Investigation of Energy-efficient 10 KVA Switchable Transformer

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Abstract: Recent studies on a switchable, energy efficient transformer has shown that by incorporating additional windings in a conventional transformer, that the overall efficiency can be improved across a wide range of load conditions. This has been achieved through the use of a series configuration to reduce the core losses at low loads, and a parallel configuration to reduce the copper losses at high loads. At current stage, a 10kVA switchable transformer has been designed and implemented, testing is performed to determine the parameter of the transformer and compare the practical result with the simulation result to confirm the accuracy of the testing. Also it justifies the lower total operation costs (TOC) through comparison with standard transformer. The scope of this research is to continue with the development and investigation to explore the potential of energy-saving in industry-sized distribution transformer which reduce needs for new generation capacities and reduced investments in electrical distribution and transmission networks and most importantly - reduction of greenhouse gas emissions.

Key-Words: Transformer, Energy-efficient, Switchable, Total operation cost, Greenhouse gas emission

1 Introduction
Transformers are needed to transport electricity economically to our homes and workplaces. They are designed to raise or lower voltage to meet special electrical needs. When “standard” transformers are used, much energy is wasted in the form of heat.

1.1 Motivation
Electricity consumption in Australia is predicted to grow steadily, at least for the period to 2015, and the capacity of transformers has grown at a 1.3% per annum through the 1990’s. As a result it is estimated that, losses are also likely to grow at an average of 1.3% per annum. the problems associated with satisfying both, constantly increasing energy demands and accompanying environmental constraints could be partially solved by improvements in energy efficiency.

Energy-efficient transformers substantially reduce the amount of this wasted energy. Since transformers have a typical service life of 20-40 years or even more, the lower operating cost of energy efficient transformers can result in substantially lower total owning costs.

Typical peak transformer efficiency range from 90% to 97%, as the load varies, so does the efficiency of the transformer. Fig.1 illustrates a typical transformer efficiency curve (red) and both the fixed core losses (blue) and variable copper losses (purple). It can be seen that before point A, the core losses are dominant, whilst after point A, the copper losses are dominant. Thus to increase the efficiency of the transformer over the whole operating range, both the core losses and copper losses need to be minimized.[3]

Fig.1. Typical transformer efficiency curves.
1.2 Significance
Optimized winding switchable distribution transformers (cost-effective and highly efficient designs and appropriately improved utilization, loading and maintenance techniques) would provide numerous global benefits to the wider public as well as local benefits to electrical distribution companies, energy efficient transformers will reduce needs for new generation capacities and reduced investments in electrical distribution and transmission networks and most importantly - reduction of greenhouse gas emissions.

1.3 Scope
The scope of this research is to continue with the development and investigation of the previous 3KVA switchable transformer with this large rating 10KVA. The purpose is to explore the potential for energy savings through the eventual development of switchable industry size distribution transformer.

2. Method
In recent research, switchable transformer has been developed with the intent to improve efficiency by decreasing both the core and copper losses over a wide range of load currents, the switchable three-phase transformer has been specially wound so that there are four individual windings within both the primary and secondary of each phase, which has allowed for the connection of three different configurations, conventional, series and parallel [4]. Fig.2 shows that the switchable three-phase transformer appears to be the same as a conventional transformer, but internal windings are quite unique.

2.1 Configuration
2.1.1 Conventional Configuration
In the conventional configuration the transformer will operate in the same way as any standard distribution transformer. The difference between the two is that the winding in both the primary and secondary coil are wound into the transformer as separate coils so that the other two configurations can be implemented.

2.1.2 Series Configuration
In the series configuration an additional 20% windings were placed in series with the three coils of the conventional windings. The additional windings reduce the working flux density and hence the core losses of the switchable transformer at low loads. The additional windings cause an increase in winding resistance and hence an increase in copper losses ($P=I^2R$). However these losses are negligible when compared to the reduced core losses in the series configuration. Fig.3 illustrates the winding arrangement of the series configuration.

