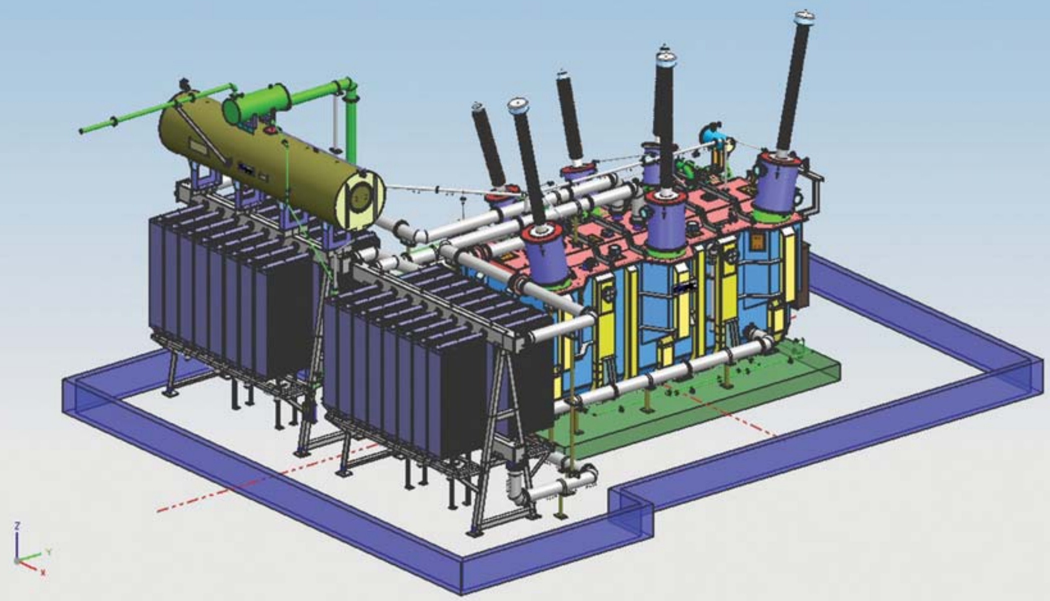
Transformer Engineering

Design, Technology, and Diagnostics

Second Edition



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S.V. Kulkarni
S.A. Khaparde

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Contents

Preface to the Second Edition

There have been considerable advancements in various aspects of transformer engineering since the publication of the first edition in 2004. Improvements can be clearly seen in computational capabilities and monitoring/diagnostic techniques. Such new developments and encouraging feedback received on the first edition prompted the authors to embark on the task of writing the second edition.

Three new chapters have been introduced in the second edition, Electromagnetic Fields in Transformers: Theory and Computations, Transformer–System Interactions and Modeling, and Monitoring and Diagnostics. The chapter on Recent Trends in Transformer Technology has been completely revised to reflect the latest and emerging trends in the various facets of the transformer technology. Chapter 6 on short-circuit strength aspects has been updated to bring more clarity on failure mechanisms involving buckling, tilting, and spiraling phenomena. Various factors of safety are defined along with procedures for calculating them. An appendix explaining a step-by-step procedure for designing a transformer is added, which should be beneficial to engineers in the transformer industry and the student community. A few improvements have been incorporated in the other chapters as well.

Understanding the basics of electromagnetic fields is an essential prerequisite for doing advanced computations. Chapter 12 explains the field theory relevant to transformer engineering in a simple manner. Concepts from vector algebra and vector calculus are first explained followed by corresponding examples which help understand the behavior and distribution of fields inside transformers. Properties of insulating and magnetic materials used in transformers are explained from a fundamental electromagnetic perspective. Finite element method (FEM) is widely used for analysis and optimization of transformers. While using commercial software, the knowledge of the FEM theory helps researchers and practicing engineers solve complex problems and easily interpret field solutions. The theory of FEM is explained through the solution of one-dimensional and two-dimensional problems that represent typical electrostatic and magnetostatic fields encountered in transformers. After explaining static, time-harmonic and transient formulations, advanced coupled field computations involving electromagnetic fields and external networks/other physical fields are elaborated. Brief theory/procedures for dealing with hysteresis and magnetization/magnetostrictive forces are also given at the end.

The second new chapter covers relevant theory and explanations required for understanding the effects of transformer–system interactions. The chapter starts with the modeling aspects of transformers essential for steady-state analysis of power systems. The usefulness of magnitude-regulating and phase-shifting transformers is demonstrated through examples. The section on harmonics briefly covers their sources and effects, followed by modeling strategies for analyzing them. Ferroresonance phenomena can be detrimental to transformers; the system conditions causing ferroresonant conditions are enumerated. Adverse effects of arc-furnace loads and geomagnetic disturbances are explained later. Internal resonances due to system transients including very fast transient overvoltages are also described. Effects of switching operations involving vacuum circuit breakers on distribution transformers are highlighted. At the end, low-, mid-, and high-frequency models of transformers used for transient studies/investigative analysis are elaborated.

A considerable amount of research and development efforts by the academic community, utility engineers, and transformer specialists have led to the availability of advanced diagnostic tools. After summarizing conventional tests on oil and windings, the chapter Monitoring and Diagnostics comprehensively covers techniques for detecting partial discharges (PD), insulation degradation, and winding displacements/deformations. Methods based on electrical, acoustic, and ultra high frequency signals are practiced for PD diagnostics. Dielectric response methods used for the condition assessment of insulation are categorized into time domain and frequency domain methods. Background theory for understanding these two types of approaches is described along with diagnostic procedures. Finally, frequency response analysis, used widely for detection of winding irregularities, is thoroughly explained.

Thus, the focus of the second edition is also on diagnostic aspects and transformer–system interactions, and therefore, it is expected to help readers comprehend operational/maintenance issues and solutions in addition to the intricacies of transformer design and the applications of advanced numerical field computations.

S. V. Kulkarni
S. A. Khaparde
(For comments and suggestions, contact: svk@ee.iitb.ac.in)

Foreword to the First Edition

It is a great pleasure to welcome this new book from Prof. S. V. Kulkarni and Prof. S. A. Khaparde, and I congratulate them for the comprehensive treatment given in the book to nearly all aspects of transformer engineering.

Everyone involved in or with the subject area of this book, whether from academics or industry, knows that the last decade has been particularly dynamic and fast changing. Significant advances have been made in design, analysis, and diagnostic techniques for transformers. The enabling factors for this technological leap are extremely competitive market conditions, tremendous improvements in computational facilities, and rapid advances in instrumentation. The phenomenal growth and increasing complexity of power systems have put tremendous responsibilities on the transformer industry to supply reliable transformers. The transformer as a system consists of several components, and it is absolutely essential that the integrity of all these components individually and as a system is ensured. A transformer is a complex three-dimensional electromagnetic structure and it is subjected to a variety of stresses, dielectric, thermal, electrodynamic, etc. In-depth understanding of various phenomena occurring inside the transformer is necessary. Most of these can now be simulated on computers so that suitable changes can be made at the design stage to eliminate potential problems.

I find that many of these challenges in the design and manufacture of transformers, to be met in fast-changing market conditions and technological options, are discussed in this book. There is a nice blend of theory and practice in almost every topic discussed in the text. The academic background of the authors has ensured that a thorough theoretical treatment is given to important topics. A number of landmark references are cited at appropriate places. The previous industry experience of S. V. Kulkarni is reflected in many discussions in the book. Various theories have been supported in the text by reference to actual practices.

For example, while deliberating on various issues of stray loss estimation and control, the relevant theory of eddy currents has been explained. This theoretical basis is then used to explain various design and manufacturing practices established in the industry to analyze and minimize the stray losses in the windings and structural components. The design and manufacturing practices and processes have significant impact on the performance parameters of transformers and the same have been identified in the text while discussing various topics.

Wherever required, a number of examples and case studies are given which are of great practical value. The knowledge of zero-sequence characteristics of transformers is very important for utilities. It is essential to understand the difference between magnetizing and leakage zero-sequence reactances of the transformer. These two types of zero-sequence reactances are explained in the book for three-phase three-limb, three-phase five-limb and single-phase three-limb transformers with numerical examples. One may not find such a detailed treatment to zero-sequence reactances in the available literature. The effect of tank on the zero-sequence reactance characteristics is clearly explained.

The discussions on the sympathetic inrush phenomenon, part-winding resonance, short-circuit withstand characteristics, and noise reduction techniques should also be quite useful to the readers. With the increase in network complexity and severity of loads in some cases, the cooperation between the transformer manufacturers and users (utilities) is very critical. The design reviews with the involvement of users at various stages of contract should help in enhancing the reliability of transformers. I am happy to note that such areas of cooperation are identified at appropriate places in the text.

The book propagates the use of modern computational tools for optimization and quality enhancement of transformers. I know a number of previously published works of the authors in which the Finite Element Method (FEM) has been applied for the stray loss control and insulation design of the transformers. The use of FEM has been aptly demonstrated in the book for various calculations along with some tips, which will be helpful to a novice in FEM.

The book is therefore a major contribution to the literature. The book will be extremely helpful and handy to the transformer industry and users. It will also be useful for teaching transformers to undergraduate and postgraduate students in universities. The thorough treatment of all important aspects of transformer engineering given in the book will provide the reader all the necessary background to pursue research and development activities in the domain of transformers.

It is anticipated that this book will become an essential reference for engineers concerned with design, application, planning, installation and maintenance of power transformers.

H. Jin Sim, PE
VP, Waukesha Electric Systems
Past Chairman, IEEE Transformers Committee

Preface to the First Edition

In the last decade, rapid advancements and developments have taken place in the design, analysis, manufacturing, and condition monitoring technologies of transformers. The technological leap will continue in the forthcoming years. The phenomenal growth of power systems has put tremendous responsibilities on the transformer industry to supply reliable and cost-effective transformers.

There is a continuous increase in the ratings of generator transformers and autotransformers. Further, the ongoing trend of using higher system voltages for power transmission increases the voltage rating of transformers. An increase in current and voltage ratings needs special design and manufacturing considerations. Advanced computational techniques have to be used which should be backed up by experimental verifications to ensure the quality of design and manufacturing processes. Some of the vital design challenges are stray loss control, accurate prediction of winding hot spots, short-circuit withstand and reliable insulation design. With increasing MVA ratings, the weight and size of large transformers approach or exceed transport and manufacturing capability limits. Also, due to ever increasing competition in the global marketplace, there are continuous efforts to optimize material content. Therefore, the difference between withstand levels and corresponding operating stress levels is reducing. Similarly, the guaranteed performance figures and actual test values can be close nowadays. All these reasons demand greater efforts from researchers and designers for the accurate calculation of various stress levels and performance figures. In addition, a strict control of manufacturing processes is required. Manufacturing variations of components should be monitored and controlled.

Many books on transformers are now more than 10 years old. Some of these books are still relevant and widely referred to for understanding the theory and operation of the transformers. However, a comprehensive theoretical basis together with applications of modern computational techniques is necessary to face the challenges of fast changing and demanding conditions. This book is an effort in that direction. The principles of various physical phenomena occurring inside transformers are explained elaborately in the text, which can also be used as a basis for teaching undergraduate and postgraduate students in universities. Wherever required, adequate references have been quoted so that the readers can go into more depth of the phenomena. In fact, a large number of very useful references (more than 400) is one of the hallmarks of this book. Some of the references, which are classical ones, date back to the early part of the last century. Using these references, many of the theories useful for transformer engineering are explained. Some of the most recent works have also been discussed to give readers a feel of the latest trends in the transformer technology.

Prof. S. V. Kulkarni worked in the transformer industry for 11 years before joining academics. He has vast experience in design and development of transformers from a small distribution range up to 400 kV class 300 MVA ratings. He had ample opportunities to investigate a number of problems in transformer works and sites. A few such case studies and site investigations, in which he was actively involved in the last decade, have been incorporated at appropriate places in the text. Also, he realized that there are some aspects of transformer engineering which have not been given adequate treatment in the presently available books. Hence, the emphasis of this book is more on these aspects, magnetizing asymmetry, zero-sequence reactance characteristics, stray losses and related theory of eddy currents, short-circuit forces and withstand, part winding resonance phenomenon, insulation design, and design aspects of transformers for rectifier, furnace and HVDC applications. The book would be particularly useful to

- Transformer designers and researchers engaged in optimization and quality enhancement activities in today's competitive environment
- Utility engineers who would like to learn more about the system interaction aspects of transformers in an interconnected power system to improve specifications and employ diagnostic tools for condition monitoring
- Undergraduate and postgraduate students who wish to understand practical issues in transformer design and pursue research for finding solutions

In Chapter 1, in addition to transformer fundamentals, various types of transformers in a typical power system are explained along with their features.

