According to the impact assessment of the EU Green Deal the share of electricity in energy end use will rise from 23 % in 2015 to approximately 30 % in 2030 and close to 50 % in 2050

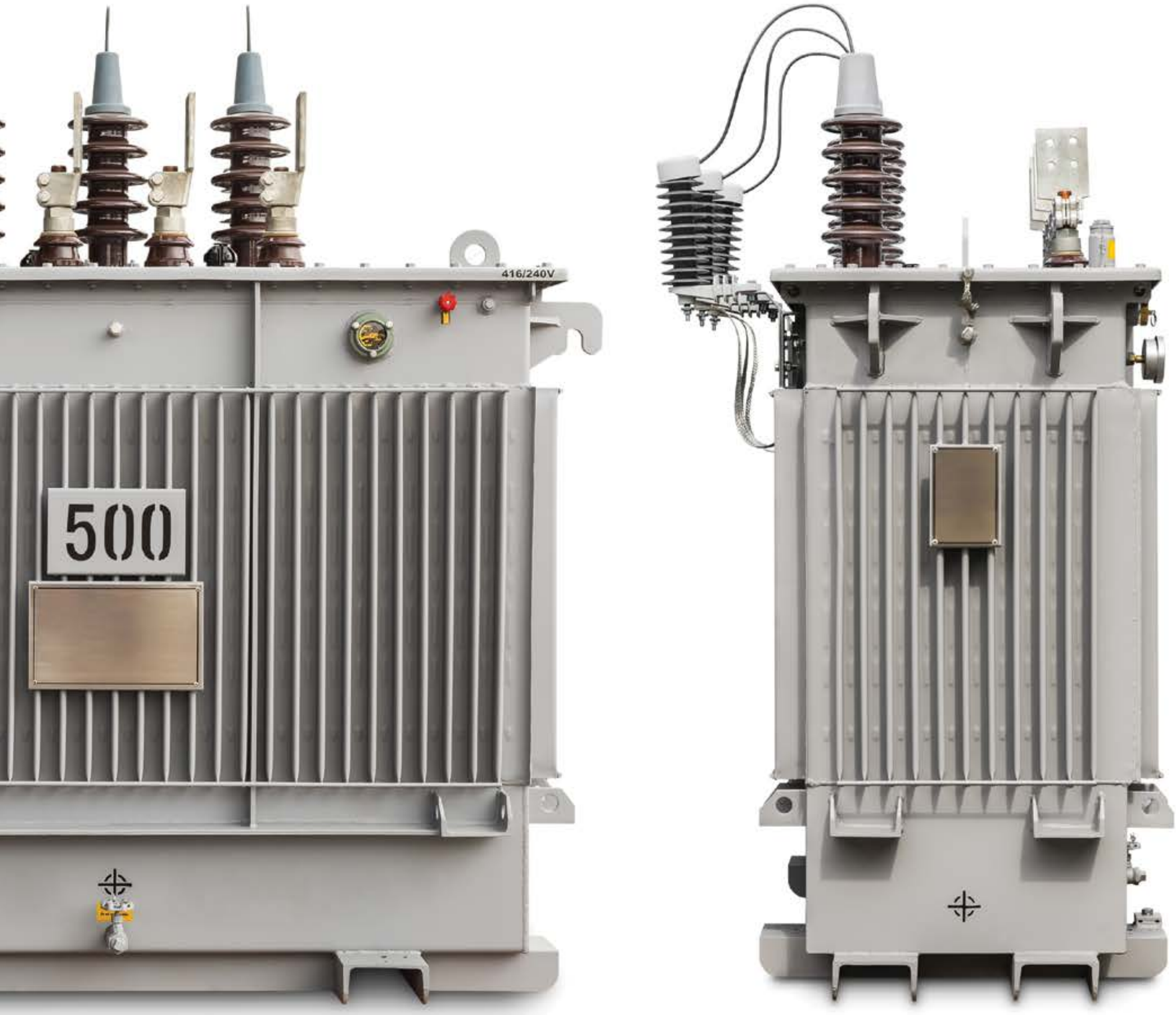
ABSTRACT

The sustainable peak load transformer complies with the energy performance requirements for a unit of its size but is allowed to be subject to temporary peak load values that are higher than usual. At the origin of the concept lies the fact that thanks to technological innovations, some transformers can withstand higher temperatures in the windings and, consequently, higher peak demand without compromising unit reliability or lifetime. This concept can be of great help in absorbing the expected peak load increases due to the energy transition. It does so in a material-efficient way and without increasing annual energy losses.

