

DEVELOPMENT OF POLE-MOUNTED DISTRIBUTION TRANSFORMER WITH ARAMID INSULATION FOR INCREASED CAPACITY AND RELIABILITY OF POWER DISTRIBUTION NETWORK

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ABSTRACT

This paper describes the development of compact, light-weight 400 kVA pole mounted distribution transformer for replacement of 200 kVA overloaded transformers installed in Pakistani distribution network and experiencing frequent failures related to degradation of their insulation. Upgrading of standard H-type pole substations was not possible with conventional transformers because of dimensional and weight constraints. Only optimal utilization of high temperature insulation materials (aramid solid insulation and silicone oil) allowed satisfactory size and weight reduction.

INTRODUCTION – WAPDA DISTRIBUTION NETWORK

WAPDA is Pakistani distribution utility consisting of a few local distribution companies. There are 501 264 transformers installed in WAPDA distribution network to serve 170 million people of Pakistan. These transformers normally have Dyn11 vector group and 11 000/415 V voltage rating. Typical installation is in the pole-type substation.

With the continuous expansion and increasing load in the existing distribution network the utility companies are facing serious issues related to the reliability of the power supply system. It has been observed that failure rate of distribution transformers is continuously increasing. Table 1 shows transformers power ratings along with their quantities

Table 1. Transformers installed in WAPDA network

kVA rating	Number of units	Relative failure rate
10	19 644	4.79%
15	20 186	5.81%
25	204 301	4.28%
50	140 888	14.97%
100	70 921	29.38%
200	40 189	38.66%
400	2 864	0.94%
630	2 271	1.18%

installed in WAPDA network and calculated relative failure rates. The relative failure rate represents number of failed transformers of particular size relative to other transformer.

Transformer data was collected and it was observed that there were several reasons for failures including mechanical issues such as leakage of gaskets or improper LV connections. However, one of the major identified reasons for failures was overloading of transformers, frequently resulting in transformer fires.

Loading of transformers is increasing day by day and transformers need continuous replacement with units of higher kVA rating. Pole-type transformers from 10 to 100 kVA can easily be replaced with larger units. However, it is not possible in case of 200 kVA transformers. They would have to be replaced with 400 kVA units which are next in the standard range of power ratings. The conventional 400 kVA unit would not fit standard H-type pole arrangement due to dimensional and weight limitations.

According to WAPDA specification for H-type pole substation, the length and width of the transformer must not exceed 1700 mm and overall weight must not exceed 1500 kg [1]. As per calculations made by Pak Elektron Limited (PEL) the minimum length of conventional design for 400 kVA unit could be 1860 mm (160 mm more than limit) and the minimum weight could be as high as 1885 kg (385 kg more than limit). With these dimensions and weight, the 400 kVA units could only be installed on new design of H-type poles which would require major investments on WAPDA side and rebuilding thousands of existing substations. As a result, the highly overloaded 200 kVA transformers are being currently replaced with units of the same power rating. Such a solution is good only for short term operation. Without upgrading, the transformer insulation is continuously exposed to high temperatures exceeding acceptable limits, which inevitably leads to its extended degradation and new failures are observed relatively quickly. Looking for possibility to build more compact pole-type transformer both WAPDA and PEL focused on investigating solution using high temperature insulation materials.

HIGH TEMPERATURE TRANSFORMERS

The definition of high temperature transformers refers to designs utilising properties of insulation materials allowed for long term operation at temperatures higher than those for mineral oil and conventional non-thermally upgraded cellulose. These transformers are designed to operate at temperature rises higher than 60 K for top oil and higher than 65 K for average winding. They use alternative fluids (silicones, esters) and alternative solid insulation materials (aramid fibre, high temperature insulating enamels).

