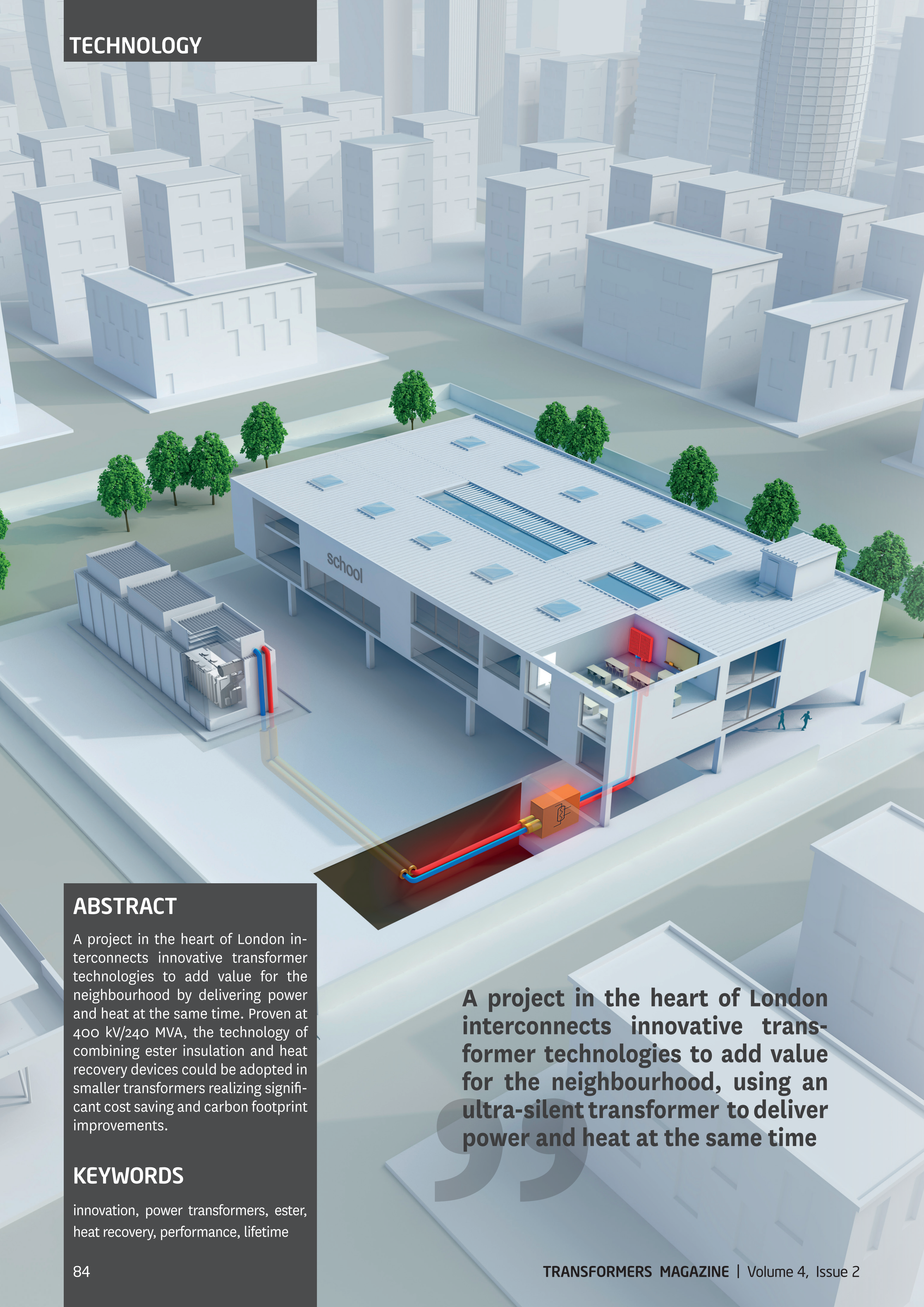

ABSTRACT

A project in the heart of London interconnects innovative transformer technologies to add value for the neighbourhood by delivering power and heat at the same time. Proven at 400 kV/240 MVA, the technology of combining ester insulation and heat recovery devices could be adopted in smaller transformers realizing significant cost saving and carbon footprint improvements.