KEYWORDS:

distribution transformer, grid upgrade, energy transmission, material efficiency, peak load

Angelo BAGGINI, Alberto CRACCO, Bruno DE WACHTER, Phil HOPKINSON, Mayur KARMARKAR, Fernando NUÑO, Alan SBRAVATI



Sustainable peak load transformers

A material and cost-efficient solution for distribution grid upgrades

1. Introduction

Electricity distribution networks and their peak load capacities will have to be reinforced substantially to facilitate the uptake of heat pumps as well as the electrification of transport. According to the impact assessment of the EU Green Deal ('Stepping up Europe's 2030 climate ambition'), the share of electricity in energy end use will rise from 23 % in 2015 to approximately 30 % in 2030 and to close to 50 % in 2050 [1]. The resulting urgency to upgrade

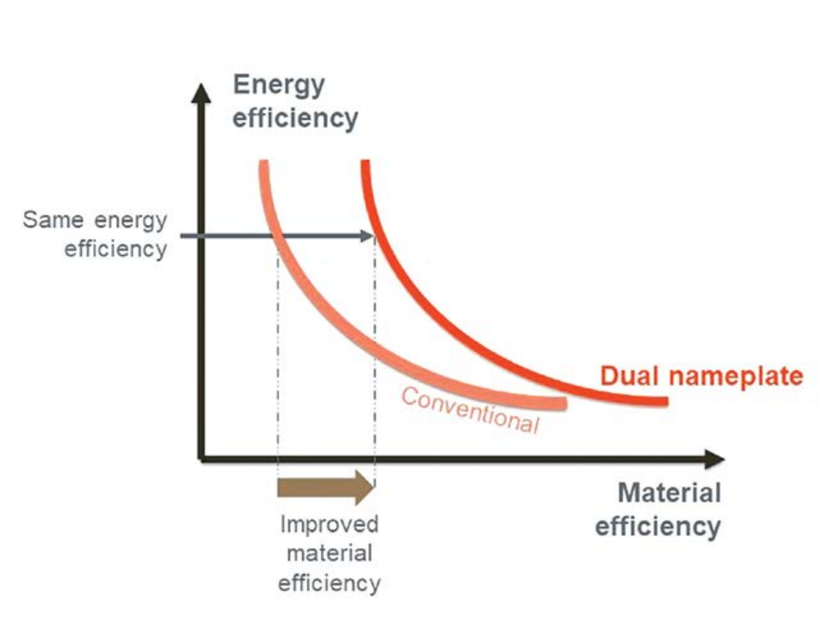


Figure 1. Energy efficiency versus material efficiency: a conventional transformer compared with a sustainable peak load transformer ("Dual nameplate")

Many transformers can now withstand higher temperature increases in the windings – up to 95 °C instead of just 65 °C, and can handle higher peak demand without compromising unit reliability or lifetime

the distribution grid does not absolve it from the other major constraints set out by the European Green Deal, namely, to maximize both energy performance and material efficiency. This last ambition is a growing focus in EU policy making, emphasized through the new Circular Economy Action Plan, published in March 2020.

The sustainable peak load concept deployed in distribution transformers provides a solution that deals with all these constraints combined. It does not change the transformers themselves but instead maximizes their peak load capacity for material efficiency without compromising their energy performance. It can be applied in all cases where the difference between peak and average demand is proportionately high, which is usually the case in public distribution networks.

The peak load capacity of the sustainable peak load transformer is fundamentally different from the temporary overload capacities that are allowed by IEC 60076-7 and IEEE C57.91. The latter are tolerated emergency situations that will have a negative impact on the transformer's expected lifespan. This is opposite to the sustainable peak load transformer, which could technically be loaded continuously at its peak load kVA rating, as this will not affect the unit's reliability or lifetime. The use of its peak load capacity will only be limited in time in order to keep the annual load losses below the desired value.

