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Innovative Design & Manufacturing Techniques for Cost Effective & Superior Performance Power Transformers

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Abstract **- The critical importance of power transformers in any power system can never be over emphasized. The transformer design and manufacturing techniques have remained more or less the same for almost 150 years. But in recent times continuous efforts to achieve energy efficiency and cost effectiveness without compromising the electrical performance of the system has compelled power engineers to move ahead from conventional transformer design and manufacturing techniques to next generation concepts thus achieving a balance of long term monetary savings and superior performance which was not possible a couple of decades ago. The aim of this research paper is to introduce new design and manufacturing techniques which are evolving to give rise of smarter use of new materials thereby changing the physical construction of traditional transformer. The paper also presents the practical advantages of the emerging designs and manufacturing techniques through theoretical design calculations and practical case studies.**

Keywords: Transformer, Design Techniques, Insulation

I. INTRODUCTION

The power transformer is a fundamental part of any power system and contributes a handsome part of the total cost of installed equipment. Furthermore, in a usual life span, a typical transformer's accumulative losses by far surpass this initial fixed cost.

Nowadays, the whole world is going through an era of economic and energy crisis. As it is an established fact that both of these factors are directly dependent upon each other hence recently the focus of power engineering community has shifted towards developing new methods and materials which are cheaper, easier to obtain and yield superior electrical performance under different operational circumstances.

Similarly, the design and manufacturing techniques are evolving to give rise to smarter use of these materials in new ways thereby changing the physical construction of a traditional transformer to such an extent that it is somewhat difficult for a novice to identify or correlate the same to a conventional transformer [1,4].

II. CONVENTIONAL TRANSFORMER DESIGN AND MANUFACTURING

The design of a transformer covers the selection of materials and engineering of Electrical &Mechanical design. Keeping in view the ever increasing diversity in the possible permutations of design characteristics, generally physical design prototypes are required before proceeding with routine production. Whereas the manufacturing process is where all of the successful design and engineering effort is put under routine manufacturing for mass production. Hence there can be cases where a design that looks great on paper might not prove to be much production friendly after all. Any transformer essentially comprises of the following main physical components:

- Magnetic Core
- LV & HV Windings
- Insulation Medium
- Tank

A conventional transformer has following salient design and manufacturing parameters:

- Manual Engineering Process for development of the transformer
- Mitred Edge, 5 Part circular, stacked lamination core
- Layer wound low voltage copper winding
- Disk wound high voltage copper winding
- Mineral based oil immersed core coil assembly
- Elliptical tubular tank construction
- A bunch of rudimentary Monitoring and Protection instruments [1, 10].

III. TECHNIQUES TO IMPROVE THE TRANSFORMER PERFORMANCE

Different cutting edge technologies and techniques are being implemented now days to replace / improve each of the above said parameters keeping in view the exact nature of application and requirement from the end product. In this regard major developments successfully being adopted around the globe are as follows:

- Computer Aided Design and Engineering Process
- Wound core type transformers
- Amorphous Core type transformers
- Foil winding technique
- Use of Aluminum conductor
- Synthetic Fluids and Dry type insulation
- Corrugated sheet tank construction
- Sophisticated monitoring and protection devices

The use of any one or more than one of above stated techniques can give desired advantages over conventional transformers for different requirement / applications on case to case basis. The decision of using any of the above will be based upon the right balance to be achieved between cost and intended benefits in the light of desired application of the transformer [1].

IV. DESIGN PROCESS

All improvements in any engineering product start from the design process. The design process mainly covers following aspects:

- Selection of materials
- Electrical and mechanical design parameters
- Development of prototypes
- Design Verification through intensive routine and type testing

Detail of modern design and comparison with conventional design is discussed in detail in next section.

V. OPTIMIZED DESIGN

Now days the design and engineering of the transformers has completely shifted to computer software's. We can design, analyze, simulate, test, get results, improve and repeat the cycle for as much iteration as we wish for. Hence the concept of "optimized" designs has emerged. "*The best possible design out of numerous possible iterations which can provide maximum performance benefits using minimum physical resources.*"

The most renowned software's for this purpose are:

- AutoCAD
- Matlab
- Pro Engineer

Three dimensional (3-D) modeling has enabled the mechanical design engineers to actually visualize the end product in a step by step assembling approach. Whereas electrical design engineers can visually observe the different electrical parameters such as electric field, magnetic field, potentials, current flows etc. at any required spot.By using these computer programs a designer can easily simulate different operational models and fault simulations to analyze the behavior in years of practical field operation within a matter of days.

