Proceedings of the 2016 International Conference on Industrial Engineering and Operations Management
Kuala Lumpur, Malaysia, March 8-10, 2016

A bibliographic review of trends in design and management of electrical power transmission transformers

J E Amadi-Echendu and J M Mafutsana
Department of Engineering and Technology Management
Graduate School of Technology Management
University of Pretoria, South Africa
joe.amadi-echendu@up.ac.za

***Abstract*—Electricity transmission substations are fixed infrastructure assets, and the power transformer is the most visible item of equipment. The technologies embedded in protection and control switchgear, as well as in power transformers change over the very long life of a substation, even though the basic functionality remains the same. Changes in equipment technologies present salient but real challenges in design of electricity transmission networks, and especially on acquisition, operation and maintenance, and disposal of transformers deployed in substations. In addition to obsolescence, some of the challenges include age-related degradation, as well as increasingly sophisticated loading requirements on substations. A bibliographic search between 1970 and 2014 indicates that new materials plus computer-aided modelling and tools are widely applied to design and manufacture transformers to achieve higher voltage and power ratings, while sensors, information and computing systems technologies and big data analytics are increasing applied to determine transformer health index. Empirical data obtained from a case study utility suggests that operators and maintainers tend to focus on technical health indices, and this raises concern as to the robustness of decisions to decommission, refurbish, replace, and dispose of transformers in electricity transmission substations.**

Keywords—electrical transformer technology trends; transformer replacement decisions; substation asset management

I. INTRODUCTION (*HEADING 1*)

A typical electricity transmission network comprises a large base of substations covering a wide geographical area. Electricity utilities have overriding concerns about costs of designing transmission networks, acquiring, operating and maintaining, and replacing of substation transformers against sophisticated customer demands for reliability, quality of supply, pricing, and sustainability. For instance, the cost of a 100MVA transformer in 2012 was over $2 million with a combined lead and replacement time of between 12 and 24 months [1]. The operation and maintenance of a substation tends to be focused on the power transformer because it carries the highest unit cost when compared to the indispensable control and protection switchgear. The failure of a transmission substation transformer typically results in power outage over a wide area, and outages consequentially influence refurbishment, renovation and/or replacement costs. Although high costs of capital and long lead times for acquisition [2] are providing impetus for electricity utility operators to implement innovative life-extension programmes [3], however, new materials are making it possible to reduce the weight while concurrently increasing the power transfer capacity and reliability of transformers [4].

Electricity networks comprise long-lived fixed infrastructure assets, and new technologies are continuously being introduced in the management of transmission substations. The integration of new technologies in substation equipment present salient but real challenges in design, acquisition, replacement and disposal of power transformers even though the basic function of the transmission substation remains unchanged. From the viewpoint of operations and maintenance, utilities have to continuously contend with issues like obsolescence and age-induced degradation of installed equipment. Electricity utilities also have to contain costs pertaining to vagarious operational requirements whilst concurrently sourcing financing to refurbish and renovate substations, to expand/increase capacity, and to acquire new, replace, and upgrade existing transformers.

This paper briefly describes a study on trends in the design, application and management of power transformers deployed in electricity transmission substations. Section 2 of the paper summarizes a bibliographic review of changes in the design and management of transformers between 1970 and 2014. Empirical data available from a case study electricity utility between 1998 and 2014 is presented in section 3, and section 4 includes commentary regarding technology changes and transformer refurbishment/replacement decisions.

II. BIBLIOGRAPHIC REVIEW

A. Technology Changes

In essence, bibliographic approaches are applied to search published literature for trends and patterns (see, for example, [5], [6]), and to provide new information that can be applied for decision making. Often, bibliographic methods are based on quantitative analysis of keywords, titles, authorship, publishing data, and other indicators to identify trends in a subject matter

or specific field of study. This paper supplements the work in [7], albeit that a major limitation in the bibliographic approach is that it relies on the availability of publications in a specific field of study. Details of changes in the design of transformers, unless published in patents, tend to be shrouded as manufacturing trade secrets and are usually not publicly available. Nevertheless, standards (e.g., IEEE Std C57.12.xx-2010) and regulations provide the impetus to improve the efficiency of transformers. From the technology and design viewpoint, there are new materials that can be applied towards reductions in the weight, improvements in insulation and safety, as well as reductions in electric and magnetic losses in transformers. Operationally, some of the technical issues for both manufacturers and electricity utilities revolve around integrity in terms of reliability, testability, diagnostics, prognostics, and safety [8]. It is worth remarking that in the case study environment, transmission substation transformers range from 5 MVA to 2000 MVA, and 22 kV to 765 kV.

The primary and secondary elements of a transformer are depicted in the hierarchy in Fig. 1. A bibliographic review from 1970 to 2014 indicates that changes to improve power and weight efficiency of transformers have focused on new designs for the core, windings, insulation, and cooling, whereas operability issues tend to be addressed through improving the design of bushings and tap changers.