There is a trend to use better materials to reduce core losses. Many times the expected loss reduction is not obtained with these better grades. The design and manufacturing practices and processes have significant impact on the core performance, which are highlighted in Chapter 2. Three-phase three-limb core has inherent magnetizing asymmetry that results sometimes into widely different no-load currents and losses in three phases of the transformer during the no-load loss measurement by the three-wattmeter method. It is shown that one of the three wattmeters can read negative depending upon the magnitude of asymmetry between the phases and the level of excitation. Even though the inrush current phenomenon is well understood, the sympathetic inrush phenomenon, in which the magnetization level of a transformer is affected due to energization of another interconnected transformer, is not well-known. The factors influencing the phenomenon are elucidated in the chapter. The phenomenon was investigated by Prof. S. V. Kulkarni in 1993 based on switching tests conducted at a site in Mumbai.

Chapter 3 is devoted to the leakage reactance of transformers, which can be calculated by either analytical or numerical methods. Procedures for its calculation for various types and configurations of windings, including zigzag and sandwich windings, are explained. The reactance for complex winding configurations can be easily calculated by using the *finite element method* (FEM), which is a widely used numerical method. The chapter gives exhaustive treatment to zero-sequence characteristics of the transformers. Procedures for the calculation of the magnetizing zero-sequence and leakage zero-sequence reactances of the transformers are illustrated through examples (such a treatment is scarcely available in the published literature). The effect of the presence of a delta winding on the zero-sequence reactance is also explained.

In order to accurately estimate and control the stray losses in windings and structural parts, in-depth understanding of the fundamentals of eddy currents starting from the basics of electromagnetic fields is desirable. The theory of eddy currents given in Chapter 4 is self-contained and useful for the conceptual understanding of the phenomena of stray losses in the windings and structural components of transformers described in Chapters 4 and 5, respectively. Stray losses in all the conducting components of the transformers have been given an elaborate treatment. Different analytical and numerical approaches for their estimation are discussed and compared. A number of useful guidelines, graphs and equations are given which can be used by practicing engineers. A few interesting phenomena observed during the load loss test of transformers are explained (e.g., half-turn effect). Various shielding arrangements used for effective stray loss control are discussed and compared.

A high failure rate of transformers due to short circuits is a major concern for transformer users. The success rate during short-circuit tests is far from satisfactory. The static force and withstand calculations are well-established. Efforts are being made to standardize and improve the dynamic short-circuit calculations. Precautions that can be taken at the specification, design, and manufacturing stages of transformers for improvement in short-circuit withstand have been elaborated in Chapter 6. Various failure mechanisms and factors that decide the withstand strength are explained.

Although, the methods for calculating impulse distribution are well-established, failures of large transformers due to part-winding resonances and very fast transient overvoltages have attracted the attention of researchers. After explaining the methods for calculation of series capacitances of commonly used windings, analytical and numerical methods for transient analysis are discussed in Chapter 7. The results of three different methods are presented for a typical winding. Methods for avoiding winding resonances are also explained.

Chapter 8 elaborates insulation design philosophy. Various factors that affect insulation strength are summarized. Procedures enumerated for estimation of bulk oil and creepage withstand would be very useful to designers. Steps for designing major and minor insulation systems are presented.

Chapter 9 deals with thermal aspects of transformer design. After explaining the modes of heat transfer, various cooling systems are described. Insulation aging processes and life expectancy are also discussed. Many failures of large transformers in the recent past have been attributed to the static electrification phenomenon which is explained at the end.

Various types of loads and tests, which decide structural design aspects, are discussed in Chapter 10. Tank stiffening arrangements are elaborated. This material is scarcely available in the literature. Due to increasing environmental concerns, many users specify lower noise levels. Different noise level reduction techniques are discussed and compared.

Chapter 11 is devoted to four special types of transformers: rectifier transformers, HVDC converter transformers, furnace transformers, and phase-shifting transformers. Their design aspects and features, which are different from conventional distribution and power transformers, are enumerated.

The text concludes with Chapter 12 by identifying current research and development trends. The chapter is intended to give enough pointers to readers desirous of pursuing research in transformers.

At the end, we would like to say that even though the transformer is a mature product, there are still many design, manufacturing, and power system interaction issues that continue to haunt researchers. This book provides answers to many of these issues and tries to give directions for solving some of the remaining ones. It encompasses most of the important aspects of transformer engineering including the recent advances in research and development activities. It also propagates the use of advanced computational tools such as FEM for optimization and quality enhancement of the transformers.

S. V. Kulkarni
S. A. Khaparde

Acknowledgments

We thank our institute for providing support and nice ambience to write the second edition. It was a major task that resulted in the addition of more than 50% of the pages to the first edition, and the work would not have taken this shape without the active support of students. Current Ph.D. students, Amit Bakshi, Ketan Badgujar, and Ajay Pal Singh Baghel, have contributed significantly to some of the new topics in the second edition. The efforts of Amit in proofreading the entire text are greatly appreciated. Interactions with Dr. G. B. Kumbhar helped considerably in refining the sections dealing with the theory and applications of the finite element method. Dr. R. S. Bhide and Dr. A. S. Bhangaonkar gave useful comments on Chapters 12 and 14, respectively. Special thanks are due to Dr. S. R. Kannan for reviewing Chapters 13 and 14; his comments on discussions dealing with various monitoring and diagnostic aspects were extremely useful.

Master's level students (Ragini Agarwal, Chikku Abraham, Vinod Parmar, Makarand Kane, R. Venkataswamy, Md. Maoyafikuddin, V. Ramayya, Rani Chacko, G. Suryanarayana, Dipak Gawai and Ved Manu) helped in many ways. The excellent quality of the figures in the new chapters is due to their efforts. Prasad Bodhayan, who did a summer internship in the institute, contributed to refining some discussions in Chapter 5. Kaushik Kalyanaraman gave useful editorial comments on Chapter 12.

Prof. S. V. Kulkarni started his professional career with Crompton Greaves Limited; the rich and ample experience gained while working in the industry (1990–2001) is thankfully acknowledged. He is grateful to all his erstwhile senior colleagues (C. R. Varier, T. K. Mukherjee, D. A. Koppikar, S. V. Manerikar, B. A. Subramanyam, G. S. Gulwadi, K. Vijayan, V. K. Lakhiani, P. V. Mathai, A. N. Kumthekar and K. V. Pawaskar) for support and practical guidance. Thanks are also due to Crompton Greaves Limited for providing the picture for the cover.

Throughout the book, many practical aspects of transformer engineering are discussed. Therefore, it was very essential to get the contents reviewed by experts from the transformer industry. Many practicing specialists gave very useful suggestions and comments that helped refine the discussions on industry practices (K. Vijayan: Chapters 8 and 9, G. S. Gulwadi: Chapters 1 and 8, V. D. Deodhar, V. K. Reddy and Parmatma Dubey: Chapter 10, Dr. B. N. Jayaram: Chapter 7, Dr. G. Bhat and Dr. Sachin Paramane: Chapter 9). V. S. Joshi had given important suggestions while reviewing the first edition; he helped in the second edition as well with his useful comments on some of the new discussions. Others who gave constructive comments while the first edition was being finalized are Prof. J. Turowski, P. Ramachandran, Prof. L. Satish and M. W. Ranadive. A few of our colleagues in the electrical engineering department supported us by proofreading the first edition. Sainath Bongane, Sachin Thakkar and G. D. Patil, who were research associates working with us, substantially helped in the editorial work. Also, Dr. G. B. Kumbhar, Dr. A. P. Agalgaonkar and Dr. M. U. Nabi, who were Ph.D. students at that time, also contributed in refining some discussions.

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Writing a book is an arduous task requiring complete support from family members. Particular mention must be made of the encouragement and backing provided by Sushama S. Kulkarni. Anandchaitanya S. Kulkarni allowed his father to work even on weekends; thanks are due to the little one for his patience and sacrifice.

S. V. Kulkarni
S. A. Khaparde

1

Transformer Fundamentals

1.1 Perspective

Transformers are static devices that transfer electrical energy from one circuit to another by the phenomenon of electromagnetic induction without any change in frequency. They can link circuits that have different voltages, which is one of the enabling factors for the universal use of the alternating current (AC) system for the transmission and distribution of electrical energy. Hence, transformers ensure that various components of the power system, viz. generators, transmission lines, distribution networks and loads, can all be operated at their most suitable voltage levels. As transmission voltages are increased to higher levels in some parts of a power system, transformers again play a key role in interconnecting the different parts of the system at different voltage levels. Transformers are therefore vital links between the generating stations and the points of utilization in any system.

The transformer is an electromagnetic conversion device in which the electrical energy received by its primary winding is first converted into magnetic energy, which is re-converted into electrical energy in other circuits (secondary winding, tertiary winding, etc.). Thus, the primary and secondary windings are not connected electrically, but coupled magnetically. A transformer is termed either a step-up or a step-down transformer depending upon whether the secondary voltage is higher or lower than the primary voltage. Transformers can be used to either step-up or step-down voltage depending upon the need and application; hence, their windings are referred as high-voltage/low-voltage or high-tension/low-tension windings instead of primary/secondary windings.

***Magnetic circuits*:** A transfer of electrical energy between two circuits takes place through a transformer without the use of moving parts; a transformer therefore has higher efficiency and lower maintenance cost than rotating electrical machines. Better grades of materials for cores are continuously being developed and introduced. Different types of silicon steels have been introduced in the following chronological order: non-oriented, hot-rolled grain oriented, cold-rolled grain oriented (CRGO), Hi-B, mechanically scribed and laser scribed. The last three types are improved versions of the CRGO class of materials. The saturation flux density has remained more or less constant around 2.0 Tesla for the CRGO grades; however, the sophisticated technologies and processes used while manufacturing the better grades have resulted in significant improvements in the watts/kg and volt-amperes/kg characteristics in the rolling direction. Transformer designers have a limited choice of grades of material; for a grade chosen based on a cost-benefit analysis, the performance of the core can be further optimized by using efficient design and manufacturing technology. The non-mitred construction used earlier was replaced by a better mitred type many decades ago, and now a far superior step-lap construction is almost universally used. A considerable increase in energy costs over the years is mainly responsible for the development (and consequent increase in the use) of the better grades of material for cores: these not only reduce the core loss but also help in reducing the noise levels of transformers. The use of amorphous steel materials results in a substantial reduction in the core loss, to the tune of 60-70% when compared to the CRGO grades. Since the manufacturing technology required for handling this brittle material has to be quite sophisticated, its use is limited to transformers with lower ratings.

***Windings*:** Paper-covered conductors are commonly used in the windings of medium and large power transformers. These conductors can be of individual-strip, bunch or continuously transposed cable (CTC) type. For the low voltage side of distribution transformers, wherein far fewer turns are involved, the use of copper or aluminum foils may be preferred. To enhance the short-circuit withstand capability, a work-hardened copper material is commonly used instead of a soft annealed type, particularly for higher-rating transformers. In generator transformers with high current ratings on the lower voltage (LV) side, CTC conductors are mostly used, which result in a better space factor and reduced eddy loss in windings. CTC conductors can be of the epoxy-bonded type to enhance their short-circuit strength. Conductors with thermally upgraded insulating paper are suitable for hot-spot temperatures of about 110°C, which help in coping with overload conditions. Moreover, a better life expectancy is possible with their use. For better mechanical properties, epoxy diamond dotted paper can be used as the interlayer insulation for multi-layer windings. High temperature superconductors are expected to be available commercially in the near future. Issues such as economic viability, manufacturability, and reliability need to be addressed prior to their large-scale deployment.

***Insulation and cooling*:** Inter-winding insulation structures consist of a number of oil ducts formed by suitably spaced insulating cylinders. Pre-compressed pressboards, manufactured using high quality materials and processes, are used in high voltage transformers. Well-profiled angle rings, angle caps, and other special insulation components are also widely used.

Mineral oil has traditionally been the most commonly used electrical insulating medium and coolant in transformers. Studies have proved that the oil-barrier insulation system is suitable even at voltages rated higher than 1000 kV. The high dielectric strength of oil-impregnated papers and pressboards is the main reason for the widespread use of mineral oil in transformers. Silicone oil is an alternative; it is non-toxic and fire-resistant. A comparatively higher cost is an inhibiting factor in its widespread use. Transformers with biodegradable natural and synthetic esters are employed in environmentally sensitive locations.