Historically, in the size range typical for distribution transformers they have been mainly used in specialty applications like traction transformers and wind turbine transformers, where compactness and high reliability is critical. Recently, there is an increasing interest observed in evaluation of the concept for application in distribution transformers for utility networks [2]. The first installations of high temperature transformers in distribution network were made in Korea a few years ago. Still, value of the concept does not seem to be fully recognised by utilities in the world. It is becoming common to specify alternative fluids for environmental or fire safety, but only combining them with high temperature solid insulation allows for full utilisation of their ability to work at elevated temperature.

Years of experiences in application of high temperature insulation systems in power and distribution transformers resulted in creating IEC guidelines for design and application of high temperature transformers [3], which will be converted to the International Standard in 2012. The document defines typical insulation systems based on insulation materials offering high temperature performance capability, and also defines temperature limits for these insulation systems.

Table 2. Temperature limits for insulation systems with alternative fluids and solid insulation of thermal class 180°C or higher, as per IEC 60076-14 (maximum ambient temperature of 40°C assumed) [3]

	Ester	Silicone
Top liquid temperature rise (K)	80	100
Average winding temperature rise (K)	115	125
Hot-spot temperature rise (K)	160	180

Allowing insulation materials to operate at temperatures higher than conventional gives the possibility for reduction of cooling system. This refers to both:

- eliminating or reducing number of cooling ducts inside the windings to improve their filling factor, or
- reducing cooling installed on transformer tank in the form of radiators of corrugated fins.

Consequently, the design becomes more compact and significant reduction of size and weight can be observed [4]. This reduction can be very important for installation or operational reasons (e.g. in case of upgrading existing

substation. In some cases the significant reduction of major construction materials can compensate for more expensive insulation system used, making the design more economical.

Coils, magnetic core, oil, solid insulation and tank are main parts of a transformer. Transformer weight and dimensions can only be reduced by reducing weight and volume of all or any of these parts. Core and coil weight are linked with no-load and load losses and properties of applied materials. Core steel and winding conductors having superior properties are not cost effective and resultant reduction in transformer volume would be very limited because of relatively small share of those components in total volume of transformer (only 12% as per Table 3). They could play more important role in weight reduction. Weight of tank is directly linked with volume of oil. So, reduction of oil volume is the key for reduction of weight and dimensions. When relatively expensive alternative fluids are used, the oil volume reduction becomes more critical also for transformer cost reduction.

Table 3. Typical weights and volumes of major transformer components

Component	% weight	% volume
Oil + solid insulation	30%	78%
Core + coil	40%	12%
Tank	30%	10%

Weight and volume of oil is linked with heat to be dissipated, voltage level to withstand and oil physical properties, both thermal and dielectric. The heat dissipation is governed by the following relation:

$$Q = (T_1 - T_2) / R \quad (1)$$

where:

- Q - heat to be dissipated (transformer losses),
- T₁ - temperature of heat source (oil temperature),
- T₂ - ambient temperature,
- R - thermal resistance.

For a given transformer with losses guaranteed at specific level the heat to be dissipated is constant. Thermal resistance depends on the tank surface area. From equation (1), if the temperature difference is increased, the thermal resistance can also be increased to dissipate the same heat. Hence, less tank surface area is required when oil can operate at higher temperature (lower tank weight and oil volume).

As per the IEC guidelines in Table 2, the top oil temperature rise can be increased from 60 to 100 K when silicone fluid is used, and the average winding rise can be increased from 65 to 125 K with aramid insulation. Such combination of materials allows increasing T₁-T₂ difference and tank surface area can be reduced significantly. The right combination of insulation materials is critical for full utilisation of their properties and achieving desired design compactness.

An inherent feature of high temperature transformers is their fire resistance. Both, insulating fluids and solid insulation typically used in such designs show low flammability, which is critical for improved safety of installations.

