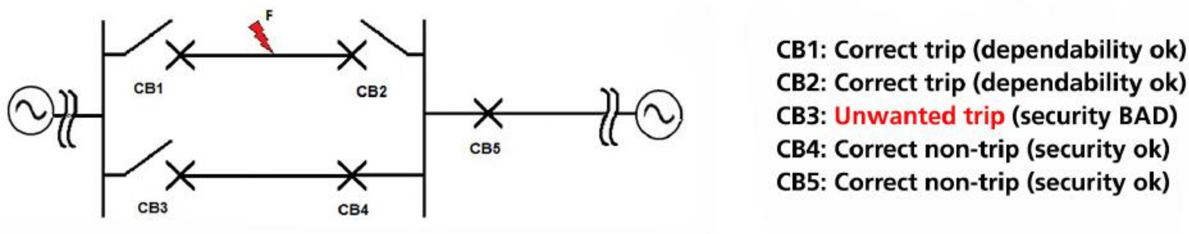


Figure 4: In this case, a simple 'unwanted trip' by CB3 stopped the end of power flow between the left and right part (probably weak) of the power system. The right part may not manage to supply the required load, leading to large frequency fluctuations, followed by possible load shedding

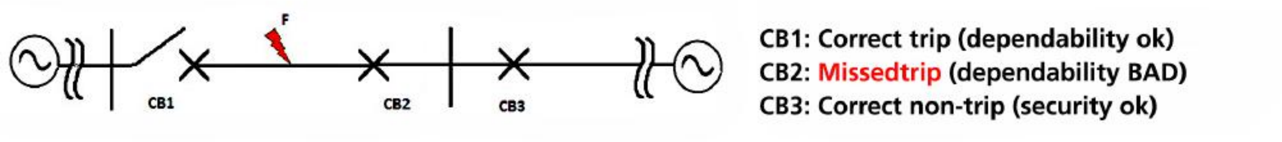


Figure 5: Even if it seems strange, CB3 behaved correctly (unless CB3 has been designated as a back-up for CB2)

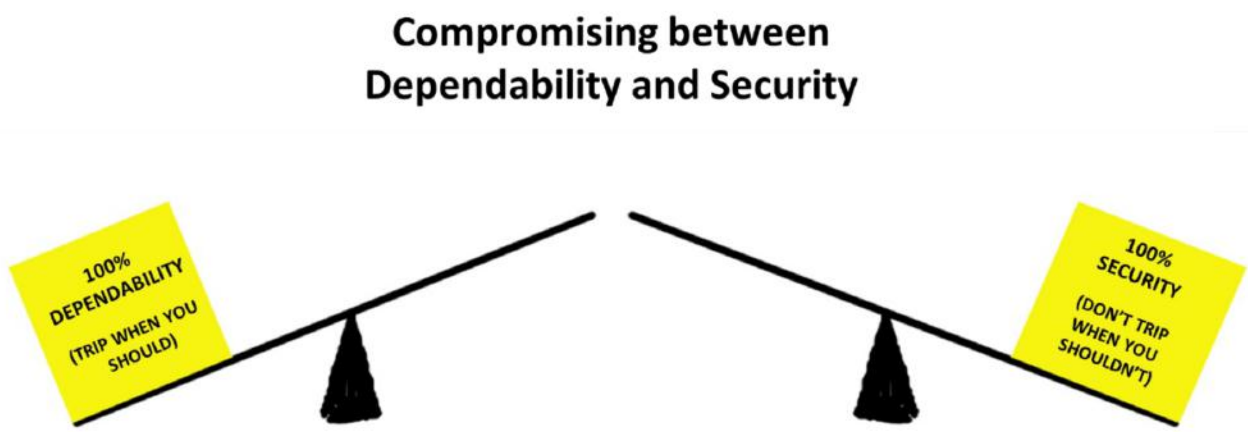


Figure 6: Another way to represent the compromise between dependability and security. A relay that's switched off will not trip for external faults, but neither will it trip for internal faults. We have 100 % security, but 0 % dependability. However, if we design the differential relay to trip for ANY difference between input and output currents, we have almost perfect dependability, but it will also trip for faults outside the protected area, so security is very low

from left to right in the system. If one line is affected by a fault, the second (parallel) line should ensure the continuity of power. Unfortunately, the fault is correctly cleared by CB1 and CB2, but CB3 also trips unnecessarily (typical reasons are current reversal phenomena, failure in the communication schemes etc. [4]). Note that usually in meshed networks, two circuit breakers are supposed to trip to eliminate the fault (CB1 and CB2) but only one of them tripping is enough to interrupt the power flow to the load.

If the power flow is interrupted and the right-hand part of the system is weak, even if CB5 is still closed the generation may not manage to sustain the necessary load. This means the power system frequency drops, causing the other breakers to be tripped by their underfrequency relays, or even triggering UFLS (underfrequency load shedding), which is a euphemistic explanation of why power has been interrupted [5].

The connection of a weak electrical system to a strong electrical system, with the frequency problems that arise when they are disconnected, is a topic that is often discussed in relation to today's power systems, where the mechanical inertia of a weak system is very low, or even zero, because the power is often generated by static inverters rather than rotating electromechanical machines [5]. The negative effect of unwanted trips is more evident in weak systems, and it is more necessary than ever to have methods for mitigating this phenomenon. In other words, an important contribution to keeping an electrical system interconnected is to find ways of increasing the security of the protection system.

Here is another example where those who are not protection specialists might be confused when considering the behaviour of the protection system. The situation is represented in Figure 5. With the fault in the position shown, CB1 operated correctly but CB2

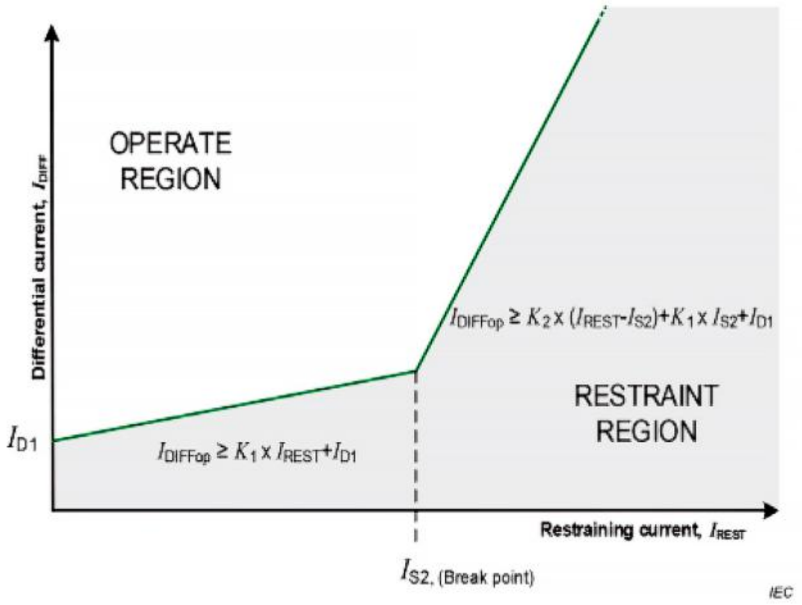


Figure 7: The so-called bias/delta characteristic, or more formally "restraint element characteristic", as shown in IEC 60255-187-1:2021 [4, p. 60255–187]. Courtesy of IEC, Copyright © IEC 2019

missed the fault (Relay switched off? Wrong settings? CT saturation? Wrong CT dimensioning?). The behaviour of CB3 is correct, if CB3 is not responsible for operating in the area protected by CB1 and CB2. The post-fault analysis should be focused on understanding why CB2 did not operate, instead of focusing on why CB3 didn't save the situation. If CB3 was not intended to operate in the area where the fault occurred, the behaviour of CB3 was correct. CB3 was 'secure', or 'stable' for the external fault.

A final example illustrates how protection dependability and security interact in differential protection. Creating dependable differential protection seems very easy; measure the currents entering the circuit to be protected and measure the currents leaving the circuit. If the difference is not zero, there is a fault, so trip! Whenever there is a fault in the protected region, the relay will trip, which means 100 % dependability. But that relay will probably also trip for a fault outside the protected region. It will probably also trip without any fault, just because of the load current flowing through the protected area. Why? Because of this sentence 'if the difference is NOT zero…'. What does 'zero' mean? What about CT errors? What about math errors in the algorithm? There are many 'what abouts'. So, in practice, that relay will have security (stability for external faults, or even for no faults at all) of 0 %!

The real challenge in the design of a differential protection relay is not its dependability, but its security. To go to the other extreme, to ensure the 100 % stability, we can simply switch off the relay. For sure, it will never trip for an external fault – that's 100 % security! But by doing this, we have destroyed the dependability – we are again facing the compromise between dependability and security.

How can we compromise between dependability and security for a differential protection relay? There are many ways of doing this but one of the most common is to implement a restrained or bias/delta characteristic. In simple terms, this means that the higher the current flowing in the protected area, the more differential current is needed for the relay to trip. The restraining or bias current is a measure of the current flowing in the protected area.

Intuitively, when the current flowing through the circuit to be protected grows, the measurement error grows, which is why more differential current is required. When more differential current is required, however, the sensitivity of the relay may be degraded (sensitivity affects the dependability because if the relay is not sensitive enough, it will not be able to detect a fault). There could be an internal fault with high fault resistance and a large through load current that increases the bias current and requires more differential current to trip. The restrained or bias/delta characteristic is detailed in the IEC 60255-187:1:2021 standard, "Measuring relays and protection equipment - Part 187-1: Functional requirements for differential protection" [6, p. 60255–187]. All rights reserved.

Designing a differential relay is not simple; in fact, designing any kind of protection relay is not simple. Also, setting protection relays to provide a good global compromise between dependability and security is no easy task, and this is probably one of the main reasons for the large amount of respect the electrical community shows towards relay protection engineers.

IMPORTANT NOTE!

The authors thank the International Electrotechnical Commission (IEC) for permission to reproduce information from its International Standards. All such extracts are copyright of IEC, Geneva, Switzerland. All rights reserved. Further information on the IEC is available from www.iec.ch. IEC has no responsibility for the placement and context in which the extracts and contents are reproduced by the authors, nor is IEC in any way responsible for the other content or accuracy thereof.

Online available: https://www.wiley.com/en-us/

About the authors:

Andrea Bonetti

Senior Specialist in power system protection and IEC 61850 applications, Megger, Sweden.

Andrea is a master science electrotechnical engineer from Sapienza University of Rome, Italy with the following work experience:

- 18 years of experience as HV power system protection specialist at HV relay protection manufacturer ABB Grid Automation Products in Västerås, Sweden, with IEC 61850 and conventional applications
- 6 years at Megger in Stockholm, as a product manager and technical specialist for relay test equipment and IEC 61850 test set and tools
- 5 years as a consultant in power system protection and IEC 61850 applications
- Holds a patent in the area of IEC 61850 testing tools and algorithms
- Is a member of the IEC TC 95/MT 4 and TC 95/WG 2, IEC committees for standardisation of protection functions and IEC 61850 application for protection
- Has received the IEC 1906 Award in 2013
- Is guest lecturer at KTH (Royal Institute of Technology, Stockholm) for IEC 61850 for Substation Automation applications, since 2008

Hongliang Zhu

Area Sales Manager – Hitachi Energy, Baden – Switzerland.

Hongliang, graduated from Xi'an university of Technology, China, with the following work experience:

- 5 years of experience as a substation automation, control, and protection commissioning and design engineer
- 10 years of experience in the bid and proposal and marketing sales area of substation automation, as well as the control and protection, and renewable business

Nikolay Ignatovski

Electricity System Operator (ESO) EAD - Independent Transmission Operator (ITO) of the Republic of Bulgaria.

Nikolay Ignatovski has an MSc degree in Electrical engineering - French department of Electrical Engineering, Technical University Sofia, Bulgaria and has the following work experience:

- 5 years of experience as a relay protection devices and automation engineer at "Power substations" dept., and 1 year as head of high/medium voltage distribution network analysis group at "Metropolitan Dispatching Center" of the Metropolitan Electricity Distribution company, "Electricity Distribution - Stolichno AD" (Member of ČEZ Group – Bulgaria since 2004), Sofia Republic of Bulgaria
- 9 years of experience as an engineer in automation - substation automation systems at the "National Dispatching Center", and 5 years of experience as an engineer in power transmission at the Electricity System Operator (ESO) EAD - Independent Transmission Operator (ITO) of the Republic of Bulgaria

REFERENCES

[1] A. Bonetti, H. Zhu, and N. Ignatovski, 'Use of IEC 61850 to increase the security of the protection system', in 2021 3rd Global Power, Energy and Communication Conference (GPECOM), Oct. 2021, pp. 220–226. doi: 10.1109/GPECOM52585.2021.9587715.

[2] 'Reliable fault clearance and back-up protection.', e-cigre. https://e-cigre.org/publication/140-reliable-fault-clearance-and-back-up-protection (accessed Nov. 15, 2021).

[3] Power System Relaying, 4th Edition | Wiley. Accessed: Jul. 13, 2021. [Online]. Available: https://www.wiley.com/en-us/Power+System+Relaying%2C+4th+Edition-p-9781118662007

[4] K.-P. Brand, V. Lohmann, and W. Wimmer, Substation Automation Handbook. Utility Automation Consulting Lohmann, 2003.

[5] A. Bonetti, J. Zakonjsek, and U. Rudez, 'Bringing ROCOF into spotlight in smart grids: new standardization and UFLS method', Oct. 2020. doi: 10.1109/GPECOM49333.2020.9248722.

[6] 'IEC 60255-187-1:2021 | IEC Webstore'. https://webstore.iec.ch/publication/32570 (accessed Nov. 02, 2021).

Watch our webinar on Protection relay testing using IEC61850 GOOSE by Megger

What became of Nikola Tesla's wireless dream?

Léonie Alvey

"When wireless is fully applied, the earth will be converted into a huge brain, capable of response in every one of its parts."

– Nikola Tesla

Over the years, we've written a lot about Nikola Tesla, of his inventions and of his life. However, we've only touched briefly on **his experiments at the Wardenclyffe Tower** and until now, have said nothing of what has happened to the site since it was abandoned. In fact, a great deal of work has gone into saving the site and drawing wider attention to it. But to fully explain what's happened, we must first revisit the site's history.

Why did Tesla build the tower?

Tesla had the revolutionary idea of creating a global, wireless communication and power transfer system. That is to say, he wanted to supply electricity to homes and businesses wirelessly, without the need of today's transmission and distribution grid. He saw the world itself as a source of 'free' energy and believed it possible to transmit electrical power through the Earth's upper atmosphere - he just needed to find a way of achieving this.

Tesla's ideas might seem far-fetched, and many in the scientific community considered them impossible, but experiments he had conducted at his Colorado Springs laboratory in 1899 had convinced him otherwise. He also had some success as he had previously managed to power three light bulbs from 30 m away without a wired connection. Unfortunately, he'd only been able to do this using near-field effects, meaning that the amount of energy transmitted decreased rapidly with increasing distance between the transmitter and receiver, making it unworkable over the large distances needed for wireless power distribution. It was this limitation that he needed to overcome to make his dream a reality and to do so, he needed to conduct larger experiments.

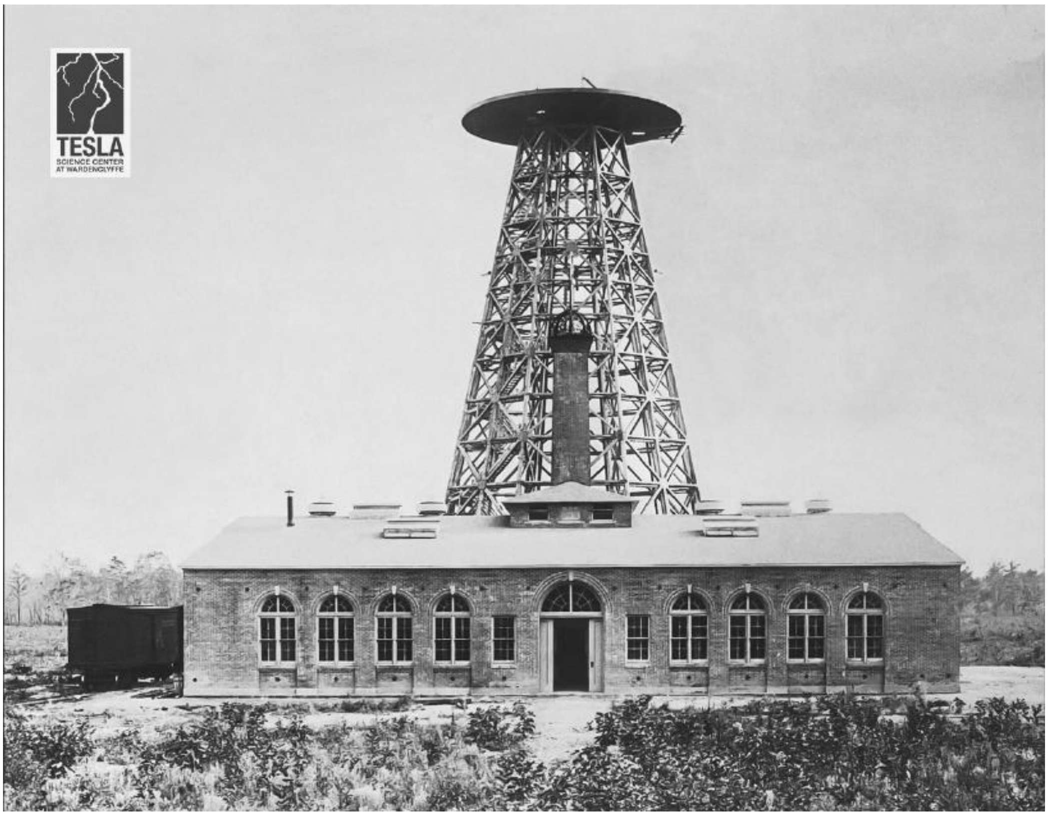
Seeing the potential in Tesla's ambitious ideas, in 1900 J P Morgan decided to back him with $150 000 (equivalent to about $5 million today). Tesla used this to commission celebrated architect Stanford White to build a red-brick laboratory on a 16-acre site in New York, along with a 187 ft wooden tower for the purpose of carrying out large-scale practical experiments that would hopefully lead to the invention of a wireless power and communication system. This would later be known as Wardenclyffe Tower. Indeed, the tower itself was intended to be a prototype broadcasting tower that would be able to broadcast music, news, reports, and even facsimile images anywhere in the world wirelessly, using the Earth as a conductor.

Sadly, Tesla would realise none of these ideas. His vision was greater than his wallet (and the patience of his patron) and he ran into financial problems before the laboratory was even finished. The construction of the tower itself consumed a huge amount of money and resources and, partly due to the 1900's economic crash, it became impossible for Tesla to get the funds he needed to finish the work. Ultimately, in 1917, the tower was dismantled and sold for scrap to pay off Tesla's debts, leaving the once revolutionary site a painful, empty reminder of his failed dream. However, not everything was removed from the site; the original red brick laboratory and the base of the tower still stand today, making it the only Tesla laboratory still in existence.

Saving Wardenclyffe

After the tower was sold, the site (including the laboratory) spent many decades being used by various companies until the last business left in 1987. The next 20 years saw the site unused and neglected until it piqued the interest of a science museum board from a local high school. The school museum was looking for a way to expand to accommodate its growing number of programs. Wardenclyffe, with its historical significance and close location, seemed like the ideal place to do this.

The museum board began by creating the Friends of Science East, Inc (FSE) with the aim of preserving Wardenclyffe and developing it into a science and education centre. Over the next few years, FSE raised awareness and gained financial support from a range of fraternal, civic, and business groups. It then began to conduct business as the Tesla Science Center at



Wardenclyffe Tower in the early 1900s, courtesy of TSCW

Wardenclyffe (TSCW), a non-profit organisation that had hopes of receiving the site as a donation.

However, in 2012 the site was put up for sale for $1.6 million by the company that owned it. They had a potential buyer who intended to use the site for retail purposes and was likely to tear down the laboratory. At this point, the TSCW needed financial support to save and preserve Tesla's legacy and one of its supporters, New York State, offered help. The State said that if TSCW could raise $850 000, it would match it, which would make it possible for TSCW to buy the site. Yet, even raising that amount of money would be a significant challenge.

The internet steps in

In August 2012, popular internet cartoonist and creator of the card game, 'Exploding Kittens', Matthew Inman (TheOatmeal.com), became aware of TSCW's fund-raising efforts. Having previously expressed his passion for Tesla in his comics, he wanted to help create America's first Tesla Museum, so he worked with TSCW to launch an online campaign to help raise funds. The original web page for this can still be viewed on theoatmeal.com/blog/tesla_museum.

With the help of Inman's large internet following, the campaign was a huge success and raised $1.37 million. What's more, Elon Musk, CEO of Tesla Motors, donated $1 million to the cause! In May 2013, TSCW at last succeeded in buying Wardenclyffe.

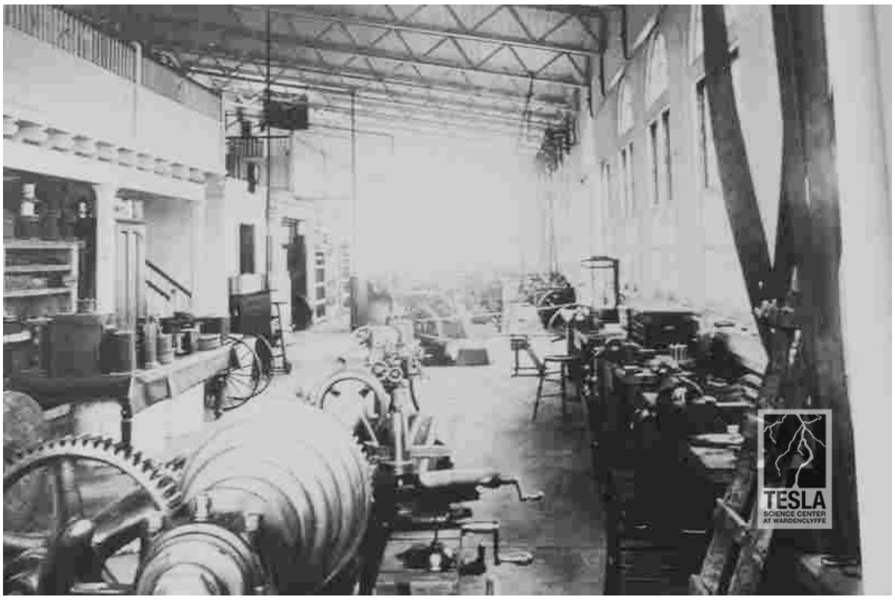
The restoration

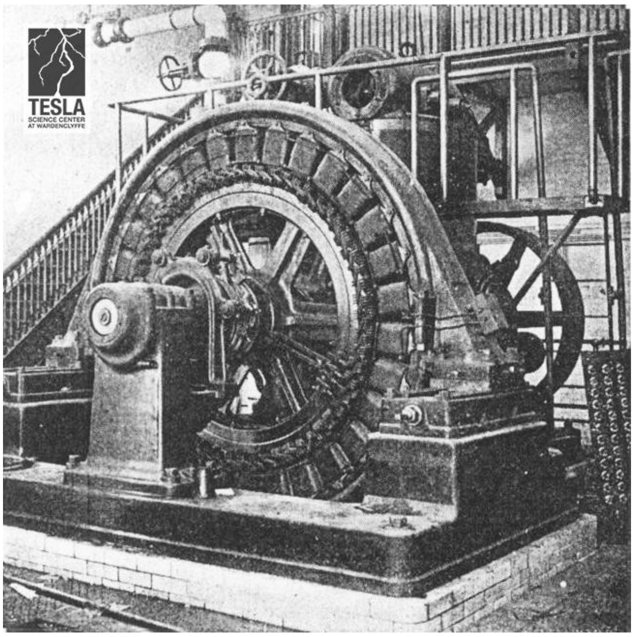
Once Wardenclyffe was safe in the hands of TSCW, the restoration and preservation work began. The site and buildings were secured and cleaned, and the grounds were cleared. Work was done to uncover the hidden parts of the tower base and to prepare for the erection of a Tesla statue, which was gifted to TSCW by the People's Republic of Serbia at a ceremony attended by over 300 people.

All this work was done by volunteers and their efforts were eventually recognised in the local press, where they were named People of the Year 2013. The work did not end there and over the next few years, TSCW continued to turn the site into an accessible campus and to remove dense and invasive vegetation. As a result, the lab and tower base are now visible from outside the perimeter fence and the TSCW headquarters are on site within the Wardenclyffe grounds.

The success of this restoration project finally got the property listed on the National Register of Historic Places in 2018. The site had been nominated for this listing many times over the course of its long history but failed to get it due to legal issues. The site's new status was a significant achievement for TSCW and recognises the historical significance of both its architecture and its relation to Tesla's work.

The most recent part of the ongoing restoration project was completed in 2020 and involved the chimney and





Early 1900s images from inside the laboratory, courtesy of TSCW

"As soon as completed, it will be possible for a businessman in New York to dictate instructions and have them instantly appear in type at his office in London or elsewhere. He will be able to call up, from his desk, and talk to any telephone subscriber on the globe, without any change whatever in the existing equipment. An inexpensive instrument, not bigger than a watch, will enable its bearer to hear anywhere, on sea or land, music or song, the speech of a political leader, the address of an eminent man of science, or the sermon of an eloquent clergyman, delivered in some other place, however distant. In the same manner any picture, character, drawing, or print can be transferred from one to another place. Millions of such instruments can be operated from but one plant of this kind. More important than all of this, however, will be the transmission of power, without wires, which will be shown on a scale large enough to carry conviction."

- Nikola Tesla, Wireless Telegraphy and Telephony magazine, 1908.

Of the many engineers and scientists who have dared to predict the future of technology few, if any, have been as successful as Nikola Tesla. That his final dream of transmitting power wirelessly remains unrealised cannot be seen as a failure – maybe he could see possibilities and solutions that are still closed off to the rest of us.

If he had had more funding, and lived a little longer, what new wonders might he have achieved?

A view from behind the laboratory, showing the tower in its entirety, courtesy of TSCW

cupola. The chimney needed emergency repair and during its restoration an arched brick opening was discovered at the base of the eastern chimney wall. This is an unusual feature that the TSCW is currently investigating with the help of experts in historic architecture and archaeology. However, this isn't the only interesting discovery the site has produced.

Tunnels under Wardenclyffe

There were rumours that Tesla built a series of four tunnels underneath the laboratory, as mentioned in some newspapers from the 1900s. In 2017, a television crew from the TV show 'Secrets of the Underground' used ground-penetrating radar to confirm the existence of these tunnels and even two potential rooms.

We interviewed TSCW's Chief Operating Officer, Douglas Borge, about these tunnels and he told us: *"There were four tunnels about 60 to 70 ft underground, three of which were 100 ft long and a fourth about 40 ft long. Above them were 'earth grippers' fanning out like spokes on a wheel. The North Tower ran parallel to a main thoroughfare known as Route 25, around 30 ft away from the base of the tower. Two tunnels crisscrossed underneath the tower and at the ends closest to Route 25, they attached to the front tunnel. The 40-ft long back tunnel attached to one of the back crossed tunnels on the east side. That short tunnel ran parallel to the front tunnel and moved inwards, west."*

The purpose of the tunnels is uncertain, and many theories have been put forward: they could act as drainage for the main building, or maybe they were designed to enhance the tower's connection with the earth, or maybe even to improve its resonance by interacting with the water table below the tower. They could even simply be paths to other buildings that weren't yet built.

When asked about this, Douglas Borge commented: *"We believe the tunnels were used to accommodate equipment for testing and experiments. It's a long way to climb six flights of stairs every time you want to do an experiment, so it could be possible Tesla's plan was to have them as staging areas. We are unsure of the purpose of the earth grippers, but they could have been used in part to map the interior of the Earth to look for precious metals and work on a global radar system. As far as we know, Tesla never wrote anything about the tunnels and earth grippers beyond what Marc J Seifer reported in his book* Wizard: The Life and Times of Nikolas Tesla. *If anyone comes across anything else about them, please let us know!"*

No further research appears to have been published on these tunnels and it seems that they have yet to be excavated. Borge explains: "*We can explore and excavate as much as we are allowed, but we face limitations from permitting and funding."* So, it is possible that the questions about these mysterious tunnels could be answered in the future.