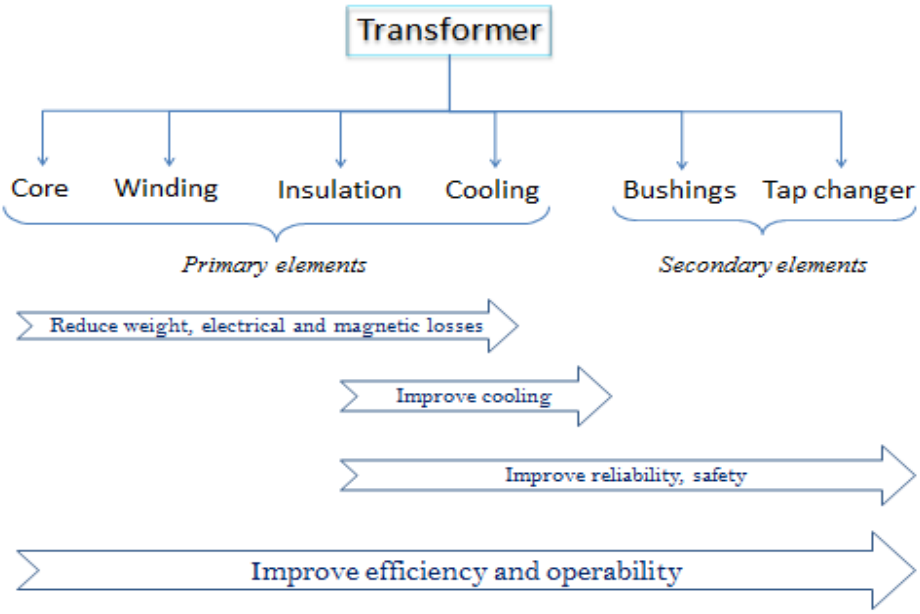


Fig. 1. A hierarchical illustration of transformer components

B. Trends in Design and Management of Transformers

The changes in the design of the core, windings, cooling and insulation as extracted from published literature are summarized in Tables 1 to 4. For the core, information in Table I indicates that the focus between 1970 and 1989 was on introducing new materials to reduce weight. Since 1990, there have been ongoing applications of computer-aided modelling and design tools towards reducing magnetic losses and improving reliability.

TABLE I. CHANGES IN CORE DESIGN

1970 - 1989	***1990 - 1999***	***2000 - 2014***
▪ Improvement in core joint designs ▪ Stacking methods ▪ Improvement in the grain-oriented steel core material References [9], [10], [11], [12], [13], [14], [15], [16]	Application of 2-D and 3-D finite element modeling tools to reduce losses References [17], [18], [19], [20], [21]	▪ Improvement on core joints from single-step-lap to multiple-step-lap design ▪ Enhancement on the 2-D & 3-D modeling using different techniques not considered by previous authors in 90's due to limitation of software packages References [22], [23], [24], [25], [26], [27], [28]

Similarly for transformer winding, the summaries in Table II indicate that since 1970, the emphasis has been to introduce new materials towards minimizing electric losses.

TABLE II. CHANGES IN DESIGN OF WINDINGS

1970 - 1989	***1990 - 1999***	***2000 - 2014***
▪ Reduction of winding strands thickness to improve transformer efficiency ▪ Superconducting vs copper material were analysed, however superconductor did not give a worth-while advantage over the conventional copper material Reference [29]	▪ An introduction of composite copper shield was introduced in minimizing local heating ▪ Transposition of stranded conductors was introduced in minimizing winding losses. ▪ There different types of conductor bunch that can be applied, however the 2-conductor bunch with center transposition yields zero circulating current losses References [21], [30], [31]	▪ Insulation of winding conductor was further analyzed to minimize eddy currents by splitting of conductors ▪ Copper foils and sheets were adopted instead of conventional wire windings, because it enhances both the thermal and electromagnetic performance. ▪ Aluminum was considered to replace the conventional copper. Aluminum thermal conductivity was less than copper and is more prone to oxide and the tank size increases, Aluminum has more disadvantages as compared to copper. ▪ Half turn phenomenon was introduced on single-phase transformers for the reducing over-fluxing on the core and on 3-phase 3-limb & 3-phase 5-limb the half turn effect was found to be harmful under balanced loads, and under unbalanced loads it becomes more significant. References [32], [33], [34], [35], [36], [37], [38], [39]

Table III reiterates the introduction of new materials from 1970, and ongoing application of computer-aided tools to design more efficient cooling for transformers.

TABLE III. CHANGES IN COOLING DESIGN

1970 - 1989	***1990 - 1999***	***2000 - 2014***
▪ Forced cooled transformers having a vertically oriented disc coil winding were commonly constructed with equal spacing between individual coils. ▪ Transformers were using oil coolant, with cooler or radiator system having inlet end with provision of pumps to circulate the oil through ducts ▪ The design included the fans in the forced air cooling circuit to produce airflow over the radiator tubes. ▪ The cooling system was designed in such a way that the coolant flow velocity was uniform for all the horizontal ducts in the winding section. ▪ Dry type and oil cooling designs were in use. Reference [40]	▪ Improved 3-D finite element modeling led to improved thermal and dielectric analysis of insulation systems in high stressed areas. As well advanced fluid and thermal dynamic modeling techniques have led to improved thermal models. ▪ The hot-spot is one of the key parameters in the designing of the transformer cooling. ▪ The development of SF6 gas cooled transformers was introduced. ▪ Ventilated dry type transformers were replaced with liquid filled transformers in most industries and commercial sectors References [41], [42], [43], [44], [45]	▪ 2-D finite difference modeling were conducted to calculate or predict the hotspot temperatures as well to determine the location, however most designs were based on theory because of the difficulty of establishing and measuring the hotspots temperatures on transformer windings. ▪ Continuous operation of fans increasing the cooling efficiency or alternatively the fans can be switched on by setting them low than the top-oil temperature by taking into account transformer rating and seasonal changes. References [46], [47], [48], [49], [50], [51]

With regard to insulation, the trend as extrapolated from Table IV indicates further integration of new materials between 1970 and 1999, and emphasis on sensing and measurement of the effects of moisture and other contaminants. The application of sophisticated sensing and condition monitoring techniques towards identification and diagnosis of insulation induced failures in transformers, supplemented by temperature and oil sampling measurements and analysis for identification and diagnosis of core, cooling, and winding-induced failures, somewhat represent technical aspects of determining transformer health index.

