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Evaluation of Highly Efficient Distribution Transformer Design and Energy Standards Based on Load

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EVALUATION OF HIGHLY EFFICIENT DISTRIBUTION TRANSFORMER DESIGN AND ENERGY STANDARDS BASED ON LOAD

by

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ABSTRACT

Evaluation of Highly Efficient Distribution Transformer Design and Energy Standards Based on Load

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Power distribution transformers have been prevalent in commercial building distribution systems since the inception of modern commercial electricity. Yet as more and more manufactures seek to improve transformer efficiencies by making changes to the design of the transformer itself, a fundamental concept may be overlooked – the impact transformer demand sizing has on power losses. When modern transformers are improperly sized for the application they will be installed for they are not being utilized at their optimum design loading range, which may impact operating efficiency.

This thesis will aim to test and evaluate modern day transformer design coupled with currently adopted energy efficiency standards and their effectiveness in conjunction with code required sizing restrictions. The evaluation will collect general transformer loading percentage data from commercial power, higher education campuses, as well as specific transformer operating characteristics from actual installed transformers. This information will be further investigated to determine how various load size and type alter the system efficiency and loaded power losses. The computer program Pspice will be used for modeling and simulated calculations while applicable energy and safety codes will be the references for transformer specifications and operating characteristics.

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CHAPTER 1

INTRODUCTION

1.1. Thesis Objective

In today's world, with rising energy costs, concerns about global warming and diminishing resources, there is a rapidly growing movement towards energy savings. Many of the new efforts seem to be trends surrounding burgeoning technologies such as renewable resource harvesting, *e.g.*, solar, wind and geothermal including associated components. Other advances are being made with respect to one of the largest potential electrical utility savings areas – building lighting – through further development of light emitting diode (LED) and lighting controls technologies. With so much focus on these more "new" technologies, sometimes it is easy to overlook savings potential in other areas that have been on the market for much longer.

Is there potential for energy savings in building power distribution transformer sizing? Although power distribution transformers have been and are continuously being researched for possible design alterations to increase efficiencies, these typically tend to be physical and/or material changes. Manufacturers look at different improvements. These improvements include considerations such as type of materials being used, construction techniques and component sizes and configurations. However, due to the nature of transformer operation, manufacturers are somewhat limited in the impact they can make on minimizing losses when a transformer is loaded under non-specified conditions.

Power distribution transformers have efficiencies relative to their loading. Depending on the percentage of the rated maximum load the efficiency and power losses of a transformer vary. Although manufacturers look for ways to advance the transformers themselves, it is only until recently that legislation has been passed in the form of National Electric Manufacturers Association (NEMA) and US Department of Energy (DOE) design standards, in order to reduce transformer losses and standardize the most optimal loading percentage point. Yet, establishing a new "maximum efficiency" point is only effective if the load is operating at this point. If the connected load is below or above this point for the majority of the operating time, the efficiencies are often not realized. Although this may have minimal impact for small differentials, the same cannot be said for larger ones. Even though a transformer may be sized properly per code requirements it is often not loaded optimally when actually installed. Are energy standards still effective if the loading percentage is significantly lower than the maximum efficiency point?

The issue at hand is that physical/material transformer improvements in addition to new efficiency standards and guidelines are only addressing one thing – the operating characteristics of the transformer itself. However, the *installed* transformer is part of an entire *system*. The rest of that system, consisting of the downstream conductors and connected equipments, translates to a load. How that load interacts with the transformer greatly impacts the power losses of a given transformer. So determining the proper size of the load and properly matching it to the correct transformer is crucial for maximum system efficiency. The building design engineer, unfortunately, is limited by the constraints of NFPA 90, also known as the National Electrical Code (NEC). How demands are calculated and transformers are sized is dependant upon the conditions and constraints outlined in the NEC. Therefore, in order to truly optimize efficiency in building transformers it may be necessary to change more than just transformer manufacturing standards, by also reviewing and considering updates to governing codes to sync better with the energy codes that are establishing how the equipment operates.

Furthermore, specifying larger transformers when a smaller unit would sufficiently – and efficiently – supply the same load presents other issues that could lead to higher upfront costs. These costs include meeting design requirements by installing larger conduit, conductors, over-current protective devices, equipment that is capable of withstanding higher available fault current and the higher cost associated with the larger transformer unit itself. Aside from costs are the added footprints the equipment must occupy in electrical rooms where square footage is already limited in general. Safety concerns may also be elevated, due to the increased current available.