KEYWORDS

innovation, power transformers, ester, heat recovery, performance, lifetime

A project in the heart of London interconnects innovative transformer technologies to add value for the neighbourhood, using an ultra-silent transformer to deliver power and heat at the same time

Paul JARMAN, Kevin HAMPTON, Mark LASHBROOKE, Georg J. PUKEL

Reliable, optimised power transformers with heat recovery for urban areas

With innovative technology, transformer losses are no longer lost

Transformers for urban areas

Power supply demands today are constantly increasing around the globe, in both established and emerging economies, where life quality and living standards continually improve. This, combined with the increase in urbanization, has meant that power generation facilities and substations are being built ever closer to where people live and work. While in past years you would only see power stations in rural areas, they are now part of the urban landscape and can be seen in major cities.

With this change of location come new, stricter requirements for power transformers. Operational safety, low noise levels and environmental protection are now critical factors for consideration. Furthermore, grid operators are faced with the added challenges of limited space and specific local municipal restrictions. In order to meet such strict requirements in urban areas, grid operators need to use a combination of new high-temperature transformer technologies for power and substations.

The use of ester fluids, both natural and synthetic, as an alternative insulation fluid provides solutions to many of these obstacles, being far safer in operation due to a higher fire point, and more environmentally friendly than conventional fluids due to higher levels of biodegradability.

One example is a substation in London, with three 240 MVA transformers with a voltage ratio of 400/132 kV, which used flexible solutions to overcome urban challenges, using not only ester fluid as a safer and environmentally friendly option, but also developing noise sensitive units and an innovative solution for waste heat utilization (see Figure 1).

Ester oil – safe, reliable and environmentally friendly

Transformers were conventionally insulated with mineral oil, which has been the standard transformer insulation fluid for over a hundred years. However, the growing interest in renewable energies due to limited resources has driven research and investment into alternative insulation oils. As a result, the transformer world has seen the use of both synthetic and natural ester fluids significantly increase in recent years, proving that alternative liquids are an established and viable alternative to mineral oils.

When comparing ester fluid and mineral oil, considerable differences can be noted. Most obviously, typical mineral oil proves to be much more flammable than ester fluid. Although the risk of a transformer catching fire or exploding is very low, explosion can occur in certain circumstances, for instance during a bushing failure or tank rupture caused by internal arcing. Using ester fluids can make operation significantly safer and more reliable, because natural and synthetic esters have a much higher flash and fire point (see Figure 2) than traditional mineral oil, and take much longer to ignite.

The flash point is the lowest temperature of the test portion at which application of a test flame causes the vapour of the test portion to ignite and the flame to propagate across the surface of the liquid (ISO 2719:2016 [2]).

The regulations impose stricter requirements on transformers operating in urban areas in terms of operational safety, low noise levels and environmental protection

The fire point is the lowest temperature of the test portion at which application of a test flame causes the vapour of the test portion to ignite and sustain burning for a minimum of 5 seconds (ISO 2592:2000 [3]).

Esters do not ignite until they reach temperatures well above 300 °C, compared to mineral oil which ignites at just 150 °C and can take only two or three minutes to do so. Consequently, the IEC 61039:2008 [4] standard has graded ester fluids as K-class materials. The London-based substation is positioned right beside a school and numerous residential buildings. This meant that the use of ester fluids as a significantly safer option was crucial in order to comply with very strict municipal safety restrictions, ensuring the highest public safety.

Furthermore, the significantly higher ignition temperature reduces the risk of tank rupture, which can occur as a result of internal arcing.