VI. MAGNETIC CORE DESIGN

The transformer core is a ferro-magnetic (Soft Iron) material placed between the windings to facilitate the magnetic flux passage and provide flux linkage.

A) Magnetic Core of a Conventional Transformer

Conventional transformer core is manufactured from Cold Rolled Grain Oriented Silicon Steel Sheet (CRGO-Si Steel).Conventional core has six air gaps at every mitered edge formed by stacking together different laminations. This results in high core losses and greater diameter requirement for higher end flux densities thereby increasing the required core material.

B) Amorphous Core for Modern Design

The amorphous core is made from non-crystalline atomic structured metal alloys which can be easily magnetized. This sort of alloy can be easily malleable into paper thin sheets. It is possible to process the amorphous core laminations of thickness 0.06 mm against Si Steel laminations of thickness 0.27 mm to drastically reduce hysteresis and eddy current losses thereby a 65~75% reduction in core losses can be achieved easily.

Fig. 1.An Assembled Amorphous Core

The amorphous core laminations are made in semi-circular form which can be assembled together into one unified core as shown in Fig 1, within 20~25% reduced assembling / stacking time as compared to conventional core

C) Advantages of Amorphous Core

Following are the advantages of amorphous core over conventional magnetic core.

1) Increased Mechanical Strength

In case of amorphous core all laminations are packed together into one unified core and the outermost laminations are welded together to hold the whole core assembly securely in place. Hence this provides increased mechanical strength against axial and radial short circuit forces during abnormal working conditions.

2) Computer Aided Lamination Cutting

The whole process of cutting and forming amorphous core laminations is carried out on Computerized Numerically Controlled (CNC) machines regulating the process to minimize the workmanship flaws and weaknesses to virtually zero level and giving precise and accurate results down to one hundredth of a millimeter.

3) Air Gap

The air gap in amorphous cores is distributed asymmetrically to reduce effective air gap effect at any specific cross section of the core. Hence we can dramatically reduce the core diameter thus leading to savings in the material requirements for even the high flux density operation **[2].**

VII. WINDING DESIGN

The transformer windings are the basic current carrying part of the transformer. It consists of conductor turns wound together to be put over the core.

A) Winding of Conventional Transformer

In a typical transformer there are two copper separate conductor windings under electrical and magnetic linkage. It is to be noted that there is no direct connection between both circuits of these windings.

B) New Materials and Techniques

1) Aluminum Conductor Winding

The extensive use of Copper in nearly all kinds of electrical equipment and the increasing disparity between demand and supply of this essential engineering community has made Copper most expensive part of a typical power transformer. Hence the low cost alternative of Copper with comparable electrical results is Aluminum. This has been used extensively in transmission lines for many decades and now slowly getting accepted into the power transformer due to following benefits.

2) Oxidation and Decay

Both Copper and Aluminum conductor oxidize over time, but Aluminum oxidizes completely to cover the conductor surface with Aluminum Oxide (Al_2O_3) which is a very good electrical insulator hence further decay is stopped. This leads to an extended life span of conductor winding and hence the whole transformer

3) Cost Effective

To achieve the same electrical conductivity of Copper is 59.6 MS/m whereas that of Aluminum is 35MS/m. Hence 66% more conductor diameter is required for Aluminum winding. But as Copper is 3 times expensive than Al by weight. Through empirical calculations we can find that there is a net saving of around 45% if we use Aluminum conductor.

4) Excellent Workability

It is very easy to work the aluminum metal which has inherently excellent malleable and ductile strength. Hence it can be rolled, extruded, drawn or formed into most shapes very easily hence customized requirement scan be met easily.

C) Foil Winding

In traditional transformer round-wire conductor winding is used in which we start at one end of the winding and proceed vertically making consecutive turns till a layer is complete till the other end. Then the process is reversed and another layer is added till we reach the starting point. Then this process is repeated for as many times as required [3]**.** Figure 2 shows the potential difference across a round wire winding.