2. Proven technology with multiple benefits

At the origin of the sustainable peak load concept lies the fact that many public distribution transformers, as currently rated, are underexploited. This has historical antecedents. Stringent rules on loss reduction, compactness, and absence of toxic substances have prompted various technological innovations, including the use of highly conductive winding material, magnetic steel with reduced losses, thermally upgraded paper, and natural esters as liquid insulation. As a result, many transformers can now withstand higher temperature increases in the windings – up to 95 °C instead of just 65 °C, and can handle higher peak demand without compromising unit reliability or lifetime. The highest thermal class can be achieved by using a combination of natural esters as a transformer liquid [2] and thermally upgraded paper as solid insulation [3][4]. These are both advanced but proven materials with multiple benefits.

Natural esters were initially developed to be a less flammable transformer liquid than mineral oil and more environmentally friendly than both mineral and PCB oils. They derive from renewable sources and are classified as carbon neutral, resulting in lower CO2 eq emissions associated with the transformer unit's production. Natural esters have been used successfully in more than 2.5 million transformers over a period of 20 years and are accompanied by a complete framework of standards and guidance for condition assessment.

Thermally upgraded paper exists in various types and with various levels of insulation. It is a proven technology which has been used in electrical equipment for more than 50 years and in transformers for more than 30 years. Examples include Kraft paper, Nomex® paper and INSULutions® DPE. The initial purpose of using thermally upgraded paper was to increase unit loading capacity without increasing its weight. These characteristics were highly valued for traction transformers and for pole-mounted transformers used in the USA. Thermally upgraded paper increases the thermal class of the insulation, resulting in higher loading capacity.

By combining the latest paper technology with natural esters as a transformer fluid, a thermal class of 140 can be achieved, which is well-suited for sustainable peak load transformers.

3. No compromise on the energy performance

The additional peak-load potential that follows from new insulation technologies is well documented but rarely exploited, as operators continue to pursue keeping power losses below the values stipulated in mandatory performance standards. Maintaining a high energy performance is