SMART® TRANSFORMER DESIGN

To increase the capacity of the distribution network and fit transformers on the existing pole layout, the 400 kVA pole-mounted Smart® transformer has been developed by PEL with cooperation of WAPDA for replacement of conventional 200 kVA units. High temperature insulation materials have been used in accordance with IEC 60076-14: Nomex® aramid insulation for solid insulation components (paper and board) together with silicone dielectric fluid. By application of rules specific for high temperature transformer design the new transformer has got the same or better electrical characteristics as that of conventional 400 kVA design but also fulfils the dimensional and weight requirements as for original 200 kVA unit to be replaced. By this, the replacement of existing units will not require any extensive work related to replacement of existing H-type poles.

Dimensions of 400 kVA Smart® transformer are even smaller than those of conventional 200 kVA unit. In the past tubular tanks were used as standard tank design. When the tubular tank was replaced with corrugated tank for 200 kVA transformer, the dimensions were reduced significantly. However, even this improvement did not allow fitting 400 kVA transformer in the space provided. Only combination of corrugated tank with concept of compact high temperature transformer has given successful results.

Table 4. Design characteristics of conventional and Smart® 400 kVA transformers

Design parameter	Conventional	Smart®
No-load losses measured (W)	851	794
Load losses measured (W)	5313	5060
Oil weight (kg)	416	256
Dielectric fluid	mineral oil	silicone
Solid insulation	cellulose	Nomex®
Top oil rise measured (K)	40	90
Avg winding rise measured (K)	41	99

Table 5. Comparison of dimensions and weights for different transformer design concepts

Design concept	Length (mm)	Width (mm)	Height (mm)	Weight (kg)
Conventional 200 kVA tubular tank	1770	1226	1204	980
Conventional 200 kVA corrugated tank	1380	980	1054	945
Conventional 400 kVA corrugated tank	1860	1055	1545	1885
Smart® 400 kVA corrugated tank	1280	805	1325	1410

SMART® TRANSFORMER PERFORMANCE

Load losses of a transformer increase with the square of loading. To compare the losses and temperatures of present WAPDA’s 200 kVA overloaded transformers and 400 kVA Smart® transformers when installed in place of 200 kVA, the curves in Fig. 1 and 2 have been plotted. These curves show the trend of increase in transformer losses and winding temperature at various loading.

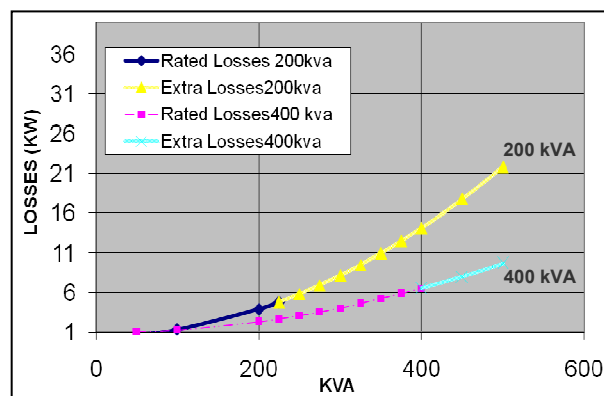


Fig. 1. Losses of conventional 200 kVA and Smart® 400 kVA at various loading

It is natural that 400 kVA transformer has rated load losses higher than 200 kVA transformer. However, if these transformers had to be installed in the same loading conditions, the losses observed in 400 kVA unit would be always lower than in 200 kVA (see Fig. 1). Hence, these must not be the rated losses to be compared to evaluate the cost of transformer operation but the real losses calculated for given loading. With respect to that, operation of 400 kVA Smart® transformer is cheaper than overloaded 200 kVA. However, keeping in mind that operation of 200 kVA units is not acceptable for the existing capacity demand in WAPDA network, the new 400 kVA design should be actually compared with two units of 200 kVA each to meet the required capacity. In such a case, the evaluated cost of losses for one 400 kVA is again lower than that of two 200 kVA units (see Table 6).