TABLE IV. CHANGES IN INSULATION DESIGN

1970 - 1989	***1990 - 1999***	***2000 - 2014***
▪ The focus was in reducing the thickness of insulation material. The all-around ducts were positioned in each winding-to-winding insulation structures to increase the insulation strength. ▪ The most common insulation used was cellulosic paper and pressboard impregnated in mineral oil. References [52], [53], [54]	▪ Statistical techniques were adopted to estimate the reliability of insulation in order to determine the transformer life. ▪ The common insulation papers used are: kraft, highly purified kraft-based, Insuldur type chemically modified kraft-based paper, and Insuldur type, chemically modified and Manila hemp-based paper, however the latter offered better resistance. References [55], [56], [57], [58]	▪ Low molecular acids constitute an important aging factor for transformer winding insulation and should be included in diagnostic schemes. ▪ The transformer insulation class should correspond to the temperature limits and the ratings should be based on the type of cooling. ▪ Studies were conducted to determine effects of moisture, oxygen and acidity on different types of papers. ▪ More studies are conducted on different insulation liquid oil (i.e. vegetable oil, conventional oil and oil based on polychlorinated biphenyl's) References [59], [60], [61], [62], [63], [64], [65], [66]

C. Condition Monitoring

The increasing availability of sensor and sensing techniques, as well as the pervasion of ubiquitous information and communications technology systems and tools, has greatly influenced the capability to monitor the condition of the various elements that comprise a transformer. The current 'buzz' is on determining a health index to describe the condition of a transformer. For obvious reasons, health index measurements are mostly carried out with the transformer and substation isolated from the power grid.

TABLE V. TRENDS IN CONDITION MONITORING

1970 - 1989	***1990 - 1999***	***2000 - 2014***
▪ Gases were monitored using chromatographic analysis and statistical methods to assess oil results. ▪ Transformer monitoring and protection schemes were based on single inputs which do not adequately encompass the transformer in its operating environment. ▪ A microprocessor based transformer analysis system was conceptually configured to provide improved transformer availability and utilization through continuous monitoring analysis when in operation. ▪ On-line monitoring systems were developed ▪ Oil laboratories were used by utilities for assessing oil condition as well to determine the type of fault by applying Duval triangle References [67], [68], [69]	An adaptive, intelligent monitoring system was developed for tracking transformer operations. References [70], [71], [72]	▪ New techniques for condition monitoring and assessment were developed, such as vibration, thermal, dissolved gas analysis, frequency response analysis and return voltage measurement ▪ Increased application of reliability-centred, and condition-based, maintenance approaches ▪ Increasing emphasis on determining health index for transformers. References [73], [74], [75], [76], [77], [78]

D. Transformer Health Indexing

References like [79], [80], [81], [82], and [83] discuss in reasonable detail the determination of health index as a measure of transformer condition. The health index tends to based on the premise of age-induced degradation and involves the integration of :

i. offline tests to calculate the amount of dissolved gas, partial discharge, moisture, oil quality, and power factor;
ii. offline measurements to determine the condition of tap changers and bushings;
iii. maintenance and load history; as well as
iv. physical observations.

An interesting challenge in determining health index remains how to assign appropriate weights to quantitative data and qualitative information arising respectively from the tests and measurements, history of loading and maintenance actions, and physical observations. With the health index as the basis for condition assessment, then the respective weightings of the indices can influence decisions as to whether to refurbish or replace a transformer. It is worth remarking that an ageing transformer may still be in a condition that balances so-called asset management cost, risk, and performance.

III. CASE STUDY

This section includes a brief presentation on 558 transformers installed in the transmission grid of a case study electrical utility. The graph in Fig.2 shows the number of transformers installed each year between 1958 and 2013. The picture depicts the trend in the expansion of the electricity network, more remarkably between 2004 and 2011, with the installation of additional 765 kV transformers.