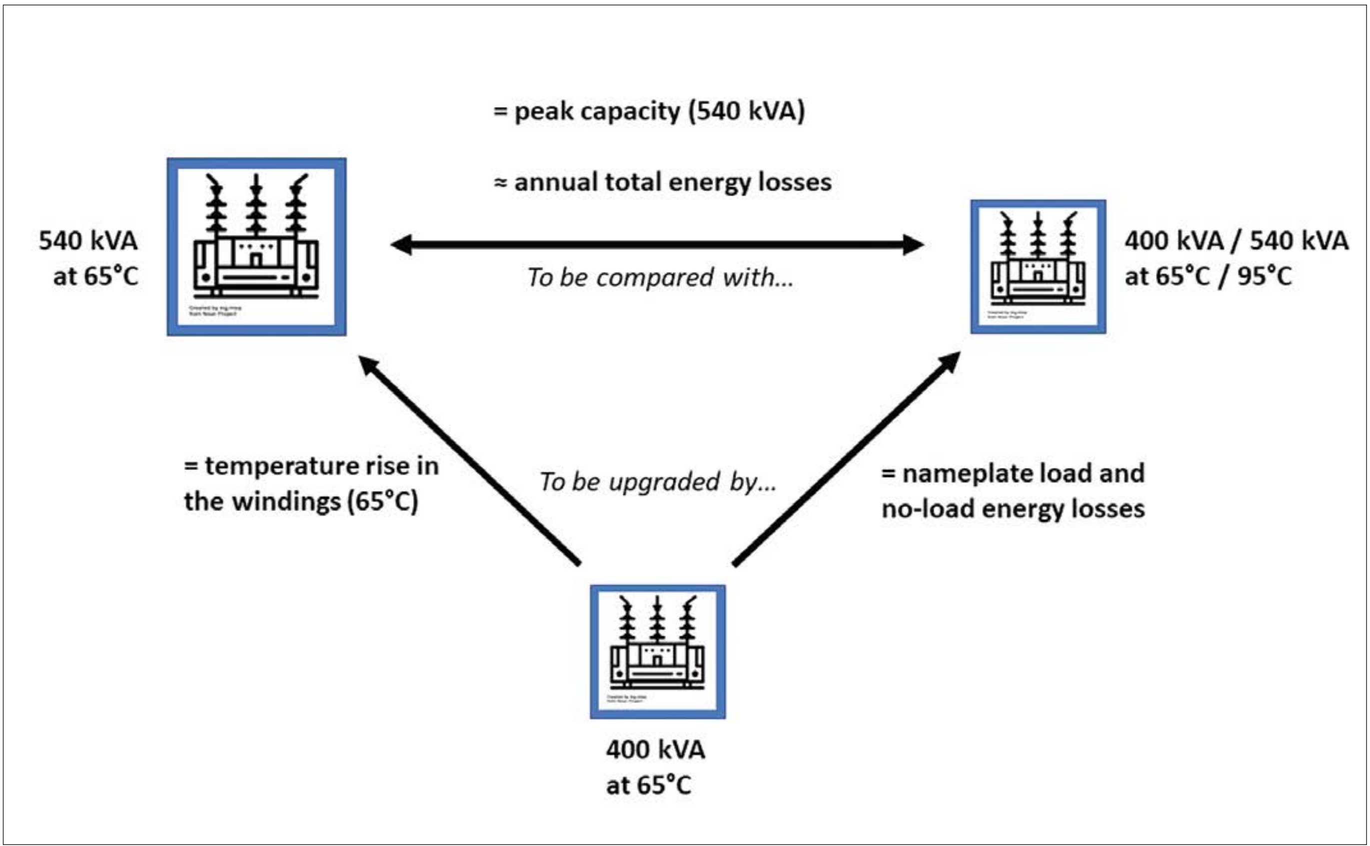


Figure 2. The sustainable peak load transformer concept (substation transformer by Ing. Mixa from the Noun Project)

obviously crucial, but a distinction should be made between the nameplate power losses of the transformer, expressed in Watts, and its annual energy losses, expressed in kWh. The former is subject to regulation, while the latter must be taken into account when evaluating the unit's environmental performance.

Studies show that distribution transformer loadings have average load factors around 15 %, root mean square (RMS) equivalent average of around 30 %, and peak loads close to 80 % of nameplate capacity

At low load levels, the relative importance of load losses diminishes, and the relative importance of no-load losses increases. The increase in load losses during peak hours will be balanced or exceeded by the 24/7 decrease in no-load losses. As a result, choosing a smaller transformer for the same job has little influence on the total annual energy losses of the unit. Public distribution networks typically have such low load levels.

Until recently, public distribution network loadings have been estimated only, not measured. With the introduction of smart meters, extensive measurement campaigns have now recorded full-year kWh data at 15-, 30- or 60-minute intervals. According to these new data, distribution transformer loadings tend to be lower than initially thought, with average load factors around 15 %, root mean square (RMS) equivalent average around 30 %, and peak loads close to 80 % of nameplate capacity [5 and 6, p. 151]. The strong growth in the installation of heat pumps and EV charging points that is to be expected in the coming ten to thirty years will lead to a substantial increase in the network peak loads, which will be only slightly mitigated by the potential storage capacity for peak shaving of both applications. As a result, distribution networks will have to be strengthened to accommodate those peak loads, while average load factors are expected to grow only moderately to around 18 % [7].

These low load factors and growing peak loads, combined with the technical overload capacity of innovative transformers with state-of-the-art insulation, leads directly to the concept of the sustainable peak load transformer. The 'rated nameplate capacity' is the value by which the transformer meets the requirements of the energy performance regulations. The 'sustainable peak capacity' of the transformer is set at a higher value. As long as the transformer operates in a network with low average loadings, allowing this kind of higher peak capacity during a limited amount of time does not increase the unit's total annual energy losses.

4. Proven by the modelling exercise

A group of experts, under the European Copper Institute's direction, conducted a modelling exercise to assess the impact of selecting sustainable peak load units for all transformer replacements in public distribution networks in the EU [7].

The model took the ubiquitous 400 kVA–24 kV / 0.4 kV transformer as a start-

Table 1. Comparing annual and cumulative energy losses (modelling exercise)

Technology	Conventional Al/Al 540 kVA	Dual nameplate Al/Al 400 kVA / 538 kVA	Conventional Al/Al 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400	540	400
Rating at + 95°C rise (kVA)		538		532
LV windings / HV windings	Al / Al	Al / Al	Al / Al	Al / Cu
Type of liquid insulation	Mineral oil	FR3	Mineral oil	FR3
Steel type	M0H	M0H	M0H	M0H
Energy losses (TWh)				
Annual average 2020 - 2050	20.9	20.8 (-0.3%)	20.9	20.9 (=)
Cumulative 2020 - 2050	647.7	645.9 (-0.3%)	647.7	647.5 (=)

While no compromise was made on the annual energy losses, the sustainable peak load transformer's material efficiency increased substantially, with reductions in total weight of between 11 and 15 %

ing point and calculated the difference between replacing all the end-of-life 400 kVA units in the EU with conventional 540 kVA units or with sustainable peak load 400 kVA / 540 kVA units.

