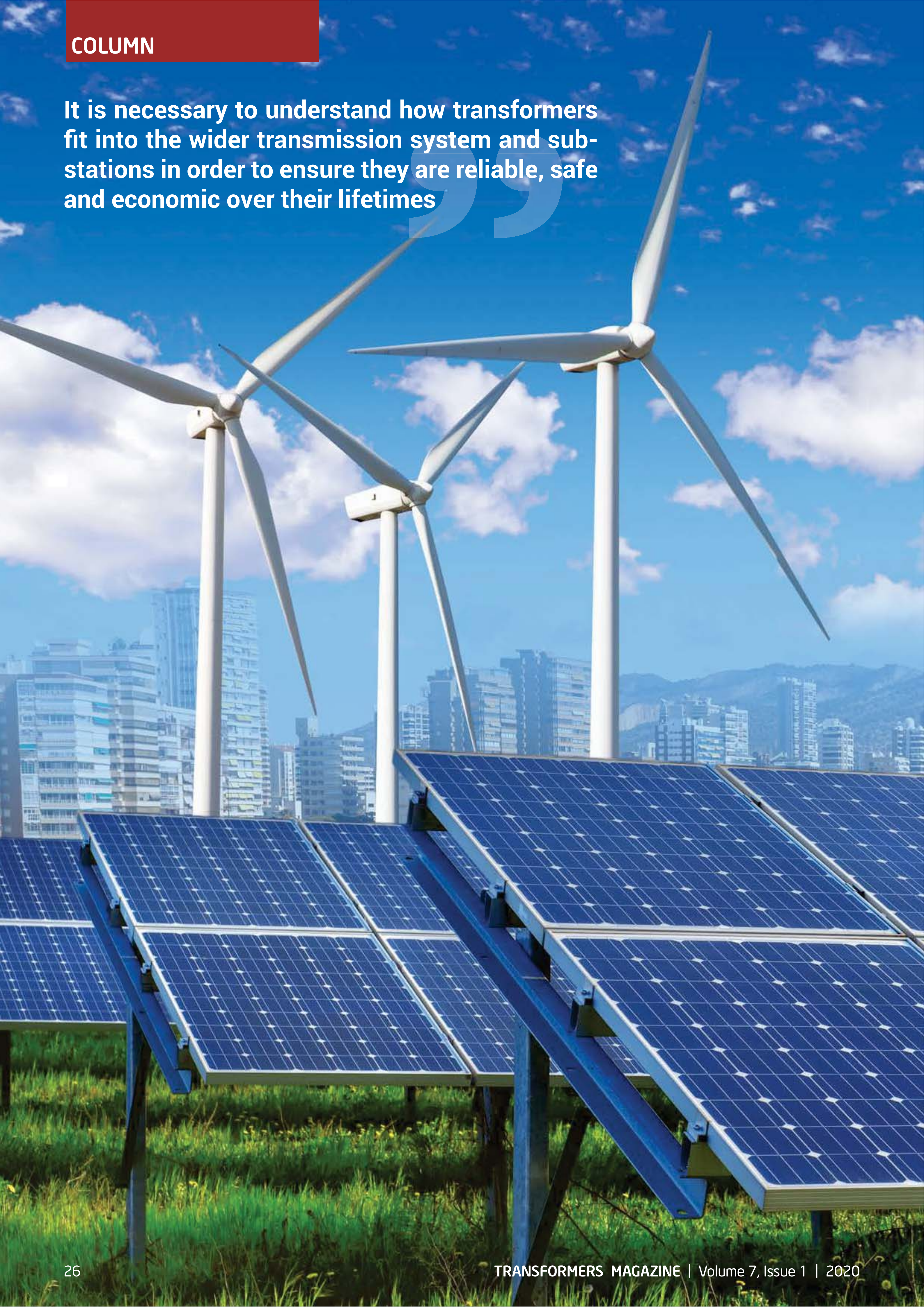
It is necessary to understand how transformers fit into the wider transmission system and substations in order to ensure they are reliable, safe and economic over their lifetimes