The objective of this thesis is to investigate transformer power losses based upon loading percentage of rated maximum loading for transformers meeting industry standards for higher efficiencies. Actual loading data will be collected and compiled by current transformer type metering devices from higher education building transformers, and analyzed using a Pspice modeled computer simulation. A general circuit will be created to simulate existing conditions. Load characteristics, such as balanced versus unbalanced loading and linear to non-linear loads will be considered. This circuit will then be altered to examine the effects of various loading points on the transformers' losses. Energy consumption values of the differing scenarios could later be converted to dollar amounts and ultimately estimated energy costs and potential savings could be predicted.

1.2. Thesis Organization

This thesis is organized into five chapters. Chapter 2 will cover the background of the information being presented in the thesis. It will consist of a study of related literature about power distribution transformers, including history, modern design criteria, applicable codes and energy standards, installed performance (including losses, operating efficiencies and variations based on loading) and additional issues that result from transformer sizing. This chapter will establish the premise for the undertaking of data collection and analysis for the thesis.

Chapter 3 will cover power distribution system theory. It will consist of an explanation of the methodology behind the thesis, including transformer operational theory and equations, loss calculations, how power distribution systems can be equivalently expressed as circuits and how these circuits can be modeled in Pspice computer software. This chapter will provide the information necessary to properly collect real-world data as well as simulate actual transformers and commercial distribution systems in software, implement changes, and examine the effects.

Chapter 4 will cover real-world data collection and simulations. It will include collected loading data, power usage, and impedances from real-world transformers. The simulations will aim to recreate the originally collected data as well as demonstrate theoretical scenarios that could be carried out. It will show the findings of the study, by the study, by looking at simulations of current existing conditions, how these results can be altered by varying the loading levels, and the impact of new or different transformer designs replacing the currently installed transformers. This chapter will allow for a complete understanding of how the power distribution system currently operates and furthermore how the system can be improved by utilizing the correct transformer size and/or design type.

Chapter 5 will cover conclusions that can be drawn from the simulations as well as recommendations based on the findings of the study. It will include a summary of the current conditions versus the optimal conditions, while providing explanation and recommendations on how these improvements can be achieved. These conclusions will explore possible code and standard changes that can be made to achieve desirable results as well.

CHAPTER 2

BACKGROUND REVIEW

2.1. Brief History of Transformers

Modern day transformers have not evolved significantly from their early counterparts. The invention of the transformer began in the 19^{th} century. English chemist and physicist, Michael Faraday, began experimentation with electromagnetic circuits in 1821, after the discovery of electromagnetism [1]. In August 1831, Faraday conducted an experiment that would give him more insight into the relationship between electricity and magnetism. In his experiment, he wrapped two insulated wires around an iron ring, connecting one of the wires to a battery and the other wire to a galvanometer [2],[3]. What he observed was that the presence of current in one wire created another current in the other wire, through magnetism. This observable incident is called “mutual inductance” which is the property that allows transformers to perform their intended function of changing voltage to different levels. Faraday’s induction ring was in actuality the first basic transformer [2].

Figure 2.1 Faraday’s induction ring, circa 1831 [2]

Further research by Irish scientist, Nicolas Callen, led to the creation of the induction coil in 1836. Callen wanted to generate a higher voltage than he had available.

Using a bar, approximately 2 feet long, made of soft iron as the "core," he wrapped two individual copper wires, each about 200 feet long, as the "coils." After connecting the first coil to a battery, he noticed that upon disconnection of the battery, a shock could be felt at the second terminal of the second coil [4]. Moving forward with these discoveries, Callen decided to increase the size of the secondary coil. Upon connection of the low voltage battery, Callen witnessed an induced higher voltage in the secondary wire [5]. This observation, that there was a relationship between the size difference in the primary and secondary coils and the effect it had in changing the induced voltage, would be one of the guiding principles for future transformer design and operational theory.

With such new discoveries being made by scientists like Faraday and Callen in the field of electromagnetism, specifically with respect to the magnetic flux and current flow relationship, it was inevitable that researchers would begin to seek more advancement in the area. Although many experiments were likely carried out after Callen's induction principle discovery in the 1830's, the next notable advancement in transformer history would not be until 1876, by the Russian engineer, Pavel Yablochkov. Yablochkov developed a system that would demonstrate the capabilities of induction coils to not only vary the voltage but also to drive a secondary connected load. His system was comprised of an alternating current (AC) power source connected to the primary of a pair of coils. On the secondary side of the coil, he had connected electric candles. The AC source was capable of successfully driving the load, functioning similarly to a modern-day transformer [6]. This primitive transformer design would eventually be surpassed in the 1880's by various transformer inventors, including the

Ganz Company in Budapest, Hungary, Sebastian Ziani de Ferranti of England, and Lucian Gaulard and John Gibbs also of England.