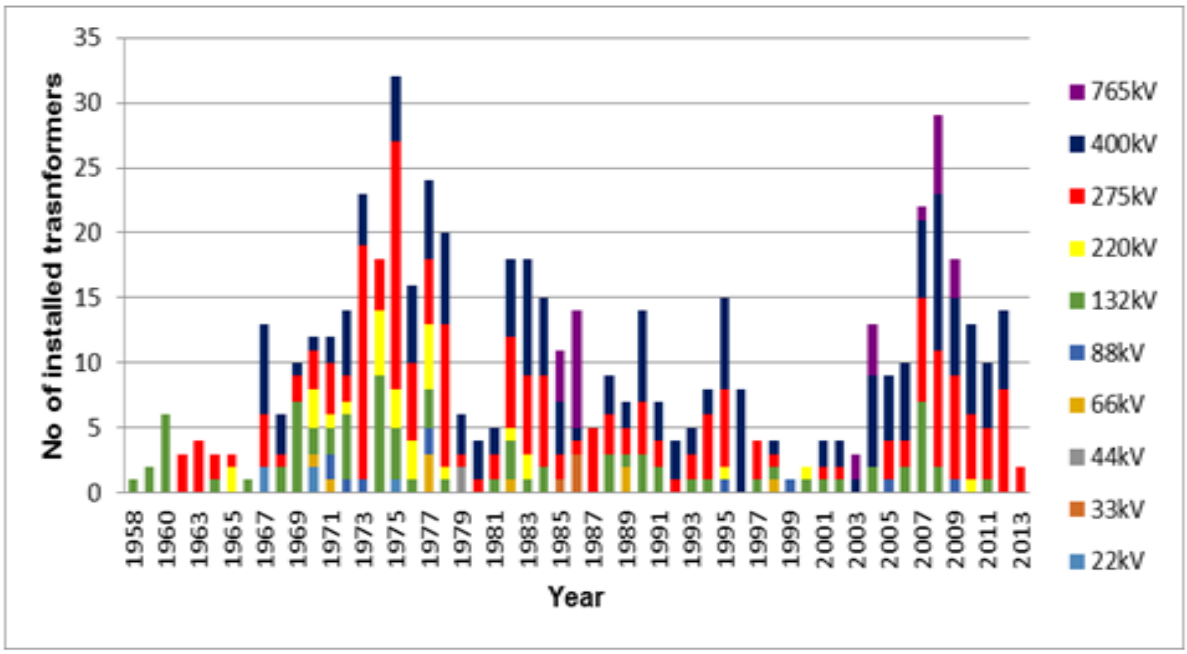


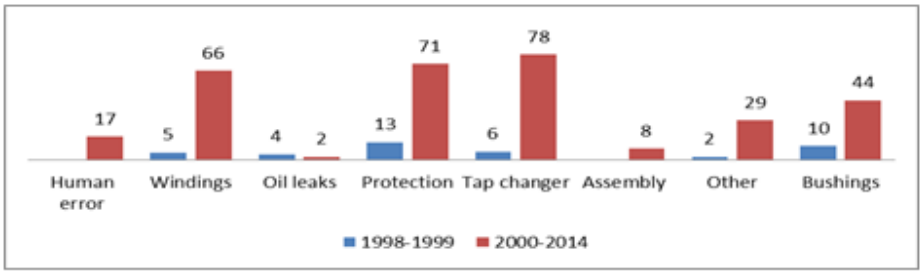
Fig. 2. Number of transmission grid transformers installed in case study utility each year from 1958-2014

Prior to 1960, the transmission network comprised 132 kV transformers, then 275 kV and 400 kV ranges were introduced in 1961 and 1967, and 765 kV transformers were first installed in 1985. Thirty-six percent of transmission grid transformers are rated at 275 kV, thirty-three percent are rated at 400 kV, while 0.36% are rated at 44 kV. Table VI summarises the slight changes in incorporated in the deployment of the transformers between 1970 and 2014. Almost all 558 transformers on the transmission network contain improved grain-oriented silicon steel laminated core, multiple stranded conductors, and ONAN/ONAF cooling triggers when oil and windings temperature respectively exceed 55 and 65°C. The records suggest that from 2010, thermally upgraded paper was used to replace prior insulation material.

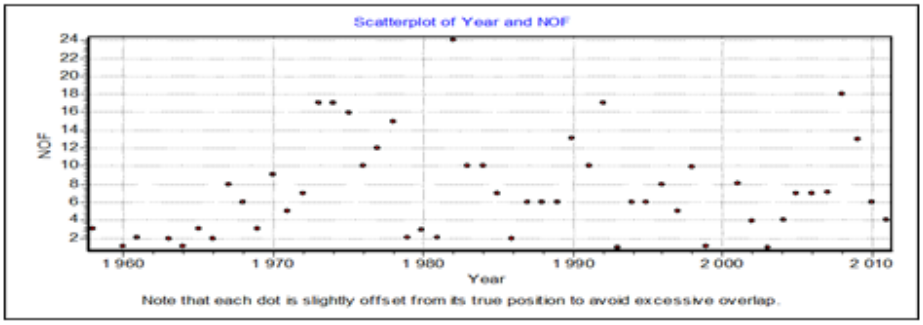
TABLE VI. APPLICATIONS WITH REGARD TO TRANSFORMER DESIGN TRENDS

1970 - 1989	*1990 - 1999*	*2000 - 2014*
▪ Improved grain-oriented silicon steel laminated core single- and three-phase transformers ▪ Multiple stranded conductors ▪ ONAN/ONAF cooling combination	▪ Improved grain-oriented silicon steel laminated core single- and three-phase transformers ▪ Multiple stranded conductors ▪ ONAN/ONAF cooling combination, fans operate when oil temperature exceeds 55°C or when winding temperature exceeds the pickup value of 65°C	▪ Improved grain-oriented silicon steel laminated core single- and three-phase transformers ▪ Multiple stranded conductors ▪ ONAN/ONAF cooling combination, fans operate when oil temperature exceeds 55°C or when winding temperature exceeds the pickup value of 65°C ▪ Thermally upgraded paper used from 2010