What is Wardenclyffe like today?

Today, even though work on the site has not been completed, TSCW regularly holds events at Wardenclyffe. The site has become a landmark for the local area and is a popular tourist destination for dedicated Tesla fans.

A major demolition project is planned as part of the next phase of restoration, in which the surrounding dilapidated factory buildings will be removed. Additionally, a private donor has funded the construction of a visitor centre on

Wardenclyffe as it stands today, courtesy of TSCW

site, enabling TSCW to welcome more guests, provide historic tours, and pilot innovative STEM-based exhibits, education, and community events.

Asked about long-term plans for the site after it has been fully restored, Borge said: *"Tesla's historic lab is at the heart of the visitor experience. It will be renovated and reimagined to showcase his legacy and inventions. It will honour Tesla's life and work by telling his story accurately so future generations can fully understand this great man, the contributions he made to the world, and his ethos of innovation. The Tesla Lab Experience will attract visitors with interactive, immersive, and engaging exhibits and activities that merge history and storytelling with technology and innovation.*

Tesla's belief in the importance of invention will be demonstrated through cutting-edge, future-oriented science exhibits and public EdTech programming, both on-site and virtual. The focus will be on exploring the process of innovation and creating a collaborative laboratory environment to inspire emerging innovators of all ages from around the world.

Additionally, we will convene a global virtual network of incubators under the Tesla brand for start-ups in Tesla-inspired industries such as alternative energy, wireless, medical devices, and electronics. A business accelerator will hold innovation challenges, both on-site and virtually, aimed at solving social and corporate problems, and a maker space will be created to help train people on the tools needed to invent."

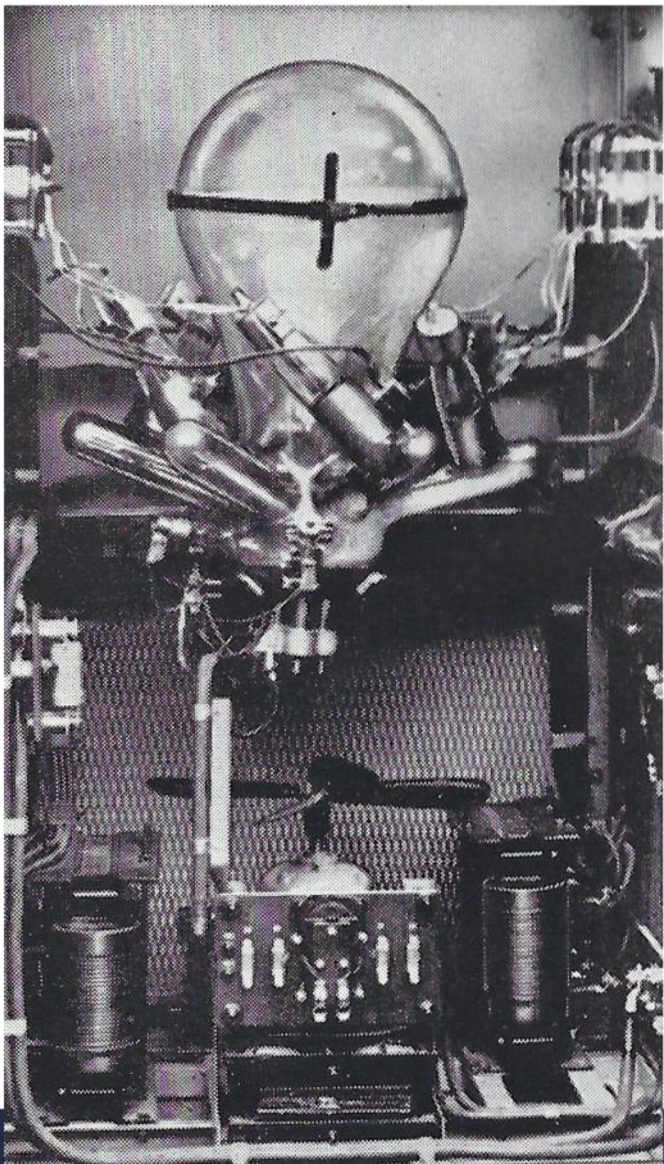
The TSCW continues to fundraise to restore the laboratory and its grounds. You can visit its official website at https://teslasciencecenter.org, where you can read the full history of the laboratory, get updates on the site's development, attend upcoming events held at the site and donate to the cause.

Nikola Tesla's statue outside the laboratory, courtesy of TSCW

Wardenclyffe Tower can be seen on the north side of Route 25A between the intersection of Randall Road and the Fire Department in Shoreham, Long Island, New York.

Geek Challenge IV

It's time for another of our popular geek challenges! This time it's one for the power engineers among you, and we're presenting you with just a single picture. The challenge is straightforward – all you need to do is to name the bulbous device in the top half of the picture and tell us what it was used for. If you can name it, you'll definitely know the answer to the second half of the question!



To give you some idea of scale, the device in question is around a metre high from top to bottom and, as an added clue, it doesn't have quite as many arms as an octopus. Until about the 1960s, these devices were very widely used in industry, but we'll say no more lest we make the challenge too easy! As usual, send your answers to electricaltester@megger.com.

A winner will be drawn at random from among the correct entries we receive, and we'll send them an Amazon gift voucher to the value of $50 USD, or the approximate equivalent in the currency of your country. The next two correct entries drawn will win a selection of Megger goodies such as mugs and the like, not test equipment - sorry! When it comes to deciding the winners, the editor's decision is final.

The closing date for entries is 30th January 2023.

Want to test your knowledge with the first Geek Challenge?

It is still online at: https://megger.com/promotion/geek-challenge

A global view of power transformer technology present and future

Dr Diego Robalino

Electrical energy, a fundamental component of human life today, has not yet become available to all societies. The need for technological growth to ensure safe and reliable energy provision is the subject of discussions globally but there are also major concerns about climate change and the effect of global warming. Certainly, it is almost impossible to envisage a perfect balance between technological growth and environmental protection, but all those involved in energy generation, transmission, distribution, and consumption have an active part to play in making life as sustainable as possible. The net effect of electrification depends most on future advances in the cost and efficiency of electric end-use technologies and their social impact.

The reliability of power systems is another global concern. The North American Electric Reliability Corporation (NERC) defines a reliable bulk power system as one that is "able to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity." NERC relies on a set of policies designed to support adequate operation of the grid to maintain a constant balance between supply and demand, as well as security to respond to and withstand sudden, unexpected disturbances, or unanticipated loss of system elements due to natural causes, as well as disturbances caused by man-made physical or cyber attacks.

The power grid is meant not only to be reliable but also safe and efficient. The grid is evolving to provide a more resilient and cleaner energy future where the methods of energy generation and distribution change and, therefore, electrical asset design and manufacturing evolve to match the current technological demand, thereby reducing losses and improving performance. Research and development, testing, and global co-operation are needed to encourage the assessment and adoption of new designs, technologies, and approaches that support this continuous evolution.

Power and distribution transformer technology

In the United States of America, the Office of Electricity manages the Transformer Resilience and Advanced Components (TRAC) Program to accelerate the modernisation of the grid by addressing challenges with large power transformers and other critical grid hardware. Interested readers are encouraged to visit the **Office of Electricity** website for more information.

The TRAC program looks after coordinated efforts to increase energy efficiency, improve operations, enhance asset utilisation and management, increase system resilience, and support increased domestic manufacturing.

TRAC envisions power transformers being flexible and adaptable for advanced applications in the future power grid. Objectivies include, but are not limited to:

- Cost comparable to conventional units
- Efficiency > 99 % at all levels of loading
- 25 % size/weight reduction
- Controllable impedance range 5 – 21 %

A flexible transformer can adapt to a range of voltage ratios and impedance levels, which leads to reduced manufacturing times and costs compared with today's transformers. One important benefit is that flexible transformers will be available to replace damaged transformers in days rather than months as it is at present.

The US Department of Energy (DOE) has regulated the energy efficiency level of low voltage dry-type distribution transformers since 2007 and has issued a new ruling on efficiency levels for low-voltage dry-type distribution transformers. The new efficiency levels, which came into effect on 1 January, 2016, are commonly referred to as the DOE 2016 Efficiency levels. Because of the new regulations, manufacturers have had to redesign their products to increase efficiency.

On 14 September, 2021, a new Federal Register was published by the DOE: 10 CFR Part 431 "Energy Conservation Program: Test Procedure for Distribution Transformers". This reports the technical analyses and results that support the evaluation of energy conservation standards for distribution transformers. Changes in test procedures are in-line with the changes in updated IEEE standards including C57.12.00-2015; C57.12.01-2020; C57.12.90-2015; C57.12.91-2020.

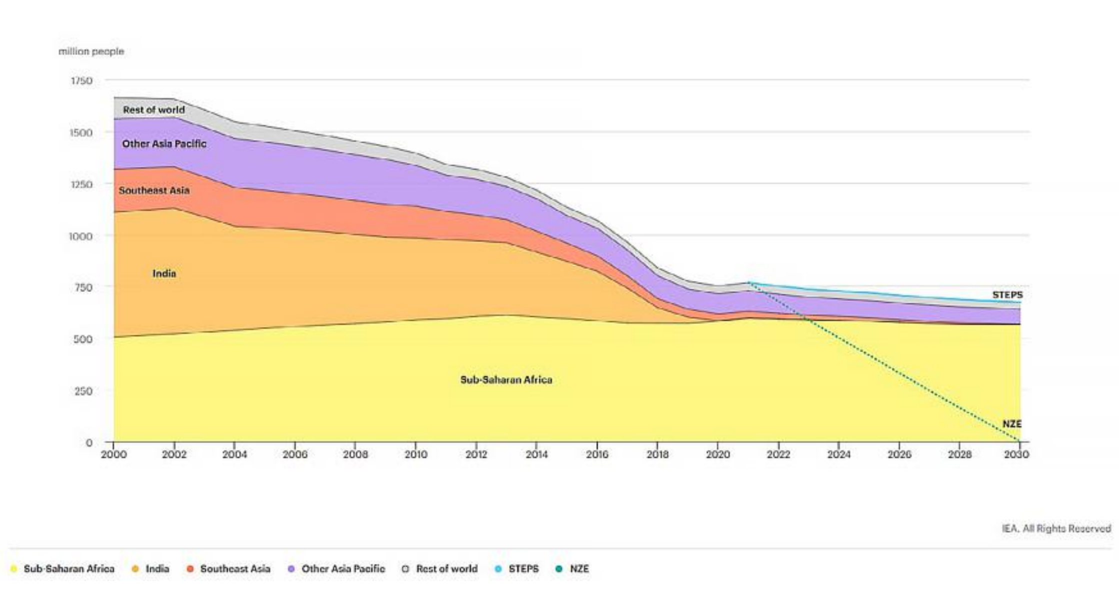


Figure 1: Population without access to electricity (source IEA [1])

Transformer efficiency is not only a current topic in the North American region. In July 2015, the minimum energy performance standard produced by CENELEC (the European Committee for Electrotechnical Standardization) specified maximum losses for both the core and the windings of distribution transformers and the minimum peak efficiency for power transformers.

Increases in distribution transformer efficiency are based on a reduction of losses, of which there are two principal varieties: no-load losses and load losses. No-load losses occur mostly in the transformer core, and for that reason, the terms 'no-load loss' and 'core loss' are sometimes interchanged. 'Load loss' arises mainly in the windings. Measures taken to reduce one type of loss typically increase the other type. Some examples of options to improve efficiency include: higher grade electrical core steels, different conductor types and materials, and adjustments to core and coil configurations.

Changes in design and construction are not easily implemented. For example, the use of amorphous steel presents a number of challenges. First, there are few suppliers: only one in the US, with international production in China, Japan, Germany, and South Korea. Second, the cost per pound of amorphous electrical steel is approximately 1.5 times that of a typical M3 grain-oriented electrical steel. As a result, amorphous cores have a very small penetration in the current market, with grain-oriented steel predominating in the manufacture of distribution transformers.

The application of distribution transformers varies significantly by type – liquid-immersed or dry – and ownership. Electric utilities own approximately 95 % of liquid-immersed distribution transformers, whereas commercial/industrial entities use mainly dry transformers.

Electrical energy, a fundamental component of human life today, has not yet become available to all societies.

The renewable energy market

The National Renewable Energy Laboratory (NREL) provides an analysis of the grid integration opportunities, challenges, and implications of renewable electricity generation for the US electric system. The NREL reports point to major factors in the energy consumption forecasts, which include:

- Vehicle electrification dominates incremental growth in annual electricity demand with the average electric vehicle being driven 12 to 14 thousand miles per year
- Addition of solar PV, supplying power to commercial and residential buildings, as well as to transportation systems

- **Changes in global climate are tending to increase the use of air conditioning and space heating**

As reported in the World Energy Outlook 2021 published by the International Energy Agency (IEA [1]), a new energy economy is emerging. It is not quite clear how the emerging process is going to evolve, but it will be different in many ways. PV and electric vehicle sales reached new records in 2020. Some of the studies presented in the IEEE Transformers Committee show loading is likely to increase by between 10 and 40 %. It is therefore important to consider a scenario where the average equivalent load is close to 50 % of the transformer's nameplate capacity, but the peak load may exceed 100 % of this capacity. One way of dealing with this potential load increase is by adopting an upgraded insulation system consisting of natural or synthetic ester fluids used in conjunction with thermally upgraded kraft paper.

To this evolution of the power grid and the integration of renewable sources, distributed generation, and microgrids, developments in power electronics are creating the possibility of solid-state transformers (SSTs). These promise to manage the highly variable, two-way flow of electricity between, say, a microgrid and the main grid. SSTs can be significantly smaller than an equivalent conventional transformer, about half the weight and a third of the volume, but there are limitations relating to cost and to voltage levels. Future research can be confidently expected to reveal more about SSTs.

Improved testing and diagnostics technologies

From time to time, new terminology appears which may sound quite daunting. For example, digitalised power transformers. In this context, digitalisation implies that sensors are embedded in the power transformer to continuously monitor its performance or condition. The sensors may support Dissolved Gas Analysis (DGA), temperature and moisture measurement, loading profile cooling control, and more. The objectives are to facilitate predictive asset management, minimise losses, and enhance efficiency.

The life of a power transformer is in reality the life of its insulation system. Due to their affordability and beneficial properties, cellulose-based materials are by far the most common type of solid insulation used in power transformers, often used in conjunction with insulating fluids. Made from pure cellulose, these materials have excellent electrical and oil impregnation characteristics, as well as good mechanical properties.

In relation to insulation materials, research objectives established by groups such as TRAC include:

- Dielectric strength > 300 V/mil
- Dielectric loss angle (tan delta) < 0.05 % at 60 Hz
- Enhanced material properties that remain stable over the useful life of assets (20 to 40 years)
- Temperature withstand > 130 °C in continuous operation

Testing is fundamental. More materials are now in the research and development pipeline and their behaviour must be well understood, not only by researchers, but also by end-users. In the last two decades, we have heard more about the use of ester fluids in power and distribution transformers. Transformers with solid insulation immersed in mineral oil represent the most significant fire safety hazard in electrical substations. Ester liquids however are less of a fire hazard than mineral oils, as they not only have higher flash and fire points but also lower net calorific value. By using a less flammable fluid than traditional oil as a coolant and dielectric insulator, the risks associated with potential transformer fires are significantly reduced.

In addition, synthetic and natural ester fluids are readily biodegradable, they show very low oral toxicity, and they are not classified as toxic to aquatic life. These factors may permit easier use in installations in sensitive environments such as water catchment areas and offshore wind farms.

Turning to solid insulation, high-temperature transformers are now quite common around the world. High-temperature insulation, including enamel and tape wrap for conductors, winding spacers, and mechanical support materials, is commonly used in mobile, locomotive, and rectifier transformers. These applications benefit from the lighter weight, improved reliability, and longer life offered by the use of high-temperature materials. For many years, these materials have also allowed manufacturers to provide solutions for repair applications and mobile transformers.

High-temperature transformers for traction applications have been produced for many years, but more recently, this technology has become increasingly common in pole-type distribution transformers and wind-turbine transformers. Those interested in the use of high-temperature insulating materials in power transformers are recommended to read IEC 60076-14.

Summary

Demand in emerging and developing economies remains on the growth trajectory that resumed in the second half of 2020, and it is likely that the projected strong economic recovery for China and India will further accelerate this trajectory. This means that reliability of supply and affordability of electricity are set to become even more critical in every aspects of people’s lives.

Solar PV and wind already represent rapidly evolving sources of new electricity generation. The renewable energy market, if it follows the plan towards the 2050 net-zero emissions scenario (NZE), will be much larger than today’s oil industry.

Research and development, testing, and global cooperation are needed to encourage the assessment and adoption of new designs, technologies, and approaches that support this continuous evolution.

Digitalisation, monitoring, and control of transformer performance are becoming more available and affordable. Predictive maintenance based on advanced data processing algorithms is enthusiastically progressing and the key concern is no longer how to handle the volume of data involved, but how to be confident in the quality of the data.

The introduction of new types of insulating fluids will help with the development of transformers to meet future requirements, but it can also be a challenge for the transformer industry when the behaviour of the new fluids is not fully understood. The performance of an insulating fluid is highly dependent on its chemistry and alternative insulating fluids such as esters behave differently from the well-known mineral oil.

Whatever the challenges, however, and irrespective of how the power grid evolves, one thing is certain: power transformers will continue to play a crucial role in transmission and distribution for years to come. As we have seen, even though transformers have been with us for almost a century and a half, progress in their design and construction continues apace, which means that the future is sure to bring developments that are both interesting and exciting.

REFERENCES

[1] IEA, Population without access to electricity in the Stated Policies and Net Zero by 2050 scenarios, 2000-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/population-without-access-to-electricity-in-the-stated-policies-and-net-zero-by-2050-scenarios-2000-2030

Stray currents in water pipes in a reverse osmosis (RO) plant

David Stockin,
E&S Grounding Solutions

This article has been contributed by David Stockin, President of E&S Grounding Solutions, a company with extensive expertise in the development, design, and implementation of grounding systems.

About reverse osmosis

Reverse osmosis (RO) water plants rely on high pressure and an electrochemical process, or more accurately, an electrochemical gradient, to clean and desalinate water. It's called an electrochemical process because it involves both chemistry and electricity. In this article, we will limit details of the process to say that too much electrical flow can not only interfere with the desalination and cleaning of the water, but can also increase the corrosion rates of the steel infrastructure at the plant.

A good rule of thumb regarding the use of seawater RO treatment to clean and desalinate water is that you will need a 480 V three-phase system supplying motors with an aggregate power rating of 300 hp (250 kW) to treat about 500 000 gallons (2 million litres) per day, which is around 20 000 gallons (80 000 litres) per hour. This treatment system, with a variable frequency drive (VFD), will draw between 400 and 450 A just to supply the pump motors!

The advantages of adding a VFD to an electric motor cannot be overstated. Not only can it improve electrical efficiency, it can provide programmable speed changes, improved torque ratings, soft starts, soft stops, smooth operations at lower speeds, improved consistency, higher braking torque, and many other benefits. But there is a downside to VFDs. While all electric motors generate some electrical noise and large electromagnetic fields that can induce unwanted currents into the surrounding steel infrastructure, VFDs are known to introduce additional objectionable resonant, harmonic, and switching frequencies into the electrical system.

Many of these objectionable frequencies will end up on the armature and shaft of the motor, which happens to be right where the impeller for the water pump is connected. This is the perfect place for stray currents to enter into the raw water side of the RO system.

There are many ways to reduce the electrical noise generated by VFDs, including the use of passive harmonic filters (a combination of reactors and capacitors), active harmonic filters, pulse width modulation (PWM) technology, isolation transformers, electromagnetic compatibility (EMC) filters, grounding bushings for motor shafts, isolated grounding electrodes, and more. This article will not examine the electrical engineering needed to reduce the impacts of a VFD, other than to say that if you are using VFDs, you probably have objectionable electrical noise, which means you should look into improving your grounding systems and using some sort of filtering technology.

Based on these factors, one might start to think that many water processing facilities seem to be almost intentionally designed to inject stray currents into the water being processed. Many folks know that clean water does not conduct electricity very well, but saltwater is highly conductive and 'raw' water – that is the water before it has passed through the treatment membranes – is typically also conductive. Once stray currents start flowing through the water, they must escape somewhere before the water becomes clean and non-conductive.

If that escape point is where the membranes are situated, these stray currents could interfere with the electrochemical processes occurring between the layers of the membranes, causing a loss of efficiency. If that escape point is only through the steel filter casings or steel piping, and currents are forced to travel great distances before they can find a path-to-ground, that longitudinal flow of current can dramatically increase the rate of corrosion on the steel structural members of the RO plant.

About grounding/earthing

There are generally two types of grounding or earthing systems: those that are designed to handle unwanted currents, and those that are designed to protect systems from those currents. Consider a high voltage electrical substation or lightning protection system; both are designed to handle objectionable electrical currents and safely conduct those currents to the earth. In these cases, we want to design a grounding system with lots of connections and parallel paths so that we can 'divide and conquer' the current. However, in the case of a sensitive electronic device inside a substation, we will only want to install single-point or 'isolated ground' connections to prevent objectionable currents from damaging the sensitive equipment. In the case of an RO plant, we want to divide and conquer the current with lots of connections from the steel components down to the earth.

Note: The term 'objectionable current' is often used by the National Electrical Code (NEC) to indicate normal neutral currents that return to the transformer via the grounding system rather than via the neutral wire. In this article, we are using the term more broadly for all kinds of stray currents, harmonic currents, switching currents, transient currents, etc. Similar concepts are employed in the various IEC standards in relation to earthing.

This might be a good time to cover a few basic principles:

First, electricity relies on the movement of free electrons and ions, which are contributed by atoms.. Where do we happen to have a lot of atoms? In the earth! So, if we have a well-designed grounding system, we can 'dump' objectionable currents into the earth to get rid of them by providing a conducting path for them.

Second, copper is 12 to 17 times more conductive than steel. Copper is also diamagnetic so the magnetic field can penetrate it to a depth some 250 to 6000 times greater than in steel, so high-frequency currents are conducted with less concentration on the surface of the conductor. This positive effect is multiplied at the high switching speeds and harmonics of VFD noise, making a direct ground system bond to the VFD an effective way of conducting objectionable currents directly to the earth and away from sensitive systems.

Third, the longitudinal flow of current on steel (and other metals) can increase the rate of corrosion. Providing an alternative and more conductive path to earth, in the form of copper, aluminum, or stainless-steel conductors, will help balance the difference in potential within the facility. It is one of the best ways to protect your facility from the hazards of objectionable currents.

So, what have we learned? First, it is very important to install electrical measures at the VFD to reduce the amount of objectionable and stray currents entering the water system during the initial pumping stage. Second, a sound well-bonded grounding system will remove the remaining currents, helping to improve the efficiency of the membranes and to reduce the rates of corrosion.

Testing grounding systems

How can we make measurements to see if we have stray currents in our water system? For this, the best tool is a Megger DET14C or DET24C Ground Resistance Clamp Tester. Similar functionality is provided by the DET2/3 and DET4 products with the so-called "stakeless" method, which uses two separate clamps. These instruments contain two transducing transformers capable of accurately measuring alternating currents as low as 0.5 mA. They can also measure resistance by inducing a test signal via one of the coils. The first coil is an active coil that injects a known test signal into whatever object is placed between its jaws. The second coil is a passive coil capable of measuring the return signal and any losses that may have occurred during its travels through the circuit, thereby allowing the instrument to calculate a resistance value for the circuit under test. We can use this instrument to test whether our RO plant has stray and objectionable currents.

There are several places around our facility where we will want to make measurements. First of all, let's measure current by setting the instrument in the ammeter mode (dial in the "A" position). In the current measuring mode, the active transducer is turned off, and the passive current transformer is turned on.

There are some key areas where we will want to make measurements:

- The Grounding Electrode Conductor (GEC) at the main electrical panel
- The GEC (X0) at the supply transformer, if possible
- The GEC to the main grounding electrode system
- The GEC, if installed, at the Variable Frequency Drive (VFD)
- The Equipment Grounding Conductor (EGC) going to the VFD

- All of the equipotential ground grid connections to the RO plant structural steel
- Any plastic water pipe you can clamp, especially on the raw water side

Megger DET14C and DET24C Ground Resistance Clamp Testers have a built-in automatic noise-current warning feature that will detect whether there is electrical noise (transients, harmonics, and other frequencies) on the circuit being tested. Make sure to note the current for each object tested and also whether or not the noise-current warning feature is activated. All of the measured currents should be less than 1 A, and they should ideally be less than 100 mA.

While it would be nearly impossible in this article to discuss all of the possible causes of higher currents, here are few examples:

- High current on the XO of the transformer – you could have an erroneous neutral-to-ground bond in a subpanel (see NEC 250.6)
- High current on the GEC or EGC of the VFD – you may need an electrical noise filtration device, as discussed earlier in this article
- High current on your grounding electrode or at the equipotential steel structural bonds – you may have an underrated grounding electrode system that is not capable of conducting the current load placed on it into the earth
- High current on your plastic water pipe – you could have stray currents in your water system

Resistance tests: practical examples

To conduct a few example tests, let's place our Megger DET14C or DET24C Ground Resistance Clamp Tester in resistance mode by setting the instrument in the ohmmeter mode (dial in the "Ω" position). As you will recall, this meter has two transducing transformers, one active and one passive. In resistance mode, both coils will be turned on; the active coil will induce a known signal into the conductor the meter is clamped around and the passive coil will read the returning signal to provide a resistance measurement up to the limitations of the instrument. If no signal is returned, the instrument will read open circuit (that is, a resistance higher than it can measure). With the instrument in resistance mode, we will want to measure the following items:

- The GEC to the main grounding electrode system
- The Equipment Grounding Conductor (EGC) going to the VFD
- All of the equipotential ground grid connections to the RO plant's structural steel

The expected results will vary greatly depending upon how the system was built, and which of the circuits we are measuring. Here are a few examples to help you evaluate your results:

- **CASE 1 – Loop**
  In some cases, when we clamp the meter around a conductor, the signal from the active transducer will travel through the conductive path of the loop back through the passive transducer, passing entirely through metal components. In this case, we are measuring 'continuity' (the resistance of an unknown metallic circuit) and we want to see a very low resistance, much less than 0.1 ohms. This confirms that there is at least one full set of conductive metallic paths (one loop) with effective bonds in that immediate area.
- **CASE 2 – Resistance-to-ground**
  In other cases, when we clamp the instrument around the conductor, the signal will travel down the conductor, through a grounding electrode, into and across the earth (which will present itself as a resistance), up another grounding electrode, then through a metallic path, thus completing the loop back to the instrument. In this case, we would expect to see a resistance of, say, 25 ohms and in some cases much more.
- **CASE 3 – Single-point or isolated ground**
  In yet another case, when we clamp the meter around the conductor, the signal will travel into a conductor that is bonded to an electrically floating object with no return path. Imagine a wood monopole with a single ground wire bonded to a metal box. In this case, we would expect the meter to return an open circuit reading, confirming that the connection is in fact single point. An ordinary ohmmeter with test leads should be used to confirm continuity back to the facility's grounding system in these cases.

In most instances in an RO plant scenario, we would want to see CASE 1 so we can confirm that continuity exists on our equipotential grounding system and that the bonds are in good condition.

E&S Grounding Solutions highly recommends using a site plan (map) of the facility and placing the results of the tests on the plan so that you can visually see where high current and/or bad resistance readings occur. Only then can you make an educated decision about how to fix any issues that have been found.

- Is your RO plant mostly composed of plastic piping and do you have stray currents in the water that are causing equipment failures and corrosion? Perhaps you need to install a short stretch of stainless steel pipe that is bonded to your grounding system so that your stray currents flowing through the water will have a path-to-ground that is not via the membrane filters.
- Does the grounding system tied to the VFD have high levels of noise and current on it? Perhaps you need an electronic filtering system and an improved Grounding Electrode Conductor (GEC) connection to your below-grade grounding electrode system.
- Do you seem to have higher than desired currents on just about everything you measured? Perhaps you need a better grounding electrode system and a good panel inspection to see if you have objectionable neutral currents traveling back to the transformer on your exposed conductive metallic parts (see NEC 250.6).