Gaulard and Gibbs transformer design was completed in 1882, which operated as a step-down transformer with an open iron core. The transformer, which they called a "secondary generator" was of linear design, and inefficient to manufactur [7]. The operating efficiency was also quite low. They would eventually demonstrate the use of the transformer publically in 1884 in Turin, Italy, by connecting the transformers in series to power a railway as well as to drive incandescent and arc lighting. Gaulard's and Gibbs' design patent was purchased by American business owner, George Westinghouse, but would still need further research to become economically feasible to produce and distribute for widespread use. Eventually, Gaulard and Gibbs would lose the patent rights to de Ferranti in court [7], however it was their demonstration in Italy that would enable the design to become globally known and further improvements to be made.

Shortly after the public viewing in Italy in 1884, three researchers from the Hungarian company, known as the Ganz Company, began seeking improvements upon the Gaulard and Gibbs transformer. The engineers, Otto Blathy, Karoly Zipernowsky, and Miksa Deri, recommended that instead of using an open iron core, a more efficient closed core type unit be constructed. The Ganz Company design was a toroidal shape known as the "Z.B.D." transformer and it was the world's first high efficiency transformer, having an operating efficiency of approximately 98 percent [8]. Besides utilizing the closed core design, the engineers made improvements in how the transformers were installed in the distribution system. Acknowledging the issue that occurred with series connected transformers, in which turning off one load would affect the voltage to the other connected loads, it was suggested instead that the transformers be connected to the distribution system in parallel [7]. The ideas developed and proposed by the three Ganz Company engineers laid the foundation for commercial transformer manufacturing and public installation.

After Westinghouse purchased the Gaulard's and Gibbs' transformer design, he tasked one of his employees, William Stanley, with conducting further research into how the design could be improved upon and manufactured effectively for sale. Stanley began his research in 1885 and completed his first prototype transformer in March 1886 [6]. Similar to the Z.B.D. transformers, Stanley's transformer utilized a closed iron core, but had an adjustable gap that would allow for variation of the electro motive force. This gap distance could be changed by means of a screw made of non-magnetic material [9]. Stanley demonstrated the transformer publicly to power various businesses on Main Street in Great Barrington, Massachusetts. Using a Siemens AC generator as a source, he then stepped-up the voltage with one of his transformers and then transmitted power through wires at the higher voltage to multiple buildings. At the basement of each building was another transformer, connected to the system in parallel, which stepped the voltage back down to a usable level for the lights [6]. This basic power transmission system had the same basic principles as the ones in use by utility companies today.

Figure 2.2 William Stanley's Original Transformer, circa 1885 [7]

In December 1886, following Stanley's demonstration in Great Barringon, Westinghouse applied for a patent for a commercially producible design based on Stanley's work. This design would allow for fast production in the factory and a feasible cost to distribute. Westinghouse's new transformer was made of stacked, thin iron plates, which were separated by an insulating material. Copper coils that were wound ahead of time could then be fitted over the core material [10]. The transformer had a square shape, similar to the transformers of today, as opposed to the toroidal shaped transformer crafted by the Ganz Company engineers. A few years later, in 1889 the first three-phase transformer was developed in Germany [7].

With the invention of the transformer came the ability for AC power to be generated remotely, stepped up to a higher voltage for transmission, transmitted, stepped down to the equipment and lighting operating voltage near the connected load, and finally utilized by the load. All of this could now be done in a much more economical and convenient manner than historical Direct Current (DC) systems. Although the majority of electrical loads in the late nineteenth century consisted of nighttime lighting, as electric motors were brought into the industry for transportation and industrial uses, the demand for power became a 24 hour per day requirement [11]. A nation-wide disagreement in the United States about whether AC or DC should be used to power homes and businesses, known as the "War of Currents," concluded in 1896, after the Westinghouse Electric Corporation successful utilized hydroelectric generators located at Niagara Falls to transmit AC power to Buffalo. The general consensus shifted to the use of AC for public utilities and has become the standard since. With the widespread use of AC systems, transformers had become a necessity, leading to further research in their designs and operating capabilities as well as improvements in these areas, from the early twentieth century continuing on until today.