Paul JARMAN

Transformers and the energy system transition

Having spent most of my career in the engineering and asset management of transformers working for National Grid in the UK, I have recently taken the opportunity of moving into the academic world as a professor at the University of Manchester. National Grid gave me fantastic opportunities to work with transformer manufacturers and see many transformer factories around the world. As well as having to understand how transformers fit into the wider transmission system and substations in particular, I had to play my part in ensuring they were reliable, safe and economic over their lifetimes. Through IEC (I had the great privilege of being chair of IEC TC14 2008-2017) and CIGRE, I was lucky enough to be able to work with colleagues from other utilities, academics and suppliers, to help the industry with standards and research, something I hope to continue doing as well as taking the opportunity to develop a broader view.

You certainly don't have to look too far to understand that the world faces an extreme challenge in reducing its net carbon emissions to zero in the next two decades or so to limit the effects of climate change [1]. I am indebted to my colleagues at the Tyndall Centre for Climate Change Research for bringing this issue into sharp focus for me. This means that we need to go further than the reduced carbon technologies already implemented in many countries such as the switch from coal to gas and improved energy

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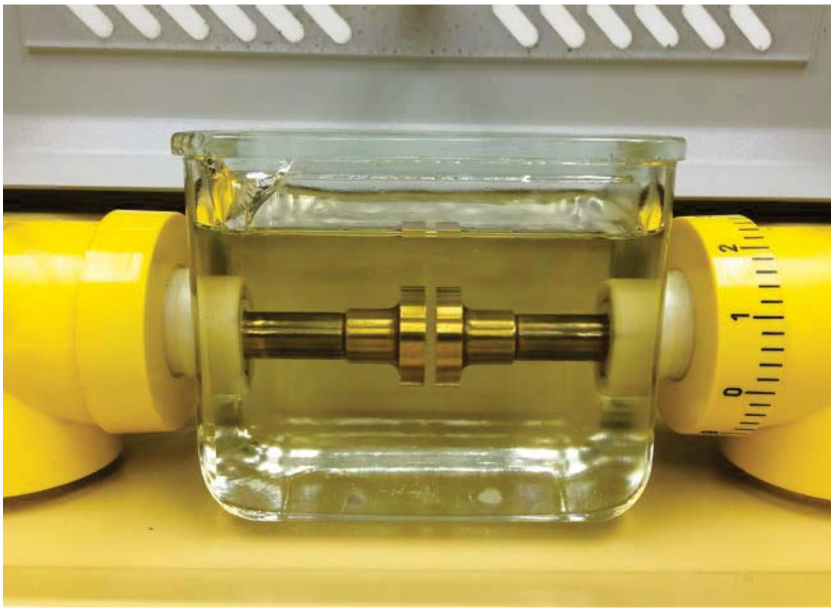
Active part inspection

The most likely scenario is that we will need greater power densities to supply increasing populations, a global trend that seems set to continue, with decarbonised heat and transport