We spoke to Alan Davies, the President of HydroDynamic Solutions, a leading installer of industrial-grade reverse osmosis systems. He tells the story of a client who spends over $100 000 USD each year on water pump losses alone, due to stray currents in the RO plant raw water system. A nearby electrical substation owned by the utility company is believed to be the culprit as he has inspected his own system carefully. Stray currents from a 'leaky' transformer at the substation are believed to be entering the water supply and damaging his client's RO plant. He is currently investigating the use of a buried anti-EMI copper curtain to protect the plant from these hazards. Of course, what he really needs is for the utility company to replace the faulty electrical gear at the substation!

Conclusion

Stray electrical currents in water are a big problem for many people, not only in industry but also in the residential environment. Over the years, we have heard from numerous homeowners about stray currents coming up from the water main and into their home causing issues not only with the water pipes, but also with cable televisioin (CATV) systems, telephone systems, and more.

An electrical isolator on the incoming water main is typically a good idea as long as you're not using your water pipe as your main grounding electrode. (Note: you need a bond to your copper water pipe to your grounding system, however you really should use a dedicated grounding electrode as your fault current path, and not use your water pipe as an electrode). Measuring the currents in the water with a Megger DET14C or DET24C Ground Resistance Clamp Tester by clamping around a plastic water pipe can be a great way to quickly see if you have alternating currents travelling through the water supply (direct currents cannot be measured using such transducers).

A properly bonded water supply system that complies with the National Electrical Code (NEC) Article 250.52(A)(1), 250.53(D), 250.68(C), 250.104(A), and other industrial codes, is always a great starting point for reducing the impacts of electrochemical issues in your water system.

Q&A

Earth/Ground testing

It's a common expression that "the devil is in the detail" and this is especially true of electrical testing. Often, a technician or operator will familiarise themselves with a new field of testing, will learn the theory, the accepted procedures, and master the fundamentals until they fully understand how and why the test is done. Then, they'll acquire the correct

Q: Do I just run the leads out, push in the spikes, and run the test?

A: Yes and no. That would be convenient, but it doesn't always work. It might give you the correct reading, but you don't know. Ground testing is more procedure dependent than many other types of electrical testing. That's because the test item isn't a discrete object; you're making a connection to the planet. You may indeed be able to run the lead set provided out to full length, make a test, and get the right answer. But it's purely a matter of luck (test leads often conform to the 62 % rule, so you'll have a pretty good chance, but it's not a sure thing). You can't be confident in the result, and a client would never accept it. You could still be within the electrical field of the ground you're trying to test, there could be a water main or live buried cable right underneath the test probe, or any of numerous other deviations from the ideal. The standard test procedures that have been devised for the industry can sort out a bad test from a good one.

Q: How far do I extend the test leads?

A: There's no simple answer to this. It depends on the variables of the test site and can only be effectively determined by trial and error. Some standard procedures – but not all of them – have a built-in proof, and your chances of clearing the proof on the first test are enhanced by following a standard table that relates the size of the electrode under test (diagonal of a ground grid, length of a deep-driven rod, etc) to lead length. These tables occur quite frequently in the literature and their recommendations may vary. This is because they are practical, not scientific. If you don't have the working space (remember, this can easily be hundreds of yards for large grids), it doesn't mean you can't test. Work within the available space and if you've followed a rigorous procedure and the results seem reasonable, all's good.

Q: What is meant by proofing a test result?

A: Numerous test procedures have been devised by field operators over the years to meet different objectives. Some are meant to overcome difficult physical conditions, some to save time, and some to provide assurance about the accuracy and reliability of the measurement. Be sure to understand the purpose of the procedure and which of these objectives it is meant to address. The most basic, accepted, and reliable of all procedures, fall of potential, provides a graph of measurements versus distance. This graph will clearly distinguish between a poorly conceived or executed test and a well-spaced and well-performed one. Other procedures use mathematics to weed out bad results. The math exercise tells the operator the accuracy of the reading and therefore its reliability. In worst-case instances, the mathematics may not calculate at all.

Q: How deep do I drive the probes?

A: Like alligator clips in more common test procedures, metal spikes provide the connection needed to execute the test. For ground tests, the connection is with the earth. It is generally not necessary to pound the probes in as far as they will go. Exceptions do exist, mainly in poor grounding soil, but in most instances, probes can be pushed in by hand. Modern testers require only minimal amounts of current and voltage to make highly accurate measurements. What's more, a quality tester will have indicators that tell the operator if there is any problem with the probes. Pounding probes all the way in is extra work and can also be a hazard to one's back and knees when pulling them out.

Q: If the probe contact is inadequate, what can I do?

A: In the 'old days', operators had to rely much more on experience and intuition in diagnosing problems when test results were questionable. There was a lot of educated guesswork. As explained above, modern testers tell you what's wrong. But it's easy to focus on those big digits – or on where they should be – and overlook the small details around the edge of the display. Always scan the whole display for potential issues. Indicators will typically tell you, for example, if the test probes aren't making sufficient contact with the soil. This is more likely to be an issue with the current probe, as it must inject the test current, but it could be with the voltage probe – or both. Probe resistance should never defeat your test. Quality testers can tolerate thousands of ohms in the test circuit. If the resistance between the probe and surrounding soil does go over limit, just reduce it by pounding the probes in deeper, tamping the soil, or possibly adding water. Remember, you are not falsifying or rigging the test by adding water to the probes. The test does not measure the resistance of the probes; it measures the test ground. If you were to water the ground rod that you're trying to measure rather than the probe, then you would be influencing the result.

Q: What about testing in a noisy environment?

A: In the 'old days', when you couldn't get the pointer to stop swinging, you averaged the swings. It's better now. Modern testers have several weapons against noise, instruments, read the instruction manuals and head out into the field to set up the test and - oops! Something unanticipated and unexplained stops the testing or creates an ambiguity that undermines confidence in the results. Answers are needed, and in this issue we look at the most commonly asked questions about earth/ground testing in the field.

Q&A

including filtering, higher test currents, and frequency adjustment. Quality testers will tell you when there is noise, so that you know what the issue is and are therefore in a better position to address it. Some testers automatically initiate corrective measures, some leave it to the operator, and some do both. Note that there are noise threats from both above and below; that is to say, air and ground. Testers are better equipped against ground noise, which is mostly composed of wandering currents trying to get back to the utility source. But don't forget that noise sources can be overhead, as from power lines, and these can be more difficult to suppress. Definitely don't run test leads parallel to power lines; try to run them at right angles if possible. Snaking leads instead of having them running parallel to each other helps, as does the use of shielded leads.

Q: Does the facility have to be de-energised during testing?

A: No. You don't have to shut down a whole switchyard in order to test! Modern testers use so little current (a couple milliamps) and such low voltage (less than 50 V) that they do not trip protective devices or damage loads.

Q: Can ground testers/testing be dangerous?

A: No and yes. There is nothing about ground testing itself that is inherently dangerous, nor are the testers. In the 'old days', yes. Higher voltages and currents were used in bygone times. Modern quality testers, with microprocessor calculation, do not require so much power and so it is not used. Be aware, though, that equipment for specialty applications – deep prospecting for oil, minerals, geologic layers, and so forth – does need higher power and so such specialty instrumentation may require an extra level of awareness and caution.

Q: But what about the test item?

A: Aha! As in much of electrical testing, that's another story. We can make testers and procedures infinitely safe, but they still get connected to potentially faulty equipment and circuitry. For ground testing, the risk is that of an 'event' occurring in the utility or on the premises while the test is in progress. The chances of this are rather remote, but still, play it safe and follow industry standard safe-working practices and employ personal protective equipment like gloves, boots, and mats. In addition, note that substantial current may be flowing on the grounding conductor even when an 'event' is not occurring. This originates from unbalanced loads and wiring shortfalls. There usually isn't enough voltage to be a risk, but there have been exceptions. It is a good idea to always have a clamp-on ammeter and check the ground current before testing starts.

Q: Do I have to lift the utility ground?

A: Yes. Usually, the on-site ground is paralleled with the utility ground feeding the site by a jumper from ground bus to neutral bus at the service. A perfectly good test can be run without lifting the jumper and you'll get a perfectly good measurement, but it is of the entire system, not just the on-site. You can lift the jumper long enough to run the test, but this leaves the facility unprotected, however briefly. A temporary ground can be installed, but that still leaves the physical hassle of breaking the connection, which is often a welded jumper. Some testers include a current clamp that can separate test current going to ground on-site from that going back to the utility, and the tester make its calculation only on the on-site current. This solution doesn't always work, as the utility ground resistance may be so low that it hogs nearly all the test current, but this solution does provide a viable option in many cases.

Q: Speaking of clamps, my clamp-on ground tester keeps reading over-range or open; is something wrong?

A: Probably not. When a clamp-on ground tester reads open circuit, you are probably trying to measure an open circuit! For the clamp-on technique to work, there must be a path that the test current induced by the clamp onto the rod can find to complete the circuit. If you're clamping over an isolated ground, such as one just installed on a site not yet connected to the utility, this type of tester cannot be used.

Q: My clamp-on ground tester keeps reading impractically low measurements; is something wrong?

A Probably not with the tester. Unlike a traditional lead-and-probe tester, where the operator is in complete control by probe placement, the clamp-on controls the test. It induces a current onto the clamped rod, and that current finds its own way back. The operator has nothing to do with it. If the readings are suspiciously low – a tenth or two of an ohm – the current has probably found an alternative path through metal, not the earth. Examine the circuit. The tester is likely to be reading continuity, not earth resistance.

Don't let lack of knowledge make you a victim of sloppy work. Ground testing requires more technique and operator involvement than many more familiar types of electrical test. Make sure you can dot the i's and cross the t's.

IEC 61850, digital substations, and the Smart Grid

Niclas Wetterstrand
and Andrea Bonetti

Niclas Wetterstrand

Andrea Bonetti

IEC 61850 was launched in 2003 as a standard for digital substations and it is widely used in such applications. In principle, however, the Smart Grid is just a regionally distributed system of electrical substations, so IEC 61850 is also very relevant to the Smart Grid and, in fact, the IEC has designated it as one of the core smart grid standards.

To find out what Megger is doing in relation to IEC 61850, Electrical Tester arranged for Niclas Wetterstrand, Megger's industry director for protection, to talk to Andrea Bonetti, the senior specialist for relay protection and IEC 61850 in Megger Sweden.

NICLAS: How long has Megger been working with digital substations and the smart grid?

ANDREA: Megger has a long history of work relating to IEC 61850. We started in 2008 with the development of the GOOSER and the MGC (Megger GOOSE Configurator) for which we were granted a patent for some key pioneering concepts such as the comparison of network data with engineering data (SCL), and the secure access point that prevented connecting a PC to the communication network of the substation. GOOSER was first marketed in 2009 and is now discontinued. Its functionality is however embedded in relay test sets in our SMRT and FREJA 5xx ranges. For process bus applications (Sampled Values), we implemented IEC 61850-9-2 LE (Light Edition) in 2010, when we participated in a commissioning project in Central America. Over the years, IEC 61850 has progressed from Edition 1 to Edition 2, and now to Edition 2.1 (which isn't really an all-encompassing new edition – **something I explained to ET readers in the first issue of this magazine**). At Megger, our job is to follow the standard and to incorporate the new concepts in our hardware and software tools.

N: I have heard a lot of discussion about the KEMA certificate. Can you explain what it is and how it relates to Megger products?

A: The so-called "KEMA certificate" for IEC 61850 is actually a test report from an accredited test institute – in this case KEMA (CESI today), although there are others. The certificate confirms a certain level of compliance with the IEC 61850 standard in terms of interoperability and, as it is produced by an independent accredited test institute, it is known as a 'Level A' certificate.

A: 'Level B' certificate also confirms interoperability, but it is released by a non-independent accredited institute, for example, the Hitachi Energy IEC 61850 laboratories in Switzerland. It is a common practice to perform the tests for the first release of a product at Level A, and subsequent small adjustments or improvements at Level B. Megger has 'Level A KEMA' certificates for GOOSE and Sampled Values.

It is widely known that the certificates alone do not fully ensure interoperability. Additional tests and a good specification from the end user are needed if an IEC 61850 project is to run smoothly. Certification is a minimum requirement which shows that the

The three pillars of the IEC 61850 are:

- **Standard signal lists**
  (modelling and signal modes →information models)
- **Standard information exchange**
  (services and protocols)
- **Standard system engineering**
  (system engineering and device configuration)

manufacturer has done what it reasonably can to provide a reliable IEC 61850 product or tool.

N: You have mentioned GOOSE and Sampled Values. Would it be correct to say that IEC 61850 is a new protocol or a new series of communication protocols?

A: This is probably the most common question about IEC 61850, and the simple answer is that it is much more than a series of protocols. IEC 61850 is built on three pillars: the Standard Signal List, Standard Information Exchange, and Standard System Engineering.

N: From what we've discussed so far, I would expect GOOSE and Sampled Values to be part of the Standard Information Exchange. Can you give some examples for the other two pillars and how they relate to each other?

A: You are right, the standardised protocols are part of the Standard Information Exchange. Before we move on, however, there are a few more things we need to consider.

The Standard Signal List provides a standardised approach for modelling the system, the equipment, and the signals associated with the system and equipment. It does this by defining 'elementary functions' called Logical Nodes (LN) along with their signals, which are Data Objects (DOs) and Data Attributes (DAs), and their descriptions, in System Configuration Language (SCL).

A key idea is that if we have a master SCL file describing the system, it also describes the data traffic through it.

Another important idea is that we can consider the SCL file as being the fingerprint of the communication in the substation.

N: What's the benefit of having the three pillars instead of a simple data communication protocol?

A: I have to admit, we've been asking the same question for many years! The answer is that the three-pillar concept is incredibly robust and future proof. Some people have even described it as beautiful! To understand its benefits, however, some examples are needed.

Let's go back to the SCL file which, as I said, can be considered as a description of the system and of the data traffic through it. If we can detect and measure this data traffic with a tool – which is sometimes called data sniffing – we can compare it with the master SCL description and if there are differences, we can give warnings. This idea initially came about because of the need to identify interoperability problems in substations. We won't go into this in detail, but it is still used in this way. Another possibility, as we have already said, is to consider the SCL file as the fingerprint of the communication in the substation.

For perspective, I gave a **keynote presentation** about these concepts at IEEE GPECOM in 2020. In one hour of presentation, I think I mentioned the communication protocols for a mere few minutes!

Video of the presentation available here

PDF Presentation available here

N: **Interesting, but this isn't really relay testing, is it?**

A: No, it's beyond relay testing! The standard, thanks to its three-pillar structure, opens a whole range of possibilities that are just waiting to be developed. One that Megger has been working on since early 2009, is the comparison of the data model, described by the standard, with the actual data traffic, in the form of GOOSE messages, in the substation. Once again, for this pioneering concept, Megger has been granted the patent.

This is possible because the IEC 61850 is much more than a standard about protocols: it provides a way to describe the electrical system. This description is formalised in the SCL language and is ultimately available in the SCL files. Megger has patented some related algorithms that allow comparison of SCL GOOSE with network GOOSE messages. As the SCL file is a fingerprint of the communication in the substation, the idea is to periodically compare the actual communication with the master (reference) fingerprint. Such a comparison provides an excellent basis for developing automatic maintenance routines. Several papers have been written by Megger on these concepts; also, Megger has contributed to the Royal Engineering School of Stockholm (KTH) for an important thesis on the same subjects.

Paper 1 available here
Paper 2 available here
Paper 3 available here
Thesis available here

N: **To make that comparison, we need to be able to read the GOOSE messages in the substations and we need to read the GOOSE messages in the SCL file. Is that correct?**

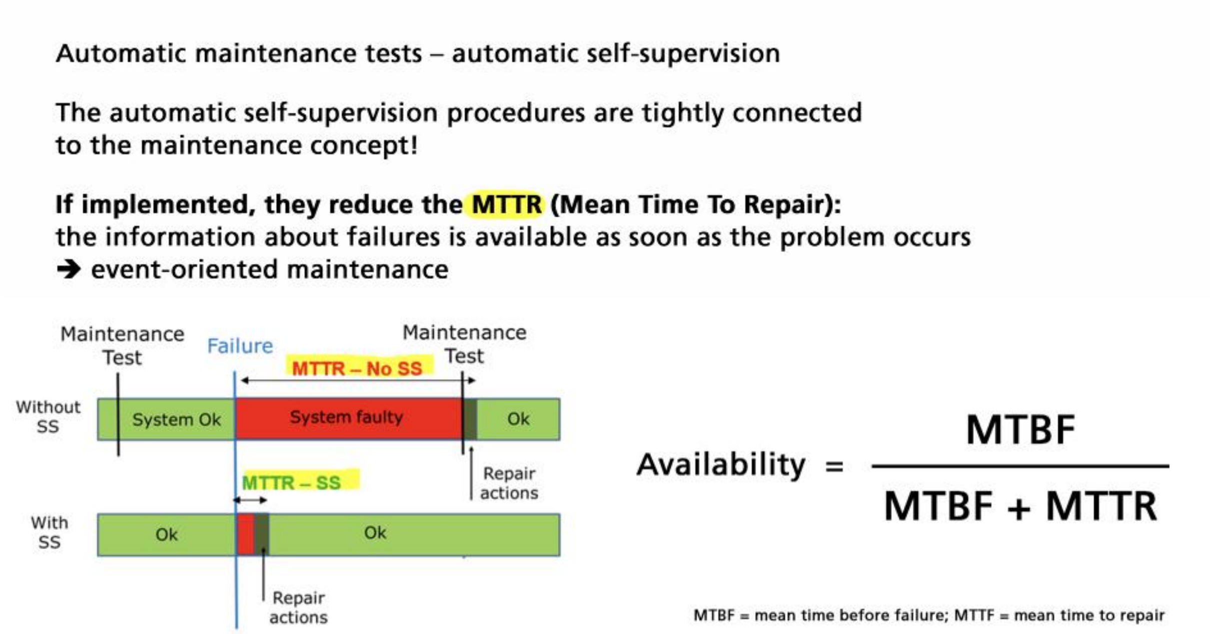
A: Yes! The tool for this is called the GOOSE sniffer. It's a device that is connected to the substation Ethernet bus and can transparently (passively) read the traffic, without sending data into the system. Megger's GOOSE sniffer is part of the Megger GOOSE Configurator (MGC) software. This software can also read SCL files, so we have a tool that can seamlessly work with GOOSE messages from the network and from the SCL file.

N: **Do you mean I go to the substation, read all the GOOSE messages, and then import the GOOSE messages from the substation SCL file?**

A: Yes! There might, for example, be 500 GOOSE messages from the substation and we'd also expect to have 500 messages from the SCL file. We'd expect the messages in these two sets to be equivalent. Or, to put it another way, we'd expect the substation messages to conform with the description given in the SCL file.

N: **Do you have examples to explain why there could be differences?**

A: In engineering, things are rarely perfect! Unfortunately, at the commissioning stage you're unlikely to have just a single version of the SCL file. Different vendors will be working on their own versions of the file, which they will use to program their devices. If the final SCL file is not completely updated with the latest information, or if there are some devices that are not programmed well, there will be differences between the substation messages and the SCL file.



For example, in a practical situation one relay could be out of service. The GOOSE messages from that relay will disappear from the network, but they are still in the SCL file. So, there will only be 80 substation messages but 85 messages in the SCL file. Or it could be that somebody has made changes to some relays but, when asked, they say they didn't change anything. A quick check will show if this is true. Or an Ethernet switch may have been replaced with a new switch that has different settings. This means the VLANs are now different, which will result in errors and warnings.

N: What sort of problems have you discovered in the field by comparing substation and SCL-file messages?

A: Issues I've identified so far include Ethernet switches replaced with the wrong settings, which meant that some GOOSE messages disappeared, and others lost their VLAN tag. I've also seen IEDs reconfigured, which meant that some substation messages didn't merge (i.e., 'were different') because of a different configuration revision (ConfRev); IEDs out of service or disconnected, which meant that some substation GOOSE messages disappeared; and additional IEDs inserted so that new substation messages appeared, which the SCL file hadn't been updated to expect. I even saw a situation where the system integrator gave the customer what was supposed to be the as-built SCL file. However, just five minutes of testing revealed that there were big differences between the GOOSE traffic and the SCL file – the SCL file did not reflect the substation!

N: How important is to have the correct description of the substation in the SCL file?

A: Very important because the SCL file is the basic documentation for troubleshooting when something unexpected happens. Moreover, it is the basic documentation for retrofitting. If the SCL file does not describe the substation, the entire IEC 61850 concept falls apart. Many utilities insist on a comparison check of the as-built SCL file and the network traffic during factory acceptance testing (FAT) and site acceptance testing (SAT). An incorrect SCL file means no acceptance and no payment! By the way, when the SCL file describes the substation, it is called an SCD (substation configuration description) file.

N: So, factory acceptance testing is yet another application of the comparison test method?

A: Yes, and it's an important application. In the hands of the end user, a comparison test is a powerful tool that enables them to determine whether or not there are discrepancies. If there are, they need to be investigated and resolved.

Some years ago, I was delivering an IEC 61850 training session for Megger. I explained how to test relays and then went on to say that every Megger user has access to the comparison test method, although they may not be aware of what they can do with it. The following day, only two out of the ten participants turned up for training. When I asked about the others – wondering whether they had a big substation problem as they were all utility employees – I was told that as a result of my presentation, they were all around the region checking their SCL files!

N: What happens if we get, say, ten difference warnings from a comparison test? What should we do then?

A: It depends on the situation. If it's a factory acceptance test, it may be enough to write a report about the warnings to withhold approval of the SCL file. Or, you may want to join in with investigating why the differences have occurred. If you use it correctly, the Megger tool can identify the differences in the comparison. This can be very difficult to determine manually, so the time savings can be enormous. The tool can't resolve the differences, but it can pinpoint them.

N: All of this sounds like it's going to be very expensive.

A: Actually, it's not. Every Megger user has access to the comparison method, since the MGC software for IEC 61850 is included as standard with Megger test equipment. But many Megger users don't realise they have it! This method does, I'll admit, need a certain level of competence in relation to IEC 61850, which goes beyond 'relay testing', but once you're used to it, it's not rocket science. Even so, it would be much more effective if comparison testing could be done automatically as some sort of continuous monitoring. Moreover, I see that others have only recently taken on this manual compare concept that we brought to the market in 2009.

N: What would be the advantages of automatic comparison testing?

A: We're talking about self-supervision procedures, automatic maintenance routines, event driven maintenance, and the like. The benefit of implementing these is that they greatly increase the availability of the system, compared with the use of periodic manual testing procedures.

N: How do these concepts relate to the smart grid?

A: I would say that one of the main associations is the cost. Nobody wants to pay for a periodic test on a system that is still working correctly. On the one hand, we want to have the best possible availability, and on the other, we want a system that's simple and inexpensive, and that gives automatic alarms when something needs to be repaired. The development of automatic maintenance procedures will therefore help the development of the Smart Grid in all areas of society, even in our homes.

N: But we don't have an automatic system in place...

A: That's correct, at the moment it's manual, but we have all the competences needed to implement an automatic system. What Megger needs is a friendly customer who is sensitive to these topics and willing to work with us to implement automatic comparison testing as a smart grid project.

N: Thank you, Andrea, for finding the time to take part in this interview. It's been both interesting and thought provoking. And I hope you'll get some positive responses relating to your search for a partner to work with you to develop your ideas. Also, I'd just like to mention that we'd welcome feedback on this interview and, if ET readers have questions, please forward them to us via the editor (electricaltester@megger.com).

POWERED BY

… *Andrea Bonetti*

At Megger, we strive to deliver exceptional innovations and great products that make life easier for everyone performing electrical measurements. It goes without saying that Megger's stellar achievements result from the efforts of its team of extraordinary people. One of these is Andrea Bonetti, whom we had the pleasure of interviewing for this month's "Powered by …" series. Here's what he had to say:

1. Andrea, what is your role at Megger?

I am a senior specialist in power system protection and IEC 61850 applications.

I work 'horizontally' between Sweden and the USA, which is great for me. I've worked for a successful international company previously, and I am grateful to have the opportunity to contribute to the growth of the Megger International Group. My role is to try to get the diverse and positive strengths out of every element of this group.

People say I am a doer, and this is true. Thanks to the many projects with IEC 61850 that I participate in, where people with very different competences need to push in the same direction, I have learned to motivate groups. Being a doer allows me to lead by example. So, I consider myself a "motivator outside of PowerPoint'".

2. What do you most enjoy about your job?

The fact that I never have the chance to get bored! Power system protection is a challenging field and, by definition, it is not an exact science. Many say that it is an artform, and I agree with that. Commissioning tests, troubleshooting, and 'making sure that the system works' are tasks full of responsibility. Every system has its own protection scheme and no two are ever the same. You can't get bored!

I also enjoy very much the team environment we have in Megger Sweden, and across the entire Megger business. Something that I'm particularly proud of is that we have clear values in Megger, and many of our managers show them upfront when they start their presentations. I think this is really motivating for the rest of the team and helps reinforce what we believe in.

3. What has been your biggest work-related challenge to date?

I think that the biggest work-related challenge has been, and still is, finding a compromise between adopting a new, forward-thinking approach and being conservative in our field – which is historically conservative. We shouldn't forget that when the lights work in our homes, this is in large part thanks to the conservatism of our field.

Power system protection has to be conservative, because of the high responsibility behind this job. On the other hand, I am convinced that we need to be open to new digital techniques, for many reasons. One reason is that new generations of engineers have grown up with these techniques, and they need to be conservatively guided to apply new thinking to power system protection. Yet adopting too many new ideas at the same time is as risky as doing nothing. Nevertheless, we don't want to discourage the new generation from entering our field, so we need to find the best compromise.

4. What do you like to do in your spare time?

I have many activities that I start, stop, and re-start. Chinese and Japanese martial arts have been a passion since I was 14. And, since I was 15, I have been a magician (https://www.magician.org/member/thebonniekids) - but this is now on hold. You need the passion to do it and at the moment, I don't have it. But it will probably come back again.

Planetary sky watching is something else that occupies my time. I would recommend everybody to look up at the night sky occasionally. I have also recently started to play golf; it is difficult and challenging – very challenging! I should have started with it many years ago. A suggestion: if you are thinking "maybe I should try it one day", just do it. The longer you wait, the more difficult it will be!

5. Tell us something about yourself that not many people know.

Well, when people find out that I am a magician, they always ask me to tell them how to cut a person into three. At that point, I tell them that they want to know "something that not many people know", and I ask them if they can keep a secret. The answer is always "yes". And the reply from me is always "me too"!

6. If you were president of the world, what would be your first executive order?

My long-term desire, inspired by Elon Musk, is to make reasonable efforts for us to become a multiplanetary species. My short-term wish would be to obligate every company to spell out its values upfront. I proudly work for Megger, where the top management drives our values, which are always visible. If I couldn't compel companies to do this, at least as president of the world I should be able to launch this message to all: don't work for companies that don't spell out their values up front, or that don't have values at all.

The art of recruiting engineers in the power system protection community

Ahmad Olia, with an introduction by Andrea Bonetti

Why this article?

I e-met Ahmad Olia some time ago because of his interest in using digital twins in relay protection testing. After our meeting, we discussed our jobs and I was curious about his, which was, in my words, a head-hunter for the electrical industry, with a focus on power systems and power system protection.

Throughout my years of experience within the power system protection industry - as a relay manufacturer, a consultant, and now a relay test equipment manufacturer - I have faced a recurring issue from my colleagues, customers, and competitors in that they find recruiting an engineer with power system protection competence rather difficult. When I heard of Ahmad's job, I exclaimed: "This is a niche in a niche! How did you come up with such a business idea?"

The explanations from Ahmad were so insightful and charged with such enthusiasm, that I asked if he was willing to contribute to Electrical Tester. I thought that Ahmad's experience could be beneficial for many readers of the magazine, no matter the role they have in the power system protection community.

The answer from Ahmad was "yes", so here's the article! Let me say this: for many reasons, I like to share my knowledge with others and appreciate articles written by others. This article from Ahmad is really captivating. I recognised so many of the descriptions that he gave in my own experience, and many times have found myself saying "so true"! How many times will you say the same?