2.2. Modern Structural Design Considerations

The most basic design of a transformer has not evolved too greatly from the original Faraday Ring: two windings insulated from one another, wound on a common core made of an appropriately magnetic core material. The primary winding is energized by an AC source. Due to the properties of the core material, usually consisting of steel or iron, magnetic flux can easily be transmitted through it. As a result of mutual inductance, the energy is transferred to the secondary winding where it is then delivered to the load. Although the final outcome for a basic design like Faraday's can be achieved through a variety of ways, the most desirable design will provide for a unit that not only has the necessary operating conditions, but is also easy to produce. There are various purposes and designs for modern day transformers, from small electronics to large utility power plants. Of particular interest for this thesis, will be the commercial three-phase, dry-type power distribution transformer found in higher education buildings, typically supplied on the primary side at 480 V, 4.16 kV or in some cases 12.47 kV. The major components for dry-type transformers are:

- *Core* – allows path for magnetic flux, discussed further below
- *Coils (or windings)* – allows flow of current, discussed further below
- *Insulation medium* – dissipates heat, usually consists of air and/or types of paper

- *Terminals* – termination points for incoming and outgoing power conductors

- *Tank/Enclosure* – Structure that houses all components

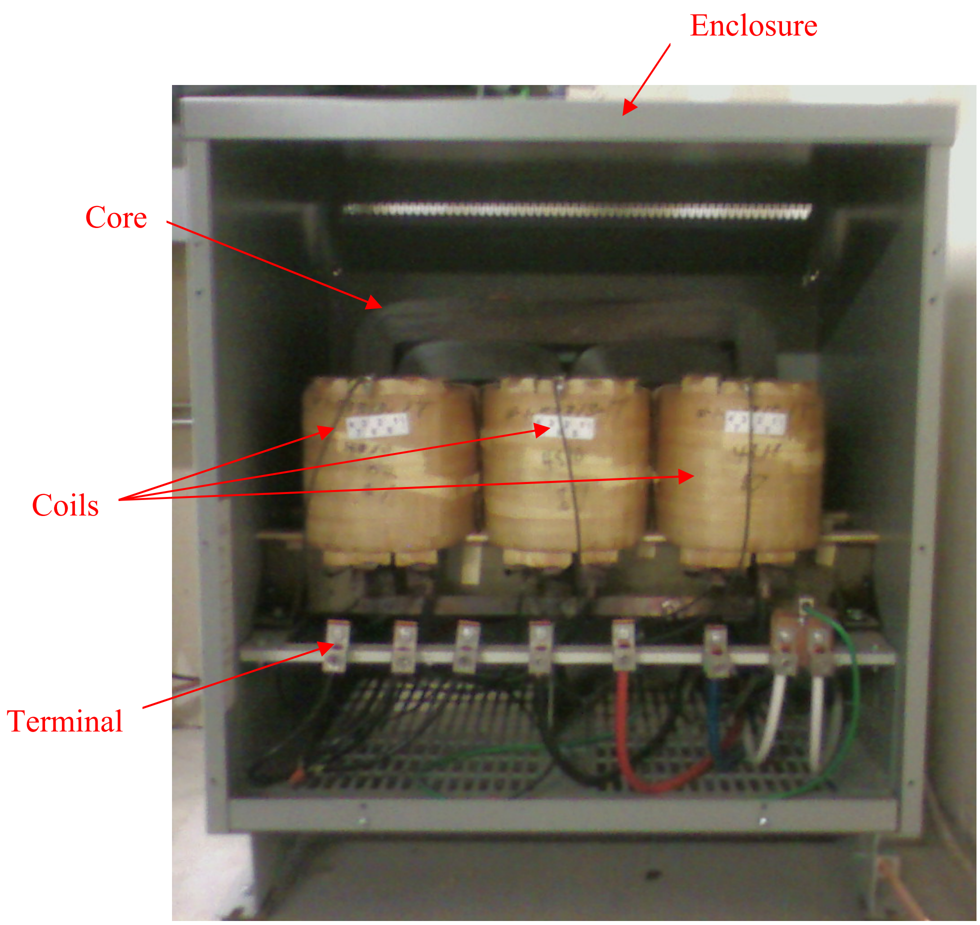


Figure 2.3 Three-phase dry-type transformer components

The purpose of the core of a transformer is to provide for a continuous path for magnetic flux [12], [13]. Ideally, the core will be as small as possible, while still maintaining the proper path, to allow for minimal material and losses. Additionally, due to the reversing polarity nature of AC, the core material will need to have molecules that can easily reverse their positions [13]. As the molecules reverse direction, friction is created which dissipates energy as heat. This phenomenon is known as "hysteresis" and contributes to a transformer's overall losses. Also, due to the magnetic flux passing through the core, stray currents are generated, known as "eddy currents." Eddy currents are dissipated as heat and contribute to a transformer's overall losses [15]. Both hysteresis and eddy current losses are not dependent upon the load but are inherent to the core itself, ensuing as a result of merely energizing the transformer.