A summary of recorded transformers failures in the case study transmission network between 1998 and 2014 is presented in Fig.3. The top half Fig. 3a indicates that more than 88% of failures occurred between years 2000 and 2014, somewhat coinciding with the rapid expansion of the network to supply electricity to previously disadvantaged areas. It is worth mentioning that 13% of 355 failures were attributed to human error and 'other'. Although it is not trivial to directly relate any of the failure causes to changes in the design of transformers, however, 71 failures were attributed to windings. The records show that secondary elements, that is, bushings and tap changers contributed nearly 40% of the failure causes. A perplexing aspect is that 84 transformer failures were attributed to protection switchgear. Human error, 'other' and protection switchgear contributed more than 37% causes of failure of transformers between 1998 and 2014. The lower half Fig.3b shows a rather haphazard pattern of transformer failures between 1958 and 2010. For example, 24 transformer failures were recorded in 1982, while only one transformer failed in 1960, 1962, 1993, 1999, and 2003 respectively.



a) Number of failed transformers and failure 'causes'



b) Number of transformers that failed per year

Fig. 3. Number of transmission grid transformer failures

IV. SUMMARY

The bibliographic review suggests that the basic design of transformers has not drastically changed since 1970, albeit that computer-aided design techniques and new materials have been incorporated to reduce weight and increase both magnetic and electrical efficiencies as well as reliability and safety. On the one hand, computer-aided modelling and tools are widely applied to design and manufacture transformers to achieve higher voltage and power ratings. On the other hand, sensors, information and computing technology systems and big data analytics are facilitating unprecedented capabilities for condition monitoring and determination of transformer health.

From the case study data, the dominance of bushings, tap changer, and protection related failures suggests that such indices should be given higher priority during condition assessments of the transmission substations. This is not often the case, as many practitioners feel that, because the transformer is the highest cost item in a substation, the focus should be on the 'high-tech' offline measurements of dissolved gas, partial discharge, moisture, and oil quality. Data obtained from actual records of the case study network rather indicates that, although technical measurements of transformer health index may show ageing related degradation, however, the actual location and cause of substation outage and downtime seem to be mostly due to control and protection switchgear instead of the transformer. This raises questions with regard to using offline measurements of dissolved gas, partial discharge, moisture, and oil quality as priority for maintenance interventions, and also as the basis for decisions to either refurbish or replace a transformer. Furthermore, if a transformer is taken offline to determine the health index, does that provide sufficient confidence that the substation is also in a condition to deliver according to the vagaries of the load demands, assuming that there are no instances of *vis major* or *casus fortuitous* events like lightning and vandalism? The conundrum is this, why should health indexing of primary elements of a transformer drive maintenance actions and

decisions, whereas empirical data indicates that secondary elements and external conditions more significantly influence the reliability of a substation?

ACKNOWLEDGMENT

The authors wish to acknowledge and thank Eskom South Africa for sponsoring the second author and the case study data presented in this paper.

REFERENCES

[1] A. A. Romero, E. E. Mombello, and G Ratta, "An overview on power transformer management: Individual assets and fleets," Transmission and Distribution: Latin America Conference and Exposition (T&D-LA), 2012 Sixth IEEE/PES, 3-5 Sept. 2012. 1-7

[2] D. Zhou, C. Li, and Z. Wang, "Power transformer lifetime modeling," in Proceedings of IEEE Conference on Prognostics and System Health Management (PHM) pp 1 -7, 2012.

[3] M. Perkins, L. Pettersson, N. Fantana, T. OOmmen, and S. Jordan, "Transformer life assessment tools with specific application to nuclear power station generator transformers," in Proceedings of IEEE Electrical Insulation Conference and Electrical Manufacturing Coil Winding Conference, pp 685-690, 1999.

[4] J. L. Velasquez-Contreras, M. A. Sanz-Bobi, and S. Galceran Arellano, "General asset management model in the context of an electric utility: Application to power transformers," *Electric Power Systems Research*, 81**,** 2015-2037.

[5] M. J. Cobo, M. A. Martinez, M. Gutierrez-Salcedo, H. Fujita, and E Herrera-Viedma, "25 years at Knowledge-Based Systems: A bibliographic Analysis," Knowledge-Based Systems, 80, pp. 3-13 (2015). doi: 10.1016/j.knosys.2014.12.035

[6] W. Li, and Y. Zhao, "Bibliographic analysis of global environmental assessment research in a 20-year period," *Environmental Impact Assessment Review*, 50**,** pp. 158-166, 2015.

[7] J. C. Olivares-Galvan, R. Escarela-Perez, P.S. Georgikalis, I. Fofana, and S Magdaleno-Adame, "A bibliographic analysis of transformer literature 1990-2000," Electrical and Electronic Engineering, 2(3), pp.96-121, 2012.

[8] M. Xose, H. López-Fernández, Bülent Ertan, Janusz Turowski (eds), "Transformers: analysis, design, and measurement – Part I : Power transformers," CRC Press, 2013. ISBN 978-1-466508825-5.

[9] A. J. Moses, and B. Thomas, B. "Problems in the design of power transformers," IEEE Transactions on Magnetics, 10**,** pp. 148-150, 1974.

[10] S. Taguchi, T. Yamamoto, and A. Sakakura, " New grain-oriented silicon steel with high permeability "ORIENTCORE HI-B". IEEE Transactions on Magnetics, 10, pp. 123-127, 1974.