There have been considerable advancements in the technology of gas-immersed transformers. SF6 is a non-flammable gas and has excellent dielectric properties. Hence, SF6 transformers are preferred for fire-hazard-free applications. Due to the low specific gravity of SF6 gas, gas-insulated transformers are lighter than oil-immersed transformers. The dielectric strength of SF6 gas is a function of the operating pressure; the higher the pressure, the higher the dielectric strength is. However, the heat capacity and thermal time constant of SF6 gas are less than those of oil, resulting in a lower overload capacity of SF6 transformers. Environmental concerns, sealing problems, lower cooling capability, and the present high cost of manufacture are the challenges that have to be overcome for widespread use of SF6 transformers.

Dry-type resin cast and resin impregnated transformers use class *F* or *C* insulation. The high cost of resins and their lower heat dissipation capability limit the use of these materials to transformers that have lower ratings. Dry-type transformers are primarily used for indoor applications in order to minimize fire hazards. Nomex paper insulation, which has a temperature withstand capacity of 220°C, is widely used in dry-type transformers. The initial cost of a dry-type transformer may be 60 to 70% higher than that of an oil-cooled transformer at current prices, but its overall cost at the present level of energy rates can be quite comparable to that of the oil-cooled transformer.

***Design*:** With the rapid development of digital computers, designers are freed from the drudgery of routine calculations. Computers are widely used for the optimization of designs. Within a few minutes, today's computers can work out a number of designs (by varying flux density, core diameter, current density, etc.) and come up with an optimum design. One of the major benefits of computers is in the area of analysis. Using commercial 2-D/3-D field computation software, any kind of engineering analysis (electrostatic, electromagnetic, structural, thermal, etc.) can be performed to optimize the design of transformers or to enhance their reliability.

***Manufacturing*:** In manufacturing technology, the superior techniques listed below are used to reduce manufacturing time and at the same time to improve product quality:

- A high degree of automation for slitting/cutting operations to achieve better dimensional accuracy for core laminations
- Step-lap joints for core construction to achieve lower core loss and noise level
- Core building without top yoke
- Automated winding machines for distribution transformers
- Vapor phase drying for effective and fast drying
- Low frequency heating for the drying process of distribution transformers
- Pressurized chambers to protect windings and insulating parts from pollution and dirt
- Vertical machines for winding large-capacity transformer coils
- Isostatic clamping for accurate sizing of windings
- High-frequency brazing for joints in the windings and connections.

***Accessories*:** Bushings and the tap changer (off-circuit or on-load) are the most important accessories of a transformer. The technology of bushing manufacture has advanced from the oil-impregnated paper (OIP) type to the resin impregnated paper (RIP) type, both of which use porcelain insulators. Silicone rubber bushings are also available for oil-to-air applications; due to the high elasticity and strength of silicone rubber, the strength of these bushings against mechanical stresses and shocks is higher. Oil-to-SF6 bushings are used in GIS (gas-insulated substation) applications.

The service reliability of on-load tap-changers (OLTC) is of vital importance; failures of transformers due to tap-changer problems are common. A majority of the failures reported in service are due to mechanical problems related to the drive system. Several monitoring methods are used for enhancing the service reliability of OLTCs, which include measurement of contact resistance, monitoring of drive motor torque/current, acoustic measurements, dissolved gas analysis, and temperature rise measurements.

***Diagnostic techniques*:** Several offline and online diagnostic tools are available for monitoring in-service transformers to provide information about their operating conditions. Dissolved gas analysis is widely used in conjunction with routine tests on oil and winding insulation. Frequency response analysis is being widely used to assess the mechanical condition of windings. Recently, online partial discharge monitoring techniques based on acoustic and ultra-high frequency sensors have also been deployed. Advanced time- and frequency-domain methods are becoming popular for the diagnostics of insulation. However, the higher costs of the advanced instruments required for this purpose inhibit their widespread use. An important factor that must be kept in mind is that field experience with some of the monitoring techniques is limited. A close cooperation between manufacturers and users is necessary for developing good monitoring and diagnostic systems for transformers.

Transformer technology is developing at a tremendous rate and computerized operations have replaced manual work in the design office. Continuous improvements in materials and manufacturing technologies along with the use of advanced computational tools have contributed towards making transformers more efficient, compact and reliable. Advanced diagnostic tools and several emerging trends in transformer applications are expected to fulfill a number of existing and emerging requirements of utilities and end-users.

1.2 Applications and Types of Transformers

Before the invention of transformers, in the initial days of the electrical industry, power was distributed through direct current (DC) at low voltages. Voltage drops in electrical lines limited the use of electricity to only urban areas where consumers were served using distribution circuits of small length. All the electrical equipment had to be designed for the same voltage. Development of the first transformer around 1885 dramatically changed transmission and distribution systems. The power generated with alternating currents at low voltages could be stepped up for transmission purposes to higher voltages (with lower currents), reducing voltage drops and transmission losses. The use of transformers made it possible to transmit power economically to areas hundreds of kilometers away from generating stations. Step-down transformers then reduced the voltage at the receiving stations for the distribution of power at various standardized voltage levels for its use by end-consumers. Transformers have made AC systems flexible because the various parts and equipment of the power system can be operated at economical voltage levels with suitable voltage ratios. A single-line diagram of a typical power system is shown in Figure 1.1. Voltage levels are different in different countries. Transformers can be broadly classified into several types, some of which are based on location and broad function, and others according to their applications:

1.2.1 Transformers classified according to location and broad function

a. Generator transformers**:** The power generated at a generating station (usually at a voltage in the range of 11 to 25 kV) is stepped up by a generator transformer to a higher voltage (220, 345, 400 or 765 kV) for its transmission over long distances. Generator transformers are important and critical components of any power system. They usually have uniform loads and are designed with higher losses since the cost of supplying power is cheapest at the generating station. Lower noise levels are usually not specified since the generators supplying the transformers are even noisier.

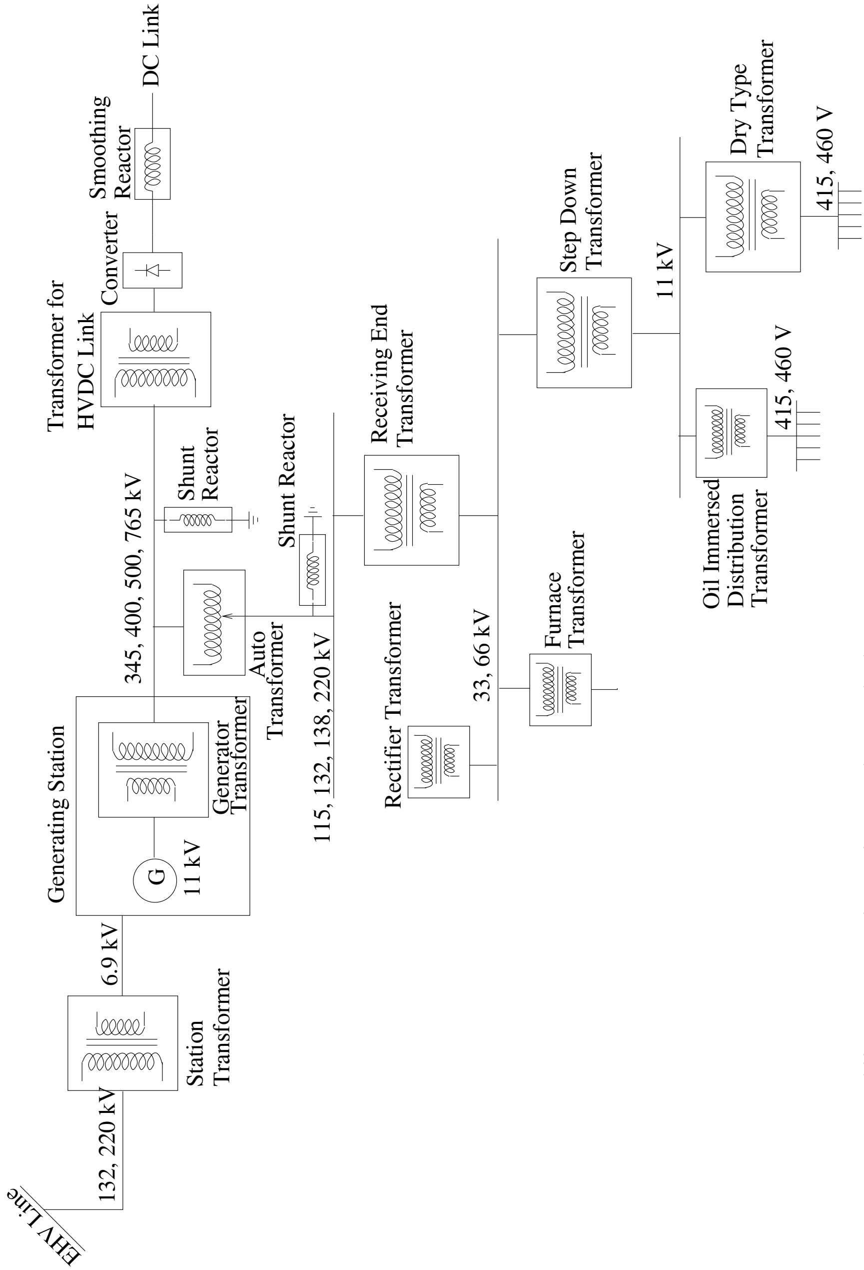

Figure 1.1 Different types of transformers in a typical power system.

A tap-changing mechanism with off-circuit taps, suitable for a small variation in the HV voltage (e.g., ± 5%), is preferred since the voltage can be easily controlled through the field excitation of the generator. Generator transformers having an on-load tap changing mechanism are used for reactive power control. They may be provided with a compact unit-cooler arrangement for want of space in the generating stations; such transformers have only one rating with oil-forced and air-forced cooling. Alternatively, oil-to-water heat exchangers can be used for the same reason. It may be economical to design the tap winding as a part of the main HV winding and not as a separate winding. This may be permissible since axial short-circuit forces are generally lower due to a small tapping range. Special care has to be taken while designing high current LV lead terminations to eliminate hot-spots in the structural parts in their vicinity. A CTC conductor with epoxy bonding is commonly used for the LV winding to minimize eddy losses and to provide higher short-circuit strength. The overexcitation conditions specified by the users have to be considered while designing generator transformers.

***b. Unit auxiliary transformers*:** These are step-down transformers with their primary winding connected to the generator output directly. The secondary voltage is of the order of 6.9 kV for supplying power to various auxiliary equipment in the generating station.

***c. Station transformers*:** These transformers are required to supply power to auxiliary equipment during the setting-up operation of generating stations and subsequently during each start-up operation. The rating of these transformers is small, and their primary winding is connected to a high voltage transmission line. This may result in a smaller conductor size for the HV winding, necessitating special measures for increasing the short-circuit strength. A split-secondary winding arrangement is often employed to achieve economical circuit breaker ratings.

***d. Interconnecting transformers or autotransformers*:** These transformers are used to interconnect two systems operating at different system voltages (e.g., 400 kV and 220 kV, 345 kV and 138 kV). There is no electrical isolation between their primary and secondary windings; some volt-amperes are conductively transformed and the remaining are inductively transformed. The design of an autotransformer becomes more cost-effective as the ratio of the secondary winding voltage to the primary winding voltage approaches unity. Autotransformers are characterized by a wide tapping range and a loaded or unloaded delta-connected tertiary winding. The unloaded tertiary winding acts as a stabilizing winding by providing a path for third-harmonic currents. Synchronous condensers or shunt reactors are connected to the tertiary winding, if required, for reactive power compensation. An adequate conductor area and a proper supporting arrangement should be provided to the unloaded tertiary winding to help it withstand short-circuit forces under asymmetrical fault conditions.

e. Receiving station transformers**:** These are step-down transformers that reduce a transmission or sub-transmission voltage to a primary feeder level voltage (e.g., 220 kV/33 kV transformers). They can be used to feed industrial plants directly. Loads on them vary in a wider range, and it is expensive for the generator to supply the power lost in them in the form of no-load and load losses. The farther the location of transformers from the generating station, the higher the cost of supplying the losses is. Automatic tap changing on load is usually necessary, and the tapping range is generally higher to account for a wide variation in the voltage. A lower noise level is usually specified for those transformers that are close to residential areas.

f. Distribution transformers**:** Using distribution transformers, the primary feeder voltage is reduced to an actual utilization voltage (~ 415 or 460 V) for domestic/industrial use. Several types of transformers fall into this category due to many different arrangements and connections. The load on these transformers varies widely, and they are often overloaded. A lower value of no-load loss is desirable to improve their all-day efficiency. Hence, the no-load loss is usually capitalized with a high rate at the tendering stage. Since very little supervision is possible, users expect a minimum level of maintenance on these transformers. The cost of supplying losses and reactive power is highest for these transformers.