Core material can be different, depending on transformer application. Some examples are soft metal, silicone steel, carbonyl steel, ferrite ceramic, and vitreous metal. Typically, cores are made of steel containing high silicone content, specifically of the grain oriented type, due to its ability to minimize hysteresis losses [13],[14]. Generally the material is assembled in the form of stacked, thin sheets of metal which are known as "laminations." By stacking the metal laminations, the core is equivalent to multiple individual circuits as opposed to one large magnetic circuit. Each sheet has only a percentage of the total magnetic flux and since eddy currents flow around those lines of flux, this arrangement greatly prevents eddy currents from flowing [15]. In between the laminations is insulating varnish, which also seek to diminish eddy currents even further by providing a high resistance path [16]. The inclusion of laminations and varnish in the design can reduce the contribution of total losses due to eddy currents. Ideally, these lamination patterns will be easy to cut and stack to ensure efficiency in the manufacturing process [12].

The purpose of the coils, also known as windings, of a transformer, is to utilize mutual inductance in order to convert a supplied voltage of one level to a voltage of a different level for use. The windings are located on the same plane, so that the magnetic field from the primary coil travels through the secondary coil. The amount that the level of voltage is either raised or lowered is determined by the number of windings in the coils. The relationship between the coils is known as the "turns ratio" which is the ratio of the number of turns in the secondary coils to the number of turns in the primary coils [17].

Coil material generally consists of a highly conductive material, usually copper or aluminum in the U.S. industry. Designers seek to achieve the required number of turns, while minimizing material and space used [18]. Although aluminum tends to be less expensive than copper, copper is more conductive. That equates to a need for using larger aluminum windings than a similarly performing copper coil transformer, which means that aluminum transformers tend to have a larger physical footprints [19]. In addition to the windings themselves, transformers must have appropriate space for insulation materials as well as heat dissipation. Common winding insulation materials include paper, shellac, varnish, enamel, glass, plastic, oil impregnated paper or a combination of these materials. Transformer coils are usually either round, square, or rectangular in shape, depending on the size of the unit [18].

Aside from cost and size restrictions, designers must also be cognizant of efficiency impacts from windings. Just as transformer cores have losses, the windings have losses as well. Two types of losses are seen, which unlike the core losses, are dependent upon the load and the amount of current being drawn. The first type of loss in the coil is known as "I^2R" losses. This occurs as a result of the actual resistance of the coil material and takes place in both the primary and secondary windings [20]. Since the current value is dependent on the load, it cannot be changed and therefore the only way to improve I^2R losses is to reduce the amount of resistance in the transformer design. The second type of coil loss is, similar to the core, eddy current loss which occurs as a result of flowing magnetic fields causing stray eddy currents to flow in the windings [20]. Both the I^2R and eddy current losses contribute to a transformer's overall losses.

A summary of the materials utilized in different types of transformers, their applications, as well as the adopted governing standards is shown in the following table:

Table 2.1 Materials Used in Transformers [24]

Material	*Applicable Standards and Grade*	*Application*
A. Insulating Materials		
1. Transformer Oil	IS 335, BS 148, IEC296	Liquid dielectric and coolant
2. Electrical Grade Paper		
i. Kraft insulating paper of medium air permeability	IEC 60554-3-1	Layer winding insulation, condenser core of oil impregnated bushing
ii. Kraft insulating paper of high air permeability	IEC 60554-3-1	Covering over rectangular copper conductor. Covering over stranded copper cable
iii. Crepe kraft paper	BS 5626-3-3, IEC 60554-3-1	Covering over flexible copper cable. Insulation of winding lead. Insulation over shield
iv. Press paper	IS 8570, BS 3255	Backing paper for axial cooling duct
v. Kraft paper with aluminum bands	IEC 60544-3-1	Line and common shield in winding
vi. Crepe kraft paper with aluminum foil	IEC 60544-3-1	Metallization of high-voltage lead and shield
3. Pressboard		
i. Pressboard moulding from wet sheet or wet wood pulp	IEC 60641-3-1	Angle ring, cap, sector, snout, square tube, lead out and moulded piece of intricate profile for insulation ends of windings, insulation between numerous other winding applications
ii. Soft calendered pressboard – solid	Type C of IS:1576, IEC 60641-3-1	Cylinder, barrier, wrap, spacer, angle washer, crimped washer and yoke insulation, etc.
iii. Soft pressboard – laminated	BS EN 60761-1.2	Block, block washer, terminal-gear cleat and support, spacer, etc.
iv. Precompressed pressboard – solid	IEC 60641-3.2	Dovetail block and strip, clack-band, cylinder, warp, barrier, spacer, block, block washer, corrugated sheet, yoke bolt, washer, etc.
v. Precompressed pressboard – laminated	IEC 60763-3.1	Top and bottom coil clamping ring, block, block washer, dovetail strip, spacer, etc.
4. Wood and laminated wood		