Ester fluids interact with water differently from mineral oil, and this fact also contributes to the lifetime of the transformer. It has been shown that de-polymerization of the insulation paper can be significantly slower when using an ester insulation fluid. The degree of polymerization, or DP, is usually defined as the number of monomeric units in a macromolecule. The degree of polymerization of a particular cellulose molecule is the number of anhydrous-β-glucose monomers, $C_6H_{10}O_5$, in the cellulose molecule (IEC 60450:2004 [5]). The lower this value, the lower the mechanical strength of the cellulose – and so the effectiveness of the paper insulation of the transformer.

Figure 3 shows the results of polymerization aging test in various insulation liquids. The first column represents the DP value for new, unaged paper, which in this case is about 1,000. The second column shows the DP value for the same paper type, but aged in mineral oil for 12 weeks with the oil temperature being raised from about 40 °C to 140 °C once a day. This variation in temperature simulates the temperature variation to which a transformer in service would be subject to. The third and fourth columns represent the results obtained with the same test method described above for the second column, but using natural and synthetic esters, respectively.

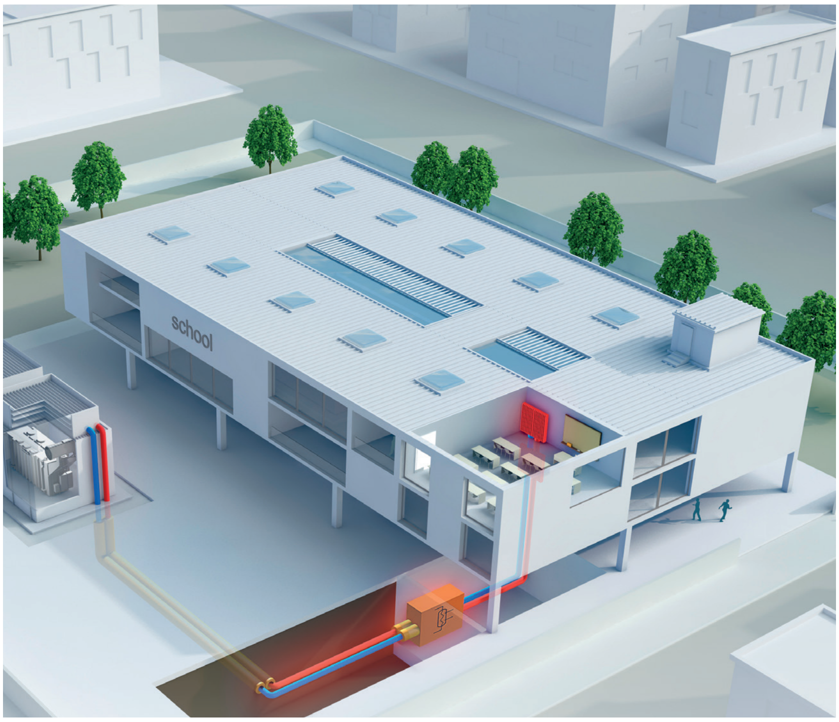

Figure 1. Schematic power substation design next to a school in London

With the London-based substation being positioned right beside a school and numerous residential buildings, the use of ester fluids was crucial to ensure compliance with very strict municipal safety restrictions

DP is a measure of the glucose chain lengths in paper and is closely related to paper strength. When the DP value drops towards 200, paper will be considered to have reached the end of useful life. Through the process of hydrolysis, ester fluids absorb and then convert water, therefore considerably reducing and preventing deterioration of the insulation paper, by keeping it as dry as possible.

What is more, compared to mineral oil, ester is notably more environmentally friendly. **One key measure of environmental impact is biodegradability, which evaluates how quickly a material will degrade when released. Standard test method OECD 301 [6] is used to assess biodegradation of chemicals and those reaching the readily biodegradable criteria are expected to rapidly degrade (see Figure 4).** In contrast to mineral oil, esters are classified as readily biodegradable, reaching high levels of biodegradation in standard tests such as OECD 301 [6]; in contrast, mineral oil biodegrades far more slowly [1]. The rapid biodegradability and non-toxic nature of ester oil is a considerable advantage as the insulation fluid can be used in environmentally protected areas, cities and even water protection zones.