1.2.2 Transformers classified according to specific applications

In this chapter, only the main features of these transformers are highlighted; details of some of them are discussed in subsequent chapters.

a. Phase shifting transformers**:** These are used to control power flow over transmission lines by varying the phase angle between the input and output voltages of the transformer. Through a proper tap-change, the output voltage can be made either to lead or lag the input voltage. The total phase-shift required directly affects the rating and size of the transformer. Presently, two distinct types of core construction are used, viz. a single-core design and a two-core design. The single-core design is used for small phase-shifts and lower MVA / voltage ratings, while the two-core design is employed for bulk power transfer with higher ratings of phase-shifting transformers. The design consists of two transformers, one associated with the line terminals and the other with the tap-changer.

b. Earthing or grounding transformers**:** These are used to provide a neutral point that facilitates grounding and detection of earth faults in an ungrounded part of the network (e.g., delta-connected systems). Their windings are usually connected in a zigzag manner, which helps in eliminating third harmonic voltages in the lines. These types of transformers have an additional advantage since they are not affected by the DC magnetization problems normally associated with power electronic converters.

c. Transformers for rectifier and inverter circuits**:** These are otherwise normal transformers except for their special design and manufacturing features which enable them to counter harmonic effects. Due to extra harmonic losses, the operating flux density in their core is kept lower (around 1.6 Tesla). The winding conductor dimensions need to be smaller to reduce eddy losses, and a proper de-rating factor has to be applied depending upon the magnitudes of various harmonic components. Thermal design aspects need to be carefully looked at for eliminating hot-spots. For the transformers used in high voltage direct current (HVDC) systems, the design of their insulation system is a challenging task because of combined AC-DC voltage stresses.

d. Furnace duty transformers**:** These transformers are used to feed the arc or induction furnaces, which are characterized by a low secondary voltage (80 to 1000 V) and a high current (10 to 60 kA) depending upon their MVA rating. A non-magnetic steel material is invariably used for the termination of LV leads and for the tank portion in their vicinity to eliminate hot spots and minimize stray losses. For applications involving very high currents, LV terminals in the form of U-shaped copper tubes having suitable inside and outside diameters are designed so that they can be cooled by oil/water circulation from inside. In many cases, a booster transformer is used along with the main transformer to reduce the rating of the tap-changer.

e. Freight loco transformers**:** These are mounted in the engine compartments of locomotives, and their primary winding is connected to an overhead line. The primary voltage is stepped down to an appropriate level for feeding to a rectifier; the output DC voltage of the rectifier drives the locomotive. The structural design of the transformers has to be good enough to take care of locomotive vibrations. The mechanical natural frequencies of the whole structure need to be analyzed to eliminate resonant conditions.

f. Hermetically-sealed transformers**:** The construction of these transformers is such that it does not permit any outside atmospheric air to get into the tank. It is completely sealed without any breathing arrangement, obviating the need for periodic filtration and related maintenance activities. These transformers are filled with mineral oil or synthetic liquid as a cooling and dielectric medium, and they are sealed completely with an inert gas (nitrogen) layer between the medium and the top tank plate. A welded cover construction is used for the tank to eliminate bolted joints and related leakage problems. Variations in the medium volume are absorbed by the inert gas layer. The tank is designed for high-pressure conditions at elevated temperatures. In another type of sealed construction, the use of inert gas is avoided; the expansion of the medium is absorbed by deformations of the structure used for the cooling arrangement, which can be an integral part of the tank.

***g. Outdoor and indoor transformers*:** Most transformers are suitable for outdoor duty and are designed to withstand atmospheric pollutants. The creepage distance of the bushing insulators is decided according to the pollution level. The higher the pollution level, the greater the creepage distance that is required between the live terminal and ground. On the other hand, transformers for indoor applications are kept in a weatherproof and properly ventilated room. Standards define the minimum level of ventilation required for effective cooling. Adequate clearances should be kept between the walls and the transformer to eliminate the possibility of higher noise levels due to reverberations.

There are other types of transformers, which have applications in electronics, electric heaters, traction, etc. Some of the applications have a significant impact on the design of the transformers. The duty (load) can be very onerous. For example, the winding current densities in transformers with frequent motor-starting duty have to be lower due to the high starting currents of the motors (which can be of the order of 6 to 8 times the full load current).

1.2.3 Reactors

Shunt and series reactors are very important components of the power system. The design of reactors, which have only one winding, is similar to that of transformers in many aspects. Their special features are highlighted below.

***a. Shunt reactors*:** These are used to compensate for the capacitive volt-amperes generated during no-load or light-load conditions in high voltage transmission networks, thereby helping to maintain the voltage profile within desirable limits. Shunt reactors are installed at a number of places along the length of the transmission line. They can be either permanently connected or of a switched type. Those that are permanently connected may result in poor voltage levels and increased losses under normal operating conditions. Hence, the switched types are better since these are connected only when the voltage levels need to be controlled. When connected to the tertiary winding of a transformer with a suitable rating, they become cost effective. The voltage drop due to a high impedance value between the HV winding and the tertiary winding must be taken into account while deciding the voltage rating of the reactors connected to the tertiary winding.

Shunt reactors can be of coreless (air-core) or gapped-core (magnetic circuit with non-magnetic gaps) design. The flux density in the air-core reactors has to be lower as the flux path is not well constrained. Eddy losses in the winding and stray losses in the structural conducting parts are higher in this type of design. In contrast, the gapped-core design is compact due to a higher permissible flux density. The gaps between core packets can be suitably designed to achieve a desired reactance value. Shunt reactors are usually designed to have constant impedance characteristics up to 1.5 times the rated voltage to minimize harmonic currents in overvoltage conditions.

***b. Series reactors*:** These reactors are connected in series with generators, feeders, and transmission lines to limit fault currents under short-circuit conditions. These reactors should have linear magnetic characteristics under fault conditions. They should be designed to withstand the mechanical and thermal effects of short circuits. The winding of series reactors used for transmission lines is of the fully insulated type since both the ends should be able to withstand lightning voltages. The value of the series reactors has to be judiciously chosen because a higher value reduces the power transfer capability of the lines. Smoothing reactors used in HVDC transmission systems smoothen out the ripple in the DC voltage.

1.3 Principles and the Equivalent Circuit

1.3.1 Ideal transformer

Transformers work on the principle of electromagnetic induction, according to which a voltage is induced in a coil linking to a changing flux. Figure 1.2 shows a single-phase transformer consisting of two windings, wound on a magnetic core and linked by a mutual flux ϕ_m. The transformer is in no-load condition with its primary connected to a source of sinusoidal voltage of frequency f Hz. The primary winding draws a small excitation current, i_0 (instantaneous value), from the source to set up the flux ϕ_m in the core. All the flux is assumed to be contained in the core (no leakage). Windings 1 and 2 have N_1 and N_2 turns respectively. The instantaneous value of the induced electromotive force in winding 1 due to the mutual flux is

$$e_1 = N_1 \frac{d\phi_m}{dt} . \tag{1.1}$$

Equation 1.1 gives the circuit viewpoint; there is a flux-viewpoint also [1], in which the induced voltage (counter electromotive force) is represented as $e_1 = -N_1 (d\phi_m / dt)$. An elaborate explanation for both the viewpoints is given in [2]. If the winding is further assumed to have zero resistance (with its leakage reactance already neglected), then

$$v_1 = e_1 . \tag{1.2}$$

Since v_1 (instantaneous value of the applied voltage) is sinusoidally varying, the flux ϕ_m must also be sinusoidal in nature varying with frequency f. Let

$$\phi_m = \phi_{mp} \sin \omega t \tag{1.3}$$

where ϕ_{mp} is the peak value of mutual flux ϕ_m and $\omega = 2\,\pi f$ rad/sec. After substituting the value of ϕ_m in Equation 1.1, we obtain

$$e_1 = N_1\, \omega\, \phi_{mp} \cos \omega t . \tag{1.4}$$

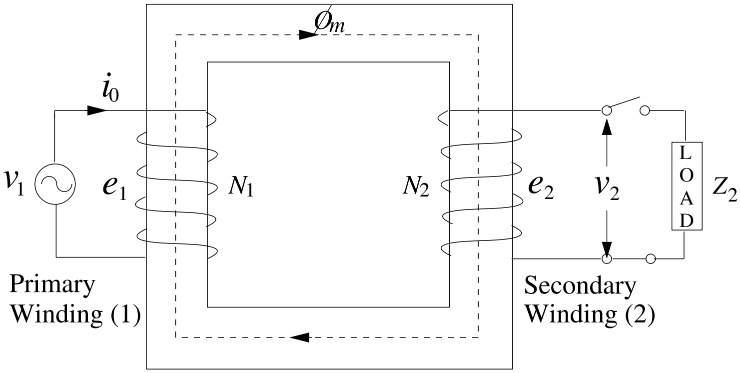

Figure 1.2 Transformer in no-load condition.

The root mean square (r.m.s.) value of the induced voltage, E_1, is obtained by dividing the peak value in Equation 1.4 by $\sqrt{2}$,

$$E_1 = 4.44\ \phi_{mp}\ f\, N_1 . \qquad (1.5)$$

Equation 1.5 is known as the *emf equation* of the transformer. For a given number of turns and frequency, the flux (and flux density) in its core is entirely determined by the applied voltage.

The voltage induced in winding 2 due to the mutual flux (ϕ_m) is given by

$$e_2 = N_2 \frac{d\phi_m}{dt} . \qquad (1.6)$$

The ratio of the two induced voltages can be derived from Equations 1.1 and 1.6,

$$e_1 / e_2 = N_1 / N_2 = a \qquad (1.7)$$

where a is known as the ratio of transformation. Similarly, the r.m.s. value of the induced voltage in winding 2 is

$$E_2 = 4.44\ \phi_{mp}\ f\ N_2 . \qquad (1.8)$$

The exciting current (i_0) is of only a magnetizing nature (i_m) if the *B-H* curve of the core material is assumed to be anhysteretic (without hysteresis) and if the eddy current losses in the core are neglected. The magnetizing current (i_m) is in phase with the mutual flux in the absence of hysteresis. Furthermore, the magnetic characteristics are assumed linear.

Now, if the secondary winding in Figure 1.2 is loaded, a current is set up in it as per Lenz's law such that the secondary magnetomotive force (mmf), $i_2 N_2$, opposes the mutual flux, thus tending to reduce it. In an ideal transformer

$e_1 = v_1$, and therefore for a constant value of the applied voltage, the induced voltage and the corresponding mutual flux must remain constant. This can happen only if the primary winding draws more current (i_1') for neutralizing the demagnetizing effect of the secondary ampere-turns. In r.m.s. notation,

$$I_1' N_1 = I_2 N_2 . \tag{1.9}$$

Thus, the total primary current is the vector sum of the no-load current (i.e., the magnetizing component, $\hat{I}_m$, since the core losses are neglected) and the load current ($\hat{I}_1'$),

$$\hat{I}_1 = \hat{I}_1' + \hat{I}_m . \tag{1.10}$$

For an infinitely permeable magnetic material, the magnetizing current is zero. Equation 1.9 then becomes

$$I_1 N_1 = I_2 N_2 . \tag{1.11}$$

Thus, for an ideal transformer with its no-load current neglected, the primary ampere-turns are equal to the secondary ampere-turns. The same result can also be obtained by applying Ampere's law, which states that the magnetomotive force around a closed path is given by

$$\oint \mathbf{H} \cdot d\mathbf{l} = i \tag{1.12}$$

where i is the current enclosed by the line integral of the magnetic field intensity **H**. For the present case,

$$\oint \mathbf{H} \cdot d\mathbf{l} = \oint (\mathbf{B}/\mu) \cdot d\mathbf{l} = i_1 N_1 - i_2 N_2 . \tag{1.13}$$

If the relative permeability of the magnetic path is assumed as infinite, the integral value is zero. Hence, in the r.m.s. notations,

$$I_1 N_1 - I_2 N_2 = 0 \tag{1.14}$$

which is the same result as in Equation 1.11.

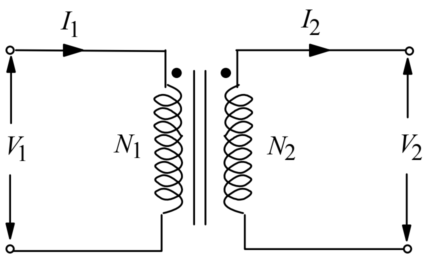

Figure 1.3 Schematic representation of an ideal transformer.