Table 6. Capitalised loss for different transformers based on guaranteed losses

	No-load loss	Load loss
400 kVA Smart®	925 W	5600 W
2 x 200 kVA conventional	990 W	6800 W
Loss difference	65 W	1200 W
Monetary saved by applying WAPDA capitalization factors	19 500 PKR	174 000 PKR
Total saving	193 500 PKR (2 250 USD)	

The cost of Smart® transformer is about 15% higher than conventional 400 kVA transformer. This is far less than cost of a new H-type pole to be installed along with a new 200 kVA transformer. This means that apart from lower

operational cost of new 400 kVA coming from evaluated losses, also the installation cost will be reduced. What must not be forgotten is also the time saved for upgrading the existing H-type pole substation with simple replacement of transformers, instead of extending substations by another H-type pole with another 200 kVA transformer.

As shown in Fig. 2, insulation materials are exposed to different temperatures in each design concept. For rated operating conditions the temperatures are naturally higher in high temperature transformer, and this is normal based on the proper insulation material selection. According to IEC 60076-7 "Loading guide for oil-immersed power transformers" the temperature for normal life expectancy of cellulose is 98°C. As indicated in Fig. 2, the hot spot in conventional transformer can reach and exceed this temperature when transformer is fully loaded and ambient temperature reaches maximum level of 45°C, as specified by WAPDA (hot spot temp = 108°C). This means that maximum ambient temperature or most overload situations would result in extended degradation of insulation system.

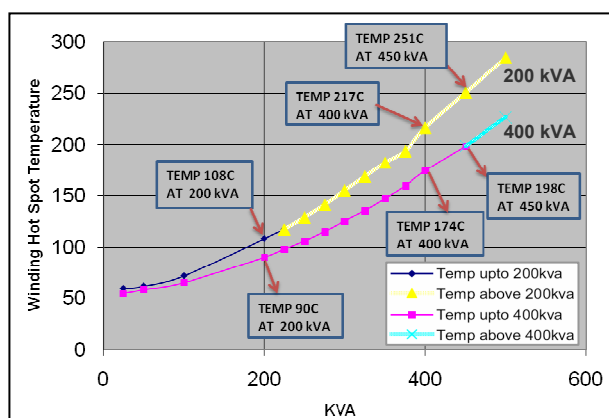


Fig. 2. Hot spot temperature of conventional 200 kVA and Smart® 400 kVA at various loading (at max ambient temperature of 45°C)

For aramid insulation, the normal lifetime temperature is about 200°C. In case of aramid insulated 400 kVA unit, the calculated hot spot temperature is below 200°C (174°C). Hence, even at maximum ambient temperature and full transformer loading the insulation still works below its full thermal capability. As a result, the aramid insulation still has some significant overload capability for loading over the rated 400 kVA. No extensive insulation degradation would be observed when transformer was loaded up to 450 kVA (198°C), and further load increase over 500 kVA would be still allowed for emergency situations. By this, the reliability of the design is improved significantly comparing to conventional design.

A prototype of 400 kVA unit was developed and thorough tests were performed and passed including type tests (temperature rise test, short-circuit test, lightning impulse test). Ten transformers were purchased by Lesco (part of WAPDA) on trial basis and installed in critical overloaded locations of the network to test their performance in real environment. Since their installation in mid 2010 until printing of this article in January 2011 no operational issues have been reported.

CONCLUSIONS

The optimal utilization of properties of high temperature insulation materials allowed substantial size and weight reduction of the transformer compared to the conventional constructions. Upgrading of network capacity was resolved without changing the layout of the pole type substations and with minimized impact on the existing infrastructure. On top of the upgraded rated capacity of the transformer developed, the overload capability is still available, which could be used in case of further unforecasted overload demands. This will have an impact on increased reliability and life of the distribution network.

The new design not only solves the critical issue but also provides more economical solution in terms of losses. The utility will save money by purchasing new transformers in the future. Although new transformers are more expensive than conventional ones, the costs related to their operation and installation are significantly lower. This proves a good development strategy at PEL and WAPDA with use of advanced technical solutions.

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