Transformer oil breakdown voltage testing

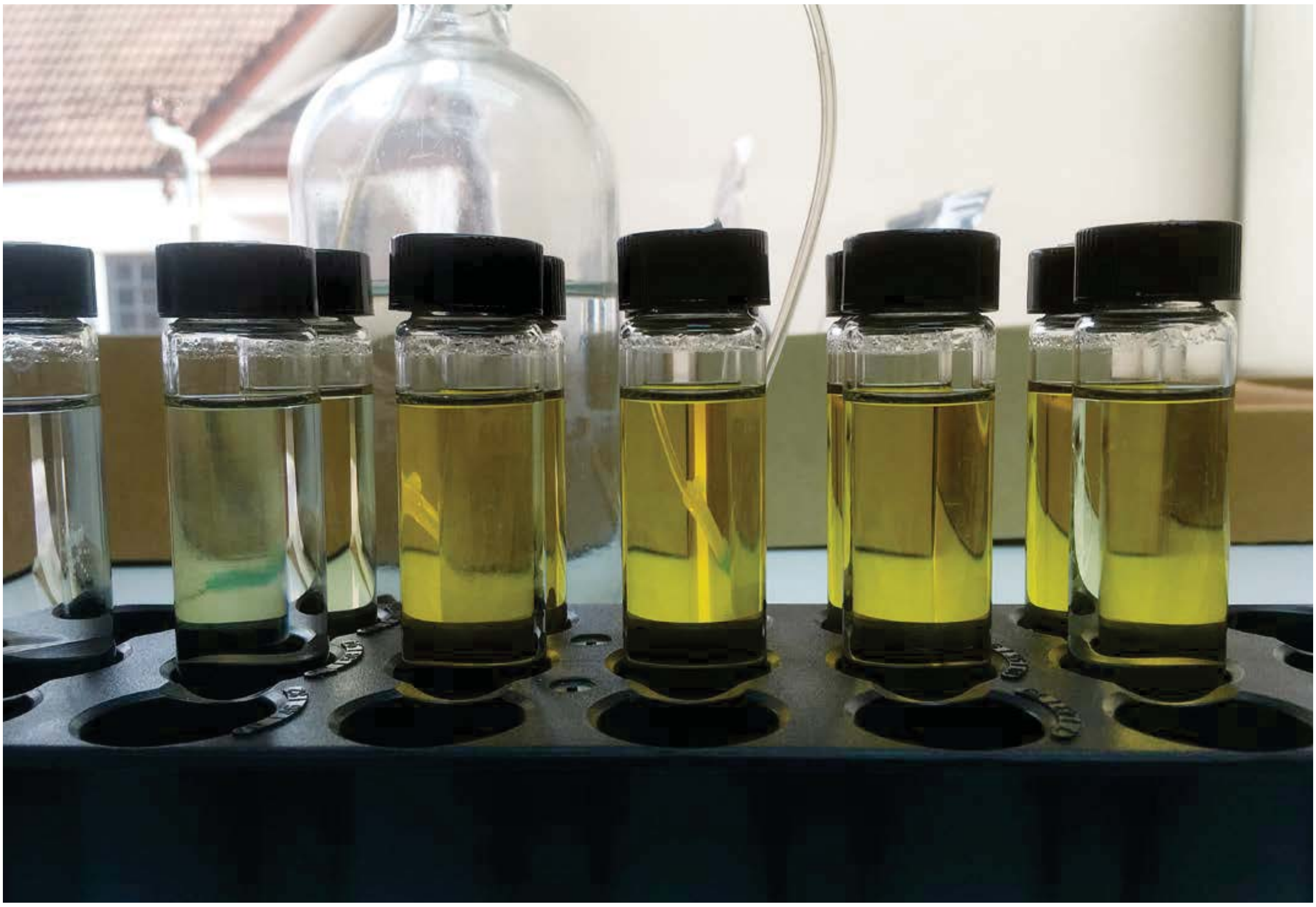
efficiency, to embrace fully carbon emissions free energy in all areas, including heating and transport [2]. Nations and individual cities are stepping up to this challenge for example Manchester in the UK has recently published its strategy for becoming carbon neutral by 2038 [3]. There are, of course, many social, economic, and engineering challenges to overcome to achieve this goal, but it is feasible. Fortunately, in the electricity transmission and distribution systems, we already have an excellent and well-developed method of supplying energy irrespective of the means of generating it. Substations and the transformers they contain will, I expect, play a vital role in this energy system transition and be the backbone of our energy exchange system for many decades to come.

Transformers are of course to be found in a very wide range of installations, from the multi-gigawatt terminal stations for long distance transmission, to the factory assembled package substation forming the last link in the local distribution system, but they all provide an access point to the electrical power network. At the University of Manchester, we have recently recognised the importance of substations by setting up a Future Substations research cluster to share ideas and pool resources in this area. This article contains my thoughts, but of course, they have been shaped by the many interactions with colleagues, both new and over the years, for which I am very grateful.