Thus, an ideal transformer (zero winding resistance, no leakage flux, infinite permeability, zero core losses) can be summarized as

$$\frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{1.15}$$

and

$$V_1 I_1 = V_2 I_2 \,. \tag{1.16}$$

A schematic representation of the transformer in Figure 1.2 is shown in Figure 1.3. The polarities of voltages depend upon the directions in which the primary and secondary windings are wound. It is a common practice to put a dot at the end of the windings such that their dotted ends are positive at the same time, meaning thereby that the voltage drops from the dotted to the unmarked terminals are in phase. Also, the currents flowing from the dotted to the unmarked terminals produce mmfs that act along the same direction in the magnetic circuit.

If the secondary winding in Figure 1.2 is loaded with an impedance Z_2,

$$Z_2 = V_2 / I_2 \,. \tag{1.17}$$

Substituting from Equation 1.15 for V_2 and I_2,

$$Z_2 = \frac{(N_2/N_1)\, V_1}{(N_1/N_2)\, I_1} \,. \tag{1.18}$$

Hence the impedance, when referred to the primary winding (1), is

$$Z_2' = \frac{V_1}{I_1} = (N_1 / N_2)^2 Z_2 \,. \tag{1.19}$$

Similarly, any impedance Z_1 in the primary circuit can be referred to the secondary side as

$$Z_1' = (N_2 / N_1)^2 Z_1 \,. \tag{1.20}$$

It can be summarized from Equations 1.15, 1.16, 1.19 and 1.20 that for an ideal transformer, voltages are transformed in the ratio of the turns, currents in the inverse ratio of the turns, and impedances in the square ratio of the turns, whereas the volt-amperes and power remain unchanged.

The ideal transformer transforms direct voltage, that is, the DC voltages on the primary and secondary sides are related by the turns ratio. This is theoretically correct since it is assumed to have infinite core permeability with linear (non-saturating) characteristics permitting the flux to rise without limit under a DC voltage application. When a DC voltage (V_{d1}) is applied to the primary winding with the secondary winding open-circuited,

$$V_{d1} = N_1 (d\phi_m / dt) . \tag{1.21}$$

Thus, $(d\phi_m / dt)$ is constant (flux permitted to rise with time without any limit) and is equal to (V_{d1} / N_1). Voltage at the secondary of the ideal transformer is

$$V_{d2} = N_2 (d\phi_m / dt) = (N_2 / N_1)\, V_{d1} . \tag{1.22}$$

However, for a practical transformer, in the steady-state condition the primary current has a value of V_{d1}/R_1, and the magnetic circuit is driven into saturation. Eventually, this reduces the values of the induced voltages E_1 and E_2 to zero. This is because, in saturation, there is hardly any change in the flux even though the current may still be increasing till the steady-state condition is reached. The value of the steady-state current, V_{d1}/R_1, is high enough to damage the transformer.

1.3.2 Practical transformer

The analysis presented for an ideal transformer is merely to explain the fundamentals of transformer action; such a transformer does not exist and the equivalent circuit of a real (practical) transformer, as shown in Figure 1.4, is now developed. Whenever a magnetic material undergoes a cyclic magnetization, two types of losses, eddy and hysteresis losses, occur in it. These losses are always present in transformers as the flux in their ferromagnetic core is of an alternating nature. A detailed explanation of these losses is given in Chapter 2.

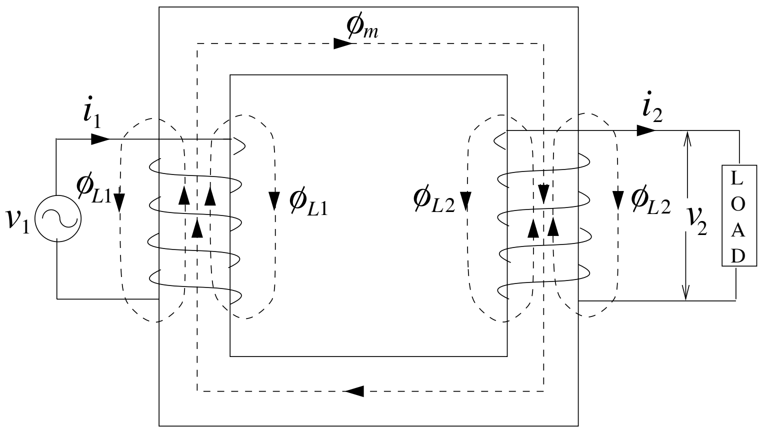

Figure 1.4 Practical transformer.

The hysteresis loss and eddy loss can be minimized by using a better grade of core material and thinner laminations, respectively. The total no-load current, I_0, consists of the magnetizing component (I_m) responsible for producing the mutual flux, ϕ_m, and the core-loss component (I_c) which accounts for the active power drawn from the source to supply the losses. The core-loss component is in phase with the induced voltage and leads the magnetizing component by 90°. With the secondary winding open-circuited, the transformer behaves as a highly inductive circuit, and hence the no-load current lags behind the applied voltage by an angle slightly less than 90° (I_m is usually much greater than I_c). In the equivalent circuit shown in Figure 1.5 (a), the magnetizing component is represented by the inductive reactance, X_m, whereas the loss component is indicated by the resistance, R_c.

Let R_1 and R_2 be the resistances of windings 1 and 2, respectively. In a practical transformer, some part of the flux linking the primary winding does not link the secondary winding. This flux component is proportional to the primary current and is responsible for a voltage drop which is represented by the inductive reactance X_{L1} (leakage reactance) and it is put in series with the primary winding of the ideal transformer. Similarly, a leakage reactance, X_{L2}, is added in series with the secondary winding of the ideal transformer to take into account the voltage drop due to the flux linking only the secondary winding. One can omit the ideal transformer from the equivalent circuit, if all the quantities are referred to either the primary or the secondary side of the transformer. For example, in the equivalent circuit of Figure 1.5 (b), all quantities are referred to the primary side,

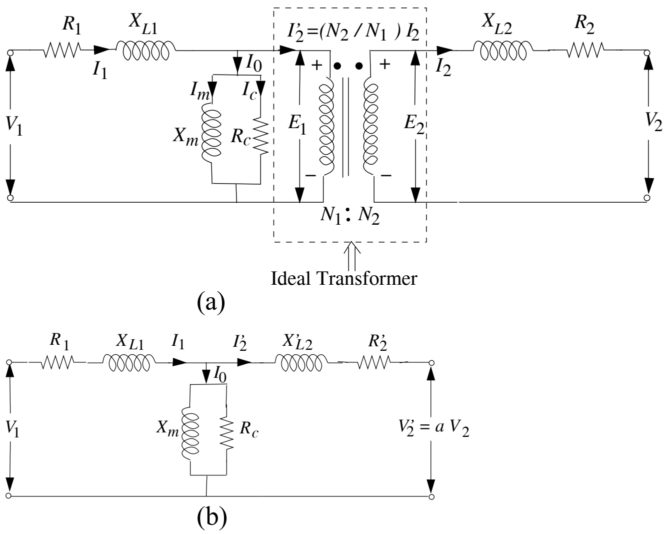

Figure 1.5 Equivalent circuit.

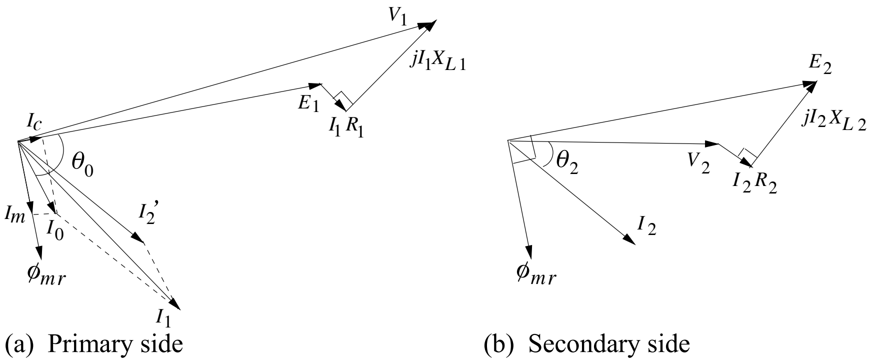

Figure 1.6 Vector diagrams.

$$X'_{L2} = X_{L2}(N_1/N_2)^2 \tag{1.23}$$

and

$$R'_2 = R_2(N_1/N_2)^2 . \tag{1.24}$$

This equivalent circuit is a passive lumped-T representation, valid generally for the sinusoidal steady-state analysis at power frequencies. For higher frequencies, capacitive effects must be considered, as discussed in Chapter 7. For transient analyses, all the reactances in the equivalent circuit should be replaced by the corresponding inductances.

While drawing a vector diagram, it must be remembered that all the involved phasors must be of the same frequency. The magnetization (*B-H*) curve of the core materials used in transformers is nonlinear and therefore it introduces higher order harmonics in the magnetizing current for an applied sinusoidal voltage of fundamental frequency. In the vector diagrams of transformers, however, a linear *B-H* curve is assumed (harmonics are not considered). The aspects related to core magnetization and losses are described in Chapter 2. For Figure 1.5 (a), the following equations can be written:

$$V_1 = E_1 + (R_1 + jX_{L1})\, I_1 \tag{1.25}$$

and

$$V_2 = E_2 - (R_2 + jX_{L2})\, I_2 . \tag{1.26}$$

Vector diagrams for the primary and secondary voltages/currents are shown in Figure 1.6. The output terminal voltage, V_2, is taken as a reference vector along the x-axis. The power factor angle of the load is denoted by θ_2. The induced voltages are in phase and lead the mutual flux ϕ_{mr} (r.m.s. value of ϕ_m) by 90°

in conformance with Equations 1.1 and 1.6. The magnetizing component (I_m) of the no-load current (I_0) is in phase with ϕ_{mr}, whereas the loss component (I_c) leads ϕ_{mr} by 90° and is in phase with the induced voltage E_1. The core loss is given as

$$P_c = I_c E_1 \tag{1.27}$$

or

$$P_c = I_c^2 R_c . \tag{1.28}$$

The mutual reactance, X_m, is

$$X_m = \frac{E_1}{I_m} . \tag{1.29}$$

The magnitude of the secondary current referred to the primary side ($I_2^{'}$) is the same as that of the secondary current (I_2), since the turns of the primary and secondary windings are assumed to be equal for the sake of simplicity. There is a finite phase shift between the terminal voltages V_1 and V_2 due to voltage drops in the leakage impedances. The voltage drops in the resistances and leakage reactances are exaggerated in the vector diagrams. The voltage drop across the winding resistances is typically less than 0.5% of the terminal voltage for large power transformers, whereas the voltage drop in the leakage impedances is much higher. For small distribution transformers (up to 5 MVA), the value of the leakage impedance is around 4% to 7% and for power transformers it can be anywhere in the range of 8% to 20% depending upon the voltage regulation and system protection requirements. The lower the percentage impedance is, the lower the voltage drop. However, the required ratings of the circuit breakers will be higher.

1.3.3 Mutual and leakage inductances

The leakage flux ϕ_{L1} shown in Figure 1.4 is produced by the current i_1, which links to winding 1 only. Similarly, the leakage flux ϕ_{L2} is produced by the current i_2, which links to winding 2 only. The primary leakage inductance is

$$L_{L1} = N_1 \frac{d\phi_{L1}}{di_1} . \tag{1.30}$$

The differential reluctance offered to the path of leakage flux is

$$\Re_{L1} = N_1 \frac{di_1}{d\phi_{L1}} . \tag{1.31}$$

Equations 1.30 and 1.31 give

$$L_{L1} = \frac{N_1^2}{\Re_{L1}} \ . \tag{1.32}$$

Similarly, the leakage inductance of the secondary winding is

$$L_{L2} = \frac{N_2^2}{\Re_{L2}} \, . \tag{1.33}$$

Let us derive the expression for the mutual inductance, *M*. Using Equation 1.6,

$$e_2 = N_2 \frac{d\phi_m}{dt} = N_2 \frac{d\phi_m}{di_m} \frac{di_m}{dt} = M_{21} \frac{di_m}{dt} \tag{1.34}$$

where,

$$M_{21} = N_2 \frac{d\phi_m}{di_m} = N_2 \frac{N_1}{\Re_m} \, . \tag{1.35}$$

M_{21} represents flux linkages in the secondary winding due to the magnetizing current (i_m) in the primary winding divided by i_m. The reluctance offered to the path of the mutual flux (ϕ_m) is denoted by $\Re_m$. Similarly,

$$M_{12} = N_1 \frac{N_2}{\Re_m} \, . \tag{1.36}$$

Thus, the mutual inductance is given by

$$M = M_{12} = M_{21} = \frac{N_1 N_2}{\Re_m} \, . \tag{1.37}$$

Let $\Re_1$ represent the total reluctance of the parallel paths of two fluxes, viz. the leakage flux, ϕ_{L1}, of winding 1 and ϕ_m. Also let

$$k_1 = \frac{\Re_1}{\Re_m} \, . \tag{1.38}$$

The self inductance, L_1, of winding 1, when $i_2 = 0$, is

$$L_1 = \frac{N_1^2}{\Re_1} = \frac{N_1^2}{\Re_1} \frac{\Re_m}{\Re_m} \frac{N_2}{N_2} = \frac{aM}{k_1} \, . \tag{1.39}$$