Using ester insulation fluid can also pay off financially for grid operators. Although initial investment in ester-insulated transformers is higher considering the purchase of the special filling equipment, a higher price for biodegradable oil and design adjustments, the capital and operational expenditure savings in construction and insurance premiums overcompensate investment in ester transformers.

Low noise levels

Noise pollution, especially in large cities, can cause major disturbances. It is no surprise that local residents are reluctant to listen to the purr of a transformer in operation and, as a result, strict noise restric-

The transformer in London meets a very stringent requirement: a sound pressure level of only 30 dB (A), which is comparable to a whisper

tions have been implemented in densely populated urban areas.

The noise from transformers is caused by vibrations generated by electromagnetic forces in windings as well as magnetostriction effects of the core material. Siemens has been working on reducing transformer noise levels for over 30 years. With the use of specialized evaluation tools, it is possible to calculate the noise level of a transformer before it is built. For example, DC magnetization must be considered to avoid amplification of core vibration. In addition, a calculation method for load current noise has been developed, as the understanding of load-current effects is the basis for noise-cancellation activities. Consistent research on these methods and material properties has made Siemens' low-noise transformers a great success (see Table 1).

As a result, noise levels in power transformers have been reduced to 50 dB (A), equivalent to the level of a household fridge. However, the London power transformer substation project was faced with even higher requirements: a sound pressure level of 30 dB (A), which is comparable to a whisper, and a distance of at least 10 meters. In order to comply with these restrictions, ultra-low noise cooling fans were developed specifically for this application and the coolers were fitted with additional silencers.

Waste heat utilisation: more than just transforming

Transformer insulation fluid acts as a cooling medium. In power transformers, heated insulation fluid rises to the top of the tank, and then it is generally cooled by an air or water cooling system. In many cases, this waste heat is then dissipated into the

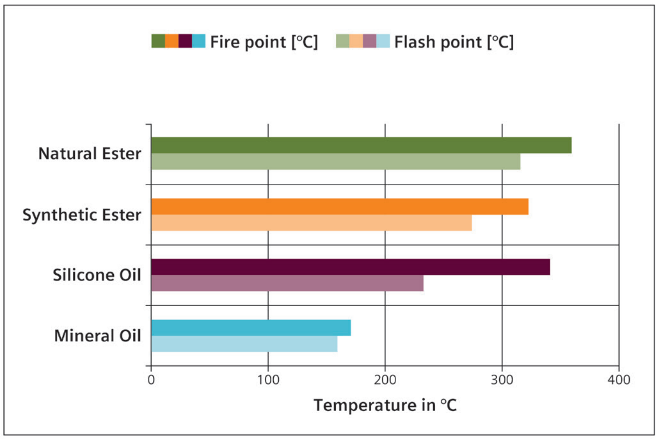

Figure 2. Comparison of the fire and flash points of various insulation oils [1]

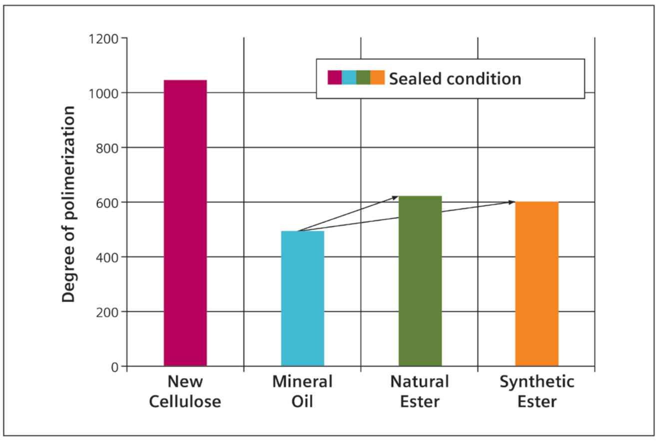

Figure 3. Results of polymerization aging test in various insulation liquids [1]