[11] G. W. Swift, "Excitation current and power loss characteristics for mitered joint power transformer cores. IEEE Transactions on Magnetics, 11, pp 61-64, 1975.

[12] S. H. Charap, and F. F. Judd, "A core loss model for laminated transformers," IEEE Transactions on Magnetics, 10, pp.678-681, 1974.

[13] T. Nakata, N. Takahashi, and Y. Kawase, "Magnetic performance of step-lap joints in distribution transformer cores. IEEE Transactions on Magnetics, 18, pp.1055-1057, 1982.

[14] Z. Valkovic, "Influence of transformer core design on power losses". IEEE Transactions on Magnetics, 18, pp.801-804, 1982.

[15] D. Davies, and A. J. Moses, "A novel method of reducing iron losses in power transformer cores," IEEE Transactions on Magnetics, 20, pp.559-563. 1984

[16] K. Lin, and E. Zook, " A desirable material for transformer cores," Journal of Materials Engineering, 11, 117-121, 1989.

[17] S. Holland, G. P. O'Connell, and L. Haydock, "Calculating stray losses in power transformers using surface impedance with finite elements," IEEE Transactions on Magnetics, 28, pp.1355-1358, 1992.

[18] D. Pavlik, D. C. Johnson, and R. S. Girgis, "Calculation and reduction of stray and eddy losses in core-form transformers using a highly accurate finite element modelling technique," IEEE Transactions on Power Delivery, 8, pp. 239-245, 1993.

[19] C. E. Lin, C. L. Cheng, C. L. Huang and J. C. Yeh, " Investigation of magnetizing inrush current in transformers. II. Harmonic analysis," IEEE Transactions on Power Delivery, 8, pp.255-263, 1993.

[20] M. Enokizono, K. Yuki, and S. Kawano, "An improved magnetic field analysis in oriented steel sheet by finite element method considering tensor reluctivity," IEEE Transactions on Magnetics, 31, 1797-1800, 1995.

[21] D. A. Koppikar, S. V. Kulkarni, G. Ghosh, S. M. Ainapure, and J. S. Bhavsar, "Circulating-current loss in transformer windings," IEE Proceedings On Science, Measurement and Technology, 145, pp. 136-140, 1998

[22] E. G. Tenyenhuis, R. S. Girgis, G. F. Mechler, and G. Zhou, "Calculation of core hot-spot temperature in power and distribution transformers," IEEE Transactions on Power Delivery, 17, pp.991-995, 2002

[23] M. Steurer and K. Frohlich, "The impact of inrush currents on the mechanical stress of high voltage power transformer coils," IEEE Transactions on Power Delivery, 17, pp.155-160, 2002.

[24] A. Ilo, "Behavior of Transformer Cores with Multistep-Lap Joints," IEEE Power Engineering Review, 22, pp. 42-47, 2002.

[25] P. Marketos, and T. Meydan, "Novel Transformer Core Design Using Consolidated Stacks of Electrical Steel," in Proceedings of IEEE International Magnetics Conference (INTERMAG) 2006.

[26] X. Wilsun, S. G. Abdulsalam, C. Yu, and L. Xian, "A sequential phase energization technique for transformer inrush current reduction - Part II: theoretical analysis and design guide," IEEE Transactions on Power Delivery, 20, pp.950-957, 2005.

[27] S. Urata, M. Enokizono, T. Todaka, and H. Shimoji, "The calculation considered two-dimensional vector magnetic properties depending on frequency of transformers," IEEE Transactions on Magnetics, 42, pp.687-690, 2006.

[28] L. Susnic, Z, Haznadar, and Z. Valkovic, "3D finite-element determination of stray losses in power transformer," Electric Power Systems Research, 78, pp.1814-1818, 2008.

[29] R. V. Harrowell, "Feasibility of a power transformer with superconducting windings," Proceedings of the Institution of Electrical Engineers, 117, pp.131-140, 1970.

[30] W. H Tang, Q. H Wu, and Z. J. Richardson, " Equivalent heat circuit based power transformer thermal model. IEE Proceedings on Electric Power Applications,149, pp.87-92, 2002

[31] B. S Ram, "Loss and current distribution in foil windings of transformers," IEE Proceedings on Generation, Transmission and Distribution, 145, pp.709-716, 1998.

[32] S. V. Kulkarni, and S. A. Khaparde, "Stray loss evaluation in power transformers-a review," . IEEE Power Engineering Society Winter Meeting, vol.3, pp. 2269-2274, 23-27 Jan 2000.

[33] W. Shishan, J. Shengcheng, and L Yanming, " The study of eddy current losses in coaxially insulated windings of power transformer," Proceedings IEEE International Conference on Power System Technology (PowerCon), pp.1392-1395, 2002.

[34] S. V. Kulkarni, J. C. Olivares, R. Escarela-Perez, V. K. Lakhiani, and J. Turowski, " Evaluation of eddy current losses in the cover plates of distribution transformers," IEE Proceedings on Science, Measurement and Technology, 151, pp.313-318, 2004.

[35] W. G. Odendaal, J. Azevedo, G. W Bruning, and R. M Wolf, "A high efficiency magnetic component with superior caloric performance," Record of the 37th IAS Annual Meeting and Industry Applications Conference, vol.2, pp.963-968, 13-18 Oct 2002.