2.1.3 Parallel Configuration
In the parallel case, the transformer windings are placed in a parallel configuration such that the overall resistance of the transformer windings is reduced. This has the effect of reducing the transformer copper losses, which are dominant at high loads as demonstrated by $P=I^2R$. There is an increase in the core losses, but it is negligible when compared to the reduction in copper losses. Fig.4 illustrates the winding arrangement of the parallel configuration.
2.2 Switching devices
To enable ease of testing the transformer in series, parallel or conventional configurations, a new switching set-up has been designed. This will enable the user to ‘force’ the transformer into a particular configuration for testing purposes with the push of a button. See Fig.5 for new switching set-up.

Fig.5: Switching setup

2.3 Controllers
The existing “Smart Transformer” has a controller system, which could monitor and control its operation in order to maximize its efficiency[14]. The controller system was micro-controller based which was found to be ideal to meet the requirements due to its robustness, flexibility and low cost. The micro-controller has been used to drive SSR’s that switch the series and parallel windings of the transformer and also to monitor the operation and condition of the transformer.

Fig.6 Switchable transformer control system

3 Simulation and Test
The short circuit and open circuit test of the switchable transformer was carried out to determine the parameter of the smart transformer, and load test is performed to compare the practical result with the simulation result to confirm the accuracy of the testing.

4 Market potential analysis
The total owning cost of a transformer consists of several components, including the purchase price, the value of energy losses, maintenance and repair costs over the lifetime, and decommissioning cost. The purchase price and the energy losses are the two key factors for comparison of the different transformers[10]. The total operation cost (TOC) of a transformer can be expressed as the sum of the purchase price (Ct), the cost of no-load losses and the cost of the load losses, or as a formula:

\[ \text{TOC} = \text{Ct} + A \times \text{NLL} + B \times \text{LL} \]

In Eq.(1) \( A \) is No-Load Loss evaluation factor [$/W], \( B \) is Load Loss evaluation factor [$/W], \( \text{NLL} \) is No-Load Loss at nominal voltage [W] and \( \text{LL} \) is Load Loss at 75°C [W].

A relatively simple method for determining the A and B factor for small transformers is provided. The total cost over the lifetime of a transformer depends on a lot of figures. This method is not entirely correct, but gives an indication of the factor A and B for the industry and is therefore better than disregarding the
costs of loss during lifetime at all. A and B are calculated as follows:

**No-load loss evaluation factor**

\[ A = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \times (p + 8760 \times q) \]  
(2)

**Load loss evaluation factor**

\[ B = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \times (p + 8760 \times q \times LLF) \times \left( \frac{I_l}{I_r} \right)^2 \]  
(3)

Where:

- \( i \) = Australian interest rate [%/year]
- \( n \) = lifetime [years]
- 8760 = number of hours in a year [h/year]
- \( I_l \) = loading current [A]
- \( I_r \) = rated current [A]

| Table 1 comparison between Conventional Transformer and “switchable” Transformer |
|-------------------------------------|-----------------|-----------------|
| Power loss on no-load (W)          | 155             | 102             |
| Power loss on full load (W)        | 695             | 558             |
| Efficiency at full load (%)        | 91.5            | 92.5            |
| Cost of no-load loss ($)           | 1122            | 738             |
| Cost of load loss ($)              | 1260            | 1012            |
| Transformer purchase price ($)     | 300             | 600             |
| Total operation cost ($)           | 2682            | 2350            |

Hence it could be deduced from Table 1 that the total operation cost of switchable transformer is lower compared to the conventional transformer. The switchable transformer pays for itself shortly compared to the lifespan of transformer.

5 Conclusion

The 10KVA prototype energy-efficient transformer prove that switchable transformer saves energy in the long run by means of switching into series configuration when it comes to light load and into parallel configuration when it comes to full load. This can be explained by the reduction of core losses in series configuration and reduction of copper losses in parallel configuration.

So it is expected that, this “smart” transformer techniques could be adopted in large rating transformer, The success of this project will offer incentive to power distribution utilities to upgrade their current stock of distribution transformer to energy-efficient transformer. In addition, this research could be innovated by integrating a fuzzy logic controller for optimization of transformer design.

References:

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