The 400 kVA / 540 kVA sustainable peak load transformer is designed according

Table 2. Comparing annual and cumulative material use (modelling exercise)

Technology	Conventional Al/Al 540 kVA	Dual nameplate Al/Al 400 kVA / 538 kVA	Conventional Al/Al 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400	540	400
Rating at + 95°C rise (kVA)		538		532
LV windings / HV windings	Al / Al	Al / Al	Al / Al	Al / Cu
Type of liquid insulation	Mineral oil	FR3	Mineral oil	FR3
Steel type	M0H	M0H	M0H	M0H
Material use (cumulative 2020-2050)				
Steel (kton)	2877	2495 (-13%)	2877	2157 (-25%)
Aluminium (kton)	1158	960 (-17%)	1158	393
Copper (kton)	0	0	0	1022
Liquid (1000 m^3)	1422	1301	1422	1147
Total weight (kton)	**7304**	**6513 (-11%)**	**7304**	**6452 (-12%)**

Table 3. Comparing the cumulative material cost and purchase price (modelling exercise)

Technology	Conventional Al/Al 540 kVA	Dual nameplate Al/Al 400 kVA / 538 kVA	Conventional Al/Al 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400	540	400
Rating at + 95°C rise (kVA)		538		532
LV windings / HV windings	Al / Al	Al / Al	Al / Al	Al / Cu
Type of liquid insulation	Mineral oil	FR3	Mineral oil	FR3
Steel type	M0H	M0H	M0H	M0H
Cost (cumulative 2020-2050)				
Total material cost (M€)	10509	10715 (+2%)	10509	13848 (+32%)
Selling price (M€)	21894	22323 (+2%)	21894	28850 (+32%)

The sustainable peak load transformer provides the opportunity to upgrade transformer peak power while keeping the same unit dimensions

to the prevailing minimum energy performance standards for a 400 kVA unit, which means that its load losses will exceed the nameplate value during the short periods of peak load up to 540 kVA. However, its no-load losses are fixed at a lower value than that of a conventional 540 kVA unit. For load profiles with short peaks and a low average loading — as is the case in distribution networks — the increase in annual load losses will be compensated by the decrease in annual no-load losses. This was confirmed by the results of the modelling exercise: the total annual energy losses of the sustainable peak load units were calculated to be very similar to those of a conventional unit.

While no compromise was made on the annual energy losses, the sustainable peak load transformer's material efficiency increased substantially, with reductions in total weight of between 11 and 15 %.

This efficiency gain in material use was achieved without increasing the unit purchase cost. The modelling exercise demonstrated that the cost of the sustainable peak load model is comparable to that of a conventional transformer if all other parameters are kept the same.

5. Conclusion

The expert assessment has led to the conclusion that widespread application of the sustainable peak load concept in the EU public distribution networks would be a welcome exercise.

A major economic advantage of the sustainable peak load transformer is its compactness. With the transition away from fossil fuels, substantial growth in electricity consumption is expected in some sectors supplied by distribution networks. The sustainable peak load transformer provides the opportunity to upgrade transformer peak power while keeping the same unit dimensions. This is a critical aspect in urban environments where space may be restricted, allowing cheaper installation and earlier upgrades, making the distribution grid more robust and secure.

Moreover, using sustainable peak load transformers in public distribution network upgrades would avoid a trade-off between the twin ambitions of energy efficiency and material efficiency, as they are expressed in the European Green Deal.