[36] C. R. Sullivan,"Aluminum Windings and Other Strategies forHigh-Frequency Magnetics Design in an Era of High Copper and Energy Costs," IEEE Transactions on Power Electronics, 23, pp. 2044-2051, 2008.

[37] J. C. Olivares-Galvan, F. De Leon, P. Georgikalis, and R. Escarela-Perez, "Selection of copper against aluminium windings for distribution transformers," IET Electric Power Applications, 4, pp. 474-485, 2010.

[38] M. Mohan, "Amorphous-Core Transformer with Copper Winding Versus Aluminium Winding-A Comparative Study," ARPN Journal of Science and Technology, 2(4), May 2012 ISSN 2225-7217

[39] G. B. Kumbhar, S. V. Kulkarni, and V. S. Josh, "Analysis of Half-Turn Effect in Power Transformers Using Nonlinear-Transient FE Formulation," IEEE Transactions on Power Delivery, 22, pp.195-200, 2007.

[40] M. Ramachandran, " Transformer with improved liquid cooled disc winding," Google Patents, 1975.

[41] D. J. Woodcock, and J. C Wright, "Power transformer design enhancements made to increase operational life. Sixty-Sixth Annual International Conference of Doble Clients, 1999.

[42] L. W. Pierce, "Thermal considerations in specifying dry-type transformers," IEEE Transactions on Industry Applications, 30, pp.1090-1098, 1994b.

[43] A. Kudo, T. Nishitani, T Yoshikawa, and C. Wan, "Development of 275kV gas cooled type gas-insulated power transformer. IEEE Transactions on Power Delivery, 8(1), pp.264-270, 1993.

[44] K. Funaki, M. Iwakuma, K. Kajikawa, M. Takeo, J. Suehiro, M. Hara, K. Yamafuji, M. Konno, Y. Kasagawa, K. Okubo, Y. Yasukawa, S. Nose, M. Ueyama, K. Hayashi, and K. Sato,"Development of a 500 kVA-class oxide-superconducting power transformer operated at liquid-nitrogen temperature," Cryogenics, 38, pp.211-220, 1998.

[45] M. Nakadate, K. Toda, K. Sato, D. Biswas, C. Nakagawa, and T. Yanari, "Gas cooling performance in disc winding of large-capacity gas-insulated transformer," IEEE Transactions on Power Delivery, 11, pp.903-908, 1996.

[46] E. I. Amoirales, P. S. Georgikalis, and E. Litsos, "Methodology for the optimum design of power transformers using minimum number of input parameters." Proc. International Conference on Electrical Machines (ICEM), pp.1-6, 2006.

[47] C. Rosas, N. Moraga, V. Bubnovich, and R. Fischer, "Improvement of the cooling process of oil-immersed electrical transformers using heat pipes. IEEE Transactions on Power Delivery, 20, pp.1955-1961, 2005.

[48] M. K. Pradhan, and T. S. Ramu, "On the estimation of elapsed life of oil-immersed power transformers," IEEE Transactions on Power Delivery, 20, pp.1962-1969, 2005.

[49] D. Susa, J. Palola, M. Lehtonen, and M. Hyvarinen, "Temperature rises in an OFAF transformer at OFAN cooling mode in service," IEEE Transactions on Power Delivery, 20, pp. 2517-2525, 2005.

[50] X. Zhang, and E. Gockenbach, "Asset-management of transformers based on condition monitoring and standard diagnosis," IEEE Electrical Insulation Magazine, 24, pp.26-40, 2008.

[51] F. Torriano, M. Chaaban, and P. Picher, "Numerical study of parameters affecting the temperature distribution in a disc-type transformer winding," Applied Thermal Engineering, 30, pp. 2034-2044, 2010.

[52] E. L Boyd, and J. P McInerney, "Insulated transformer windings," Google Patents, 1976.

[53] R. J. Musil, E. Schopper, and H. Foschum, "Behavior of transformer insulation under short-time overvoltage," IEEE Transactions on Power Apparatus and Systems, 96, pp.614-618, 1977.

[54] E. L. Brancato, "Insulation ageing: A historical and critical review," IEEE Transactions on Electrical Insulation, EI-13, pp.308-317, 1978.

[55] D. Allan, C. Jones, and B. Sharp, "Studies of the condition of insulation in aged power transformers - Insulation condition and remnant life assessments for in-service units," Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials, 2, pp. 1116-1119, 1991.

[56] V. Sokolov, and B Vanin, "Evaluation of power transformer insulation through measurement of dielectric characteristics," Proceedings of the 63rd Annual International Conference of Doble Clients, sec 8-7, 1996.

[57] W. Mcnutt, "Insulation thermal life considerations for transformer loading guides," IEEE Transactions on Power Delivery, 7, pp.392-401, 1992

[58] M. Lessard, L. Van Nifterik, M. Masse, J. Penneau, and R. Grob, "Thermal aging study of insulating papers used in power transformers," IEEE 1996 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, pp.854-859, 1996.

[59] L. Lundgaard, W. Hansen, S. Ingebrigtsen, D. Linhjell, and M. Dahlund, "Aging of Kraft paper by acid catalyzed hydrolysis," Proc. IEEE International Conference on Dielectric Liquids (ICDL), pp. 381-384, 2005.