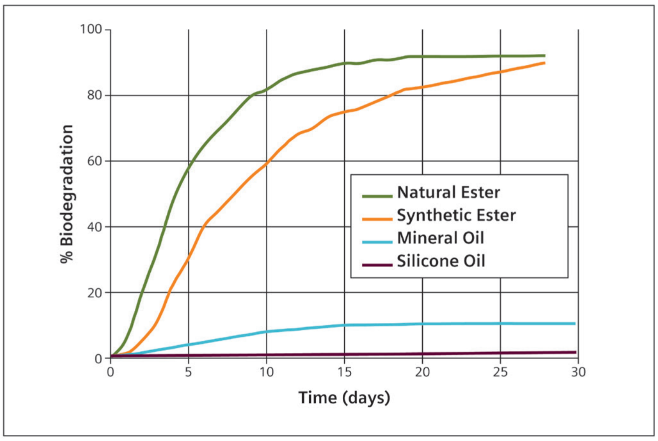

Figure 4. Comparison of biodegradability of insulation fluids [7]

Table 1. Siemens low-noise transformers – references

Rated power MVA	Sound pressure level at full load [db (A)]100 % U_{rated} + 100 % I_{rated}	Transformer type	Year	Units produced
183	53.7	transformer	2013	6
234	49.1	autotransformer	2007-2009	6
234	49.8	phase-shifting transformers	2007 2010	4
242	51.1	transformer	2009 2011	5
300	53.4	transformer	2005 2007 2009 2011	6
300	53.7	phase-shifting transformer	2013	2
420	52.4	autotransformer	2005 2010	6
500	55.2	autotransformer	2008	2
575	58.9	phase-shifting transformer	2006	1
700	50	phase-shifting transformer	2006	1

Note: For the human ear, a 56 db (A) sound pressure level is comparable with a domestic refrigerator.