Enjoy the article and make sure your next recruitment, no matter what your role is in the process, will not be a 'flight risk'.

Introduction

When it comes to recruitment, companies - depending on their size, industry, and needs - utilise a combination of different solutions to find the right talent for their organisation. Human resource professionals invest in solutions such as job postings on multiple job boards, employing internal recruiters and talent acquisition teams, participating in academic and industrial job fairs, and if all of that is not effective, hiring external recruitment agencies. Despite all these investments in time, effort, and money that companies put towards talent acquisition, often, the result is not what they were looking for. There are some missing pieces in this puzzle. In this article, we are going to first highlight some of the most important challenges that the electrical industry faces in recruitment and then we offer a road map to complete this puzzle.

Challenges in the recruitment process today

When hiring managers have an opening on their team, they often know exactly the specific skills and knowledge that this person should possess to be impactful in the role. Based on that, a job description is created, and the recruiters will start looking for that unicorn candidate based on the job description and some keywords. But can keywords help with getting access to the candidates of interest? Let's review some of the most important challenges when it comes to recruitment for the electrical industry.

Complexity of the electrical industry

The electrical industry is a vast and sophisticated industry with multiple fields of work and expertise. Workers in this industry can specialise in different fields such as power systems, electronics, control and automation, telecommunications, etc. In an industry like this, titles and keywords don't necessarily define one's specialty, but their work does. 'High voltage' in electronics and 'high voltage' in power systems share the same letters but they represent two very different worlds. 'Relays' in power system protection and 'relays' in control and automation offer the same word but convey two separate meanings. Therefore, in this industry, keywords and titles are not only unhelpful in finding the right talent but can also cause confusion, and waste time and resources. All of this means that strong knowledge of the industry while looking for a candidate is one of the most important missing pieces of the puzzle for 'efficient and successful recruitment'.

Cherry-picking the correct candidate is not an easy task, especially in the power system protection industry.

Lack of effective networking

Another challenge that recruiters have is effective networking. Many of the groups, forums, and conferences are exclusive to industry experts. An electrical engineer, for instance, can get into these hubs easily and network with other industry experts because they share a similar technical background. With access to these networks, the talent acquisition team could effectively start a targeted talent search and find the right candidates for the position.

> **...strong knowledge of the industry while looking for a candidate is one of the most important missing pieces of the puzzle for 'efficient and successful recruitment'.**

Scarcity of experienced talent

There is also a scarcity of some of the specialties in the electrical industry. Let's take relay and protection engineers as an example. Out of 100 electrical engineers, it is not unusual to have only a handful of relay and protection engineers. Discussions on LinkedIn suggest that less than 10 % of all electrical engineers specialise in power system protection. When there is a shortage of experienced workforce in a field, such as protection, companies use different methods to retain their experienced employees. Methods such as offering higher than average salaries, attractive perks like company shares, longer paid vacations, better retirement contributions, and so on. Experienced engineers in high demand rarely need to look for a new job, or in a better word, they are never active job seekers. In a market like this, it's very common that these engineers also get multiple messages from different recruiters on a regular basis to engage them in a job change. The question is, how can your approach and your job stand out and grab their attention?

Interview challenges

Interviewing can be an uncomfortable process for many people, especially technical experts. These individuals are strong in technical topics - math, logic, developing algorithms, etc. - but they might not be strong speakers or writers.

Many of the experts come from different backgrounds and sometimes there is also a language barrier. On top of that, many in this field only interview a few times in their entire career, and as a result, employers often decide to pass on these candidates, no matter how good of a fit they are. Companies should be more creative with the way they interview their technical staff to effectively assess the technical and interpersonal skills of the candidates.

When it didn't go as wished (at the beginning at least)

The process of recruitment and changing jobs is complicated. This is because the subject of this transaction is a personal one; a future is at stake and, in many cases, a family's too. People make career changes for multiple reasons such as better compensation, long-term career growth opportunities, a change of lifestyle, technical skill growth, or a desire to work with leaders in a particular technology, etc. Successful recruitment happens when the candidate has a valid reason for a career move, otherwise the placement is what we call in recruitment, a 'flight risk'.

Let me give you an example. I was asked to work on an assignment where my client needed a candidate with the combined skillsets of a senior electrical engineer and a civil engineer in order to work as a senior distribution engineer. They also had a strong preference towards finding a person who already had worked with a particular utility company. It is hard to find both electrical and civil design skills in one person, let alone experience with a specific utility. The key was to find a candidate with compelling reasons for a career change. In my search, I came across a candidate who was doing the same line of work with the utility of interest. When I talked to her, she told me that at this branch of the utility, there is no further room for growth until someone retires. She was not able to relocate to another city due to family concerns and felt stuck in her current job. This meant that the candidate was looking for a company where she could use her skills and be able to look forward to growth in her long-term career plan. Long story short, my client offered her the job to work remotely and both employer and the candidate were happy because she is a long-term hire.

The key points that made me think about this business opportunity

When I was close to the end of my bachelor's degree in electrical engineering, I became very interested in power systems, especially power system protection. I decided to do a master's degree in protection to strengthen my technical background with the purpose of joining a relay manufacturer as an engineer, but fate had a different plan.

Right after finishing my master's degree, like everyone else, I was actively looking for employment opportunities. I was shocked to see that even well-known companies in our industry had positions left open for months. At the same time, I was approached by multiple recruiters who were offering me opportunities that were not relevant to my background nor my interest.

When I investigated the reason, I realised that I was appearing as a good match for the roles based on their keyword search results and the recruiters couldn't differentiate me from an electronics engineer or a communications engineer. This was because of a lack of relevant technical background of the recruiter. That's when I realised that there is a unique need in this industry for a technical recruitment firm that has the knowledge and the network of industry experts at its disposal for talent acquisition purposes. It was from this realisation that MeshGrid HR was born!

Very special gratitude:

I would like to express my sincere gratitude to Andrea Bonetti and the team of ET Magazine that provided me with the opportunity to share MeshGrid HR's story. We are dedicating our education and experience to improving a key service in our industry and I hope the readers find this article and MeshGrid HR as a solution for their technical staffing challenges.

About the authors:

Ahmad Olia
Owner and President of MeshGrid HR

Ahmad Olia is a Master of Applied Science in electrical engineering specialising in power system protection. He spent three years in the renewable energy industry as a consultant before getting into technical recruitment. Ahmad is the founder of MeshGrid HR, a fast-growing technical recruitment agency with the purpose of improving recruitment experience in the electrical industry. To this end, MeshGrid HR has gathered a team of electrical engineers and industry experts who have the desire of serving their industry differently by contributing their expertise and networks to match the right talents with the right opportunity.

For any inquiries about Ahmad or MeshGrid HR and our services please reach out to:

Email: ahmad@meshgridhr.com
LinkedIn: https://www.linkedin.com/in/ahmad-olia/
MeshGrid website: www.meshgridhr.com

Andrea Bonetti
Megger Sweden AB

Senior specialist in power system protection and IEC 61850 applications.

Read all about it!

ICYMI: IPS Energy joins the Megger family

I•P•S Intelligent Process Solutions

IPS, a company specialising in energy and process solutions, is now a Megger strategic partner. This partnership marked the culmination of many months of discussions and is a significant milestone in our evolution as a company. It is the building of these long-term relationships that help us to grow as a business and to widen the scope of our operations.

Our partnership with IPS Energy will extend our capabilities for providing insight and diagnostics relating to electrical network assets by integrating off-line and on-line test and measurement data to provide full asset performance management. We will be able to serve our customers better by supporting the adoption and implementation of predictive maintenance practices.

Megger's business strategy is based around three levels of offering for its customers: test and diagnostics (the core of what we currently offer), condition monitoring, and asset performance management. The acquisition of Power Diagnostix was our first step into condition monitoring and our partnership with IPS Energy takes us further on that journey into asset performance management.

"We were thrilled to announce our partnership with IPS, and since then, we have been excited about our working together on a global basis", Jim Fairbairn, CEO of Megger, said of the acquisition. *"We were very impressed with the company during diligence and in particular the quality of the team at IPS. The move was aligned with the Megger strategy of extending our leadership in electrical test and measurement to include condition monitoring, enabling asset performance management insights into electrical power systems through advanced analytical capabilities."*

Both businesses have continued as usual and will do so for the foreseeable future, operating as two separate companies within a joint partnership. Rickard Jonsson was appointed as Liaison Officer between the businesses and manages product integration opportunities between test and measurement hardware and IPS Energy software products, as well as actively promoting collaboration throughout the partnership.

The Megger family thanks IPS; together, we will continue to create greater customer value through enhanced test and measurement capabilities. This will strengthen our relationships with current customers and allow us to create excellent opportunities with new ones.

Megger acquires Metrycom, a technology leader in Smart Grid monitoring solutions

Metrycom, a provider of grid network sensors and analytics to the electrical supply industry, is the latest organisation to join the Megger family.

Metrycom supplies unique grid sensor and analytics solutions for on-line measurements, condition monitoring, and fault location using extensive detection and prediction algorithms for medium and high voltage grid networks. Smart grid sensor networks bring insight to grid operators, enabling them to track real-time energy consumption, phase imbalance, and power flows across the grid including distributed energy resources.

Analytics provide decision makers with predictive analysis of future faults, supporting predictive maintenance practices along with improved detection and location of unplanned outages. This also enables improved grid system reliability year over year, with improvements in SAIDI, SAIFI, and CAIFI grid reliability indices.

Jim Fairbairn, Megger's Chief Executive Officer, said *"We are delighted to bring Metrycom into the Megger family. Metrycom's Smart Grid sensor technology is best-in-class, enabling power utilities better visibility into MV networks to assist in grid operation management and preventative condition-based maintenance, all of which improve grid reliability.*

On the purchase supporting Megger's growth strategy, he said, "The addition of Metrycom supports the longer-term industry move to on-line monitoring solutions and complements Megger's partial discharge monitoring solutions for substation GIS and GIL assets. This acquisition underpins our medium-term vision to become a connected, digitally fluent, value-added analytical partner for electrical utilities and all customers engaging in power management."

Liron Frenkel, Chief Executive Officer of Metrycom said: *"We are very pleased to have been acquired by Megger as this complements the Metrycom business, providing outstanding business development opportunities and extended reach to new customers who can benefit from our high-quality Smart Grid monitoring solutions".*

Batteries are not 'fit-and-forget' assets!

Megger North America
Technical Support Group (TSG)

Regular testing of storage batteries, particularly those used to provide emergency supplies, is essential. The batteries often sit unnoticed and unused for long periods, and they give little outward indication of deterioration or failure. Yet if they fail to perform as expected when called upon to do so, the result can be catastrophic.

The two most widely adopted approaches to assessing battery condition are impedance testing and discharge testing. Impedance testing is an on-line procedure that can be carried out frequently to identify individual weak cells before they fail. This test estimates the performance that can be expected from the battery in its current condition. It provides valuable information, but the results are always 'best estimates' rather than a definitive evaluation.

In contrast, the discharge test, which is also known as a load test or a capacity test, is an off-line test that measures the actual output of the whole battery string. It is the only test that can accurately measure the true capacity of a string, and for this reason, it is required by IEEE standards. A discharge test reveals what will actually happen if the battery is required to take the load.

Relevant standards are IEEE 450-2002 Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications, and IEEE 1188-1996 Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications.

Because they are time consuming and they require the battery to be taken off-line, discharge tests are, in most applications, performed infrequently. Typically, it is recommended that this type of test be performed in any of the following conditions:

- **When the battery is new, as part of the acceptance test.**
- **Within two years of the initial test, for warranty purposes.**
- **Subsequently, as a minimum, every 25 % of the battery's expected service life or every 6 years, whichever is the shorter interval.**
- **Annually, when the battery has reached 85 % of expected service life, or if the capacity has dropped more than 10 % since the previous test, or is below 90 % of the manufacturer's rating.**
- **If the impedance value of the battery has changed significantly.**

Concerns are sometimes expressed that discharge testing reduces the life of a battery: in fact, it has been called destructive testing because weak cells may fail during the test. It is, however, better to discover these weak cells during a test than when the battery is required to supply its load!

In theory, the test does indeed slightly shorten the life of the battery. However, a typical battery will have a life of at least 1000 charge/discharge cycles, and discharge tests are likely to be performed only four or five times over the battery's entire life. Since this is such a small percentage of the total available charge/discharge cycles, the impact on battery health and overall life, in practical terms, is negligible. In reality, it is far better to know the true capacity of the battery and to confirm that it will actually support the required load, than to worry about the minuscule effect that load testing may have on overall battery life.

Problem-free discharge testing

While discharge testing is the only true test of the capacity of a battery string, it undeniably requires a considerable amount of time and effort, hence it is important to make sure that it proceeds smoothly and without the need for re-runs. The following steps will help to ensure that this is achieved:

1. **Make sure that the battery (or batteries) to be tested has been maintained in its fully charged condition (typically by float charging) for at least 72 hours before starting the test. This will ensure that the discharge test results accurately represent the battery's capacity.**
2. **Carry out an impedance test and measure the resistance of the inter-cell connections before starting the discharge test. This will ensure that the electrical path in the battery string has been checked thoroughly before high current discharge commences.**

Discharge Rates in Amperes to 1.75Vpc at 25°C (77°F)

PowerSafe® DDm Battery Type	Ah* Capacity	Minutes					Hours									
		1	15	30	40	50	1	2	3	4	5	6	8	10	12	24
DDm35-07	105	252	148	101	84	72	63	38	28	22	19	16	13	11	9.6	5.6
DDm50-09	200	361	242	184	157	138	123	75	55	43	36	31	25	21	18	10
DDm50-13	300	541	364	275	236	207	184	113	82	65	54	47	38	31	27	16
DDm50-17	400	722	485	367	315	276	246	150	110	86	72	63	50	42	36	21

Figure 1: Sample battery discharge test specifications sheet

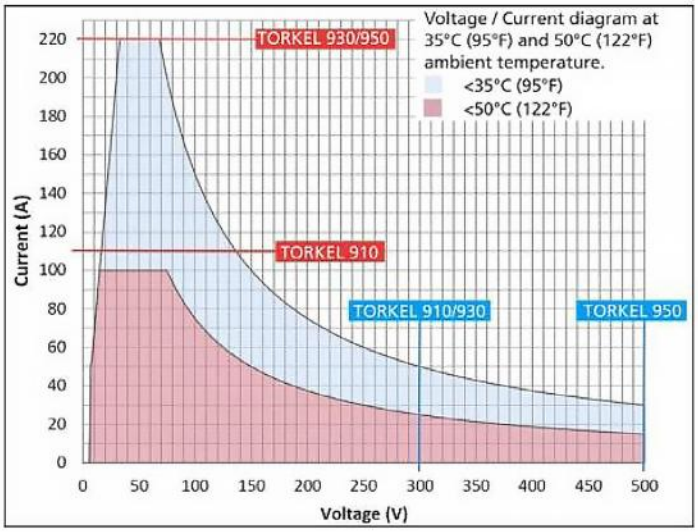


Figure 2: Current capacity vs voltage for the TORKEL 900 Series

3. Decide on the type of discharge test to carry out. There are many different types of discharge test including constant current, constant power, constant resistance, and load profile. Constant current is the type of test performed most frequently.

4. Check the discharge test specifications for the battery under test. This will help with planning the test. The specifications will include the end cell voltage (which is typically 1.75 V or 1.8 V per cell for lead-acid batteries) and a table of discharge rates. Using the table, the test duration can be chosen based on the duty cycle of the battery and this will allow the corresponding test current to be determined. As an example, with the table shown in Figure 1, a test current of 19 A would be needed for a 5-hour discharge test on the selected battery model.

5. Arrange for a backup battery bank if needed. A backup battery bank can be used to supply the load while the battery string under test is off-line. The backup battery will also be needed after the test is completed to allow time for the string which has been tested to be recharged.

A discharge test reveals what will actually happen if the battery is required to take the load.

6. Make sure that the load bank can handle the required test current. With high test currents, a single load bank may not be sufficient. This issue can be addressed by using additional load banks connected in parallel, or by using a lower test current and increasing the duration of the test. For load banks in the TORKEL 900 series, comprehensive information about discharge capability is given in the data sheet (see Figure 2). As a further aid, the TORKELCalc software package can be used to determine the configuration needed to suit a particular discharge current.

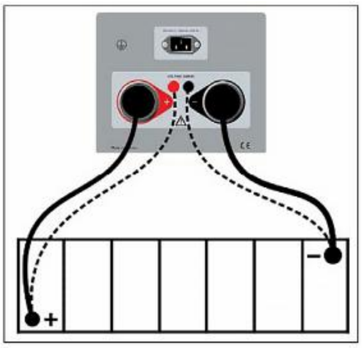


Figure 3: Voltage sense leads connection

Figure 4: Discharge test setup with BVMs for cell voltage measurement

Figure 5: Screenshot from the TORKEL GUI showing the test limits

7. Make the test connections safely while the battery to be tested is still connected to the charger. The connections need to be properly made to ensure that the high current flowing during the test does not lead to excessive heating. The battery terminal voltage can be measured accurately by using separate voltage sense leads, as shown by the dotted connections in Figure 3. This arrangement eliminates the effect of voltage drop in the current leads between the test set and the battery under test.

8. Monitor individual cell voltages. Bad cells in a string can discharge much faster than good ones. To allow the discharge test to continue, bad cells may need to be bypassed to avoid effects like polarity reversal. It is therefore important to monitor the voltage of each individual cell in the battery string while the discharge test is being performed. This can be done with battery voltage monitor (BVM) accessories, as shown in Figure 4. The correct voltage probes should be used to ensure that the connections to individual cells can be made easily.

9. Program the test parameters in the discharge test set. These include the test method, capacity calculation method, test temperature, test current, test duration, nominal capacity (test current x test duration), warning limits, and stop limits. A warning limit could be set for the individual cell voltage (for example at 1.75 V per cell). In addition, a stop limit could be set for the battery voltage (for example, 1.75 V per cell x 24 cells = 42 V). Examples of these settings on a TORKEL test set are shown in Figure 5. An additional warning limit could be set at a voltage slightly higher than the end battery voltage, so that the person performing the test is alerted when it is almost complete.

10. Be aware that some cells will reach the end voltage earlier than the others. The discharge test discharges all cells, and inevitably some will discharge sooner than others. The test should not be stopped when one cell reaches the end cell voltage, rather it should carry on until the average cell voltage is equal to the end cell voltage. For example, if the end cell voltage for the battery under test is 1.75 V and the battery has 60 cells, the test should continue until the battery voltage is 60 x 1.75 V = 105 V. At this point, it is perfectly possible that some cells will be at 1.8 V while others are at 1.6 V.

11. Be ready to bypass bad cells. Some cells in the battery string will discharge faster than others. IEEE test procedures for lead acid batteries (VLA and VRLA) state that the discharge test may be paused once for bypassing cells that are nearing polarity reversal. The maximum permitted duration of this “downtime period” is 10 % of the test duration or 6 minutes, whichever is shorter. After the bypass, the end battery voltage needs to be adjusted based on the remaining number of cells in the string. It is also necessary to evaluate the need for bypassing cells. If there are only a few bad cells in a string, the test can continue, but if, for example, half

the cells in the string discharge prematurely, the test should be stopped and the battery replaced.

12. Record the float voltage for each cell. Having BVMs connected makes this much easier. For a lead-acid battery, the float voltage will typically be around 2.2 V.

13. Prepare to start the test. Turn off the charger, disconnect the load, and if necessary, transfer it to the backup battery bank (testing a battery with the load connected is possible, however, by using an accessory CT to measure the external current flow).

14. Start the test.

15. Monitor the discharge data to ensure the test is progressing smoothly. Real-time data capture makes it possible to view live test values and evaluate progress in relation to the programmed test limits.

16. At the end of the test, save the discharge data and note the percentage capacity. For a discharge test that runs for one hour or longer, the following formula can be used to calculate the percentage capacity:

$$C = \left(\frac{t_A}{t_S \times K_T} \right) \times 100$$

Where:
C is the percentage capacity

tA is the actual time taken to reach the end voltage in the discharge test

tS is the calculated time to reach the end voltage

KT is the temperature correction factor

. The calculated time to reach the end voltage should be available in the battery manufacturer's data (see Figure 1). The manufacturer may also provide the temperature correction factor but, if not, the values provided in IEEE 450 can be used.

17. Reconnect the battery to the charger. Note that the charging current will initially be high as the battery has been heavily discharged during the test. The charger will need to be in good condition to supply the current required.

> **In reality, it is far better to know the true capacity of the battery and to confirm that it will actually support the required load, than to worry about the minuscule effect that load testing may have on overall battery life.**

A sound investment

Batteries are costly assets that play an important and often critical role in modern power systems. It is therefore essential to ensure that they are maintained in good order and that their performance is regularly and accurately assessed. The key to achieving this is to implement a program of testing that includes both routine impedance testing and, at less frequent intervals, carefully planned discharge testing. Modern test instruments, such as those in Megger's battery test portfolio, deliver dependable results and make both types of testing easier to perform. For all battery users, such testing is a sound investment that will yield an excellent return, not least by helping to eliminate the risk of batteries failing to perform when they are needed most.

Watch our webinar on 'Introduction to battery Testing_ Bite, BGFT and Torkel'

Protecting wind turbines through effective grounding

Sameer Kulkarni and
Dr Ahmed El-Rashed

The share of wind power in electricity generation is expected to increase, and with that comes a requirement for this carbon-free source to be more reliable. The wind turbine, which is the most important component of a wind power system, is exposed to harsh environmental conditions and electrical transients, such as lightning strikes. Naturally, understanding the lightning protection scheme of a wind turbine and checking its integrity is vital to protecting it during lightning strikes so that continued, reliable operation is achieved.

Recent international studies have shown that in one European country, 80 % of insurance claims on wind turbines resulted from lightning-related damage. Similarly, a major US utility reported that over 85 % of its wind turbine downtime was due to lightning-related damage.

This article provides a general overview of the lightning protection system of a wind turbine, best practice for lightning protection on wind turbines, and verification of effectiveness. It discusses the need and advantages of various tests performed to verify the continued integrity of lightning protection systems, and shares reference values for testing parameters along with expected results, while reviewing some practical and safety considerations.

Wind power

Renewable energy — and wind power in particular — is growing at a rapid pace. In 2020, new wind power installations provided 93 GW globally. The year-on-year growth is 53 %, with both the United States and China leading the world in new installations of wind power generation. Wind power answers the pressing needs and circumstances of today. It is a relatively inexpensive and green energy source that addresses constrained infrastructure budgets as well as climate change policies. Most market analysts indicate that wind power will continue to grow at a fast rate because all the driving factors for its adoption persist.

This is great news for the electrical power industry, as there will be growth and opportunity for many years to come. However, this growth will require improved maintenance programs to protect investments and maximise the profits from wind power.

Lightning strikes

The biggest maintenance problem for wind power is lightning strikes (Figure 1a and Figure 1b). According to Vestas CEO Henrik Andersen, intense lightning strikes were the biggest driving force behind the record warranty claims that amounted to €175 million (US $212 million) in the second quarter of 2020 alone. Wind turbine manufacturers and installers, such as Vestas, recognise the immense danger of lightning strikes and take great care in the design of turbines. Nevertheless, operators and owners of wind turbines must implement a robust and effective maintenance program for their assets.

Lightning protection systems

A growing number of studies speculate that rotating wind turbines may be more susceptible to lightning strikes than stationary structures. Wind turbines are at a high risk of being struck by lightning due to their height and the locations used for wind farms, and lightning faults cause more loss in wind turbine availability than other faults. Wind turbines are equipped with lightning protection to minimise damage from direct lightning strikes and to shield sensitive equipment integral to wind turbine operation. Lightning strikes not only produce large current flows but also impress unwanted electromagnetic fields across components housed in the nacelle and base of the tower. The lightning protection system (LPS) performs the function of directing the current from strikes to ground.

Lightning protection zones

To facilitate the coordination of protection functions, it is prudent to divide the wind turbine into lightning protection zones (LPZ). The lightning protection zone concept is a structuring measure for creating a defined, electromagnetically compatible environment in an object while being cognisant of the object's stress withstand capability. IEC 62305, Standard for Lightning Protection, defines the LPZ for structures and can be applied to a wind turbine. The zones are classified as external or internal based on their exposure to direct lightning.

External zones

- LPZ 0A is the zone where the threat is due to the direct lightning flash and the full lightning electromagnetic field. The internal systems may be subjected to full lightning surge currents.
- LPZ 0B is the zone protected against direct lightning flashes but where the threat is

Figure 1a: Lightning damage to a wind turbine

Figure 1b: Lightning damage to a wind turbine

due to the full lightning electromagnetic field. The internal systems may be subjected to partial lightning surge currents.

The rolling sphere method is used to determine LPZ 0A — the parts of a wind turbine that could be subjected to direct lightning strikes, and LPZ 0B — the parts of a wind turbine that are protected from direct lightning strikes by external air-termination systems or air-termination systems integrated in parts of a wind turbine (for example in the rotor blade), as seen in Figure 2 and Figure 3.

Internal zones

- LPZ 1 is the zone where the surge current is limited by current sharing and isolating interfaces and/or by surge protection devices (SPD) at the boundary. Spatial shielding may attenuate the lightning electromagnetic field.
- LPZ 2 to LPZ n are the zones where the surge current may be further limited by current sharing and isolating interfaces and/or by additional SPDs at the boundary. Additional spatial shielding may be used to further attenuate the lightning electromagnetic field.

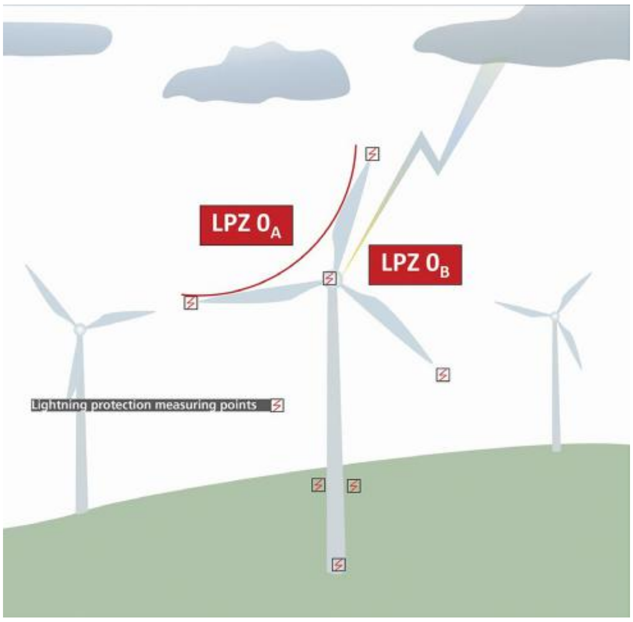


Figure 2: Simplified wind turbine, external LPZ

The LPS essentially works by providing a low resistance path-to-ground. The path goes from the blade's tip to the base of the turbine. This path is shown in Figures 4 and 5.

In the event of a lightning strike, current will flow to ground through the LPS, not the sensitive equipment in the wind turbine. As lightning current is dissipated through the grounding system, it is important that it should not cause thermal or mechanical damage or arcing that may lead to fires or injuries to personnel. To ensure that the protection will work effectively when needed, the resistance of the path-to-ground should be measured at regular intervals to check that it meets the limits specified by the turbine manufacturer (typically limited to 15 to 30 mΩ, depending on turbine size). For these tests, use of a low resistance ohmmeter is recommended.

Figure 3: Air termination systems installed for wind turbine nacelle

Methods for verifying lightning protection systems

Measurement of low resistance is affected by factors such as measurement type, test current magnitude, length of test leads, and placement of leads/probes.

Four-wire method

The four-wire method (Figure 6) is most appropriate because it uses separate current probes to inject direct current (DC) and separate potential probes to measure the voltage drop across the test specimen.

In some practical cases, a Kelvin measurement, where current and potential probes are 180 ° apart, is also employed to measure low resistance values. The use of any other methods such as a two-wire method may not be suitable, as the measurement will include the contact resistance values of the probes, which makes the results less certain.

Testing wind turbine lightning protection

The most important test on an LPS is to test the conductor from the blade tip to the down conductor inside the hub that ultimately connects to the ground grid, as was shown in Figure 5 and is depicted in Figure 7 and Figure 8.