Similarly let

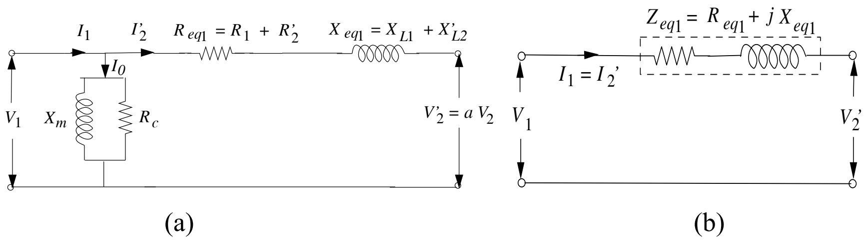

Figure 1.7 Simplified equivalent circuit.

$$k_2 = \frac{\Re_2}{\Re_m} \tag{1.40}$$

and we obtain

$$L_2 = \frac{M}{ak_2}. \tag{1.41}$$

Hence,

$$M = \sqrt{k_1 k_2}\sqrt{L_1 L_2} = k\sqrt{L_1 L_2}\,. \tag{1.42}$$

Coefficient $k = \sqrt{k_1 k_2}$ is a measure of coupling between the two windings. From the definitions of k_1 and k_2 (e.g., $k_1 = \frac{\Re_1}{\Re_m} = \frac{1/\Re_m}{1/\Re_1} = \frac{1/\Re_m}{1/\Re_m + 1/\Re_{L1}}$), it follows that $0 \le k_1 \le 1$ and $0 \le k_2 \le 1$, giving $0 \le k \le 1$. For $k = 1$, the windings are said to have a perfect coupling with no leakage flux, which is possible only for the ideal transformer discussed previously.

1.3.4 Simplified equivalent circuit

Since the no-load current and voltage drop in the leakage impedance are usually small, it is often permissible to simplify the equivalent circuit of Figure 1.5 (b) by doing some approximations. Terminal voltages (V_1, V_2) are not appreciably different from the corresponding induced voltages, and hence little error is introduced if the no-load current is made to correspond to the terminal voltage instead of the induced voltage. For example, if the excitation branch (consisting of X_m in parallel R_c) is shifted to the input terminals (excited by V_1), the approximate equivalent circuit will be as shown in Figure 1.7 (a). Such an equivalent circuit is derived for a sample design in Appendix A. If we totally neglect the no-load excitation current, as it is much less as compared to the full load current, the circuit can be further simplified as shown in Figure 1.7 (b). This simplified circuit, in which a transformer can be represented by just the impedance, Z_{eq1}, is considered to be sufficiently accurate for a modeling purpose in power system studies. Since R_{eq1} is much smaller than X_{eq1}, a transformer can be represented just as a series reactance in most cases.

1.4 Representation of a Transformer in a Power System

As seen in the previous section, the ohmic values of resistance and leakage reactance of the transformer depend upon whether they are referred on the LV side or the HV side. A great advantage is realized by expressing voltage, current, impedance, and volt-amperes in per-unit or percentage of the corresponding base values. The per-unit quantities, once expressed on a particular base, are the same when referred to either side of the transformer. Thus, the value of the per-unit impedance remains the same on either side obviating the need for any calculations by using Equations 1.19 and 1.20. This approach is very handy in power system calculations, where a large number of transformers, each having a number of windings, are present.

Per-unit values are derived by choosing a set of base values for the above-mentioned quantities. Although the base values can be chosen arbitrarily, it is preferable to use the rated quantities as the base values. The per-unit quantity (p.u.) is related to the base quantity by the following relationship:

$$Per\text{-}unit\ quantity = \frac{Actual\ value\ of\ the\ quantity}{Base\ value\ of\ the\ quantity}. \tag{1.43}$$

The actual and base values must be expressed in the same unit. Usually, the base values of voltage and volt-amperes are chosen first, from which the other base quantities are determined. The base values of voltages on the LV side and HV side are denoted by V_{bL} and V_{bH}, respectively. The corresponding values of base currents for the LV side and HV side are I_{bL} and I_{bH}, respectively. If the rated voltage of the LV winding is taken as the base voltage (V_{bL}) for the LV side,

$$\text{p.u. rated voltage on LV side} = \frac{\text{Rated voltage of LV side}}{V_{bL}} = 1.0\,. \tag{1.44}$$

Hence, the per-unit values of rated quantities are equal to unity when rated quantities are chosen as the base quantities. Per-unit quantities are ratios and dimensionless, which have to be multiplied by 100 to obtain percentage values.

The value of base impedance on the LV side is

$$Z_{bL} = \frac{V_{bL}}{I_{bL}} = \frac{V_{bL}^2}{V_{bL}\ I_{bL}} = \frac{V_{bL}^2}{(VA)_b} \tag{1.45}$$

where $(VA)_b$ denotes base volt-amperes. Similarly for the HV side,

$$Z_{bH} = \frac{V_{bH}^2}{(VA)_b}. \tag{1.46}$$

For the simplified equivalent circuit of Figure 1.7, the total equivalent resistance referred to the primary (LV) side can be expressed in per-unit notation as

$$(R_{eq1})_{pu} = \frac{R_{eq1}}{Z_{bL}}. \tag{1.47}$$

If R_{eq2} is the total equivalent resistance of the windings referred to the secondary (HV) winding, it follows from Equations 1.24 and 1.47 that

$$(R_{eq1})_{pu} = \frac{R_{eq2}\left(N_1/N_2\right)^2}{Z_{bL}} = \frac{R_{eq2}}{Z_{bL}\left(N_2/N_1\right)^2} = \frac{R_{eq2}}{Z_{bH}} = (R_{eq2})_{pu} = (R_{eq})_{pu}. \tag{1.48}$$

Similarly, it can easily be verified that the per-unit values of impedances on the LV and HV sides are equal.

The per-unit impedance can be expressed as

$$(Z_{eq})_{pu} = (Z_{eq1})_{pu} = \frac{Z_{eq1}}{Z_{bL}} = \frac{Z_{eq1}\,I_{bL}}{Z_{bL}\,I_{bL}} = \frac{Z_{eq1}\,I_{bL}}{V_{bL}}. \tag{1.49}$$

Thus, $(Z_{eq})_{pu}$ denotes the per-unit value of the leakage impedance voltage drop on the LV (or HV) side. For example, if 1000/100 V transformer has $(Z_{eq})_{pu}$ of 0.1, the voltage drop across the equivalent leakage impedance referred to the LV side is 0.1 times 100 volts, i.e., 10 volts; the corresponding voltage drop on the HV side is 100 volts (= 0.1×1000). Similarly,

$$(R_{eq})_{pu} = (R_{eq1})_{pu} = \frac{R_{eq1}}{Z_{bL}} = \frac{R_{eq1}\,I_{bL}\,I_{bL}}{Z_{bL}\,I_{bL}\,I_{bL}} = \frac{R_{eq1}\,I_{bL}^2}{V_{bL}\,I_{bL}}. \tag{1.50}$$

Thus, the per-unit value of the equivalent resistance, $(R_{eq})_{pu}$, is the ratio of the ohmic loss at the rated current to the rated volt-amperes. For example, $(R_{eq})_{pu}$ of 0.02 for 50 kVA, 1000/100 V transformer means that the total ohmic loss at the rated current is 0.02 times (2% of) 50 kVA, i.e., 1000 watts.

Another advantage of using the per-unit system is that the impedances of transformers of the same type (irrespective of their ratings) lie usually within a small known range of per-unit values although the ohmic values may be widely different. For large power transformers, the base voltages are usually expressed in kV and the base volt-amperes in MVA. Hence, the base impedances on LV and HV sides can be calculated as

$$Z_{bL} = \frac{(\mathrm{kV})_{bL}^2}{(\mathrm{MVA})_b} \quad \text{and} \quad Z_{bH} = \frac{(\mathrm{kV})_{bH}^2}{(\mathrm{MVA})_b}. \tag{1.51}$$

For three-phase transformers, the total three-phase power in MVA and line-to-line voltage in kV have to be taken as the base values. It can be shown that when ohmic value of impedance is transferred from one side to the other, the multiplying factor is the ratio of squares of line-to-line voltages of both sides irrespective of whether the transformer connection is star-star or star-delta [3].

1.5 Open-Circuit and Short-Circuit Tests

Parameters of the equivalent circuit can be determined by open-circuit (no-load) and short-circuit (load) tests. The open-circuit test determines the shunt parameters of the equivalent circuit of Figure 1.5. The circuit diagram for conducting the test is shown in Figure 1.8 (a). The rated voltage is applied to one winding and the other winding is kept open. Usually, LV winding is supplied since a low voltage supply is generally available. The no-load current is a very small percentage (0.2 to 2%) of the full load current; lower percentage values are observed for larger transformers (e.g., the no-load current of a 300 MVA transformer can be as small as 0.2%). Also, the leakage impedance value is much smaller than those of the shunt branch parameters. Therefore, the voltage drop in the LV resistance and leakage reactance is negligible as compared to the rated voltage ($\therefore V_1 \cong E_1$ in Figure 1.5, and θ_0 can be taken as the angle between V_1 and I_0). The input power measured by the wattmeter consists of the core loss and the primary winding ohmic-loss. If the no-load current is 1% of the full load current, the ohmic-loss in the primary winding resistance is just 0.01% of the load loss at the rated current; the value of the winding loss is negligible as compared to the core loss. Hence, the entire wattmeter reading can be taken as the core loss. The equivalent circuit of Figure 1.5 (b) is simplified to that shown in Figure 1.8 (b).

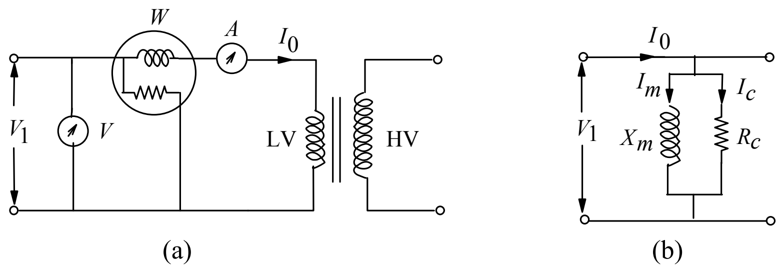

Figure 1.8 Open-circuit test.

The no-load loss, P_c, measured by the wattmeter is

$$P_c = V_1 I_0 \cos\theta_0 . \tag{1.52}$$

From the measured values of P_c, V_1 and I_0, the value of no-load power factor can be calculated from Equation 1.52 as

$$\cos\theta_0 = \frac{P_c}{V_1 I_0} . \tag{1.53}$$

With reference to the vector diagram of Figure 1.6, the magnetizing component (I_m) and the core loss component (I_c) of the no-load current (I_0) are

$$I_c = I_0 \cos\theta_0 \tag{1.54}$$

$$I_m = I_0 \sin\theta_0 . \tag{1.55}$$

The shunt parameters of the equivalent circuit are calculated as

$$R_c = \frac{P_c}{I_c^2} \quad \text{or} \quad R_c = \frac{V_1^2}{P_c} \tag{1.56}$$

$$X_m = \frac{V_1}{I_m} . \tag{1.57}$$

These values refer to the LV side, since the measuring instruments are placed on the LV side. If required, they can be referred to the HV side by using the operator a^2, i.e., $(N_1/N_2)^2$. The value of magnetizing reactance is very high as compared to the leakage reactance. For a no-load current of 0.2% (and with the assumption that $I_0 \cong I_m$), the value of X_m is 500 per unit.

A short-circuit test is done to measure the load loss and leakage impedance of the transformer. In this test, usually the LV winding is short-circuited and a voltage is applied to the HV winding in order to circulate the rated currents in both the windings; the applied voltage required for the purpose is called the impedance voltage of the transformer. For a transformer having 10% leakage impedance, the voltage required to circulate the rated currents is 10% of the rated voltage, with one of the windings short-circuited. The circuit diagram for the short-circuit test is shown in Figure 1.9 (a), in which the LV winding (secondary winding 2) is short-circuited. For an applied voltage of 10% and assuming for the equivalent circuit of Figure 1.5 (b) that the primary and referred secondary leakage impedances are equal, 5% of the voltage appears across the shunt parameters. With a no-load current of 2% at the rated voltage, the total current drawn by the two shunt elements for a 5% voltage is just 0.1% of the rated current (assuming linear B-H characteristics). Hence, the shunt parameters can be neglected giving the simplified circuit of Figure 1.9 (b) for the short-circuit test. Since the core loss varies approximately in the square proportion of the applied voltage, with 5% voltage across R_c, it is just 0.25% of the core loss at the rated voltage. Hence, the entire loss measured by the wattmeter is almost equal to the load loss of the transformer.