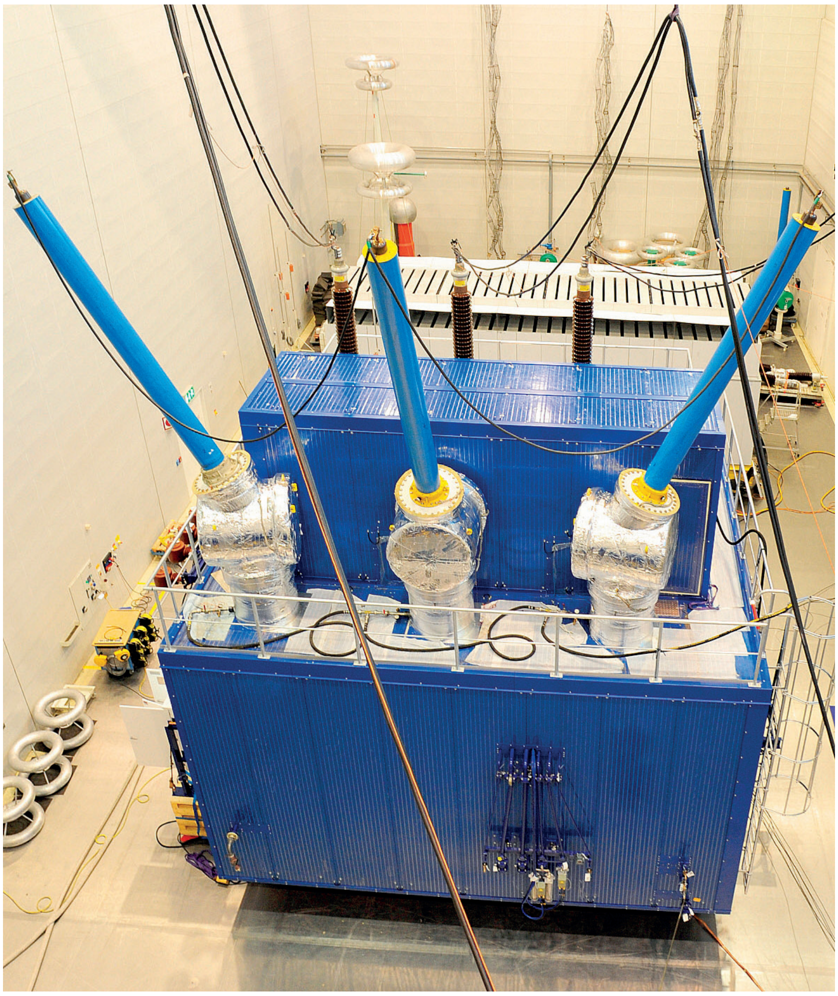

Figure 5. Transformer with thermal insulation (enclosure) in the test bay

atmosphere, unused. However, in heavily populated urban areas, this waste heat can serve another purpose. The ester-filled power transformer (see Figure 5) in London put the waste heat to good use, using a heat exchange water system device to feed a local district heating scheme, serving a nearby school and residential buildings.

In the event that there is no demand for heat on the part of the users of the district heating scheme, there are freestanding cooling banks that are mounted on the substation roof to ensure the full cooling capacity. With this the power transformer can be fully loaded in a steady state condition. This compact design reduces the transformer footprint to a minimum. Furthermore, the cooling system design maximises total efficiency of the substation and simultaneously minimises the amount of waste heat produced. In order to guarantee the efficiency of the cooling system, the transformers are configured so that the power supply for each transformer's cooling system is fed from the transformer itself to ensure that it is not reliant on the operation of another substation.

To maximize the efficiency of waste heat utilization, dissipated heat must be kept to an absolute minimum. In order to achieve this, the temperature of the cooling water must be kept constant, regardless of the load loss level. The solution is a combination of good insulation of the transformer and the development of a PLC-based control system (programmable logic controller) in order to regulate operation temperatures. The 240 MVA/400 kV auto transformers generated 1025 kW of waste heat at 60 % load, which is equivalent to the amount of heat needed to heat seventy households. Table 2 shows how the system was configured (see Figure 6).

This logic can equally be applied to smaller transformers. For example, 0.5 MW could be recovered from a 40 MVA transformer operating at 80 % load. If the heat can be used in urban, industrial or agricultural applications, this could result in savings with higher ROI (return on investment).

The transformers and cooling systems for the London substation were supplied by the transformers factory in Weiz, Austria. The transformers were successfully tested in 2015 and shipped to the London location where installation works are currently underway. The units are expected to enter into service in the urban area in 2018.