i. Unimpregnated densified laminated wood – low density	IEC 61061	Cleat and support, core/yoke clamp, wedge block, winding support block, sector, core-to-coil packing, etc.
ii. Unimpregnated densified laminated wood – high density	IEC 61061	Coil clamping ring, block, cleat support, etc.
5. Insulated copper conductor and cable		
i. Paper covered rectangular copper conductor	IEC 60317, IS 13730	For making windings
ii. Paper covered continuously transposed copper conductor	IEC 60317	For making windings
iii. Paper covered stranded copper cable	IS 8572 conductor to IS 8130, IEC 60228	For making lead and terminal
iv. Crepe paper covered flexible copper cable	Conductor to IS 8130, IEC 60228	For making lead and terminal required to be bent to a small radius
v. PVC insulated copper cable – single and mulicore	IS 1554, BS 6346, IEC 60502	Control wiring in marshalling box, nitrogen sealing system
6. Insulating Tape		
i. Cotton tape	IS 1923	For various taping purposes
ii. Cotton newar tape	–	For taping and banding
iii. Glass woven tape	IS 5353, IEC 61067-1	Used in core bolt insulation
iv. Woven terylene tape	IS 5351, IEC 61068-1	For taping purposes at places requiring higher strength
v. Polyester resin impregnated weftless glass tape	–	Banding of transformer cores
7. Phenolic laminated paper base sheet	IS 2036, BS 2572	Terminal-gear support and cleat, gap filler in reactor, tap changer
8. Phenolic laminated cotton fabric sheet	IS 2036, BS 2572	Terminal board, for making core duct, support and cleat
B. Sealing Materials		
9. Synthetic rubber bonded cork	IS 4253 (Part II)	As gasket to prevent oil leakage from joints viz. tank rim, turret opening, inspection cover and with mounting flange of various fittings, etc.
10. Nitrile rubber sheet and moulding	BS 2751	As gasket to prevent oil leakage from joints, 'O' ring in bushings, moulded component in fittings
C. Ferrous Materials		
11. Cold rolled grain oriented silicon Steel (CRGO)	BS 6404, ASTM A876M, DIN 46400	For making transformer core
12. Cold rolled carbon steel sheet	IS 513, ASTM A620M, BS 1449-1.1	For making radiator
13. High tensile strength structural steel plate	IS 8500	Core clamp plate, anchoring and clamping core to bottom tank
14. 1.5% Nickel-chromium-Molybdenum steel bar and sections hardened and tempered	IS 5517	Lifting pin, roller shaft
15. Austenitic chromium nickel steel titanium stabilized plate (stainless steel)	IS 6911, BS 1449	Turret opening, non-magnetic insert, etc. to neutralize the effect of eddy currents
16. Stainless steel sections (austenitic)	IS 6603, BS 970	Non-magnetic bar for high current applications
17. Structural steel – standard quality	IS 2062	Tank, end frame, clamp plate, 'A'

(plate, section, flat, bar, channel, angle, etc.) 18. Bright steel bar and sections – cold drawn	 IS 7270	frame for radiator, conservator, turret, cable box and for structural purposes Threaded and machined components
D. Non-Ferrous Materials		
19. High conductivity copper		For various current-carrying applications, e.g., bushing and conductor, terminal lead, divertor and selector contacts of on-load tap changers, winding shield, cable box components, off-circuit switch items, etc.
i. Sheet, strip, foil – hard and soft	IS 1897	
ii. Rod	IS 613	
iii. Tube	BS 1977	
iv. Casting and forging	BS EN 1982	
v. Tinned foil	IS 3331	
vi. Flexible cable	IS 8130,IEC 60228	
vii. Flat flexible Braid	–	
20. Copper alloys		
i. Free machining brass rod, square and hexagon	IS 319	Tie rod and for making different components
ii. Phosphor bronze rod	IS 7811	Tap-changer components
iii. Nickel silver strip	IS 2283	For making winding shield
21. Aluminum		
i. Aluminum alloy plate	Alloy 54300M (NP 8-M) of IS 736	Flange in bushing, cable box, and non-magnetic applications
ii. Aluminum plate (99 percent)	Alloy PIC of IS 736	Shielding of reactor tank
iii. Aluminum foil	–	Condenser layer in bushings

Although the core and coils are separate components with different functions, the two must work together as a complete system to achieve the proper effects. The configuration that the core and windings are arranged in can vary in modern transformers, but typically there are two major configurations in use. The principle transformer construction types are *core-type* and *shell type* [12], [16]. Core type transformers consist of a single ring of the steel core that is surrounded and encircled by the winding material. Usually the secondary voltage coils are located right next to the core, with the primary voltage coils surrounding them concentrically, having a thin layer of insulation between the two [18]. The primary voltage coils will therefore be the ones viewed externally. However, larger capacity transformers, in the MVA range, tend to frequently have alternating or interleaving primary and secondary coils [12]. They are characterized by having a smaller area of core material. Although core type construction can be used for all sizes of power transformers, it is more often selected for use in smaller, distribution transformers.