A global trend that seems set to continue is the urbanisation of the population [4]. With present day technology, high rise cities are not an obvious candidate for widespread adoption of renewable distributed generation (although, of course, with sufficient ingenuity who can say what future technologies might emerge) so the most likely scenario is that we will need greater power densities to supply increasing populations with decarbonised heat and transport. This means higher voltage substations in the already expensive and crowded urban areas: key to doing this safely and sensitively are the low fire, low noise compact solutions using equipment such as the synthetic

Internal inspection of an OLTC

Thermal lifetimes of transformer designs that will pass the temperature rise test can range from less than 15 years to well over 300 years



Samples of transformer oil for chemical testing

The need for good information leads to the concept called a ‘digital twin’, which is essentially a computer simulation capable of predicting how a transformer will behave both thermally and electrically

ester filled transformers recently installed in London and New York. Minimisation of the concrete infrastructure required for transformer installation can cut costs and carbon emissions and this is possible with low fire biodegradable synthetic and natural ester liquids. The use of alternatives to mineral oil has, of course, been widely researched over the years underpinning their recent use at high voltage where substation design considerations make it favourable. The use of esters in transformers was the subject of a special session at the IEEE International Conference on Dielectric Liquids in Rome in 2019 [5].

Over many years of managing transformer assets, I have become convinced of the value of performing post-mortem examinations on all large transformers taken out of service, to inform the future condition assessment of similar units and to understand the long-term consequences of decisions made at the design and manufacturing stage [6]. It has been a surprise to me, based on this information, just how wide the difference in lifetime is between transformers with a good thermal design and ones with specific design or manufacturing flaws causing high hotspot temperatures. All of these transformer designs will of course have passed the temperature rise test but still the range of observed thermal lifetimes (observed or extrapolated from observations) is from less than 15 years to well over 300 years [7]. Analysis of cooling systems using computational fluid dynamics by several research groups including the one at Manchester as well as manufacturers, is providing great insights into the thermal design problem and should result in better designs or at least better techniques for identifying problematic designs [8]. This is particularly important when considering that the energy system transition (EST) will require possibly heavier and certainly more sustained loads on substations taking into account the development of battery and thermal storage systems capable of significantly flattening demand curves.

Part of the EST challenge is the fact that the total energy suppled as gas and fuel for heat and transport is significantly larger than that presently supplied by the electrical system. On the face of it, this implies that large-scale uptake of electric heating and transport will overload the system without significant additional investment. This may be true in some cases, but often the system is designed with sufficient capacity to cater for maximum demand with some equipment out of service for faults or maintenance (n-1 or n-2) and demand has reduced in some areas in recent years as energy efficiency measures become effective, resulting in spare capacity for much of the time. Smart grid technologies particularly involving local storage, for example, vehicle to grid (V2G) systems allowing for charging of vehicle batteries at times of low demand and support for the grid at peak or if capacity is reduced, have great potential to utilise this spare capacity delaying the need for reinforcements. How quickly this vision of the future comes depends on the uptake of electric vehicles and whether they will be used on the road like most private cars are now for less than 10 % or so of the time, but surely it has to be worth investing in the V2G technology now so that EVs become a solution rather than a problem.

National Grid ESO has recently issued a report on operating the UK grid at times of high wind/solar generation without input from fossil fuel power stations by 2025

The demand for multiple rapid vehicle chargers at some locations does lead to the potential for a significant new role for transmission substations and transformers in supplying local loads in the 10 – 100 MW range. Connection of grid-scale battery storage is another new challenge that can be accommodated in larger substations. In some cases, it is possible to use existing transformer tertiary connections, raising new challenges for thermal ratings and voltage limits, but offering the opportunity for new methods of voltage and load flow control. It always seems to me in transformer design reviews that the specification and design of tertiary windings takes up more time than almost anything else, these additional requirements added to the traditional ones for auxiliary supplies and reactive compensation will make this even more interesting! However, I'm sure my colleagues in the utilities and transformer manufacturers are tackling this issue already.