The parameters of the equivalent circuit, viz. $R_{eq1}(=R_1+R_2^{'})$, $X_{eq1}(=X_{L1}+X_{L2}^{'})$ and $Z_{eq1}(=R_{eq1}+jX_{eq1})$ can now be determined from the measured quantities of power (P_L), voltage (V_{SC}), and current (I_{SC}) as

$$Z_{eq1}=\frac{V_{SC}}{I_{SC}} \tag{1.58}$$

$$R_{eq1}=\frac{P_L}{I_{SC}^2} \tag{1.59}$$

$$X_{eq1}=\sqrt{Z_{eq1}^2-R_{eq1}^2}\ . \tag{1. 60}$$

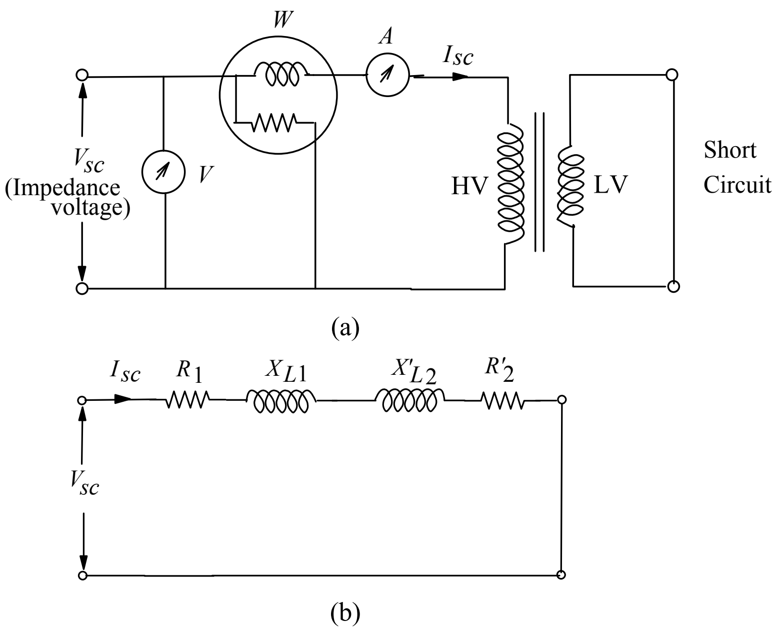

Figure 1.9 Short-circuit test (with LV terminals short-circuited).

R_{eq1} is the equivalent AC resistance referred to the primary (HV) winding, which accounts for the losses in the DC resistance of the windings, the eddy losses in the windings and the stray losses in structural parts. It is not practical to apportion the stray losses to the two windings. Hence, if the resistance parameter is required to be known for each winding, it is usually assumed that $R_1 = R_2^{'} = (1/2)\ R_{eq1}$. Similarly, it is assumed that $X_{L1} = X_{L2}^{'}$, although it is not strictly true. Since % R is much smaller than % Z, in practice the percentage reactance (% X) is taken to be the same as the percentage impedance (% Z). This approximation, however, may not be true for small distribution transformers.

1.6 Voltage Regulation and Efficiency

Since many electrical devices and appliances operate most effectively at their rated voltage, it is necessary that the output voltage of a transformer be within narrow limits when the magnitude and power factor of loads vary. Voltage regulation is an important performance parameter of transformers as it determines the quality of electricity supplied to consumers. The voltage regulation for a specific load is defined as a change in the magnitude of the secondary voltage after removal of the load (the primary voltage being held constant) expressed as a fraction of the secondary voltage corresponding to the no-load condition.

$$\text{Regulation (p.u.)} = \frac{V_{2oc} - V_2}{V_{2oc}} \tag{1.61}$$

where V_2 is the secondary terminal voltage at a specific load and V_{2oc} is the secondary terminal voltage when the load is removed. For the approximate equivalent circuit of Figure 1.7 (b), if all the quantities are referred to the secondary side, the voltage regulation for a lagging power factor load is given as [4]

$$\text{Regulation (p.u.)} = \frac{I_2 R_{eq2}\cos\theta_2 + I_2 X_{eq2}\sin\theta_2}{V_{2oc}} + \frac{1}{2}\left(\frac{I_2 X_{eq2}\cos\theta_2 - I_2 R_{eq2}\sin\theta_2}{V_{2oc}}\right)^2 \tag{1.62}$$

where R_{eq2} and X_{eq2} are the equivalent resistance and leakage reactance of the transformer referred to the secondary side respectively. The secondary load current (I_2) lags behind the secondary terminal voltage (V_2) by angle θ_2. For a full load condition, with the rated values taken as base quantities,

$$\text{Regulation (p.u.)} = \varepsilon_r \cos\theta_2 + \varepsilon_x \sin\theta_2 + \frac{1}{2}\left(\varepsilon_x \cos\theta_2 - \varepsilon_r \sin\theta_2\right)^2 \tag{1.63}$$

where, $\varepsilon_r = \dfrac{I_2\, R_{eq2}}{V_{2oc}}$ represents the per-unit resistance drop and $\varepsilon_x = \dfrac{I_2\, X_{eq2}}{V_{2oc}}$ represents the per-unit leakage reactance drop. For a leading power factor load (I_2 leads V_2 by angle θ_2),

$$\text{Regulation (p.u.)} = \varepsilon_r\, cos\,\theta_2 - \varepsilon_x\, sin\,\theta_2 + \frac{1}{2}\left(\varepsilon_x\, cos\,\theta_2 + \varepsilon_r\, sin\,\theta_2\right)^2 . \tag{1.64}$$

The square term is usually small and may be neglected, simplifying Equations 1.63 and 1.64 as

$$\text{Regulation (p.u.)} = \varepsilon_r \cos\theta_2 \pm \varepsilon_x \sin\theta_2 . \tag{1.65}$$

The efficiency of a transformer, like any other electrical device, is defined as

$$\eta = \frac{output\ power}{input\ power} . \tag{1.66}$$

The percentage efficiency of transformers is in the range of 95 to 99%. For large power transformers with low loss designs, the efficiency can be as high as 99.7%. There is a possibility of error if the efficiency is determined from the measured values of output and input powers. It is therefore determined using the values of their losses measured by the open-circuit and short-circuit tests. The efficiency is then given as

$$\eta = \frac{output\ power}{output\ power + losses} \tag{1.67}$$

$$\therefore \eta = \frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + P_c + P_L} = \frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + P_c + I_2^2 R_{eq2}} . \tag{1.68}$$

Although the load power factor has some effect on the mutual flux and hence the core loss, the effect is insignificant, allowing us to assume that the core loss is constant irrespective of the load condition. For assumed constant values of P_c and V_2, the condition for maximum efficiency at a given load power factor can be derived by differentiating the expression of η with respect to I_2 and equating it to zero:

$$\frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + (P_c + I_2^2 R_{eq2})}\right] = 0. \tag{1.69}$$

Solving it further, we obtain

$$P_c = I_2^2 R_{eq2}. \tag{1.70}$$

Thus, the efficiency is maximum at a load at which the load loss value equals the constant core (no-load) loss value. Further,

$$\frac{I_2^2}{I_{2FL}^2} = \frac{P_c}{I_{2FL}^2\ R_{eq2}} \tag{1.71}$$

where I_{2FL} is the full-load (rated) current and $I_{2FL}^2 R_{eq2}$ is the corresponding load loss. Therefore, the per-unit load at which the maximum efficiency occurs is

$$(per\text{-}unit\ \ load)_{\eta_{\max}} = \frac{I_2}{I_{2FL}} = \sqrt{\frac{P_c}{(P_L)_{FL}}}. \tag{1.72}$$

The value of maximum efficiency can be calculated by substituting the value of I_2 from Equation 1.72 in Equation 1.68. Similarly, it can easily be shown that the efficiency for a given load condition (i.e., constant I_2) is maximum for the unity power factor condition ($\cos\theta = 1$).

Example 1.1

A single-phase transformer is designed to operate at 220/110 V, 60 Hz. What will be the effect on the transformer performance if the frequency reduces by 5% to 57 Hz and the primary voltage increases by 5% to 231 volts?

Solution:

The emf equation is

$$V_1 = 4.44\ \phi_{mp}\ f\ N_1.$$

Now $\phi_{mp} = B_{mp}\ A_c$

where B_{mp} is peak value of the flux density in the core (wb/m^2)

A_c is cross-sectional area of the core in m^2.

Hence, for a given number of turns (N_1) and core area (A_c),

$$\frac{(231)_{57Hz}}{(220)_{60Hz}} = \frac{4.44\,(B_{mp})_{57Hz} \times A_c \times 57 \times N_1}{4.44\,(B_{mp})_{60Hz} \times A_c \times 60 \times N_1}$$

$$\frac{(B_{mp})_{57Hz}}{(B_{mp})_{60Hz}} = \frac{231 \times 60}{220 \times 57} = 1.10\,.$$

Thus, with the reduced frequency and higher applied voltage, the flux density in the core increases. This increase will in turn increase the no-load current, the core loss and the noise level of the transformer. This example shows that the operating peak flux density in the core has to be correctly chosen depending on specified overexcitation conditions by the user.

Example 1.2

Tests on 31.5 MVA, 132/33 kV star/delta 3-phase transformer gave following results (loss values given are for three phases):

- Open-circuit test: 33 kV, 5.5 A, 21 kW
- Short-circuit test: 13.2 kV, 137.8 A, 100 kW

Calculate: a) equivalent circuit parameters referred to the LV side
b) efficiency at full load and half of full load with unity power factor
c) regulation at full load with 0.8 lagging power factor

Solution:

a) Unless otherwise stated, the specified values of voltages should be taken as line-to-line values. The equivalent circuit representation is on a per-phase basis, and hence per-phase values of the losses should be used in the calculations.

The open-circuit test is performed on the LV side with the application of the rated voltage of 33 kV. For the delta connected LV winding, the line and phase voltages are equal; the phase current is the line current divided by $\sqrt{3}$. Hence, we obtain

Per-phase no-load excitation current $= \dfrac{5.5}{\sqrt{3}} = 3.2$ A

Per-phase core loss $= \dfrac{21000}{3} = 7000$ W

Core-loss component $= I_c = I_0 \cos\theta_0 = \dfrac{P_c}{V_1} = \dfrac{7000}{33000} = 0.21$ A

Magnetizing component $= I_m = \sqrt{I_0^2 - I_c^2} = \sqrt{3.2^2 - 0.21^2} = 3.19$ A.

The values of the core-loss resistance and the magnetizing reactance referred to the LV side are calculated as

$$R_c = \frac{V_1}{I_c} = \frac{33000}{0.21} = 157 \text{ k}\Omega$$

$$X_m = \frac{V_1}{I_m} = \frac{33000}{3.19} = 10.34 \text{ k}\Omega$$

$$\text{LV side base impedance } = \frac{\text{kV}^2}{\text{MVA}} = \frac{33^2}{(31.5/3)} = 103.7 \ \Omega \, .$$

Thus, the per-unit value of X_m is 100 $\left(=10.34 \text{ k}\Omega / 103.7 \ \Omega\right)$.

Now the short-circuit test is performed on the HV side (the applied voltage of 13.2 kV is a fraction of the rated HV voltage, i.e. 132 kV).