This conductor is placed under significant strain as the blade flexes with the wind during normal operation. Under strain, the conductor may fracture. Unfortunately, it is not enough to simply check continuity because, if the fractured conductor is touching at the break point during a continuity test, the result of the test will be misleading. Because of this, a test current magnitude of 1 A or more is recommended for this test.

The length of a typical turbine blade can be seen in Figure 9. The size of the turbines poses a problem because low resistance ohmmeter test leads are typically very short. Due to the size of the wind turbines, extra-long leads are required, often up to 100 m. This is a huge increase in length over standard test leads for low resistance ohmmeters. The long leads must be designed with a low enough resistance to ensure that a measurement is still possible. To achieve this, it is important to understand the test instrument design.

Some instruments have a compensation factor to allow

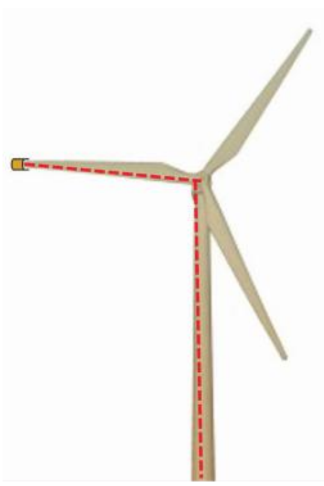


Figure 4: Current path for lightning discharges

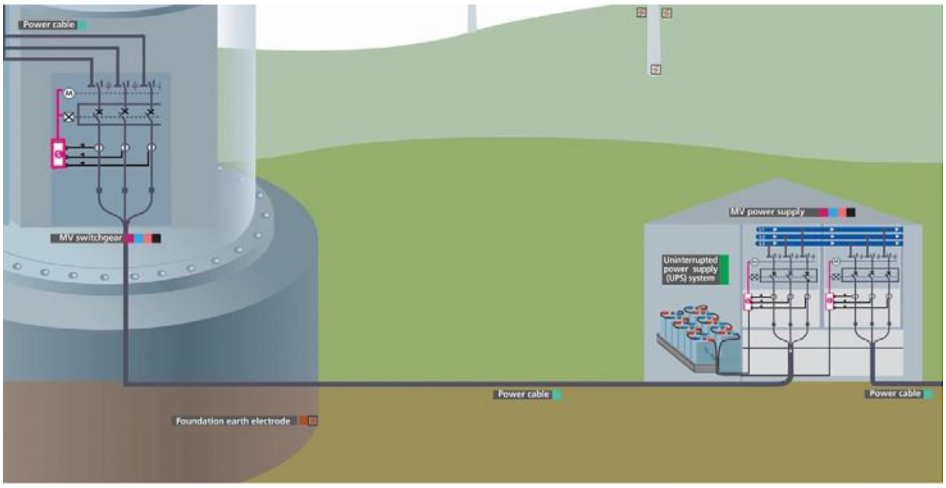


Figure 5: Foundation earth electrode at wind turbine base

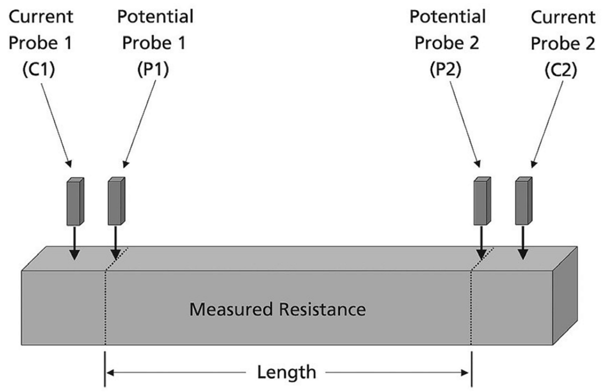


Figure 6: Four-wire method

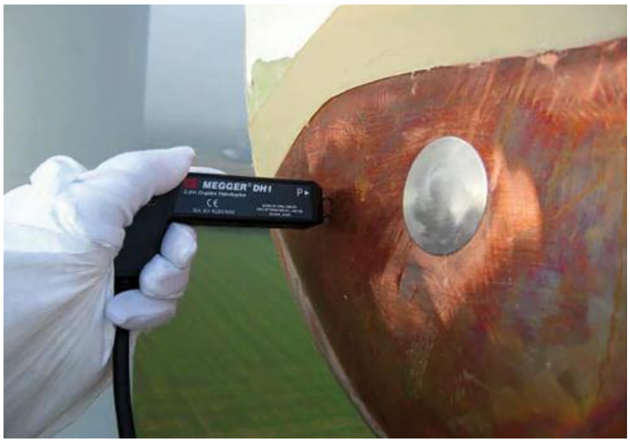


Figure 7: Lightning conductor resistance measurement at blade tip

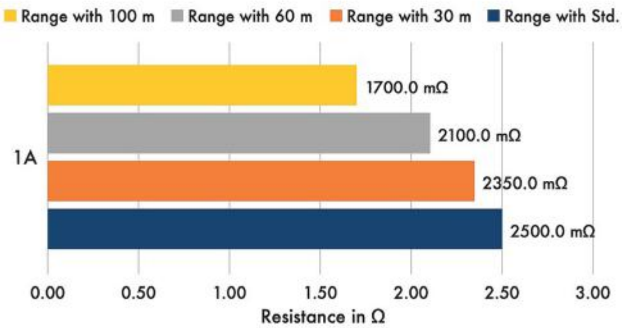


Figure 8: Lightning conductor resistance measurement at wind turbine hub

for power loss in standard test leads. When using long test leads, this compensation will no longer be sufficient and the test range of the instrument will be reduced. When the resistance of the test leads is increased, the value of R in the following equation will also increase.

$$P = I_2R$$

Where:

R is (resistance of load) + (resistance of test leads)

P is output power of the test instrument

I is output current of the test instrument

Since the maximum power output (P) of the test equipment cannot change, the rise in test lead resistance will cause the maximum current (I) to be reduced. Table 1 shows how lead length impacts the ability of an instrument to measure low resistances. It is clear that accurate and repeatable measurements will depend on a combination of test current, lead length, and resolution.

As seen in Figure 10, the performance of the low resistance tester at 1 A (2.5 W) is the most suitable for the lead lengths that are typically employed for testing wind turbine LPSs. For wind turbine applications, it is important to use an appropriate range and test current because it is essential for the length of test leads to accommodate the length of the wind turbine blades.

Results

In one such example, the LPS on a wind turbine with 32 m (105 ft) blades was tested using a low resistance ohmmeter. The instrument was used in its 'long test lead' mode, which applies a 1 A test current and can measure accurately down to 0.01 mΩ when using 100 m long (330 ft) test leads. Testing consisted of measuring the system's resistance from the tip of each blade to the hub, and from the hub to the base. The lightning system in this case terminated with interconnected ground rods at the base of the turbine tower.

Each measurement was taken three times to evaluate repeatability. The variance meter on the instrument automatically recorded three measurements in a row and calculated their variance. The raw results from this test can be seen in Table 2; total results are shown in Table 3.

The low variance provides confidence in the measurement. In the field, test engineers must take every care to remain safe and follow best practice. This will provide the best possible measurements.

The manufacturer of this wind turbine prescribes a pass level for the lightning system of 20 mΩ or less. This test proves that the lightning system has been installed correctly and is in good working order. Therefore, this turbine has good lightning protection in line with the manufacturer's specification.

Figure 9: Wind turbine blade before installation

Test Current	Range of leads				Resolution	Comments
	Standard	30 m	60 m	100 m		
0.1 mA	0 to 2500.0 Ω	0 to 2499.9 Ω	0 to 2499.6 Ω	0 to 2499.2 Ω	0.1 Ω	Test current insufficient Resolution inaccurate
0.1 mA	0 to 250.00 Ω	0 to 249.85 Ω	0 to 249.60 Ω	0 to 249.20 Ω	0.01 Ω	
1 mA	0 to 25.000 Ω	0 to 24.850 Ω	0 to 24.600 Ω	0 to 24.200 Ω	1 mΩ	
10 mA	0 to 2500.0 mΩ	0 to 2350.0 mΩ	0 to 2100.0 mΩ	0 to 1700.0 mΩ	0.1 mΩ	
100 mA	0 to 250.00 mΩ	0 to 100.00 mΩ	Out of range	Out of range	0.01 mΩ	Insufficient range
1 A	0 to 25.000 mΩ	Out of range	Out of range	Out of range	1 μΩ	
10 A	0 to 2500.0 μΩ	Out of range	Out of range	Out of range	0.1 μΩ	
1 A (2.5W)	0 to 2500.0 mΩ	0 to 2350.0 mΩ	0 to 2100.0 mΩ	0 to 1700.0 mΩ	0.1 mΩ	Optimum conditions (Figure 10)
10 A (25W)	0 to 250.00 mΩ	0 to 100.00 mΩ	Out of range	Out of range	0.01 mΩ	Insufficient range

Table 1: Resistance range for varying test current magnitudes for a popular low resistance tester

Section Tested	Test 1 (mΩ)	Test 2 (mΩ)	Test 3 (mΩ)	Variance	Average (mΩ)
Blade A	7.81	7.81	7.79	0.9%	7.80
Blade B	7.85	7.86	7.86	0.4%	7.86
Blade C	7.51	7.52	7.52	0.4%	7.52
Tower	3.17	3.20	3.20	1.3%	3.19

Table 2: Raw measurements, variance, and averages

Manufacturer's Pass Level: ≤ 20 mΩ		
Lightning Path	Total Resistance (mΩ)	Pass/Fail
Blade A to Ground	10.99	PASS
Blade B to Ground	11.05	PASS
Blade C to Ground	10.71	PASS

Table 3: Total resistance values and results

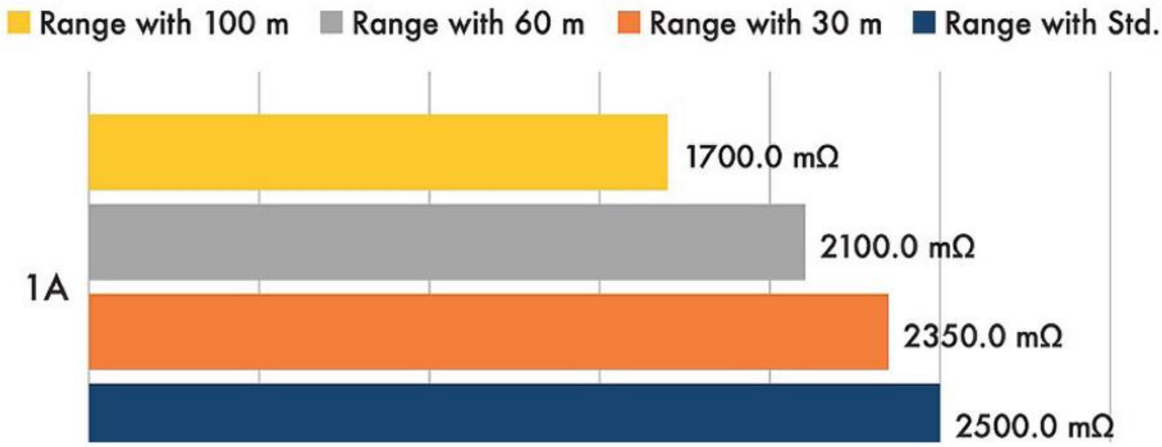


Figure 10: Optimum testing parameters with 1 A test current and long leads

Conclusion

Lightning is a hugely damaging threat to wind turbines and, as wind power installations continue to spread across the world, the requirement to protect these assets is becoming ever more important.

Manufacturers of wind turbines take great care in designing lightning protection systems, but owners and operators of turbines must ensure that these systems have been installed correctly. Additionally, the owners and operators must regularly check the lightning protection system as part of the maintenance program.

Testing and verifying the lightning protection system is based primarily on low resistance measurements. There are some challenges to measuring resistances at milliohm level when dealing with large structures like a wind turbine, so a balance between test energy, accuracy, resolution, and test lead length must be established. However, the right tools for the task make it a simple job.

It is highly recommended to make lightning protection system maintenance a key regular task for owners and operators of wind turbines. This will minimise the risk of lightning damage and ensure that these valuable assets are properly protected.

About the authors

Sameer Kulkarni, PE, is an Applications Engineer at Megger. He previously worked for Entergy at River Bend Nuclear Generating Station as a systems engineer responsible for power distribution, large power transformers, and NERC. Sameer obtained his BS in Mumbai, India, and graduated with an MS in electrical engineering from Arizona State University. He obtained his Professional Engineer licence in June 2019 and is an IEEE Member.

Dr Ahmed El-Rasheed is a Business Development Director at Megger and has over 14 years' experience in electrical engineering. He is a member of several international standards organisations and has published papers on ground testing, insulation testing, and multi-sensor integration using AI.

Watch our webinar 'Prevent your wind turbines from future failures' here.

Watch our webinar 'Fundamentals of Low Resistance Testing' here

BIBLIOGRAPHY

[1] Dehn International. "Lightning and Surge Protection for Wind Turbines," 2015. [Online]. Available: https://www.dehn-usa.com/sites/default/files/uploads/dehn/pdf/white-papers/ab-juli15/wp016-e-wind_turbines.pdf.

[2] Megger Instruments Ltd. Wind Farm Testing – Growth Applications, 2021.

[3] Vestas Wind Systems A/S. Installation of Copper Tip – Work Instruction, Vestas.

[4] A. Z. Kattamis and M. Pooley. "Lightning Protection for Wind Turbines," Electrical Engineering & Computer Science, 2017.

[5] Megger Limited. "Testing Wind Turbine Lightning Protection," Application Note, June 2019.

[6] Furse. Guide to BS EN/IEC 62305.

[7] American Clean Power. "Wind Power Facts," [Online]. Available: https://cleanpower.org/facts/wind-power/.

[8] Global Wind Energy Council. "Global Wind Report," Global Wind Energy Council, Brussels, 2021.

Assessing high voltage substation equipment at 1 Hz

Dr Diego Robalino,
Vince Oppedisano,
and Ken Petroff

E
T

It is common practice to evaluate the average insulation condition of high voltage (HV) substation equipment in the field by measuring dielectric losses. This practice involves applying an AC signal to an insulation system at a frequency close to the line-frequency (60 or 50 Hz) and measuring the current and the angle between current and applied voltage to determine the insulation dissipation factor (tan delta) or power factor.

Line-frequency (LF) insulation dissipation factor (DF) or power factor (PF) depends on the frequency of the applied signal, the dielectric properties of the insulation material, the insulation temperature, and the geometrical design, as well as aging and contamination that might be present within the insulating medium.

Field experience suggests that tables of factors for temperature correction do not reflect the true thermal behaviour of the insulation system and, consequently, a DF or PF trend analysis may be misleading due to incorrectly temperature-compensated test results. Throughout the service life of an electrical asset, line-frequency dissipation factor (LF DF) may stay the same, may increase or sometimes may even decrease and the reason for these changes is not always clear.

Research carried out by the authors shows that even an apparently 'good' line-frequency DF is not always 'good', and that to reliably determine the condition of the insulation system, assessment of the insulation should also consider an additional DF value obtained at another, very specific, frequency.

This article provides a clear demonstration of the benefit of measuring insulation DF at LF (50 or 60 Hz) and at 1 Hz. This simple combination of procedures carried out at the same time and with the same test instrument provides a more reliable and more efficient way to evaluate the condition of critical high voltage substation equipment, including power transformers, bushings, and instrument transformers.

Theoretical background:

Dielectric response in the frequency domain

Non-invasive and non-destructive methods for determining the dielectric characteristics of insulation systems have evolved significantly in the last two decades. The methods typically involve applying a sinusoidal signal to the insulation system. This is not done to stress the insulation but to measure its dielectric properties: capacitance, dissipation factor (DF), complex permittivity, and conductivity.

The ratio of imaginary to real components of the complex permittivity is the insulation DF (tan delta, δ).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = DF$$

Equation 1

Physical and/or chemical properties of organic and inorganic materials can change due to aging and due to thermal, chemical, electrical, or mechanical stress. A non-invasive and non-destructive method to trend these changes in insulating materials is the measurement of dielectric losses performed over wide ranges of frequencies or temperatures. The dielectric frequency response provides an instantaneous image of the condition of the insulation system, and it therefore allows on-site assessment and comparison against historical values – but only if accurate temperature correction is carried out in line with the Arrhenius equation (Equation 2), which defines the relationship between frequency and temperature.

This article provides a clear demonstration of the benefit of measuring insulation DF at LF (50 or 60 Hz) and at 1 Hz.

$$\omega_2 = \omega_1 \cdot e^{-\frac{E_a}{k_B}\cdot\left(\frac{1}{T_1}-\frac{1}{T_2}\right)}$$

Equation 2

Where Ea is the activation energy of the insulation material in eV, kB is the Boltzmann constant (8.617 x 10-5 eV/K), and T is the Kelvin temperature of the object. Activation energies are in the range of 0.70 - 1.18 eV for oil impregnated cellulose insulations.

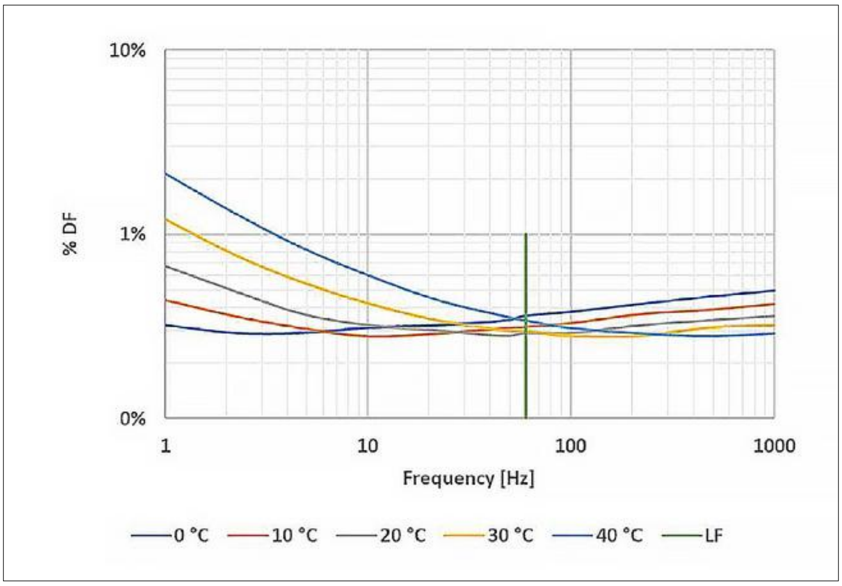


Figure 1: Dielectric response of OIP insulation (new oil and paper with 2 % moisture) tested from 0 °C to 40 °C

The Arrhenius equation allows normalisation of the dielectric response to a reference temperature, which is typically 20 °C. This approach is known as individual temperature correction (ITC). The effect of temperature on an oil-impregnated paper (OIP) sample is shown in Figure 1.

Line-frequency dissipation factor (LF DF)

The measured LF DF value by itself does not provide much information unless it is properly corrected to 20 °C. In a power or distribution transformer, the interwinding insulation, as well as the winding-to-ground insulation systems, are tested using an applied voltage of 10 kV (or below rated voltage of the winding under test) at line frequency. The resulting normalised values are subject to at least one of three typical evaluations: comparative analysis, trending analysis, and acceptance within limits established by international standards. It is not only the LF DF value that is of importance but also the capacitance value. Field experience has, however, shown that HV equipment may fail even after an LF DF test with apparently acceptable results.

Reasons for not detecting insulation problems with LF DF are related to the temperature dependence of DF and the very marginal effect of emerging contaminants at LF. Carrying out the test at an additional frequency is a practical approach to improving the assessment by providing two measurement points within the dielectric response spectrum.

Dissipation factor at 1 Hz

More than 25 years of information that was obtained using full spectrum (1 mHz to 1 kHz) dielectric frequency response (DFR) in the field to assess the condition of power transformers has been thoroughly analysed at various frequencies.

As can be seen in Figure 1, at LF (60 Hz) the variation of DF as a function of temperature is very small compared to the variation observed at 1 Hz. The differences at LF are quite difficult to observe, particularly for a specimen in very good condition, with no contamination, less than 0.5 % moisture in the solid insulation, and very low oil conductivity.

Here is the where the importance of the 1 Hz test comes in. As shown in Figure 1, the higher frequency region of the response represents a relatively linear low-loss system. At a resonant frequency ω_r, the dielectric response transitions into a lower frequency region represented by higher losses and greater dispersion of the dielectric response. The resonant frequency will shift to higher values when temperature increases and lower values when temperature decreases, as shown in Figure 2. It is important to know to what degree a change in test temperature has caused the resonant frequency to shift because changes in the vertical or horizontal axis imply a change in the dielectric condition. Therefore, to eliminate temperature as a factor for an observed change, the entire response must be properly normalised to 20 °C every time a measurement is made at a non-20 °C temperature.

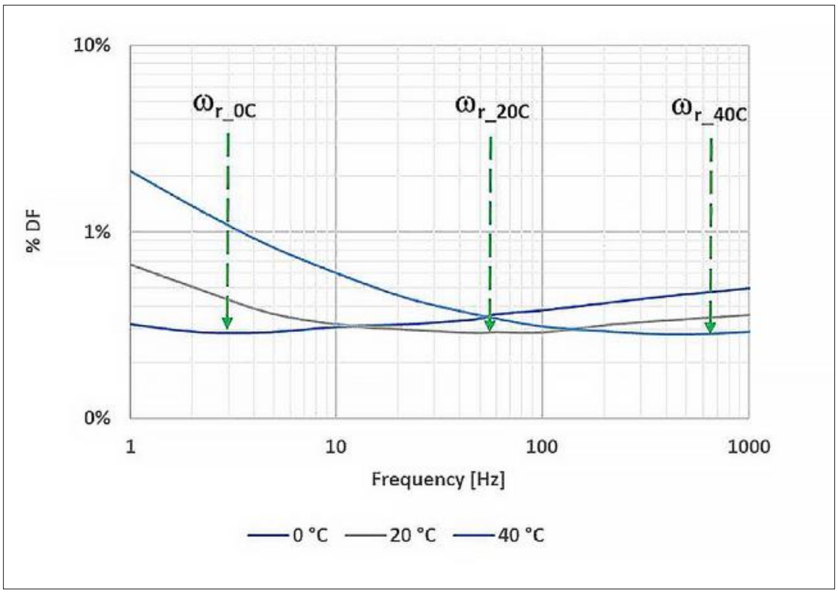


Figure 2: Resonant frequency shift in a dielectric response at different temperatures

Field applications:

Bushings

Condenser-type bushings, more commonly known as capacitance graded bushings, have been in service for a long time and have been tested in many ways. The dielectric response of a bushing in the time or frequency domain is mainly dominated by its construction, the temperature during the test, and the properties of the materials. In most HV and EHV (extra high voltage) bushings, a geometric design for the main insulation replicating a graded capacitor is commonly used. Oil-impregnated paper (OIP) insulation is used in the vast majority of field-installed bushings, wherein the liquid insulation is mineral oil, and the solid insulation is typically kraft paper with a 55 °C rise thermal rating. Both materials possess well known and excellent mechanical and dielectric characteristics. Other common types of HV bushings are resin-impregnated paper (RIP) and resin-impregnated synthetic (RIS).

Because the failure of bushings has a large impact on transformers, the condition assessment of HV bushings has been extensively investigated and CIGRE has recently published a very detailed document describing the reliability of HV and EHV bushings [1]. Several of the methods used for testing HV bushings are sometimes ineffective and the results inconclusive. Off-line testing of capacitance and dissipation factor is generally carried out at line frequency as part of acceptance, commissioning, routine testing and troubleshooting, or after corrective maintenance work. Changes in capacitance may be indicative of a short between capacitive layers in C1 (the main core insulation) and changes in dissipation factor (or power factor or tan delta) may indicate insulation degradation and/or contamination. Contamination of the insulation due to overheating or excessive generation of partial discharge (PD) and consequently of PD by-products such as X-wax, has a clear influence on dielectric response [2].

As presented in [3], the influence of contamination on dielectric response may be significantly more pronounced at non-line frequencies than at LF. Assuming accurate temperature correction using the ITC algorithm, the authors suggest that the insulation condition of OIP bushings can be assessed as shown in Table 1.

OIP Bushing Insulation Condition	1 Hz DF at 20 °C
As new	0.2 – 0.5
Good	0.5 – 0.75
Aged	0.75 – 1.25
Investigate	>1.25

Table 1: OIP bushings assessment for 1 Hz DF at 20 °C

Transformers

The dielectric response of power and distribution transformers over a wide range of frequencies has been

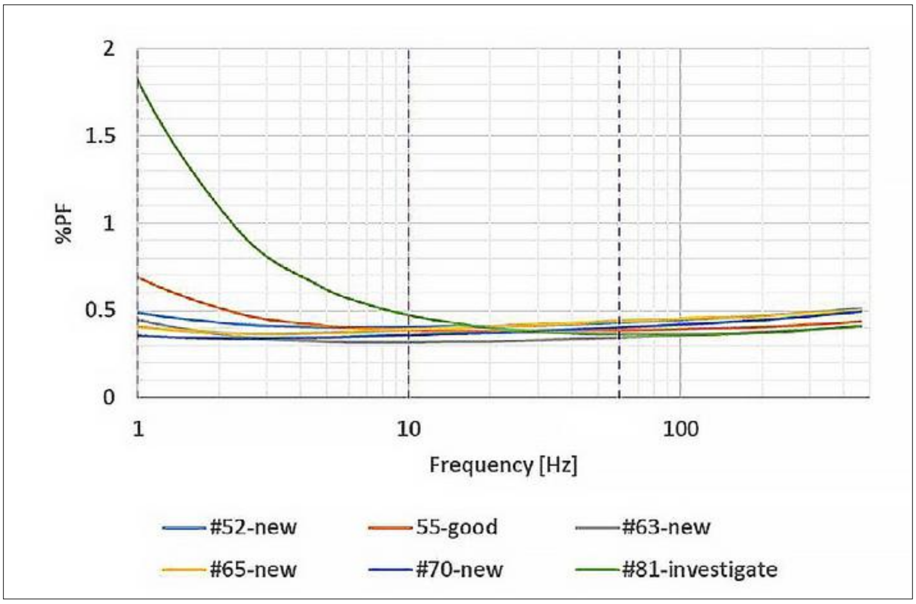


Figure 3: Randomly selected OIP transformers - LF DF within acceptable limits

investigated for the last 25 years. In the last decade, several accelerated aging experiments have been carried out and published, particularly for distribution transformers [4]. Aging of distribution transformers has been shown to have very little effect on the LF DF value, but much greater changes were observed at lower frequencies, specifically at 1 Hz.

Assuming accurate temperature correction using the ITC algorithm, the authors suggest assessing the insulation condition of OIP transformers as shown in Table 2.

OIP Transformer Insulation Condition	1 Hz DF at 20 °C
As new	0.2 – 0.75
Good	0.75 – 1.25
Aged	1.25 – 2.0
Investigate	>2.0

Table 2: OIP Transformers assessment for 1 Hz DF at 20 °C

Instrument transformers (CTs, VTs, and CVTs)

Instrument transformers monitor power flow and serve several purposes, including metering (for revenue purposes), protection, and control. For current transformers (CTs), the insulation system is like that of HV bushings, and an assessment is made on the dissipation factor of the overall insulation. Voltage transformers (VTs) and capacitive voltage transformers (CVTs) also have something in common with CTs and HV bushings. Instrument transformers usually have insulation consisting of kraft paper and mineral oil, and the volume of paper insulation is dominant. The measured capacitance of instrument transformers and HV bushings is typically less than 800 pF. Therefore, to make measurements at low frequencies, an HV source may be required to offset the negative influence of EMI and to increase the signal-to-noise ratio (SNR).

Dielectric frequency response (DFR) testing has been used to monitor the dry-out process of CTs and CVTs in the factory [5], down to levels below 1 % moisture in the solid insulation. For CTs, DF at 1 Hz and LF should reach values below 0.3 % at 20 °C. Similar values apply to CVTs. It is shown in [6] that the insulation condition of HV and EHV CTs can be readily evaluated in the field by using LF DF values in conjunction with 1 Hz DF values. The authors suggest that the assessments shown in Table 1 for OIP bushings can also be applied to instrument transformers.