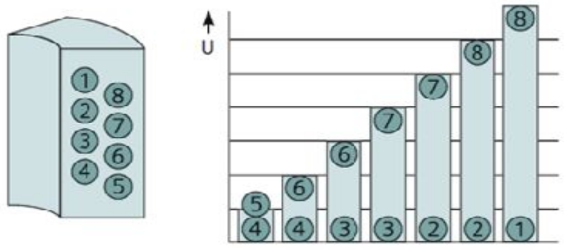

Fig. 2. Potential Differences in a Round-Wire Winding

In round wire winding the inter turn voltages can add up to twice the interlayer voltage. Instead of winding with round-wire conductor strand(s), a thin foil of conductor is used in modern design where each turn of foil shall correspond to each layer and turn of the winding simultaneously. Figure 3 shows the potential difference across a foil winding

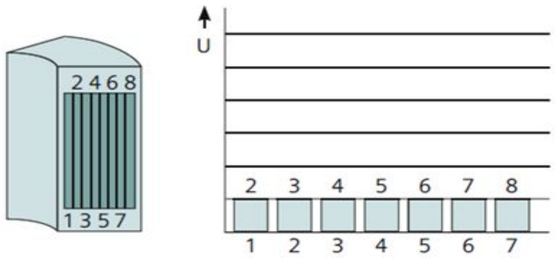

Fig. 3. Potential Differences in a Foil Winding

Compared to round winding in this new winding technique interlayer voltage is equal to the inter turn voltage.

1) Foil Winding Advantages over Round Winding

- Uniform voltage gradient per layer and/or per turn
- Uniform current and electric field intensity throughout the layer
- Reduced Hot-spot temperatures
- Superior mechanical strength as mechanical axial forces during transients or short circuit condition can be withstood easily
- Winding looseness due to repetitive stress caused by surges and transients is greatly reduced
- The overall size and dimensions of the winding can be made compact and space efficient
- CNC winding process to reduce the workmanship error and manufacturing flaws

VIII. THE INSULATION MEDIUM

The insulation medium is required to provide electrical insulation between different parts of transformer and to prevent the core and windings from getting excessively hot due to heat dissipation.

A) Insulation Medium of Conventional Transformers

In traditional transformers highly refined mineral based transformer oil is used. Most energy efficient transformer is oil immersed type but conventional transformer oil has some disadvantages few are mentioned below:

2) The disposal of transformer oil is an issue due to bio-hazardous Polychlorinated biphenylor PCBs present in the transformer oil.
3) Sludge formation due to degradation of oil and cellulose (paper) may occur overtime making routine maintenance more and more difficult
4) Oil hydration due to moisture content in air may cause abrupt premature failure of insulating properties of the oil [4].

B) Innovative Insulation Solution

1) Silicon Fluids & NOMEX

Instead of ordinary mineral based transformer oil and class "A" cellulose (paper) insulation with flash point of 140*C which gives a temperature range limited to only 105*C at ambient design of 40*C, we can use Silicon based Transformer oil with flash point of 300*C with class "C" NOMEX® synthetic insulation allowing Conductor temperature rise of 180*C for oil immersed transformers. NOMEX® is a brand name of special highly stable synthetic insulation material developed by world renowned synthetic products manufacturer DUPONT. NOMEX® retains its dielectric properties even at relative humidity in the range of 90~95%. Hence in such cases where moisture contamination in breather-conservator type transformers degrades the overall dielectric strength of the insulation system, the winding is still safe from inter-turn insulation failure in case of voltage surges and spikes during normal and abnormal transient conditions.

2) Ester Based Bio-degradable Fluids

Ester fluids are vegetable oil based products essentially originating from plant extracts. The major development in this regard has been made by Cooper Power System, USA in the 1990's. Ester based fluids have a remarkable ability to bio-degrade up to 97% in just 3 weeks' time. Moreover, there is no harmful gaseous discharge in case of any short circuit or flashing in the transformer.

Fire-resistant Ester based fluids have been successfully used in new or retro-fitted transformers in field operation for more than 15 years and there has not been even a single incident reported where such kind of transformer caused fluid pool fire. Hence this is becoming the prime choice for transformers installed new human vicinity and public places.