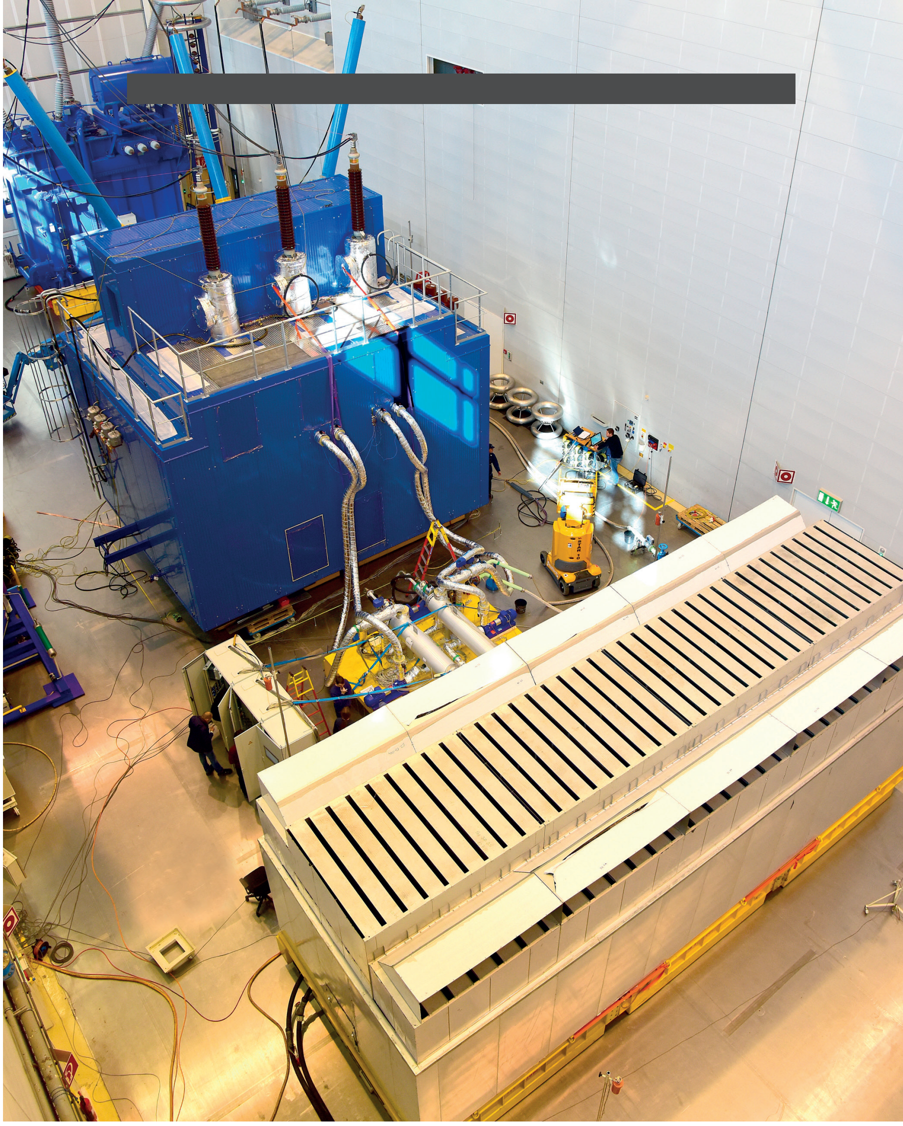

Figure 6. Transformer cooling system (heat exchanger) special silencers in the test bay

Conclusion

Together with the customer, National Grid, Siemens has developed an economical solution that allows waste heat from three power transformers to heat a school located next to the substation. Depending upon the electrical energy used in this area, more than 1 MW of waste heat from the transformers can be recovered to heat local homes, shops and schools in the future.

To maximize the efficiency of waste heat utilization, dissipated heat must be kept to a minimum, which was achieved by a combination of good insulation of the transformer and a noise-optimized cooling solution using frequency-regulated fans

When installing transformers in urban areas, noise plays a key role, as do reliability and safety. The transformer and cooling devices need to operate silently regardless of transformer load. The transformer with ester-filling and waste heat utilization is manufactured with a low-noise design. Bespoke housing as well as noise-optimized cooling with frequency-regulated fans was added to the low-noise-concept. These measures result in units that are inaudible from the adjacent road and nearby flats in normal operation.

Table 2. Heat output at nominal tap for three transformers

	Energy recovered
Heat at no load	84 kW
Heat at 10 % load (24 MVA per transformer)	110 kW
Heat at 17 % load (40 MVA per transformer)	159 kW
Heat at 33 % load (80 MVA per transformer)	368 kW
Heat at 50 % load (120 MVA per transformer)	738 kW
Heat at 60 % load (144 MVA per transformer)	1,025 kW

Safety, reliability and environmental impact are crucial for transformers, espe-

Proven at 400 kV/240 MVA, the technology of combining ester insulation and heat recovery devices could be adopted in smaller transformers leading to significant cost saving and carbon footprint improvements

cially in large cities. Occupied premises must be safe from the risk of fire or explosion from installed electrical assets, supply disruption must be avoided though high network reliability and environmental considerations are a high priority.

Ester insulation greatly reduced the risk of fire and explosion. The firepoint and flashpoint of synthetic ester are very high compared to mineral oil. Esters are fully biodegradable, which adds to the environmental credentials and reduces risks to the environment.

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