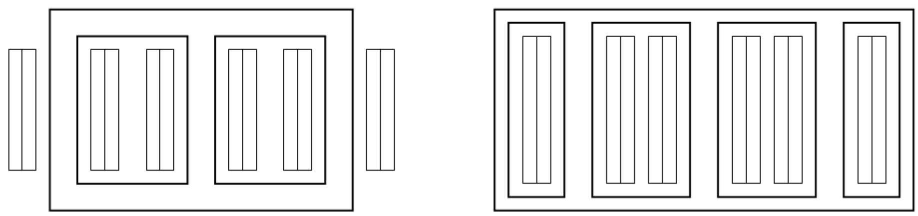


Figure 2.4 Three-phase core type transformer construction [23]

Shell type transformers consist of a single ring of primary and secondary windings that are surrounded and encased by the core material. The primary and secondary coils are constructed in the form of “pancakes” where the different voltage level coils are alternately stacked, usually with a layer of insulation and gaps for heat dissipation separating them [18]. The most common configuration is the primary-secondary-primary coil grouping, as seen in Figure 2.5 for a three-phase shell type transformer [12]. They are characterized by having a higher ratio of steel to copper weight. Since shell type constructed transformers tend to have less reactance between coils and operate more efficiently under large current conditions, they are more often used for larger station or power plant applications.

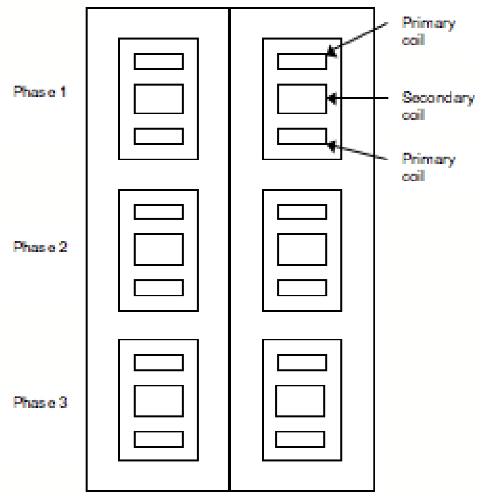


Figure 2.5 Three-phase shell type transformer construction [23]

2.3. Modern Design Process

Although transformers can be designed in either the core or shell type configurations, with the exception of extreme current ratings, there is no major operating advantage of one over the other [12]. Construction type is left to the discretion of the manufacturer, unless the customer specifically requests a preference. Typically the decision will be based on economic factors for material and labor. Total manufacturing costs for each type ultimately determine the core and coil relationship. The more important requirements for design are the customer specifications regarding the electrical characteristics. Important transformer characteristics include:

- *Voltage* – the desired primary side and secondary side voltages
- *Turns ratio* – the ratio of the number of turns in the secondary winding to the number of turns in the primary winding
- *Power rating (capacity)* – the maximum power rating that the unit is capable of operating at, which is limited by the allowed temperature rise. This rating is only for an in-phase current

- *Impedance* – the opposition of the flow of current in the transformer winding, consisting of resistance (R) and inductive reactance (X). Resistance is a structural property that contributes to load losses while inductive reactance causes the current to lag the voltage and does not contribute to losses [22]

- *Efficiency* – the ratio of transformer output power to input power

- *K-factor* – a constant developed to classify and rank the transformer's ability to operate effectively in the presence of distribution system harmonics. Transformers with a *K*-factor rating are designed for use with nonlinear current loads assumed to have a similar calculated *K*-factor [41]

These characteristics will be discussed further throughout the thesis. However, it is important to have a brief understanding of the characteristics, as they are the basic parameters that influence how transformer designers have traditionally made their design decisions. Once design engineers have the correct specifications, they can begin the design process. This process begins with a conceptually establishing predetermined winding arrangement as well as the dimensions for the components [23]. The electrical characteristics of the initial "foundation" design will then be calculated and compared to the sought after characteristics. Some examples of these characteristics include number of turns, leakage flux density, reactance, resistance and eddy current losses [23]. Based on the results of the comparison, the initial dimensions will be adjusted to bring the design closer to specifications. The calculations and comparison, generally carried out by computer software, will be repeated to ensure maximum effort in arriving at the desired design characteristics. Designers must also take into consideration the physical properties, including the dielectric properties of the insulation material and the magnetic properties of the core, as well as how the actual and design properties compare and consider the impact of manufacturing procedures [23]. The final calculated values are also compared to test data from similar transformers to ensure accuracy of the design.