Field experience:

Commissioning new 69 kV RIP bushings

Commissioning tests conducted in the field in early 2021 involved dielectric assessment of new 69 kV RIP bushings. Nameplate data is provided in Table 3.

Designation	Type	kV	Year	C1 @ 20 °C	
				% LF DF	Cap (pF)
Y1	RIP	69	2020	0.32	509
Y2	RIP	69	2020	0.32	499
Y3	RIP	69	2020	0.32	530

Table 3: New RIP bushings C1 nameplate information

An LF DF test was performed at 3 °C. The curves provided in section 5.2.2.2 of [1] were used for LF DF temperature correction.

Desig.	Test kV	Cap (pF)	Line – frequency (60 Hz)		
			% DF measured	% DF @ 20°C	Δ @ 20°C
Y1	10.0	501.0	0.56	0.39	0.07
Y2	10.0	491.4	0.43	0.30	0.02
Y3	10.0	522.2	0.55	0.38	0.06

Table 4: Tertiary winding new RIP "Y" bushings LF DF results

The results, as presented in Table 4, fall within the 'acceptable' limits prescribed in CIGRE guidelines [1] for new RIP bushings – (see Table 5).

Bushing insulation type	RBP	OIP	RIP
tanδ/% (new bushing), [2.1]	< 1.5	< 0.7	< 0.7
PF/% (new bushing), [2.2]	< 2.0	< 0.5	< 0.85
Typical value range, %	0.5 to 0.6	0.2 to 0.4	0.3 to 0.4

Table 5: Limiting values LF DF at 20 °C [2]

During commissioning, a Megger DELTA 4310A dissipation factor test set was used for DF tests at LF and at 1 Hz. The application software corrected the % DF values from 3 °C to 20 °C using the individual temperature correction (ITC) algorithm. The results are shown in Table 6.

Desig.	60 Hz					1 Hz		
	Test kV	Cap (pF)	% DF			Test kV	% DF	
			Measured	@ 20°C	Δ @ 20°C		Measured	@ 20°(
Y1	10.0	501.0	0.56	**0.67**	0.35	0.25	1.24	**1.86**
Y2	10.0	491.4	0.43	0.34	0.02	0.25	0.31	0.35
Y3	10.0	522.2	0.55	**0.86**	0.54	0.25	1.88	**2.21**

Table 6: RIP LF and 1 Hz DF values corrected by ITC

The results in Table 6 show a significant difference in the temperature correction of the 60 Hz % DF results for bushing Y2 compared with bushings Y1 and Y3: the correction decreases the value for Y2 but increases the values for Y1 and Y3. With a good bushing, temperature correction would be expected to decrease the value obtained at 3 °C to yield its 20 °C equivalent value, as was the case for Y2. Tests conducted on a sister transformer did, in fact, confirm that temperature correction decreased the values for all three bushings, as expected.

After applying ITC to the results, the Y1 and Y3 bushing LF DF values at 20 °C are above the acceptance limit (> 2 times nameplate DF value according to IEEE guidelines). These two bushings were therefore assessed as ‘investigate’. The large difference observed between the corrected DF values at 1 Hz for bushings Y1 and Y3, which are more than five times higher than the value for Y2, is clear indication of an insulation issue.

When the results were discussed with the commissioning team, it was reported that the Y bushings had been improperly seated during transport and water had been observed in the plastic wrapped around them. They asked for action to be taken to remedy the problem and the transformer manufacturer decided to have the bushings returned to a maintenance facility for inspection, repair, and drying out. To confirm improvement, when the bushings were returned to the site (approximately six weeks after the original tests) they were retested at 5 °C. The results are shown in Table 7.

The ability to make early and conclusive decisions about insulation condition is critical for the reliability of HV electrical power systems.

Desig.	60 Hz					1 Hz		
		Cap (pF)	% DF				% DF	
	Test kV		Measured	@ 20°C	Δ @ 20°C	Test kV	Measured	@ 20°C
Y1	10.0	503.4	0.41	0.33	0.01	0.25	0.27	0.20
Y2	10.0	493.4	0.41	0.33	0.01	0.25	0.29	0.29
Y3	10.0	520.2	0.42	0.34	0.02	0.25	0.27	0.21

Table 7: Reconditioned RIP bushings – LF DF and 1 Hz DF results

Drying out improved Y1 and Y3, resulting in all Y bushings coming within 0.02 % of nameplate values. These tests allowed the Y bushings to be approved for use in this new transformer.

New transformer (2019) – 16 MVA 138 kV – elevated moisture

The presence of moisture in power and distribution transformers has a negligible effect on the LF DF value obtained at 20 °C. It is only when the moisture concentration is typically greater than 2 % that significant changes are seen in this value.

A new transformer was tested after assembly and before energisation. Dryness of the solid insulation is critical to ensure the longevity of the transformer and reliability during operation. Figure 4 shows the influence of temperature and moisture on the service life of a typical transformer [7], while Table 8 shows the LF DF and 1 Hz DF results obtained for the new transformer under test.

Designation	% LF DF ITC 20°C	% Moisture/contamination
H1	0.288	0.7
H2	0.349	2.8

Table 8: Interwinding insulation DF results

The LF DF values corrected to 20 °C using ITC are excellent. Nevertheless, reference to Table 2 will show that the 1 Hz temperature-corrected DF ITC corresponds to a 'good' transformer rather than a 'new' transformer as expected.

Full-spectrum DFR confirmed the presence of 1.6 % moisture in the solid insulation, and the need to dry out the unit before energisation. After seeing the LF, 1 Hz, and DFR test results, the customer requested a complete oil analysis. The physical-chemical analysis of the oil confirmed the presence of moisture (see Table 9) exceeding the acceptance level of 10 ppm suggested in IEEE Std. C57.106 Table 2.

Oil Sample #	Oil Temp (at time of extraction) °C	Water content (ppm)
1	26	15
2	26	16

Table 9: ASTM D1533 results

EHV Capacitive voltage transformer (CVT) – 765 kV

Instrument transformers and, more specifically, CVTs have no monitoring instrumentation mounted on them to detect any changes in the insulation condition. Oil sampling is only an option during planned outages, and it is not a simple process. EHV CVTs typically have no oil sampling ports available for each capacitive section (stack) and therefore accurate assessment of the insulation condition through non-invasive and non-destructive methods is extremely important for utility operators.

In this example, during planned maintenance on an A-phase CVT, a small oil stain was seen on the surface of the adjacent B-phase CVT C1-1 stack. As shown in Table 10, LF DF results are higher than the results for sister stacks, but these results on their own are not necessarily enough to take decisive action.

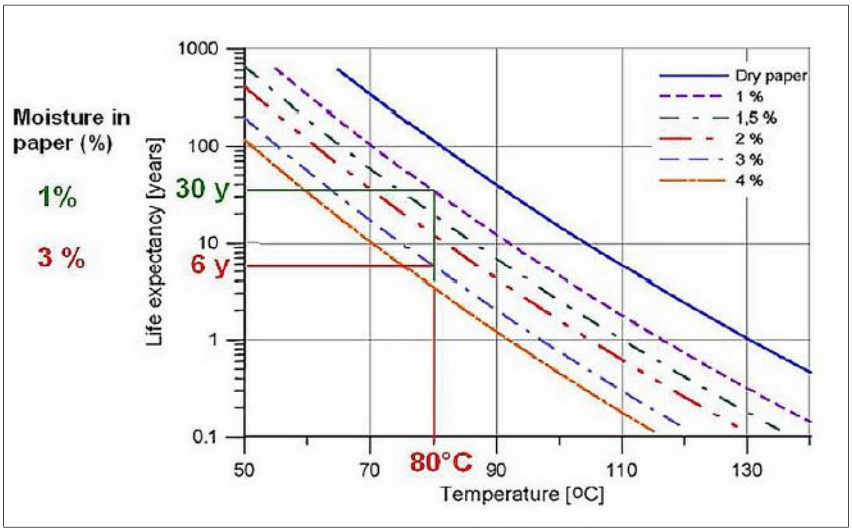


Figure 4: Influence of temperature and moisture on solid insulation lifetime [8]

Insulation	Porcelain Units	60 Hz		1 Hz	
		Test kV	% DF	Test kV	% DF
C1-1 (B1-POT)	Bottom	10.0	**0.25**	0.25	**0.59**
C1-2 (B2-B1)	Second		0.07		0.05
C1-3 (B3-B2)	Third		0.08		0.13
B1-4 (B4-B3)	Fourth		0.07		0.05

Table 10: LF and 1 Hz DF values obtained from B-phase EHV CVT

Once again, however, 1 Hz DF results confirm that the C1-1 insulation is degrading. Such degradation may result in catastrophic failure affecting adjacent equipment, the environment, and personnel working in the area. The unit was removed from service for investigation. Upon disassembly, a puncture was found in the C1-1 stack, which was allowing the oil to leak.

Conclusions and recommendations:

Insulation condition is the most important factor in determining the life expectancy of a transformer. The ability to make early and conclusive decisions about insulation condition is critical for the reliability of HV electrical power systems. The use of LF DF together with 1 Hz DF results, all properly corrected to 20 °C using the Individual Temperature Correction (ITC) algorithm, provides high sensitivity to changes in the insulation system of HV equipment.

The combined analysis of LF DF plus 1 Hz DF (ITC corrected) allows quantitative condition assessment of new and service-aged transformers and bushings as suggested by the authors in Tables 1 and 2. The 1 Hz DF with ITC assessment does not require trend analysis, although it is also possible to trend the results.

Traditional line frequency measurements and reference temperature correction tables based on averages may be misleading and using them may sometimes make it impossible to carry out reliable assessments in both hot and cold environments.

Supplementing traditional 10 kV LF DF measurements with 1 Hz DF (ITC corrected) testing marginally increases the overall time required for testing – usually by less than one minute – but it helps to extend the life of HV and EHV assets by providing reliable support for sound technical and financial decisions, or for future investigations and definitive analyses using DFR technology.

REFERENCES

[1] CIGRE TB 755, 'Transformer bushing reliability', CIGRE WG A2-43, 2019

[2] Güner I., Robalino D. M., Werelius P., 'HV and EHV bushing condition assessment – field experience', Proceedings of the 2016 CIGRE-IEC Colloquium, Montreal, Canada, 2016

[3] Robalino D., Alvarez R., 'Advances of Dielectric Frequency Response Testing for HV OIP Bushings', Proceedings of the CIGRE Session 48, paper A2-206, Paris 2020x

[4] Robalino D. M., Breazeal R… C., 'Evaluation of Distribution Class Transformers Using Narrowband Dielectric Frequency Response Measurements'. Proceedings of the IEEE 2020 Electrical Insulation Conference, 2020

[5] Perrier C., Roman Z., Kieffel Y., 'Monitoring of active part drying for instrument transformers by dielectric measurements', Proceedings of the CIGRE Session 48, paper D1-122, Paris 2020

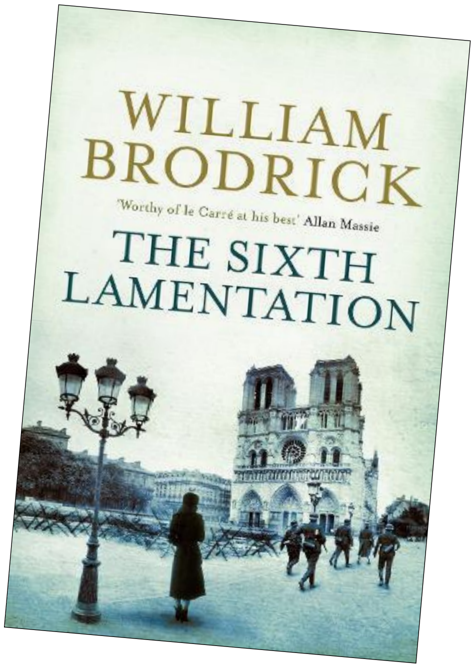
[6] Robalino D., Güner I.,'HV and EHV current transformer dielectric condition assessment and root cause analysis', Proceedings of the 2019 CIGRE Canada Conference, paper CIGRE-133, Montreal, 2019

[7] CIGRE TB 445, 'Guide for Transformer Maintenance', CIGRE WG A2-34, 2011

BOOK CLUB

The 6th Lamentation

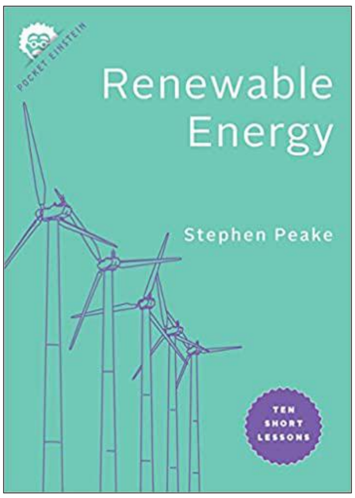
by William Brodrick



This is the first book in William Brodrick's Father Anselm series and one of the best I have read in the past two decades. Brodrick is a former Franciscan friar who left the order to become a barrister. His main character, Father Anselm, left the law to become a monk. The story interweaves various mysteries tied to the French Resistance in WWII. Seemingly unrelated events wind together through the pages to challenge the reader's perceptions of reality, betrayal, vengeance, and justice. Not only could I not put the book down, but I also slowed my reading as I neared the end because I did not want the story to be over – this is truly a 'hidden gem' of a book.

Graeme Thomson

Sales and Marketing Transition Leader



Pocket Einstein: Renewable Energy – ten short lessons

By Stephen Peake

This book is written by one of my university professors. It's a short book that covers the key issues and technologies for a sustainable energy future.

The book opens by exploring that energy is a mysterious property that has fascinated many for millennia, and that it is not a simple 'thing'. It goes on to look at the six major renewable energy sources of solar, wind, biomass, hydro, geothermal, and ocean; the technologies used and how they may play a part in the future of electricity generation.

It's summed up in a thought-provoking chapter on how collective human imagination on a global, political, engineering, and economic scale is needed to harness renewables and become low or zero carbon.

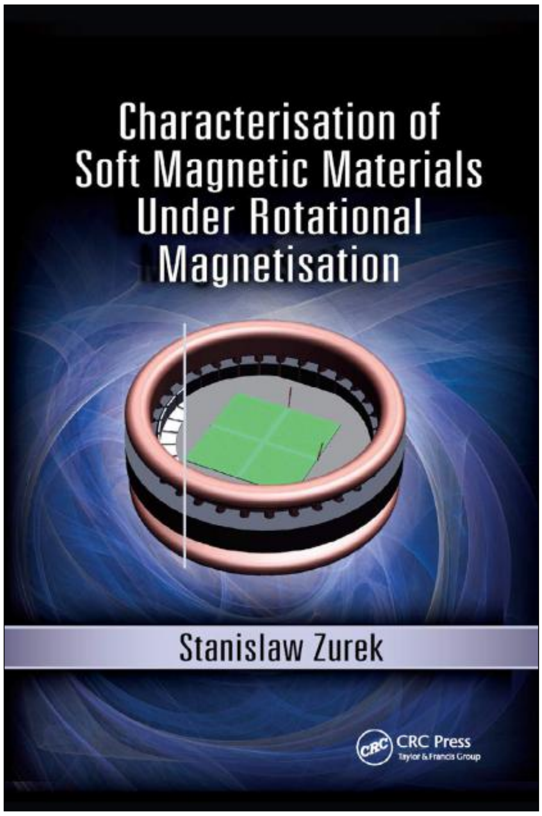
It's a small book that is useful for someone interested in renewables to get background information in an easy-to-read, jargon-free manner. It's written for a non-scientific audience, (although it does include some equations) and is highly topical with current climate change and carbon emission concerns. Although it's unlikely to add much value to existing engineers, it's still worth a read and adding to your book collection!

Amanda Kinbrum, engineering student

BOOK CLUB

Characterisation of Soft Magnetic Materials Under Rotational Magnetisation

By Dr Stanislaw Zurek



Soft magnetic materials are at the heart of motors and generators of every kind and, in these applications, they experience rotational magnetic fields. The response of the materials to these fields and, in particular, the magnetic losses involved have, over the years, received much attention. In this book, Dr Stan Zurek, who is Head of Research and Innovation at Megger, offers an up-to-date review of the measurement techniques employed to evaluate the performance of soft magnetic materials under rotational magnetic field. The rotational magnetic loss has a very peculiar behaviour such that it is much higher than under ordinary alternating magnetisation, but it reduces when the material approaches magnetic saturation. While theoretical aspects are covered in some detail, the focus throughout is on practical applications and examples, and the book features numerous "Practical Comments" that clarify the real-world implications of the topics under discussion.

The book opens with a brief introduction to magnetism, and proceeds to look at methods of measurement, sensing techniques and magnetising apparatus suitable for the rotational measurements, which are much more challenging from the technical viewpoint than those under alternating magnetisation. Later sections deal with the important but frequently neglected topic of measurement uncertainty analysis, where Zurek's stated aim is that the text 'clarifies many of the confusing concepts of uncertainty.' A comprehensive list of references, which includes numerous PhD theses, is provided and will prove invaluable for those looking for extended discussions on particular aspects of the material covered in the book.

Given its theme and scope, the book necessarily contains many mathematical equations, but they are clearly explained and thus the content remains accessible to those with a degree-level education in engineering, and can serve as an excellent reference for all readers. With this in mind, Characterisation of Soft Magnetic Materials Under Rotational Magnetisation can be strongly recommended as a useful, comprehensive and well-presented source of information that is often hard to find elsewhere, and as an excellent reference book for all those whose work involves measurement of magnetic properties of soft magnetic materials.

Keith Wilson, electrical engineer

"Books are the ultimate Dumpees: put them down and they'll wait for you forever; pay attention to them and they always love you back."

John Green, An Abundance of Katherines

How is Megger connected with reindeer herding?

Rickard Jonsson, Senior Advisor – Substation Business Development

Read on to find out how Megger provided support for a business that has been operating continuously for thousands of years.

Sustainability and growth have aspects that may seem contradictory – and sometimes they are. But the truth is that many possibilities open up when there is engagement and willingness to find solutions for a sustainable future. And that's exactly what happened recently when Megger Sweden AB needed to expand.

Megger Sweden AB has seen tremendous growth since 2007 when it became part of the Megger Group. Sales of its substation test and diagnostic equipment have almost tripled in recent years. Even though the company moved to new, larger facilities in 2012, these have proved to be too small to cope with recent growth and further expansion became essential.

Fortuitously, an opportunity arose to lease more space in the existing building, but it was necessary to remove fixtures and fittings belonging to the restaurant that had previously occupied the space before it could be reconfigured as offices. Some of the items were sold, but there remained professional walk-in cooling and freezer rooms. These were fully functional and in good condition, but they were definitely not items that would be easy for buyers to carry away! However, some Megger employees had an inspired idea and so they used their free time to carefully dismantle the rooms, including the temperature control equipment and the compressors.

They then made contact with a group of people in a Sami village in Ammarnäs, in the northern part of Sweden. After discussions, it was agreed that the cooling and freezing rooms would be donated to a young family who were going into the business of processing meat from traditional Sami reindeer herding. Truly green meat production! Re-using the surplus equipment will help to bolster the economy of this small and authentic mountain village, keeping old traditions alive.

The Sami are recognised by the UN as the only indigenous people remaining in Europe. They populate northern Norway, Sweden, Finland, and the Kola Peninsula in Russia, and their culture is very much centred on reindeer herding. Their tradition has always been to maintain balance and harmony in their relationship with

nature, and to ensure that little or nothing taken from nature goes to waste. In comparison, today's 'modern' societies have a lot to learn!

Ammarnas is in the Vindelfjallens Nature Reserve, which is one of the biggest nature reserves in Europe, covering 5,650 square km.

These photographs are from Ella-Kari Skum, for more information, you can follow her Instagram: https://www.instagram.com/ellakariskum/

Inductance measurements can be confusing – a deeper dive

Dr Stan Zurek, DSc, PhD

An apprentice asked: "Master, I measured the value of an inductance and it was X. Is this correct?" The master replied: "It is correct." Then the second apprentice said: "But I measured the same inductance and the value was Y, am I wrong?" And the master answered: "You are also correct. Indeed, you are both correct." The third student objected: "They cannot be both right if the two results differ!" And the master agreed: "You are also correct." All three students were perplexed…

Introduction

Inductance L is the property of an electric circuit which quantifies its ability to store energy in a magnetic field. The amount of energy stored is proportional to the value of inductance and to the square of electric current I flowing through it:

$$E = L \cdot I^2/2$$

Hence, a component with a higher inductance can store more energy for the same current. In inductors without a magnetic core, the maximum practical current is limited only by the heat dissipated in the wire.

Inductance is directly proportional to the effective relative permeability μr of the material enclosed by the coil:

$$L = \mu_r \cdot \mu_0 \cdot N^2 \cdot A/l$$

(Where μ_0 – permeability of vacuum, N – number of turns of the coil, A – area of the coil, l – length of the coil).

The relative permeability of air or any non-magnetic material is very low (μr = 1), and therefore the inductance is low for a given number of turns. An advantage of this is that non-magnetic materials cannot saturate magnetically, so inductors with a non-magnetic core have a very linear characteristic even for extremely large currents.

On the other hand, magnetic materials can have very high permeability (μr >> 1). They are used extensively for 'magnetic circuits', to concentrate and guide the magnetic flux, so that components can be designed to be smaller, more efficient, and less expensive. The operation of every 50/60 Hz power transformer is based on the presence of a suitable magnetic core. The same applies to motors and generators. Magnetic cores are designed to operate at as high a level of excitation as possible (to minimise size), but at a level low enough to avoid saturation. This way, maximum benefit can be gained from the presence of the core.

The windings in motors, generators, and transformers exhibit significant inductance, and certain electric, magnetic, and even mechanical faults can be diagnosed or detected by measuring the value of inductance for each accessible winding. The more accurate the measurement, the better the fault diagnosis. But what does it mean to measure inductance accurately?

Variation of permeability and inductance

Even though permeability of magnetic materials can be very high (typically μr > 1000 for electrical steel under nominal operating conditions), it is also highly non-linear and, at a sufficiently high current, the material saturates and permeability decreases significantly (contributing to such phenomena as the inrush current in transformers). The value of permeability depends on a plethora of factors, significantly more so on some than others, such as the few listed here:

- Level of excitation – at low excitation, the so-called initial permeability is low and increases significantly (see Figure 1) to some peak value (called maximum permeability) before dropping again towards saturation (not shown).
- Previous history of magnetisation – if the material has been exposed to a high magnetic field, for instance due to a fault current in the device, then some magnetisation remains in the core and affects the permeability (this is why some magnetic devices need to be 'degaussed' or 'demagnetised' before a measurement).

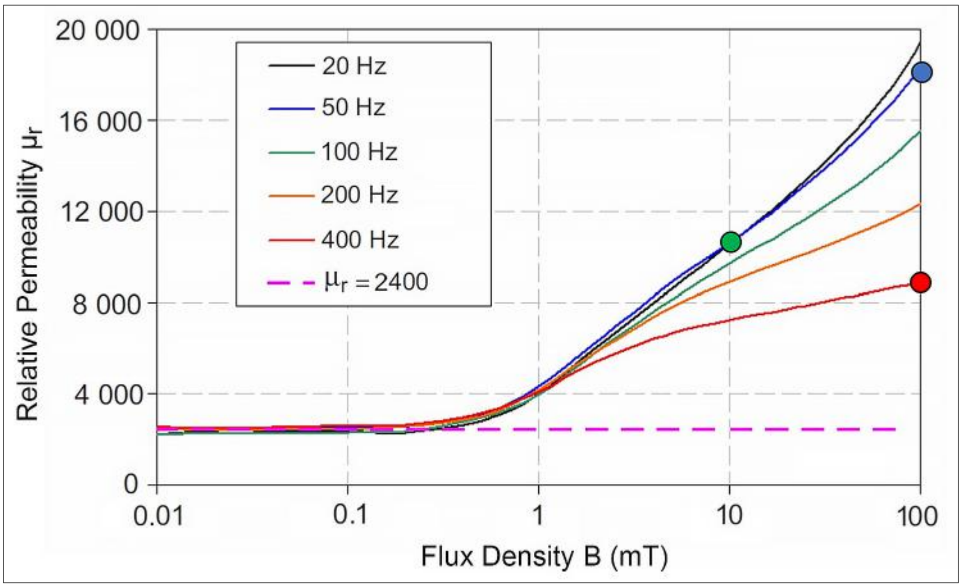


Figure 1: Typical magnetic permeability curves for grain-oriented electrical steel, at low excitation up to B = 100 mT. (Transformers are typically used with B = 1.5 T). For a given magnetic core, flux density B is a function of the applied current.

- Frequency of excitation – the internal magnetic structure (alignment of internal magnetic domains) behaves differently at different frequencies (Figure 1). At lower frequencies the differences are small, but with increasing frequency an additional phenomenon called the 'skin effect' (magnetic field cannot penetrate the inside of the lamination or the core) begins to play a dominant role, and the permeability reduces to a much smaller value.
- Mechanical stress – typically, compressive stress introduced during manufacturing (such as clamping of the laminations for assembly and mounting) lowers the magnetic permeability of the core.
- Temperature – the direct effect of temperature is rather small, but measurements performed on a still-hot motor can differ from those made on a cold machine, because different internal stresses will be acting on the magnetic core. Additionally, resistivity of the laminations will also differ, which might impact measurements at higher frequencies.
- 'Proximity effect' in the windings – this is an additional high-frequency effect linked to the skin effect, which leads to further non-linear behaviour of the current distribution in the windings. For this reason, in some high-power synchronous generators, the windings are made with continuously transposed conductors (CTC, or 'Roebel cable'). It is the winding itself that will behave differently at higher frequencies (rather than the magnetic core). The effect is more pronounced for windings with more layers.

The impact of each of these effects depends on the actual type of device and magnetic core, so it is not possible to define some hard rules as to which effect is dominant in a given case.

Useful effects of changing permeability and inductance

Some of the effects listed above give useful information about the condition of the device under test. For example, when sweep frequency response analysis (SFRA) is performed on transformer windings, the level of excitation and frequency range are standardised. Therefore, the excitation conditions are always the same, and changes between impedance measurements (which are affected by changes in inductance) can indicate that some physical change has taken place, such as a displaced winding, or damage to the core. Hence, a fault can be detected.

However, by looking at Figure 1, it is clear that the excitation level and the frequency range must be the same for comparable tests, because otherwise the permeability can differ significantly, and thus apparent differences in measurements may be found even where there are no changes in the magnetic properties, material, or device. The magnetic core could be demagnetised or degaussed on purpose to make sure that the same reference point is available for each test.

However, if the test is carried out for fault finding, then degaussing could be counterproductive, as it could mask the presence of a fault.

Transformer turns ratio tests rely on the assumption that the voltage ratio reflects the turn ratio. This approximation holds better for magnetic cores that have higher permeability. These tests are typically performed with a very small test signal, because it is not conveniently possible to generate nominal AC voltages for a high voltage transformer. This would require tens or even hundreds of kV which is not practical in a portable instrument, and would in any case be very costly. So, the excitation used during a test makes the core operate at a fraction of the nominal range (tens of volts) where, unfortunately, the permeability is much lower (Figure 1).

It is therefore beneficial to use a test configuration which generates higher flux in the core, because the permeability will be higher and the measurement more accurate. This is easily achieved by applying excitation to the winding with lowest nominal voltage. This winding will have a lower impedance and thus the same test voltage will result in a higher current, making the measurement more accurate. This approach is employed, for example, when using the Megger TTRU3, a true three phase transformer turns ratiometer. Using this approach, smaller differences can be discerned, and incipient faults can be diagnosed more reliably.

Changes in inductance are also used to diagnose faults in motors and generators. For example, all three phases should have very similar inductance, and if one winding is significantly different, this typically indicates some problem with the winding, the core, or even a mechanical problem with the bearings (because the shaft could be misaligned and thus affect the eccentricity of the air gap).

In motor testing, the inductance of the windings changes significantly when measured with the motor fully assembled (rotor in place) and with the rotor out. This is because of the difference in the amount of magnetic material in the magnetic circuit in the two cases. Air has a much smaller permeability than the rotor, so the effect on the measured inductance is large. However, the lack of rotor makes the stator more difficult to magnetise. Therefore, with the same test current, significantly less magnetisation is produced in the core and hence there is an additional change of permeability, as shown in Figure 1.