[60] P. Sen, and S. Pansuwan, "Overloading and loss-of-life assessment guidelines of oil-cooled transformers," Rural Electric Power Conference Little Rock Arkansas USA, pp B4/1-B4/8, 2001.

[61] T. K. Saha, H. Ma, C. Ekanayake, D. Martin, and D. Allan, "Pattern Recognition Techniques for Determining the Health Index of Oil-Paper Insulation of In-service Power Transformers. Cigre, 2014.

[62] M. Darveniza, T. K. Saha, D. T. J. Hill and T. T. Le, "Investigations into effective methods for assessing the condition of insulation in aged power transformers," IEEE Transactions on Power Delivery, 13, pp.1214-1223, 1998.

[63] Z. Poniran, and Z. Malek, "A. Life Assessment of Power Transformers via Paper Ageing Analysis," International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), pp 460-465, 2007.

[64] C. McShane, K. Rapp, J. Corkran, G. Gauger, and J. Luksich, "Aging of Kraft paper in natural ester dielectric fluid. , 2002. ICDL 2002. Proceedings of 14th IEEE International Conference on Dielectric Liquids, pp 173-177, 2002.

[65] K. Rapp, C. P McShane, J. Luksich, "Interaction mechanisms of natural ester dielectric fluid and Kraft paper," Proc. IEEE International Conference on Dielectric Liquids (ICDL), pp. 393-396, 2005.

[66] C. Dervos, C. D. Paraskevas, P. Skafidas, and P Vassiliou, "Dielectric characterization of power transformer oils as a diagnostic life prediction method," IEEE Electrical Insulation Magazine, 21, pp.11-19, 2005.

[67] R. Rogers, "IEEE and IEC codes to interpret incipient faults in transformers, using gas in oil analysis," IEEE Transactions on Electrical Insulation, 13(5), pp 349-354, 1978.

[68] T. D. Poyser, R. N. Avery, J. W. Bankoske, J. D. Borst, C. W. Kimblin, A. H. Maxwell, D. W, McElroy, C. A. Peterson, J. R. Rostron, and D. R. Smith, "Method and apparatus for monitoring transformers," Google Patents, 1987.

[69] M. Duval, "Dissolved gas analysis: It can save your transformer," IEEE Electrical Insulation Magazine, 5, pp. 22-27, 1989.

[70] C. Bengtsson, "Status and trends in transformer monitoring," IEEE Transactions on Power Delivery, 11, pp. 1379-1384, 1996.

[71] J. L. Kirtley, W. Hagman, B. Lesieutre, M. J. Boyd, E. P Warren, H. P Chou, and R. Tabors, "Monitoring the health of power transformers," IEEE Computer Applications in Power, 9, 18-23, 1996.

[72] B. Pahlavanpour, and A. Wilson, "Analysis of transformer oil for transformer condition monitoring," An Engineering Review of IEE Colloquium on Liquid Insulation (Digest No. 1997/003), 1/1-1/5, 7 Jan 1997.

[73] Z. Radakovic, and K. Feser, "A new method for the calculation of the hot-spot temperature in power transformers with ONAN cooling," IEEE Transactions on Power Delivery, 18, pp. 1284-1292, 2003.

[74] K. Pylvanainen, K, Nousiainen, and P. Verho, "Studies to utilize loading guides and ANN for oil-immersed distribution transformer condition monitoring," IEEE Transactions on Power Delivery, 22, pp. 201-207, 2007.

[75] P. M. Nirgude, B. Gunasekaran, Channakeshava, A. D. Rajkumar, and B. Singh, "Frequency response analysis approach for condition monitoring of transformer," Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 186-189, 2004.

[76] A. E. B Abu-Elanien, and M. M. A Salama, "Asset management techniques for transformers," Electric Power Systems Research, 80, pp. 456-464, 2010.

[77] S. Borucki, "Diagnosis of technical condition of power transformers based on the analysis of vibroacoustic signals measured in transient operating conditions. IEEE Transactions on Power Delivery, 27, pp. 670-676, 2012.

[78] L. Kai, X. Hoghua, L. Yong, Z. Yu, M. Hongzhong, L. Jiufu, and G. Jiewei, "Simulation test method for vibration monitoring research on winding looseness of power transformer. Proceedings of International Conference on Power System Technology (POWERCON), pp.1602-1608, 2014.

[79] A. Jahromi, R. Piercy, S. Cress, J. Service, and W.Fan, "An approach to power transformer asset management using health index," IEEE Electrical Insulation Magazine, 25, pp.20-34, 2009.

[80] A. Naderian,, S. Cress, R. Piercy, F. Wang, and J. Service, J, "An approach to determine the health index of power transformers," Conference Record of the IEEE International Symposium on Electrical Insulation (ISEI), pp.192-196, 2008.

[81] S. Blake, "Calculating a health index to make decisions on asset replacement," A presentation on Mathematical Methods in Reliability Research. Strathclyde University, 31 August 2012.

[82] G. Tanasescu, P. V. Notingher, O Dragomir, B. Gorgan, and L. Voinescu, "Health index calculation of electrical equipment using DiagConsole software," 8th International Symposium on Advanced Topics in Electrical Engineering, Bucharest, Romania, May 23-25 2013. 978-1-4673-5980-1/13 ©IEEE

[83] D. Zhou, "Transformer lifetime modelling based on condition monitoring data," International Journal of Advances in Engineering & Technology,6(2), pp.613-619, May 2013.