3) SF_6Gas Filled Transformers

Sulphur-Hexaflouride or SF_6 is a gas which possesses excellent insulation properties and decomposes into its constituents upon coming into contact with electric arc. There is no sludge formation in SF_6 filled transformers and heat exchange is through the gas chamber surface. When we wish to reduce the overall dimensions of the transformer by reducing the necessary clearances between live and grounded parts of a transformer, we have to fill the overall live part in a SF6 filled chamber. In this way we can squeeze a transformer in less than one-third ($1/_3$) size of conventional transformer. Therefore such kind of transformers are used in such cases where least possible dimensions of equipment is the first priority e.g. on top of wind turbines or inside nuclear submarines.

4) Vapour Filled Transformers

This type of transformers uses Tri-tetrachloro-benzene (TTCB) which in the liquid form at room temp but its boiling point corresponds to the normal operating temperature of the transformer typically 65~70*C. At this temperature, TTCB vaporizes by absorbing the heat from the winding. These vapours are then condensed in the radiators either through natural air circulation or through secondary water circulation. These type of transformers are used where winding temperature is expected to shoot-up within short span of time such as transformer used for arc furnaces

5) Resin Casted Dry Type Transformer

In these transformers the whole live part is encapsulated inside a resin which is in liquid form when put in the molds along with hardening agent as shown in Figure 4. Depending upon the type of resin used, curing takes place at room temperature or some other higher temperature typically in the range of 20~140 ^{o}C and finally the resin solidifies around the live part.

Fig. 4. Resin Casted (encapsulated) Transformer

This way, there is no access to any live part of the transformer except the cable termination points. In case of any internal fault, the transformer live part is not accessible for repair. There is no circulation of air or any other coolant hence no direct heat exchange, except for whatever is taking place through the resin, is possible. Whereas this type of transformer will be essentially a zero maintenance transformer [5, 8].

6) Open Ventilated Transformers

Open ventilated transformers are mostly Vacuum Pressure Impregnated (VPI) type transformers where the live part is impregnated under pressure by epoxy varnish in vacuum chamber. Figure 5 shows the Resin Casted Transformer design. This gives the zero maintenance advantage of resin casted transformers with added advantage of access to live part for repair in case of any internal fault. As direct heat exchange through natural or forced air takes place in VPI transformer hence the overall size is also reduced as compared to resin casted transformers. These transformers have inherent 33% long term (10~12 hours/day) overloading capabilities due to non-degrading insulation class “F” [6, 7].

Fig. 5.Vacuum Pressure Impregnated Transformer

IX. INTEGRATED COMPACT SAFETY DEVICE

The most advanced transformer Monitoring & Protection unit is an Integrated Compact Safety Device R.I.S which can perform all of the above stated functions in one compact, aesthetically superior and functionally well-coordinated unit. Integrated safety device shown in Fig 8.

Instead of using a number of different transformer accessories, each performing its own specific function, we can install one integrated device for all possible protection and monitoring. Hence we can have maximum protection in a reasonably justified price tag which is quite economical as compared to individual accessories. Moreover, the incidents of false alarm and nuisance tripping are also overcome by using a single composite unit [9, 10].

Fig. 8. Integrated Safety Device RIS

XI. CONCLUSIONS

- Transformer design and manufacturing techniques have come a long way since its beginning nearly 150 years ago. New materials and sophisticated computer aided manufacturing machines have made it possible to implement recent technological advances into a commercially feasible product.
- Now we can take decisions regarding the design / manufacturing parameters depending upon the exact nature of application, place of installation, loading cycle etc. to choose from one of many latest options such as VPI Ventilated Dry Type to Bio-degradable Ester-Based Fluid filled transformers.
- We are living through a global economic recession and energy crisis. In today’s energy deficient global environment we cannot afford to waste a single kW of electrical energy. Hence most efficient electrical equipment is need of the hour.
- Throughout the average service life span of a conventional transformer, it can produce more losses than three times its own fixed initial cost.
- Per day interruption cost of a transformer (non-reliability) in any utility or process industry may become more than the cost of transformer itself hence most reliable and robust transformers are required to ensure continuous and trouble free operation.
- By using latest materials in modern design and manufacturing techniques we can either considerably extend the life of a transformer (30~35%) or have a continuous energy saving in terms of iron and copper losses.
- If new technologies are adopted for design and manufacturing of distribution transformers its long term benefits will make the overall electricity distribution system more efficient and cost effective.
- Innovative design and manufacturing techniques should be included in university level academics to better equip our young professionals with coming challenges of near future

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