If the same test instrument is used to measure inductance of the windings in all three phases, the level of excitation and the test frequency will be the same and relative changes can be detected. These techniques are used extensively in testing motors and generators, for example with the Megger Baker ADX and the MTR105.

Not-so-useful effects

It is true that some frequencies are more suitable for detecting particular types of faults, whereas other frequencies are better for different purposes. But referring again to Figure 1, it is very clear that even if the same test equipment is used for performing measurements on the same winding – but at two different frequencies – the results will differ significantly, yet both measurements will be correct! For example, at an excitation of 100 mT (the maximum value on the horizontal axis), the permeability at 400 Hz is around 9000 (red circle), whereas at 50 Hz it is as much as 18 000 (blue circle). This is a 'factor of two' difference yet both values are correct. The difference in measurements is simply a result of the real behaviour of the magnetic core, as dictated by the fundamental properties of the magnetic material.

For this reason, direct comparison of absolute values measured with different test equipment is largely useless. This is because the level of excitation is almost certain to be different due to differences in the internal hardware design. For example, if a handheld LCR meter tests with 0.5 V excitation, rather than 5 V as might be used by a larger device, then for the 50 Hz curve in Figure 1, the measured value could be 10 000 (green circle) rather than 18 000, which is a difference of 80 %. It should be stressed that such a difference is not an error of the test equipment! Both values are correct, and also neither of them is correct, because there is no single value which can be used as a 'fixed' reference point, which applies under all conditions. Comparisons can be made only if the excitation is the same.

Why are different excitation levels used for different testers, even by the same manufacturer? One reason is the amount of power available. A handheld LCR will have

only small batteries (low power) and so the test signal will be limited. Also, test equipment may be designed with appropriate input protection. Such safety measures can put additional requirements on permissible levels of excitation and the way the signals are measured. For example, there could be an additional impedance in the internal measuring circuit which will affect the amount of available drive signal depending on the measured value of inductance.

Who is right?

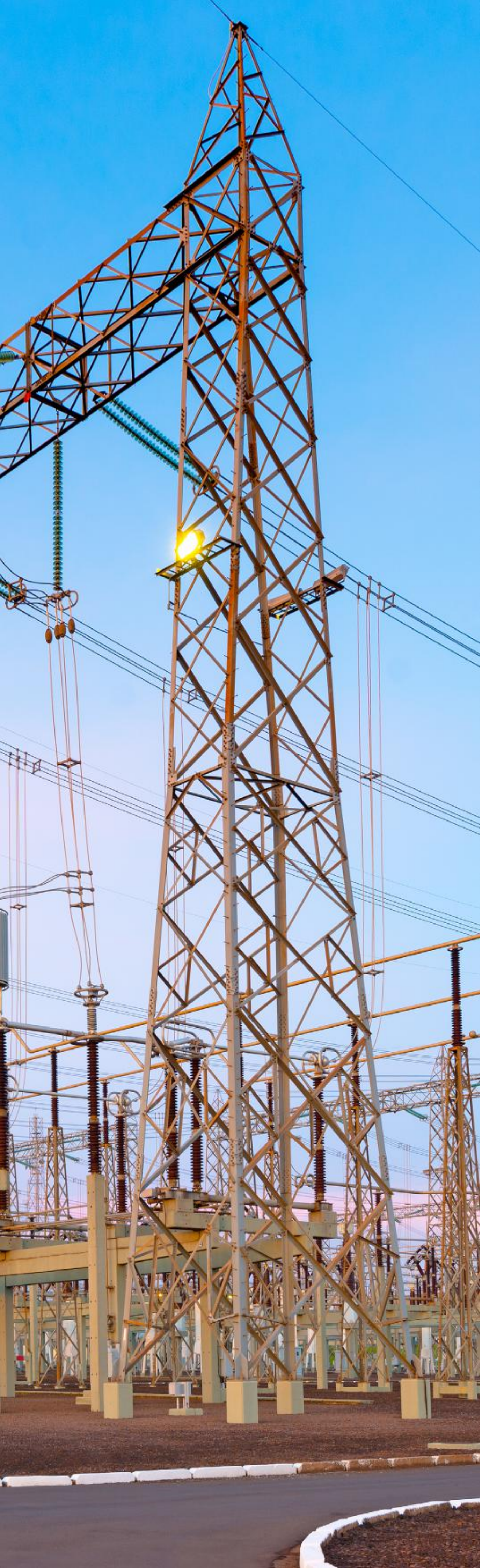
It is therefore very difficult to verify in the field which inductance measurement is 'correct', or which test equipment gives more 'accurate' readings. Even extremely precise measurements performed with a calibrator class instrument can and will differ significantly if the level of excitation is changed.

Worse still, even the accuracy specification of the instrument cannot be trusted, for precisely the same reasons. In addition, some manufacturers are known to be less than honest with the actual performance of their instruments, claiming an unlikely level of accuracy. Therefore, it is always advisable to use test equipment from a trustworthy manufacturer with well recognised brand, that is known to state measurement accuracy honestly, in line with the true capability of the instrument.

So, who is correct? The actual accuracy of a measurement can be only verified in laboratory conditions, not in the field, unless specially designed stable inductors are used and are measured at the same frequency. Nevertheless, relying on reputable test equipment from a trustworthy brand is always the best line of attack.

Watch our webinar on 'Inductance Test on a 3 Phase Motor'

Watch our webinar on 'Surge Test For Electric Motors Modern Variables for the Diagnostic of the Winding Insulation Condition'



Coupling Capacitor Voltage Transformers (CCVTs)

Volney Naranjo

Introduction

Instrument transformers perform the important function of providing windows on the power grid's electrical behaviour. Protection, control, and measuring devices require these 'windows' yet they also need electrical isolation from the grid as they function at much lower voltages and currents. Instrument transformers provide the solution; they are go-betweens that provide isolation by magnetically coupling secondary monitoring and measuring devices to the grid. There are several types of instrument transformers, but one of the most common on higher voltage transmission systems is the coupling capacitor voltage transformer (CCVT).

CCVTs are devices capable of dual function. One function they can perform is to provide highly accurate voltage conversion for measuring devices, protection relays, and automatic control systems, while the other is to couple high-frequency power-line carrier (PLC) signals onto the transmission system for communication and control purposes.

CCVT construction

In terms of construction, a CCVT is both a capacitor voltage divider (CVD), and an electromagnetic unit. The capacitor divider is an assembly of capacitor elements that steps down the primary high or extra high voltage to an intermediate voltage level (typically 5 to 20 kV) and the electromagnetic unit (EMU) steps the voltage further down to the required output level, which is usually below 120 V. The EMU typically incorporates trimming windings to ensure that the required levels of accuracy are achieved.

Essentially a CVD is composed of two capacitors, C1 and C2, although in practice C1 either may be made up of a single capacitor stack or several capacitor stacks connected in series. When there are several stacks, these are designated C1-1, C1-2, etc., or in infrequent cases, B1, B2, etc. Every CVD has, as a minimum, a C2 and a C1-1 (or B1) capacitor. When only these two capacitors are present, the CCVT is referred to a single-unit or single-stack device. The C1-1 capacitor is located directly above the C2 in the bottom-most housing (insulator) of the device, and the appearance of the CCVT resembles a terminal box with an insulator on top. A two-unit CCVT, where C1 is made up of C1-1 and C1-2, has two insulators with C1-2 in the top insulator and C1-1 and C2 in the bottom insulator; a three-unit CCVT has three insulators with C1-3 in the top insulator, C1-2 in the middle insulator, and C1-1 and C2 in the bottom insulator, and so on.

The EMU, in addition to an inductive voltage transformer, contains a tuning circuit and protection against ferro-resonance (Figure 1). The tuning circuit is a reactor that compensates for magnitude errors and phase shift caused by the CVD, making it possible to have the CCVT with a characteristic on the secondary side that is similar, in terms of error and phase deviation, to that of a purely inductive voltage transformer.

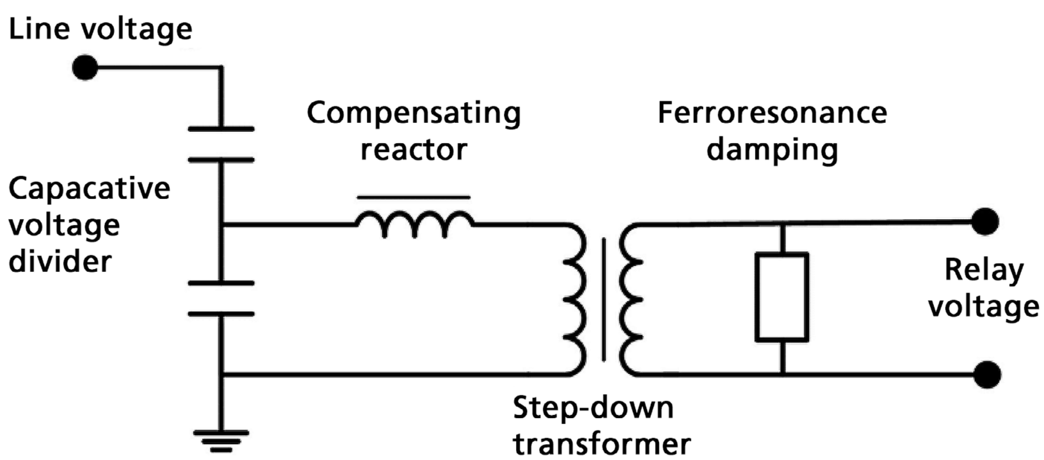


Figure 1: Typical CCVT circuit diagram

In some circumstances, the CVD capacitive reactance can resonate with the magnetizing reactance of the inductive voltage transformer and the compensating reactor cores. This unwanted effect is called ferro-resonance and can give rise to large and damaging voltages across the inductive and capacitive elements. To avoid this, a ferro-resonance damping circuit is installed in parallel with one of the secondary windings.

Testing CCVTs

Compared with purely inductive voltage transformers, at voltages of approximately 72 kV and above, CCVTs are lower cost components. Therefore, if replacement cost was the only consideration, extensive testing would be hard to justify. However, single or multiple failures can occur in the capacitor stack causing a decrease in ratio and an increase in phase error. Degradation of the dielectric in the capacitor stack can also lead to a catastrophic equipment explosion. The EMU can suffer degradation because of aging, exposure to vibration, or for other reasons, resulting in reduced accuracy or insulation failure. As an aid to guarding against these eventualities, testing is fully justified. Various test techniques, as described in the following sections, can be used.

Insulation tests

Capacitance and line frequency power factor (PF) measurements should be made routinely on CCVTs. Insulation power factor tests are most informative when the amount of insulation included in the test is minimised. For this reason, tests are performed on each individual component of the CVD (e.g., C1-1, C1-2, …, and C2). Typical overall PF values range from 0.2 % to 0.5 %, but power factor values under 0.05 % are normal depending on the insulating materials used for construction.

C2 testing is generally thought to be more difficult because isolating the C2 component is not always straightforward. C2 is ‘bookended’ by a potential terminal and a carrier terminal. The carrier terminal, located in the ‘terminal box’ (when available), provides access to the bottom of C2. This terminal, labeled ‘HF’ by some manufacturers, is identifiable and easy to access in most CCVTs. This is not always true of the potential terminal, which is located between C2 and C1 (or between C2 and C1-1 for multi-stack CCVTs).

On older style CCVTs, the potential terminal is typically accessible. However, for modern CCVTs such as those supplied by Trench, the potential terminal is inaccessible. Even in these cases, however, C2 can still be tested. CCVTs have a potential ground switch that provides the means to ground the potential terminal. With the potential ground switch closed, the carrier terminal can be energised, a low voltage lead connected to the line terminal (top of C1), and a C2 test performed in the GST-guard mode. Note that the carrier terminal must be disconnected and isolated from ground potential and the drain coil (also, if applicable, from any accessory leads) for the C2 test. In addition, the test voltage (typically 500 V) used to energise the carrier terminal must not exceed the voltage rating of the terminal. In summary:

- Carrier output terminal to be disconnected from ground
- Grounding switch: CLOSED
- Carrier assembly ground switch: OPEN
- Test mode: GSTg-R
- Maximum test voltage: 2 kV RMS

Capacitance test results should be compared with nameplate values and to other previous capacitance test results, if available. Unfortunately, such comparisons often result in confusion. The CCVT nameplate, affixed to the base box, frequently provides the rated design capacitance value CN (also called CT). CN for a capacitor divider is the resultant capacitance calculated from the C1 and C2 measurements by using the formula (C1*C2/ (C1+C2)). On Trench CCVTs, CN is found on another smaller nameplate attached to the top of the first (i.e., bottom) stack. This represents the capacitance of the entire bottom stack, or C1-1 in series with C2. It is also important to note that the nameplate data may give design values rather than measured values. This is particularly likely if the nameplate values are round numbers.

The nameplate typically includes the C2 measured value. However, for a two-unit CCVT, C1-1 and the C1-2

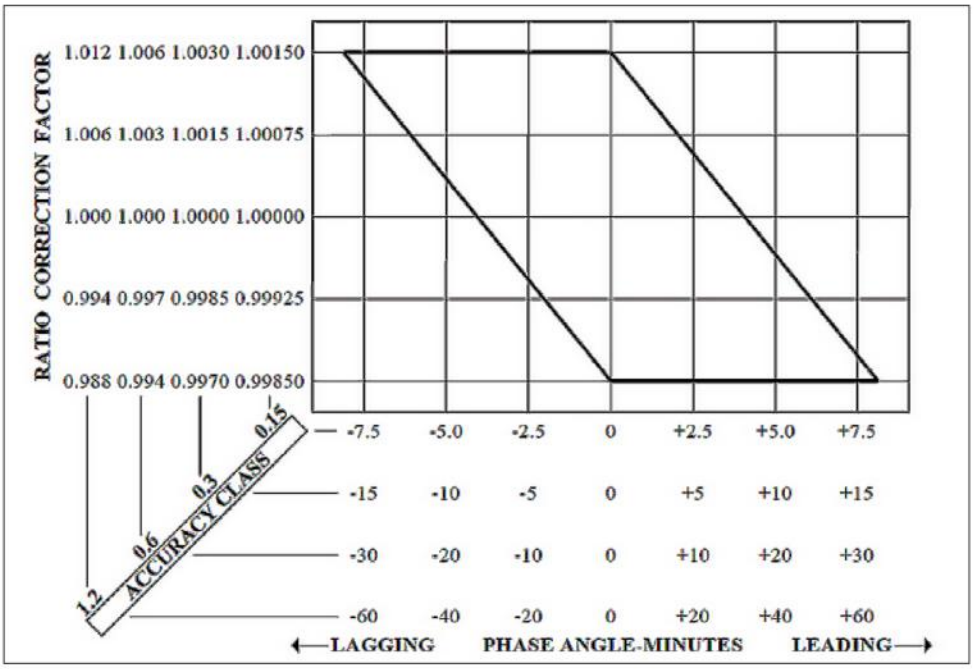


Figure 2: Limits of accuracy classes for voltage transformers for metering (from IEEE Std. C57.13-2016)

capacitance values may not be shown separately on the nameplate; often just the C1 capacitance is given. If testing a three-unit CCVT, then the C1-3 capacitance value may be stamped on another small nameplate affixed on the top-most insulator stack. Capacitance test results should be within 1 % – 2 % of nameplate values and previous measurements.

'More searching' insulation diagnostics, including narrowband DFR testing, on CCVTs

The basic insulation tests just described can be usefully augmented by adding PF measurements at different frequencies and a tip-up test. A PF test at 1 Hz specifically, provides a better indicator of developing issues, facilitating early detection. 1 Hz PF is particularly sensitive to moisture contamination, a commonplace CCVT failure mode. Narrowband DFR tests include power factor tests at several discrete frequencies, including 1 Hz up to 505 Hz.

The tip-up test looks at how the PF value changes as the test voltage increases. If the PF value increases as the voltage increases, this may indicate a mechanical problem in the capacitance stack. Tip-up tests can be performed on the overall stack or, as an aid to localising problems, on the individual capacitors that make up the stack.

Ratio tests

A basic ratio test can be carried out by exciting the primary side of the CCVT with a 10 kV source and measuring the secondary voltage with a digital multimeter. However, this supplies no measurement of phase deviation, which is required to validate the accuracy of the CCVT.

Ratio validation to confirm that the performance of the CCVT matches its nameplate values for ratio and phase accuracy requires the use of specialised test equipment. For this reason, it is not commonly carried out in the field. If validation testing is performed, however, the results should fall within the appropriate accuracy parallelograms given in standards, such as IEEE C57.13-2016. One such example is provided in Figure 2, wherein a CCVT is used for metering purposes.

Testing in practice

Validation of insulation, ratio and burden at rated voltage requires large and heavy test equipment used in conjunction with expensive instrumentation. For this reason, these tests are commonly used during the manufacture of CCVTs but are impractical in the field. Nevertheless, field measurements of the CCVT burden, as an aid to ensuring that the burden rating of the device is not exceeded, are possible.

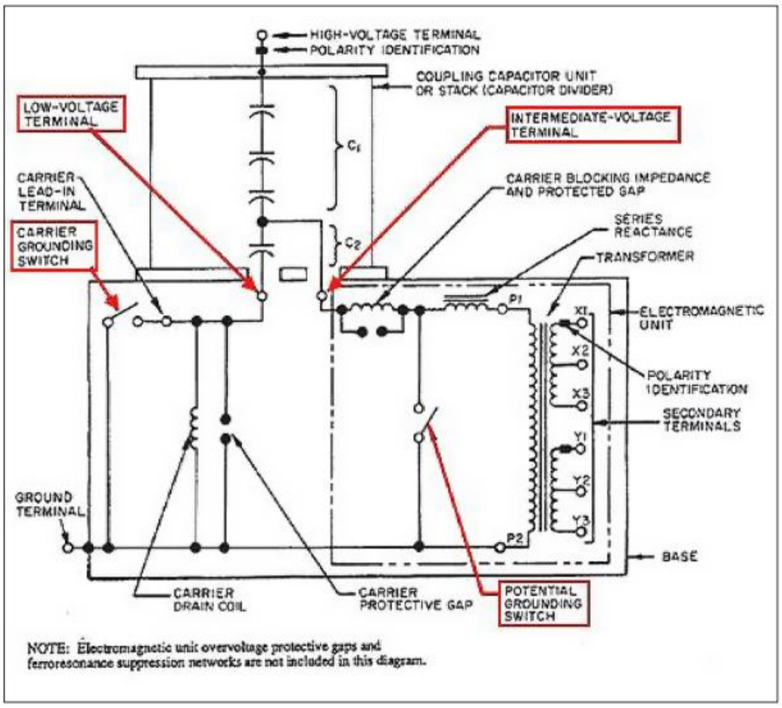


Figure 3: Typical CCVT with carrier coupling accessories (From ANSI C93-1)

Basic insulation testing, PF tests at 1 Hz, and tip-up testing can be performed with the Megger Delta4000 test set and, with the addition of a DMM, a basic ratio test can be carried out. Ratio validation to an accuracy of ±0.1 % can be carried out with the Delta4000 test set and an accessory. The Megger MRCT test set can also perform basic insulation testing and ratio validation to an accuracy of ±0.1 %, with the added benefit of being able measure the overall burden of the CCVT, thus ensuring that the burden rating has not been exceeded.

CCVT construction varies between manufacturers, models and year of fabrication. Knowledge of the construction is critical when deciding what and how to test. As mentioned previously, some CCVTs are equipped with a potential grounding switch located below C1, at the intermediate voltage terminal (IVT), and a carrier grounding switch below C2 at the low voltage terminal (LVT), as shown in Figure 3. In some CCVTs, however – mainly modern types – the low voltage terminal may not accessible. Understanding the construction characteristics and location of the IVT and LVT is therefore important when determining appropriate connections for testing and deciding whether the ground switches need to be open or closed for the required measurements to be made.

Conclusion

Virtually all modern power networks incorporate CCVTs, and for the continued safe and dependable operation of these networks, it is essential that the CCVTs perform reliably, delivering consistently accurate results. Regular testing is the key to ensuring that this is achieved. As this article has shown, most types of tests can readily be carried out on CCVTs in the field, provided that the construction and configuration of the CCVT is properly understood, and that an appropriate test set is used. Hopefully, this short article has provided insights into both areas but, if further advice or guidance is required, the Megger technical support team will be pleased to help. For contact information, please visit megger.com and choose the dedicated site for your country or location.

Watch our webinar on 'Test Field Practices for Testing Instrument Transformers - CTs, VTs, CVTs'

User-driven development in circuit breaker testing

Niclas Wetterstrand and Nils Wäcklén

Circuit breaker analysers are key items in the toolkits of the hard-pressed test engineers in the power sector. There is no shortage of analysers on the market, but do they really meet users' needs? Megger asked them. Niclas Wetterstrand, Megger's Industry Director Utilities – Protection, and Nils Wäcklén, product owner of circuit breaker products at Megger, report on their answers and explain how these guided the development of an innovative instrument that sets new standards for speed, convenience, and safety in circuit breaker testing.

Our customers told us that the vast majority of circuit breaker tests they perform these days are standard measurements of contact resistance and main contact timing. There are two main reasons for this. First, circuit breaker reliability has improved over the years, which means that asset owners are now asking for less information to validate correct operation. Second, time and cost pressures have driven the adoption of a streamlined set of measurements, which are sufficient to confirm that the asset is working as intended, but no more.

In the past, there was time to acquire additional information by making a wider range of measurements, but now tests are often carried out by a subcontractor who gets paid a fixed amount per circuit breaker. This leaves no opportunity to carry out measurements that have not been explicitly requested. What's needed today is the fastest possible way to get the job done, and this includes everything from collecting the test equipment from the stores, through to the test itself, and right up to returning the equipment to the stores.

With this in mind, Megger has developed a new circuit breaker analyser – the EGIL200 – to provide standard measurements that include main contact timing, PIR contact timing, auxiliary contact timing, station voltage and coil current. All these measurements can be made without the need to disconnect and reconnect the instrument. Additional facilities, which can be activated if and when needed, include motor current and motion measurements.

Main contact resistance (and PIR resistance value measurement) is also included in the standard measurements and is acquired with an external unit. Some instruments from other suppliers integrate contact resistance measurement within the main instrument and this might initially seem an attractive feature. Indeed, during discussions with customers, many asked for this, but after the pros and cons had been discussed, almost all changed their minds to favour a separate lightweight unit.

The only advantage of a built-in resistance measurement is that when they bring the instrument to the test location, users know they have everything they need to conduct the full range of standard measurements. However, this can easily be arranged when a separate resistance measurement unit is used simply by providing a transport case that will accommodate both this unit and the main instrument. On the other hand, the integrated solution has many disadvantages. For example, it means extra weight in the main unit, it limits options for performing measurements on items other than circuit breakers, and it requires the use of longer cables that add even more weight.

Another topic which came up frequently in the discussions with users is why it often takes around an hour to figure out how to connect the test cables, when actually performing the measurements takes only a few minutes. We have addressed this issue by looking carefully at every aspect of the design of the instrument

and its associated accessories, including the transport case, cable bags, cables, test preparation, connection guidance, result evaluation, report creation, etc. We have found, for example, that with well thought out cable bag and cable design, colour coding and connection support, big savings can be made in overall testing time.

In particular, the cabling arrangements for our new instrument are convenient and practical for field use. Since users have told us that cable wear is an issue, the cables are designed to be durable, with thicker insulation and liberal use of cable sleeves. The cable bag has also been optimised to make it easy to carry while keeping the cables properly organised. For further convenience, the bag is equally suitable for use as a backpack, or as a handbag.

Test preparation and setup are other areas that our users told us were important and we've made a lot of effort to streamline these processes. Many instruments have a setup procedure that focuses on the test channel rather than the test object. By focusing on the test object and what needs to be measured, we have been able to reduce setup to a few clicks, with big time savings. Furthermore, if a similar asset of the same design needs to be tested, the basic tests can be repeated without the need for further settings.

Another thing we discovered from our discussions with users was that, in this era of outsourced breaker testing, the test engineer often does not have a specific test plan relating to the asset under test. Most often, the engineer will arrive on site and set up the test on the fly. Once again, this calls for a fast and streamlined setup procedure. To provide this, we involved a range of customers in trials of user-interface mock-ups during an early stage of the development project for our new instrument. We found that the biggest challenge was to provide a streamlined setup for basic measurements with a minimum of settings, while not unduly limiting the user's flexibility.

We have achieved this by arranging for our new instrument to start with a quick-test menu, where the user selects the type of breaker to be tested, what needs to be measured and what operation should be performed. Initially, a connection screen is displayed to show how the test connections should be made and to confirm that they are correct. After that, the measurements are performed using the results and analysis screen. Last but not least, the instrument generates a report to provide evidence that the test was performed in line with contractual requirements and that either the circuit breaker meets its specification, or there is an issue that needs action or further investigation.

The option to produce professional reports with recommendations for further action without having to spend hours working on them in the office or hotel room was something engineers particularly wanted as an aid to reducing their workload. In addition, accurate and professional reports have been shown to give the contractor higher credibility with network owners and, in most cases, if the report recommends further action, the contractor is asked to provide it, which generates extra income.

As we have explained, the development of Megger's new EGIL200 has been driven by the input from users, which ensures that it accurately and efficiently meets the requirements of today's engineers. This means that EGIL200 is not just another test instrument, it's a long-term partner which will help and support those who commission and maintain circuit breakers during difficult times as well as good times.

Primary injection testing of low voltage circuit breakers

Megger North America

Technical Support Group (TSG)

> **Primary injection testing has the important benefit that it tests all parts of the protection system, whereas secondary injection testing tests only the trip unit.**

Too important to leave to chance

Circuit breakers used in low voltage (LV) applications include air, insulated-case, and moulded-case types, as well as miniature circuit breakers. They typically function as the incoming device on low voltage switchboards. In the event of an overload or short circuit, current sensors in the breaker measure the increased current and send feedback to the trip unit.

The trip unit is the brain of the circuit breaker; its built-in logic determines how the circuit breaker operates. Many moulded-case circuit breakers (MCCBs) now incorporate electronic trip units but, in smaller frame sizes, these may not be as sophisticated as the trip units found in air circuit breakers. Older MCCBs may have electromechanical thermal and magnetic trips.

To properly isolate a fault, the circuit breaker must act in a timely and reliable manner. Failure of a circuit breaker to do this can result in a widespread outage area, loss of revenue, damage to equipment, injury and, in a worst-case scenario, loss of life. Hence, it is essential to carry out regular maintenance on the circuit breaker at regular intervals throughout its service life. Typically, a preventative maintenance program will include a range of activities, but this article focusses on the electrical testing of LV circuit breakers.

Testing low voltage (LV) circuit breakers

The ANSI/NETA MTS Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems recommends the electrical tests detailed below as part of maintenance testing on LV circuit breakers. The first two tests assess the integrity of the breaker's original construction. Tests in the third group are functional checks, not only of the breaker itself, but also of the whole protection system, including current sensors, trip unit, and tripping mechanism, as well as the internal wiring and connections.

Resistance measurement

By measuring the contact resistance on each pole of the circuit breaker, it is possible to check for contact-related issues that may interfere with the circuit breaker's ability to conduct current adequately. For instance, contact erosion over time can lead to heating issues that eventually result in breaker failure. Contact resistance values should typically be in the micro-ohm range, although in the case of MCCBs with low current ratings, values can be around 1 mΩ. As current ratings increase, contact resistance values tend to be smaller. Similar values should be measured on all poles of the breaker, with deviations greater than 50 % warranting investigation. Breaker manufacturers can provide information about expected contact resistance values for their products.

Insulation resistance measurement

Insulation resistance can be measured between phases, from each phase to ground with the breaker closed, and across each pole with the breaker open. The measured values will depend on the type of breaker and the application, but any values less than 1 MΩ definitely indicate a need for further investigation.

Primary injection testing

Primary injection testing involves injection of current through the poles of the circuit breaker to verify that the breaker will operate according to the trip unit logic. This contrasts with secondary injection testing where the test current is injected directly into the trip unit. Primary injection testing has the important benefit that it tests all parts of the protection system, whereas secondary injection testing tests only the trip unit. However, primary injection requires higher test currents and hence larger test sets (for a more detailed discussion of primary versus secondary injection testing, see the December 2019 issue of Electrical Tester, which is available on the Megger website).