Sometimes standards can enable change, but there is also a danger that standardisation too early in the life of a new product can stifle innovation

The increasing complexity of loading and the probability of more switching operations and multiple operating regimes increase the need for utilities to have a clear picture of how their transformers and other substation plant will operate under many possible scenarios. This need for good information and modelling leads to the concept often called a 'digital twin', which is essentially a computer simulation capable of predicting, with some accuracy, how a transformer will behave both thermally and electrically. There is some work to do on this concept, but many of the elements are already in place and with the right development and standardisation, this could become a powerful tool to allow the rapid development of new operating regimes enabling the flexibility required for energy system transition. Non-traditional loading patterns, including sustained very high reverse flows from distributed generation, are already a feature in many networks and this is likely to become more pronounced as these technologies become cost competitive even without subsidies.

I was lucky enough to visit the Offshore Renewable Energy Catapult site at Blyth in the UK. This site has the capability of testing 15 MW wind generators and 100 m long turbine blades, awesome technology that is reducing the amount of carbon that has to be burnt to supply the UK with electricity. Larger offshore substations are going to be required and there are new challenges associated with floating platforms for deeper water use. National Grid ESO has also recently issued a report on operating the UK grid at times of high wind/solar generation without input from fossil fuel power stations by 2025 [9]. There are significant challenges in voltage and frequency management that require solutions, some of which are likely to involve wound equipment such as transformers and reactors, possibly in novel configurations.

Electric vehicle charging station

With all these rapid changes comes a particular challenge for standardisation, a subject that has occupied much of my time over the years. Sometimes standards can enable change, typically, for example, for connectors and information exchange protocols, but there is also a danger that standardisation too early in the life of a new product can stifle innovation. I hope that, as convenor of the revision of IEC 60076-1 for power transformers, we get this right for the benefit of the industry. The particular challenge at the moment is seeing how far the standard needs to be changed to accommodate emerging technologies. Although oil/paper is and is likely to continue to be the dominant insulation technology, it is important that other insulation systems can be incorporated seamlessly and without disadvantage in standards compliant equipment where they are the most appropriate solution. There is a new version of the standard for wind turbine transformers published recently which was developed jointly between IEC and IEEE [10]. Hopefully this incorporates the important learning points from the early years of that part of the industry, but I would like to emphasise just how important it is for experts with relevant knowledge to take part in standards making, to make sure they are as good as they can be. Thank you to all those people and their organisations who have and continue to give up their time for the benefit of the industry in this way.

Having recently installed solar panels and a battery storage system in my suburban home, I was feeling very pleased at the reduced energy bills and income they are generating, but attending a seminar on fuel poverty and also renting a flat in central Manchester really brought home to me that not everyone is in a position to benefit from this technology. The same is true of many energy efficiency measures. Indeed, usage-based charging regimes tend to load network costs onto those least able to pay. It may seem strange to bring this up in a technical industry journal such as this, but it is important not just for the social aspect but because consumers ultimately pay for transformers. The undoubted benefits of a high voltage network enabling the connection of, for example, offshore wind and international interconnectors need to be paid for and finding a way of equitably distributing the costs is a matter that should concern us.

There are many problems to solve and very significant changes to come, but my experience is that such changes provide great opportunities for engineers and a stimulus to the whole industry. Interesting times ahead!

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The undoubted benefits of a high voltage network need to be paid for and finding a way of equitably distributing the costs is a matter that should concern all of us

Author

Paul Jarman was born in London and graduated from Cambridge University in 1984 with a degree in Electrical Science. After 6 years in research looking at bushing condition monitoring and transformer frequency response analysis for the CEGB, on privatisation of the industry in 1990 he transferred to National Grid as a Transformer Engineer becoming Head of Transformers in 1998. From 2001 to 2018 Paul was National Grid's Technical Specialist/Manager for transformers. Paul was chairman of IEC TC14, the international committee for power transformer standards from 2009 to 2017 and was the UK regular member of CIGRE study committee A2 for transformers 2008-2016. He is a chartered electrical engineer and member of the IET. Since January 2019 Paul has taken up the position of Professor of Electrical Power Equipment and Networks at the University of Manchester on a part-time basis and is also a part-time Applications Engineering Specialist for M&I Materials manufacturers of Midel Ester liquids.