Bibliography

[1] European Commission, *Impact Assessment / Stepping up Europe's 2030 climate ambition*, 2020

[2] Cargill, *FR3 Technical Perspectives*, FR3fluid.com, 2020

[3] C. Ballard, *High Temperature Distribution Transformers*, IEEE, PES T&D Panel Session #PS31, 2020

[4] M. Franchek, A. Levin, *Advanced INSULutions® DPE Paper / Most cost-effective 100 percent cellulose insulating paper qualified for up to 140 °C Thermal Class in liquid-immersed transformers*, 2015

[5] P. J. Hopkinson (PE, IEEE Life Fellow), D. Mulkey (PE, IEEE Senior Member), K. J. Rapp (IEEE Member), New Dual Nameplate kVA for Distribution Transformers, IEEE T&D Conference - Panel session, 2020

[6] VITO for European Commission DG ENTR unit B1, Lot 2: Distribution and power transformers, Task 1-7, 2011

[7] B. De Wachter, ECI, *Maximizing distribution transformer resource efficiency*, 2021

PEER REVIEWED

Authors

Angelo Baggini has a PhD in electrical engineering in the University consortium of Pavia, Pisa, Cagliari, Firenze (Italy) in 1997. He is an aggregate professor of Electrical Engineering at the University of Bergamo (Italy) and an international consultant in the electrical energy sector (ECD Pavia Italy), since 2013, he has been chairman of Cenelec TC14. He started his research work both in the CESI Metrological Lab in Milan and in the Electrical Engineering Department of the University of Pavia, focusing on EMC and PQ aspects of electrical measurements and electrical machines. Author of over 200 technical and scientific papers and of PQ Handbook (2008) and Electrical Energy Efficiency (2012), both published by Wiley and Sons. Prof. Baggini is a member of IEC TC14, convenor of IEC TC14 AHG35, and chairman of CEI TC97.

Alberto Cracco is a management engineer with a long track record in transformer and energy business Management. Graduated in 2003 from the University of Padua, he started his career working as Management consultant for the biggest private consultant company in the Nord East of Italy. During this period, Alberto completed an MBA program in Italy. From 2006 up to 2014, Alberto worked as a sales manager and business development manager for a transformer company. Since 2014 Alberto has been Managing and Sales Director of Westrafo.

Bruno De Wachter has 25 years of experience as a freelance engineer-copywriter in B2B and EU advocacy communication. He combines his technical background with a passion for employing precise forms of expression and wide-ranging knowledge of the energy transition and policy-making. Since 2011 he has been an in-house consultant and copywriter for the European Copper Institute on topics related to renewable energy systems, transformers, motors and electrical safety.

Phil Hopkinson is a Life Fellow of IEEE and presently working as President and CEO of HVOLT Inc. in Charlotte, NC., a position that he has held for 21 years. His 56--year career includes design and engineering management assignments at GE, Cooper, and Square D/Schneider. He holds a BS EE from Worcester Polytech, a Master's in System Science from Brooklyn Polytech and is a graduate of GE's Advanced Engineering Courses A-B and C. He is a registered PE in North Carolina and is Technical Adviser to the USNC for Power Transformers, IEC TC 14, a position he has held since 1996. He has 15 US Patents and is a long-time member of the IEEE Transformers Committee.

Mayur Karmarkar is Managing Director, International Copper Association India (ICA India), and the Sustainable Energy Team Leader of the Copper Alliance, the global network whose mission is to promote the use of copper, a sustainable element that is an essential contributor to the sustainable development of communities, buildings, infrastructure and the environment. In his over two-decades-long role with the parent body, ICA Inc. and the copper Alliance, Mayur has worked in multiple geographies across the globe in the area of Sustainable Development.

Fernando Nuño graduated as an energy engineer in Bilbao (Spain) and ENSPM School (France) in 1998. He worked in the development of combined heat and power plants at Air Liquide company, and then he joined the French Energy Regulatory Commission, where he was in charge of electricity markets regulation. Later on, he worked in the automotive sector at Renault powertrain division before joining the International Copper Association in 2007, where he was in charge of regulatory and technology aspects of copper-based technologies, notably transformers, cables and motors. He also manages promotional campaigns and leads multiple publicly-funded EU Horizon projects.

Alan Sbravati counts over 20 years in the transformers industry. He started in a large transformer manufacturer, both as a transformer designer and in R&D activities. During the second half of his career, he has been involved with insulating materials, especially ester liquids. He lives in the USA and has already published dozens of papers on transformers. His current position is Global Customers Application Manager with Cargill. Alan is an active member of the IEEE Transformer Committee.