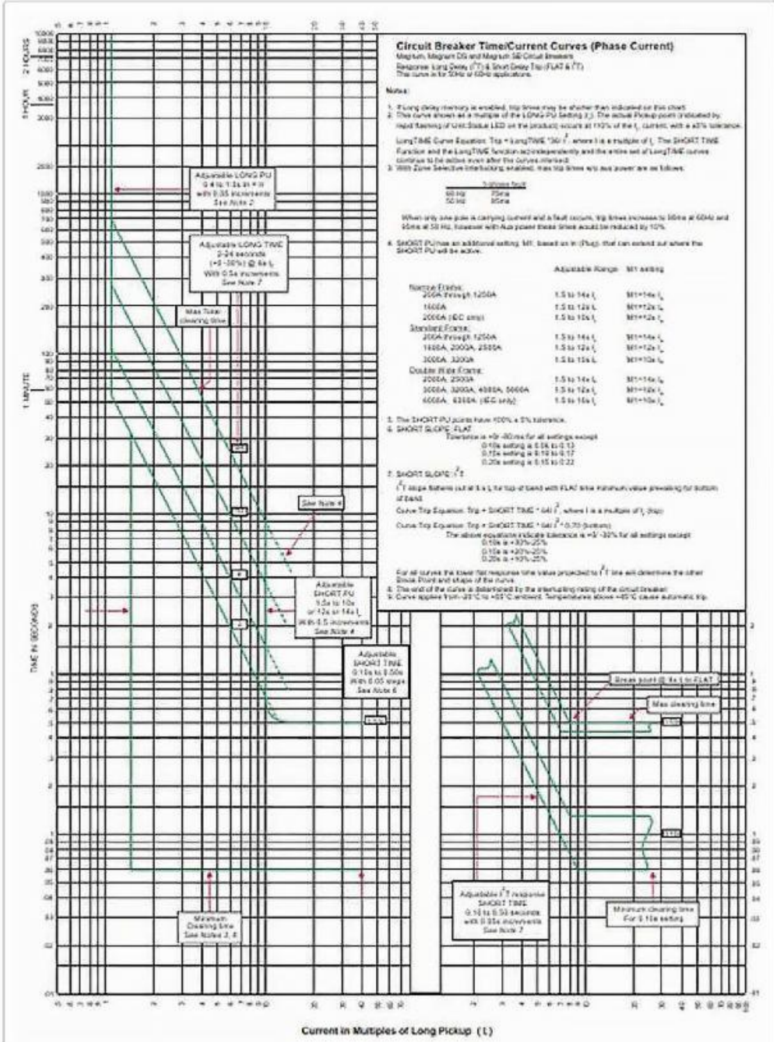


Figure 1: Sample time-current curve

Primary injection testing for LV circuit breakers involves four tests:

1. Long-time delay and pickup. A breaker's long-time delay characteristic provides overload protection. The pickup value is typically set to the overcurrent protection device's continuous current rating. The test current injected is usually three times the long-time pickup value. The test current is injected successively through each pole, and the trip time is recorded for each. The results are validated by referring to the time-current curves provided by the manufacturer. To avoid unnecessary tripping caused by short duration overcurrents, the trip time is usually in the order of seconds.

2. Short-time delay and pickup. A breaker's short-time delay characteristic provides protection against short-circuit or high current fault conditions. An intentional delay is provided for coordination or selectivity with other protection devices. The short-time pickup setting is higher than the long-time pickup setting. The test current typically used is 1.5 to 2.5 times the short-time pickup setting. The test current is injected successively through each pole of the breaker, and the trip time is recorded for each. The results are validated by referring to the time-current curves published by the manufacturer (Figure 1). The trip time recorded is typically in the order of milliseconds, or a few cycles of the supply.

3. Instantaneous pickup. The instantaneous trip characteristic provides protection against short-circuit or fault conditions but doesn't include any intentional time delay. In this test, pulses of current (pulse duration between 5 and 10 cycles) with steadily incrementing magnitudes are injected through each pole until the circuit breaker trips. The starting pulse is set at around 70 % of the expected pickup. The value of the pickup at which the breaker trips is recorded. Manufacturers typically allow a tolerance of ±10 % to ±25 % on the pickup.

4. Ground-fault delay and pickup. This characteristic provides protection against ground faults. The ground-fault pickup

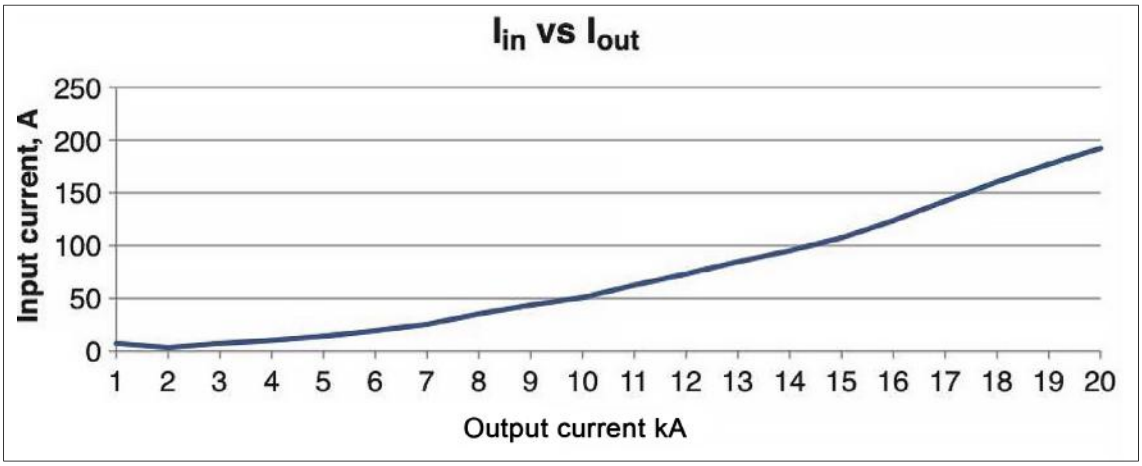


Figure 2: Input current of primary injection test system as a function of output current

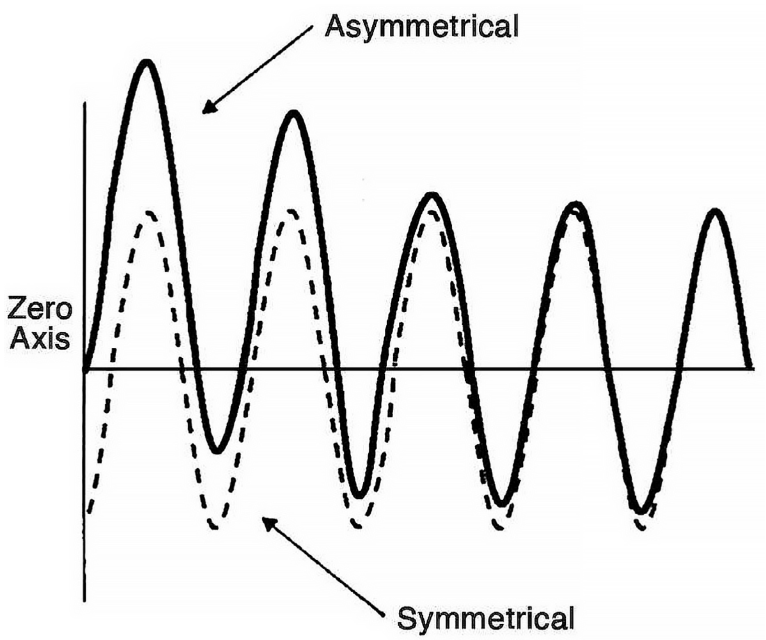


Figure 3: DC offset as shown in NEMA AB-4

is typically a fraction (20 % to 60 %) of the continuous current rating of the overcurrent protection device. The test current injected is typically between 1.5 and 2.5 times the pickup. This test is required for many service entrances by NFPA 70, National Electrical Code (NEC 230.95).

Primary injection test procedure considerations

Several factors, such as the input specifications, test connections, DC offset, and ground fault protection on the trip unit, must be carefully considered if a primary injection test is to be carried out successfully.

Input specifications

The input voltage will determine the output of the primary injection test set. It is essential that the input voltage is within ±5 % of that specified by the manufacturer of the test set. In addition, the input breaker must be sized appropriately. As the test set is operated at higher currents, higher losses occur. As a result, the relationship between the input current and the output current for primary injection test sets is exponential (Figure 2). When working with a high current test set, it is important to install an input breaker that is sized to handle the input power required for the maximum test currents that will be used for testing the breakers.

The connection leads between the input voltage supply and the input voltage terminals on the test set also must be suitably sized and short in length. Long connections can result in a drop in voltage at the input terminals, thus affecting the performance of the test set.

Test connections

As high current test sets have a very low open-circuit voltage (typically 5 to 10 V), the maximum output from the high current source is limited by the circuit impedance, which in turn primarily depends on the impedance of test connections. For breakers with low current ratings, the test connections are typically made using cables, and it is important that these connections have an adequate current rating. This may necessitate connecting multiple cables in parallel but, in all cases, the shortest possible cables should be used. Where possible, the cables can also be twisted together to further reduce the impedance of the circuit.

During instantaneous trip tests, errors can occur because of DC offset in the current pulse.

High current test sets used for testing draw-out-type circuit breakers use stab sets for connections to ensure the circuit impedance is as low as possible. Stab sets of various types are available to suit different types of circuit breakers.

To overcome the problem of high circuit impedance while testing at relatively lower currents, some high current test

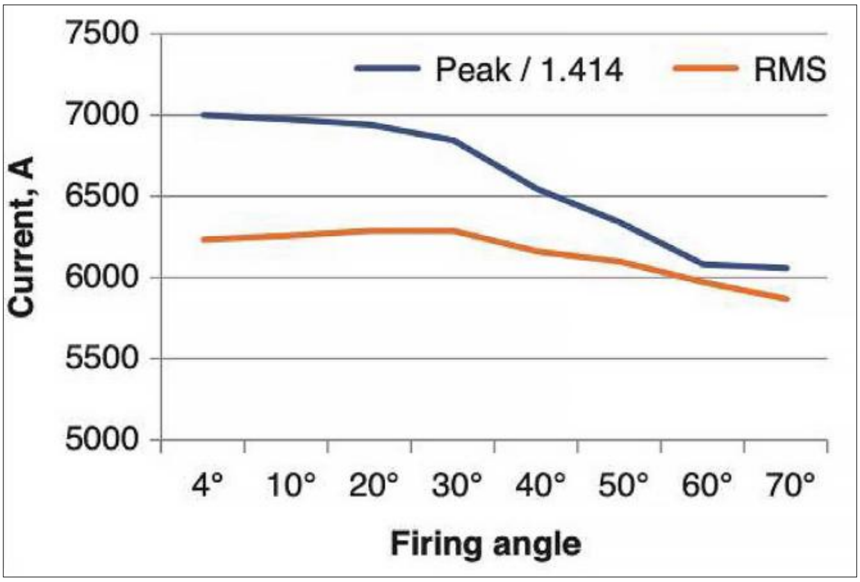


Figure 4: Difference between peak/√2 and true RMS values observed in output current for various firing angles

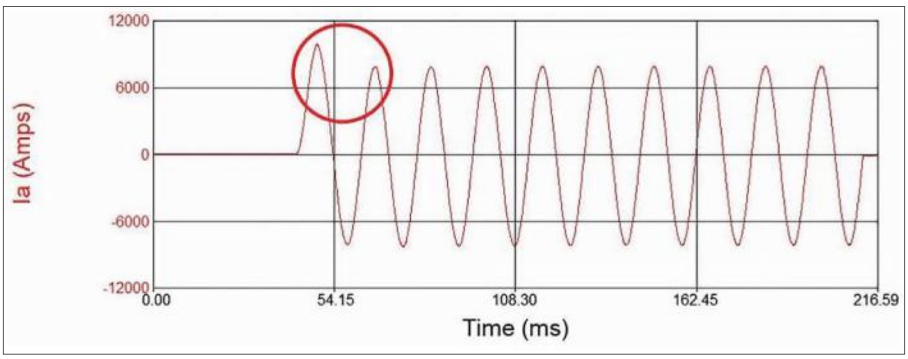


Figure 5: Current waveform at firing angle of 4 °

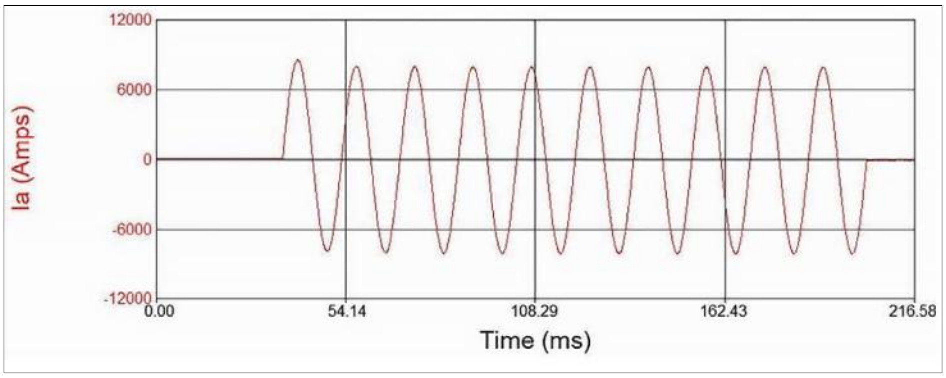


Figure 6: Current waveform at firing angle of 70 °

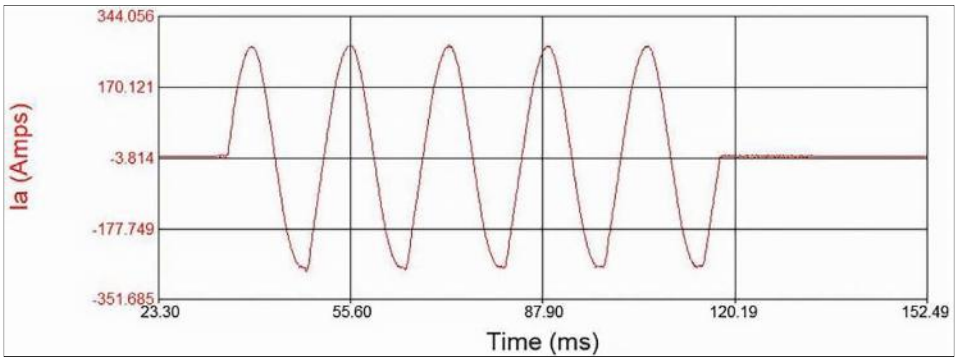


Figure 7: Current waveform with automatically adjusted firing angle

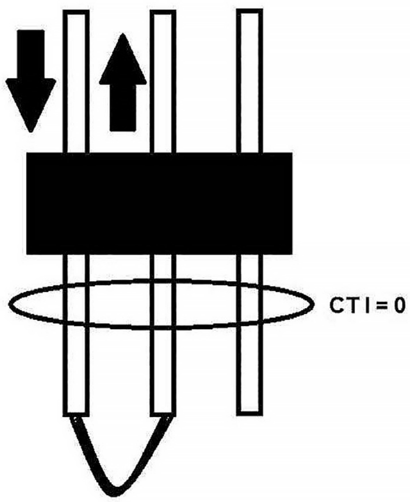


Figure 8: Two poles connected in series to bypass ground-fault protection

sets have a modular design that allows multiple current sources to be connected in series to achieve a higher open-circuit voltage.

DC offset

During instantaneous trip tests, errors can occur because of DC offset in the current pulse (Figure 3).

The asymmetrical nature of the first few current cycles results from a high X/R ratio in inductive circuits. The DC offset can be minimised by manually or automatically adjusting the firing angle (the point on the voltage wave at which the output is energised). A measure of the DC offset is the difference between the peak/√2 and RMS values (see Figures 4, 5, 6, and 7). For a perfectly sinusoidal waveform, these values would be equal.

Ground-fault protection on trip unit

When testing circuit breakers equipped with trip units that provide ground-fault protection, it is necessary to disable the ground-fault function while running the other

tests, as the currents involved in these tests tend to be higher than the ground-fault pickup. Some trip units provide an option for disabling ground-fault protection, but breakers where this option is not available can still be tested by injecting the test current through two poles connected in series, as shown in Figure 8.

Selecting a primary injection test set

Primary injection tests have been carried out for decades and traditional technology is still relevant, although it is now augmented by newer developments that provide useful benefits. Primary injection test sets are available in a range of sizes depending on their output current rating. The test sets used for testing power circuit breakers are typically large and weigh hundreds of pounds/kilos.

Primary injection test sets that operate at relatively low currents can be mounted on wheeled carts, which facilitates testing outdoors in substations. Having a portable test set also helps if testing needs to be done in elevated or difficult-to-access locations. Portable primary injection test sets can deliver currents up to a few thousand amps.

As previously mentioned, primary injection test sets sometimes feature a modular design that gives the tester some flexibility in achieving different output currents and voltages. Higher currents can be achieved by connecting multiple sources in parallel, whereas a higher open-circuit voltage can be achieved by connecting multiple sources in series. Some primary injection test sets include additional features like secondary measurement channels, which allow them to be used in other applications, such as CT ratio testing or the measurement of circuit parameters (Z, R, etc.).

Traditionally, the output current of primary injection test sets has been controlled manually, but newer technology permits automatic current control. This eliminates the additional step of adjusting the output setting to achieve the desired current prior to starting the test, as well as the need to manually adjust the output current to maintain it at a constant level during a long-time test.

A further useful feature is software that includes a library of time-current curves from various manufacturers. If the test set incorporates software of this type, the user doesn't need to spend time finding and interpreting the manufacturer's published time-current curves to determine the trip-time limits for specific tests.

The wide variety of primary injection test systems now available gives users the opportunity to make an informed choice of equipment to suit their own individual requirements, based on multiple factors such as portability, ease of use, size of breakers to be tested, and the test currents required.

Conclusion

Primary injection testing can be seen as the 'gold standard' for low voltage circuit breaker testing as it verifies that every part of the protection system is functioning correctly. This includes the current path through the poles of the circuit breaker, the current sensors, the wiring, the trip unit, and the breaker operating mechanism. It is true that primary injection testing can be somewhat more difficult to implement than secondary injection testing, and that it often requires larger test sets. Modern test equipment helps to minimise the impact of these issues and, given the many benefits of primary injection testing discussed in this article, the extra effort involved is amply repaid in almost every case.

REFERENCES

[1] National Fire Protection Association. NFPA 70, National Electrical Code (NEC 230.95). Quincy, Massachusetts.

[2] National Electrical Manufacturers Association. NEMA AB 4-2017, Guidelines for Inspection and Preventive Maintenance of Moulded-Case Circuit Breakers Used in Commercial and Industrial Applications. Arlington, Virginia.

The IEC 61850 Week Conference 2021

Jill Duplessis

The 8th annual IEC 61850 Week Conference took place from 18th to 22nd October 2021 via the Swapcard virtual event platform. The year's event was more interactive and engaging than the first virtual event held in 2020, with lengthier and more frequent live Q&A sessions, interactive speaker hangout sessions during refreshment breaks, and many more roundtable discussions. Megger and Schneider Electric were gold sponsors for the event.

The week began with a practical workshop on 'System Specification' led by Christoph Brunner with contributions from Thomas Sterckx of Elia and Joerg Reuter of Helinks. This provided utilities with a solid framework for the end-to-end specification of next-generation digital substations, enabling them to leverage their suppliers' expertise whilst remaining in the driving seat of the specification and implementation processes.

The main three-day conference showcased a series of utility implementation case studies covering a range of topics that would enable a culture of 'rapid replacement' to help utilities meet new regulatory pressures. Among the top-rated presentations were sessions on 'Implementing IEC 61850 between the Substation and Control Centre' delivered by Renaud Renaud-Drouin of Hydro Quebec, 'Top-Down Engineering' delivered by Bas Mulder of TenneT, and 'Metering Data Accuracy' delivered by Rannveig Løken of Statnett.

The week was rounded off with an in-depth seminar addressing cybersecurity considerations for digital substations. With presentations on the threat landscape, defence-in-depth strategies, and standards such as IEC 62443 and IEC 62351, participants came away with a comprehensive overview of the cyber-physical security implications of next generation IEC 61850 digital substations.

Megger experts Niclas Wetterstrand and Andrea Bonetti delivered an informative presentation on Digital Twin Advances for Virtual Relay Protection Testing, where digital twins of Siemens protection devices and Megger test sets were used.

Digital Twin technology has been a hot topic in recent years, but this is the first time that the technology has been used to achieve virtual relay protection testing. The presentation attracted interest from the IEC (International Electrotechnical Commission), which published an article mentioning it on its blog (https://www.iec.ch/blog/digital-grid-transformation-boosted-pandemic).

Smart Grid Forums, the organisers of the IEC 61850 Week Conference, are now starting the planning process for the 9th annual event which will take place from 17th to 22nd October 2022 in person, in London.

Asked what sets this event apart from others in the calendar, Mandana White, CEO of Smart Grid Forums, commented: "*Our programmes of content-heavy implementation-focused conferences and seminars provide the in-depth insights that smart grid teams need to drive the implementation, operation, and maintenance of new technologies. Time and again, we see individual specialists and cross-functional teams come to our forums with a combination of excitement and trepidation at the implementation task at hand and leave with exponentially greater insights and awareness that empowers them to drive investment decisions and implementation action with greater confidence and ease.*"

These forums are immersive peer-to-peer exchanges focused on progressive outcomes that support rapid change and embed new ways of working through the perfect alignment of people, processes, and new technologies. Mandana regularly hears success stories about how the forums have helped utilities to sharpen their business plans, speed up board approval, secure new resources, and propel teams into action at a pace previously unimagined.

She believes this is the result of a perfect alignment between the aims of the forums as learning providers, and those of the participants as pioneering change makers. The formula is simple yet highly impactful. The combination of objective audience research, in-depth technical content, end-user driven speaker selection,

and well-facilitated networking provides a dynamic environment where participants are stimulated to think deeply and laterally. They can open up fully and express their real-world issues, challenge the technology innovators and the status quo, and be receptive to new partnerships and alliances that compound efforts and drive deployment at the speed of the digital age.

At time of writing, as the 9th annual IEC 61850 Week 2022 drew near, here are the key ingredients that Mandana and her team kept front-of-mind to ensure that the programme remained immersive, extensive, and outcomes-focused:

1. Deep technical insights – Implementation-focused sessions will provide a depth of technical information sharing that will allow participants to clearly foresee just how technological choices will impact implementation and operational efficiency, well in advance of investment decisions being made and deployment actions being taken.
2. Extensive benchmarking – Hearing from 20+ utilities over three days will provide an immersive experience with a depth and breadth of real-world insights that will significantly enhance business plans, bring new concepts to life, and drive speedy board approval.
3. Influencing standardisation – When direct working group participation is not an option, the programme provides a perfect opportunity for end-user voices to be heard and their influence felt through an indirect, but highly effective, channel for driving standardisation progress in favour of end-user needs.
4. Influencing technology innovation – Far from simply being on the receiving end of technology innovations, the forums provide an opportunity for end-users to influence the direction of new product development and ensure their ongoing progress fits with real-life techno-commercial needs.
5. Forming partnerships and alliances – Through a series of facilitated networking activities, participants get the opportunity to meet potential new partners and understand their needs in great depth and on multiple levels, providing a sound springboard for post-event relationship building and business development activity.

To find out more about how you can get involved in the future IEC 61850 Weeks visit the event website at: www.smartgrid-forums.com/iec-61850-week or contact Smart Grid Forums at: **registration@smartgrid-forums.com**

Special thanks to Mandana White and her team

The editor would like to send a particular thank you to Mandana White and her team for the assistance in writing this article.

Read all about it!

IEEE electrical insulation conference: a doubly unique event!

Held as an in-person event for the first time since 2019, the 40th Electrical Insulation Conference, which is fully sponsored by the IEEE Dielectric and Electrical Insulation Society (DEIS), was not only an outstanding success, but it was also unique in two ways. It was the first time that this globally recognised conference has partnered with the Impulse Power Modulator and High Voltage Conference (IPMHVC) to form a single joint event, and it was also the first time that the conference was chaired by someone who had chaired a previous conference: Megger's Dr Diego Robalino.

The joint conference had, in fact, been planned for 2020 but COVID intervened to prevent the plans from coming to fruition until this year. Dr Robalino also owes his second term as conference chair to the COVID disruption, as he first took up the role in 2020 when the conference had to be held as a virtual event.

This year's event, held in Knoxville, Tennessee, USA, attracted a huge amount of interest and enthusiasm from around the globe. Almost 160 abstracts were received from 23 countries and, ultimately, 104 papers were presented during the conference, which was attended by over 400 delegates. Given the ongoing travel restrictions in many parts of the world, this level of attendance was a remarkable achievement and a clear demonstration of the feeling that there are big benefits to be gained by meeting in person.

The broad scope of the event is demonstrated by the range of sessions offered. These included cables and accessories, failure analysis, new materials, partial discharge, rotating machines, switchgear and outdoor insulation, transformers, and testing technologies. The papers delivered in these sessions were complemented by a wide range of workshops and poster presentations.

Among many other conference highlights was the presentation of two prestigious awards. The 2022 IEEE DEIS Thomas Dakin Distinguished Contributions Award was presented to Dr J Keith Nelson, Professor Emeritus, Rensselaer Polytechnic Institute, who has made important contributions to understanding the ageing of electrical insulation. The 2021 Eric O Foster Distinguished Service Award was presented to Professor Paul Lewin, IEEE Fellow, the University of Southampton, UK, in recognition of his sustained leadership, support, and contributions to the advancement of the field of electrical insulation and dielectrics.

In addition to chairing the conference, Dr Robalino co-presented two papers: Parameter Identification of the Electrical Debye Model for Power Transformer Multilayer Insulation Systems, which he co-authored with Giovanni Hernandez and Abner Ramirez of VTC West in Mexico, and Practical Considerations for the Usage of Ester Fluids in Distribution Transformers, co-authored with Alan Sbravati of Cargill USA and Robert Breazeal of Southern California Edison.

Dr Robalino noted that, like almost all of the other papers presented at the conference, his papers were the result of close cooperation between two or more organisations. Like the conference itself, he sees this as an important demonstration of the way businesses in the sector and educational institutions are happy to work together to further the advancement of the science and technology of electrical insulation.

Léonie Alvey, Content Editor

Read all about it!

Thousands attend Megger's virtual renewable energy maintenance congress in Latin America

During 2021, Megger Latin America organised a host of events related to new technologies and regulations, including the Energy Efficiency Congress in Guatemala and a Congress in Chile on the Requirements of the New Electrical Regulation. However, none were as popular as the virtual Renewable Energy Maintenance Congress.

According to IRENA (International Renewable Energy Agency), Latin America has some of the most innovative energy markets in the world, with a large majority of primary energy coming from renewables, including a strong investment in solar, wind, and photovoltaic (PV) power.

The facilities that make up renewable energy generation are well established in the area, with some operating for many years. As with any electrical system, constant monitoring and maintenance is required. The three-day congress focused on reviewing the aspects that these actions involve, especially in electrical installations that support renewable generation.

Over the course of the event, 38 high-level academic speakers shared their knowledge and exchanged information with colleagues, organisations, suppliers, and customers. The main topics discussed included commissioning, diagnosis, and electrical maintenance in PV and wind farms, as well as innovation in renewable energies and regulations.

Almost 4000 attendees heard from guest speakers such as Hector Pagani from the Argentinian Wind Energy Association, Santiago Barbero from the National University of La Plata, and Marcelo Alvarez from the Argentine Chamber of Renewable Energies. Attendees also had the opportunity to 'visit' virtual booths from Megger, Hitatchi Energy, Comulsa, ANXOR Ingenieria, and Artec Ingenieria.

As large, face-to-face events were not possible in 2021, taking advantage of available technologies to be virtually present and be involved in technical communities was essential.

Roberto Sartori, Regional Manager (Argentina)

Karen Becerril, CSA Marketing Manager

ELECTRICAL TESTER

ELECTRICAL TESTER MAGAZINE I004 2022