Per-phase applied voltage to the star-connected HV winding $= \dfrac{13200}{\sqrt{3}} = 7621$ V

For the star connection, the phase and line currents are equal (=137.8 A).
Now, the ohmic value of the leakage impedance and resistance referred to the HV side can be calculated as

$$Z_{eqH} = \frac{V_{sc}}{I_{sc}} = \frac{7621}{137.8} = 55.3 \ \Omega \, .$$

Per-phase value of the load-loss = $\dfrac{100000}{3}$ W

$$R_{eqH} = \frac{P_L}{I_{sc}^2} = \frac{100000/3}{137.8^2} = 1.755 \ \Omega$$

$$\therefore X_{eqH} = \sqrt{Z_{eqH}^2 - R_{eqH}^2} = \sqrt{55.3^2 - 1.755^2} = 55.27 \ \Omega \, .$$

Now, the equivalent circuit quantities calculated on the HV side can be referred to the LV side using the transformation ratio a ,

$$a = \frac{N_1}{N_2} \cong \frac{V_{pL}}{V_{pH}}$$

where V_{pL} and V_{pH} are the phase voltages of the LV and HV windings respectively.

$$\therefore R_{eqL} = a^2 R_{eqH} = \left[\frac{33000}{132000/\sqrt{3}}\right]^2 \times 1.755 = 0.329 \ \Omega \, .$$

Similarly,

$$X_{eqL} = a^2 X_{eqH} = \left[\frac{33000}{132000/\sqrt{3}}\right]^2 \times 55.27 = 10.36\ \Omega .$$

In per-unit quantities,

$$\varepsilon_r = (R_{eqL})_{pu} = \frac{R_{eqL}}{Z_{bL}} = \frac{0.329}{103.5} = 0.0032$$

$$\varepsilon_x = (X_{eqL})_{pu} = \frac{X_{eqL}}{Z_{bL}} = \frac{10.36}{103.5} = 0.1 .$$

We could have directly found the value of $(R_{eqL})_{pu}$ by using line-to-line and 3-phase quantities in Equation 1.50 as

$$(R_{eqL})_{pu} = \frac{100\times10^3}{31.5\times10^6} = 0.0032 .$$

Similarly, we can directly infer the value of $(X_{eqL})_{pu}$, which is almost equal to $(Z_{eqL})_{pu}$, from the short-circuit test results because the applied voltage of 13.2 kV is able to circulate the rated currents in the windings.

$$(X_{eqL})_{pu} = (X_{eqH})_{pu} = (X_{eq})_{pu} = \frac{13.2\times10^3}{132\times10^3} = 0.1 .$$

b) Efficiency can be worked out either by using per-phase or 3-phase quantities. The percentage efficiency at the full load and unity power factor $(\cos\theta = 1)$ condition can be calculated by using Equation 1.68 as

$$\eta_{FL} = \frac{31.5\times10^6\times1}{31.5\times10^6\times1 + (21\times10^3 + 100\times10^3)}\times100 = 99.62\ \%$$

and at half the full load,

$$\eta_{0.5FL} = \frac{0.5\times31.5\times10^6\times1}{0.5\times31.5\times10^6\times1 + (21\times10^3 + (0.5)^2\times100\times10^3)}\times100 = 99.71\% .$$

The maximum efficiency occurs at a load of 45.8% ($=\sqrt{21/100}\times100$) as per Equation 1.72.

c) Regulation at the full load and 0.8 power factor lagging condition is calculated from Equation 1.63 as

$$\text{Regulation } = (\varepsilon_r \cos\theta_2 + \varepsilon_x \sin\theta_2) + \frac{1}{2}\left(\varepsilon_x \cos\theta_2 - \varepsilon_r \sin\theta_2\right)^2$$

$$= (0.0032\times 0.8 + 0.1\times 0.6) + \frac{1}{2}\left(0.1\times 0.8 - 0.0032\times 0.6\right)^2 = 0.066.$$

Example 1.3

A 500 kVA single-phase transformer is designed to have a resistance of 1% with its maximum efficiency occurring at 250 kVA load. Find the efficiency of the transformer when it is supplying a full load at 0.8 lagging power factor.

Solution:

The percentage resistance is given as

$$\%R = \frac{Load\ loss\ at\ full\ load}{Base\ VA}\times 100$$

$$\therefore \text{Load loss at full load} = \frac{1}{100}\left[500\times 10^3\right] = 5000 \text{ W.}$$

Now from Equation 1.72, for the same terminal voltage,

$$\frac{I_{\eta_{max}}}{I_{FL}} = \frac{250}{500} = \sqrt{\frac{P_c}{5000}}$$

$\therefore P_c = $ No-load loss= 1250 W.

Total loss at full load = 1250 + 5000 = 6250 W.

Efficiency at full load and 0.8 power factor =

$$\frac{output\ \ power}{output\ \ power + losses}\times 100 = \frac{500\times 0.8}{500\times 0.8 + 6.25}\times 100 = 98.5\%.$$

All-day efficiency: Distribution transformers supply loads that vary over a wide range. Their performance cannot be judged only by the efficiency value calculated as in the above example. For them, a parameter called *all-day efficiency* is more relevant, which is defined as

$$\eta_{all-day} = \frac{(output)_{\text{kWh}}}{(input)_{\text{kWh}}} = \frac{(output)_{\text{kWh}}}{(output)_{\text{kWh}} + (losses)_{\text{kWh}}}. \qquad (1.73)$$

The output and losses are computed for a period of 24 hours using the corresponding load cycle. The no-load loss is constant (i.e., independent of loading conditions); hence it is important to design the distribution transformers with a lower value of the no-load loss so that a higher value of the all-day energy-efficiency is achieved.

Why rating in volt-amperes? The rating of transformers is expressed in volt-amperes and not in watts because the rated output is limited by the losses, which depend on the voltage (no-load loss) and the current (load loss), and are almost unaffected by the load power factor. The amount of heat depends on the r.m.s. values of the current and the voltage and not on the power factor. Hence, the power delivered through a transformer may not be a unique value. The rating of a transformer is therefore not expressed in terms of the power rating (watts); it is defined in terms of the apparent power (volt-amperes) that it can deliver.

Let us now prove that the load power factor does not influence the losses. The phasor diagram for the equivalent circuit of Figure 1.7 (b), wherein the secondary quantities are referred to the primary side and the shunt branch is neglected, is shown in Figure 1.10. The apparent power across the series impedance in Figure 1.7 (b) is given by,

$$P + jQ = \left(\overline{V}_1 - \overline{V}_2'\right)\overline{I}_1^* = \left(V_1\angle\alpha - V_2'\angle 0\right)I_1\angle\theta = V_1 I_1\angle\left(\alpha+\theta\right) - V_2' I_1\angle\theta. \tag{1.74}$$

Writing the right hand side in the Cartesian system and rearranging the terms,

$$P + jQ = V_1 I_1\cos\left(\alpha+\theta\right) - V_2' I_1\cos\left(\theta\right) + j\left(V_1 I_1\sin\left(\alpha+\theta\right) - V_2' I_1\sin\left(\theta\right)\right). \tag{1.75}$$

Thus, the real part of the power is

$$P = V_1 I_1\cos\left(\alpha+\theta\right) - V_2' I_1\cos\left(\theta\right) = I_1\left(V_1\cos\left(\alpha+\theta\right) - V_2'\cos\left(\theta\right)\right). \tag{1.76}$$

The bracketed right hand side of Equation 1.76 is the difference between the projections of phasors V_1 and V_2' on I_1 phasor in Figure 1.10, which is nothing but the $I_1 R_{eq1}$ drop. Therefore, the real power *P* is

$$P = I_1\left(I_1 R_{eq1}\right) = I_1^2 R_{eq1}. \tag{1.77}$$

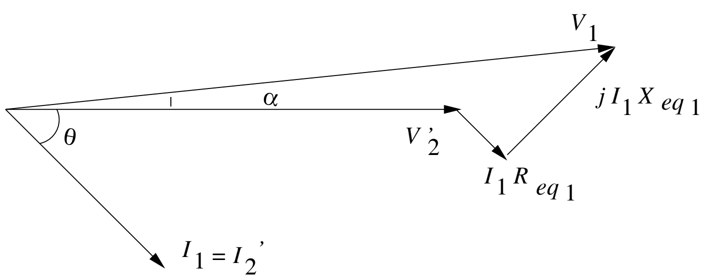

Figure 1.10 Vector diagram corresponding to the circuit in Figure 1.7 (b).

Thus, we obtained the expected expression for the load loss occurring in the transformer, which is independent of the load power factor (θ). Also, if the shunt parameters are made to correspond to the applied voltage as shown in Figure 1.7 (a), then the no-load loss is also independent of the load power factor for a given value of load VA. Hence, under the assumptions made the losses in the transformer do not change as the load power factor varies. Hence, the rating of transformers is expressed in volt-amperes and not watts. Contrary to this, the losses in motors vary with the power factor of the rotor circuit. For example, in induction motors, the loss is a function of the slip and hence the mechanical load on the shaft; the rotor side power factor changes with the slip. Hence, the rating of motors is expressed in watts.

For the transformer, if the shunt branch is connected after the primary series impedance as in Figure 1.5 (b), it can be proved that the load loss is a function of the load power factor (the dependence is usually neglected since the no-load current is a small fraction of the rated load current). Likewise, the voltage across the shunt parameters is a function of the load and its power factor, and hence the core loss depends on them. This is also explained by the fact that the loss in the core is actually decided by the vector sum of the mutual flux and the leakage flux; the latter's phase being governed by the load power factor. Thus, the core loss in actual operating conditions is a function of the load power factor (as discussed in Section 5.12); however, the effect may usually be small and neglected.

1.7 Parallel Operation of Transformers

For supplying a load in excess of the rating of an existing transformer, another transformer is usually connected in parallel with it since replacing it with a single larger unit is a costly alternative. The cost of a spare smaller rating transformer is also lower. Also, it is preferable to have a parallel transformer in case of emergencies; at least half the load can be supplied when one of the transformers is taken out of the service. For paralleling of transformers, their primary windings are connected to source bus-bars and secondary windings are connected to the load bus-bars. Various conditions that must be fulfilled for paralleling of transformers are given below.

1. The line voltage ratios of the transformers must be equal (*at each tap*): If the transformers connected in parallel have slightly different voltage ratios, then due to the inequality of the induced emfs in the secondary windings, a circulating current flows in the loop formed by the secondary windings under the no-load condition; the circulating current may be much higher than a normal no-load current. When the secondary windings are loaded, this circulating current will tend to produce unequal loadings on the two transformers, and it may not be possible to supply the full load (one of the transformers may get overloaded).

2. The transformers should have equal per-unit leakage impedances and the same ratio of the equivalent leakage reactance to the equivalent resistance (X/R): If the ratings of both transformers are the same, their per-unit leakage impedances should also be the same for equal loading. If the ratings are unequal, their per-unit leakage impedances based on their own ratings should be equal so that the currents carried by them will be proportional to their ratings. In other words, for unequal ratings, the numerical (ohmic) values of their impedances should be in inverse proportion to their ratings to have the currents in them in line with their ratings. A difference in the *X/R* ratio of the two components of their per-unit impedances results in different phase angles of the currents carried by them; one of the transformers works with a higher power factor and the other with a lower power factor than that of the combined output, and the real power will not be proportionally shared by them.

3. The transformers should have the same polarity: The transformers should be properly connected with regard to their polarity. If they are connected with incorrect polarities then the two emfs, induced in the secondary windings that are in parallel, will act together in the local secondary circuit and produce a short circuit.

The previous three conditions are applicable to both single-phase as well as three-phase transformers. In addition to these three conditions, two more conditions need to be fulfilled for the parallel operation of three-phase transformers:

4. The transformers should have the same phase sequence: The phase sequence of the line voltages of both the transformers must be identical. If the phase sequence is incorrect, pairs of phase windings will be short-circuited in every cycle.

5. The transformers should have the zero relative phase displacement between the secondary line voltages: Windings can be connected in a variety of ways that produce different phase displacements of the secondary voltages with respect to the primary voltages. The winding connections can be classified into distinct vector groups. Each vector group notation consists of an uppercase letter denoting the connection of the three phases of the HV winding, followed by a lowercase letter denoting the connection of the three phases of the LV winding, and lastly a *clock number* representing the displacement of the line-to-ground voltage phasor of any phase of the LV winding with respect to the corresponding HV winding phasor placed at 12 o'clock. Commonly used three-phase connections can be classified into four groups:

Group 1: Zero phase displacement (Yy0, Dd0, Dz0)
Group 2: 180° phase displacement (Yy6, Dd6, Dz6)
Group 3: –30° phase displacement (Yd1, Dy1, Yz1)
Group 4: +30° phase displacement (Yd11, Dy11, Yz11)

Letters y (or Y), d (or D), and z represent star, delta, and zigzag connections respectively. In order to have zero relative phase displacement of the secondary-side line voltages, the transformers belonging to the same group can be paralleled. For example, a Yd1-connected transformer can be connected in parallel with a Dy1-connected transformer. A transformer belonging to group 1 or group 2 can be paralleled only with its group-mate. On the other hand, a transformer from group 3 can be paralleled with a transformer from group 4 by reversing the phase sequence of one of them. For example, a Yd11-connected transformer (group 4) can be paralleled with a Dy1-connected transformer (group 3) by reversing the phase sequence of both primary and secondary terminals of the Dy1-connected transformer.

Many other vector groups are also used; these along with the above four groups are described through phasor diagrams in Appendix B.

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