Although these procedures will produce a sufficiently operating transformer, an important characteristic that can not be overlooked in the design process is transformer efficiency, which is determined by transformer losses. By definition transformer efficiency is:

$$\% \quad Efficiency = \frac{Output}{Input} \times 100 \tag{2.3.1}$$

$$\% \quad Efficiency = \frac{Input - Total\ Losses}{Input} \times 100 \tag{2.3.2}$$

$$\% \quad Efficiency = \left(1 - \frac{Total\ Losses}{Input}\right) \times 100 \tag{2.3.3}$$

From this equation set, it is easy to see that as the total transformer losses increase, the overall efficiency of the transformer decreases. Thus, a highly efficient transformer will have a minimum of losses. Transformer loss and efficiency equations will be explained in greater detail in Chapter 3.

Losses are generally broken down into two categories: the *no-load* losses, which are present when the transformer is merely energized even if the secondary is open-circuited and change negligibly as the load varies; and the *load* losses, which occur whenever the transformer is placed under load and change as the size of that load varies. The sum of the no-load and load losses produces the *total* losses. No-load losses consist of the following components:

- Iron losses (sum of below components)

    - Hysteresis losses in the core laminations
    - Eddy current losses in the core laminations
- I^2R or copper losses due to no-load current in the primary winding
- Stray eddy current losses in core clamps, bolts and other core components
- Dielectric losses

Since the majority of the no-load losses – typically more than 99 percent – are a result of the iron losses, the remaining losses are often considered negligible when calculating overall efficiency [25]. Iron losses depend upon grade of steel, flux density, type and weight of the core and manufacturing techniques. The direction of flux travel also impacts the amount of losses. Flux traveling parallel to the grain orientation is most efficient, so cores are designed to maximize this type of flux travel. Perpendicular grain orientation flux travel, which occurs at joints, increases losses and is designed to be minimized [26]. Both types of flux travel are used to calculate no-load losses and optimize transformer designs. Load losses consist of the following components:

- I^2R or copper losses due to the current in the both the primary and secondary windings
- Eddy current losses in the windings

Loaded losses are more difficult to calculate as they are based on the transformer loading. Accurate determination often requires transformer loading data over time. Also, the load losses are dependant on temperature and are generally assumed at a reference of 75^{o}C [26]. Finding improvements in load loss minimization is limited, as aside from utilizing a less resistive material for winding construction, the only ways to reduce the copper losses is by increasing the cross-sectional area of the conductor or by reducing the length of mean turn of the conductor [25].

Other factors to consider in transformer design are temperature rise and temperature rating. Temperature rise is the amount of heat that the coil will produce and thus rise in temperature under operating conditions. This takes into consideration the insulation life as affected by operating temperature and the ambient temperature assumed to exist throughout the life of the transformer [44]. Standard transformer temperature rise is 150^{o}C [29]. Manufacturers also produce transformers that run cooler than standard temperature rise models, with common examples having temperature rises of 80^{o}C and 115^{o}C. These transformers are designed to have larger core and coil sets which raise the no-load losses and lower the loaded loses. The end result is a transformer that operates more efficiently overall at higher loads than a 150^{o}C temperature rise unit.

Temperature rating is the maximum internal amount of heat that the transformer insulation system can withstand under operating conditions before it begins to deteriorate and ultimately fail [30]. The temperature rating is the sum of the winding temperature rise, maximum ambient temperature, and the hot spot allowance inside the windings. Winding temperature rise can vary (commonly 80, 115, or 150^{o}C), while maximum ambient temperature is usually calculated at 40^{o}C and hot spot allowance at 30^{o}C, for a maximum total of 220^{o}C. Most modern transforms are incorporated with a Class 220^{o}C insulation system temperature rating, even if the winding temperature rise is lower than 150^{o}C [30].

Also considered in the design process, specifically for end-users whose systems have large amounts of non-linear (or non-sinusoidal) current present is transformer *K*-

factor rating. Harmonics, which are frequencies of varying multiple orders of the fundamental frequency, can cause excess heat build up in a transformer, leading to decreased performance, lowered efficiency and shortened lifespan. This will be discussed in greater detail in Chapter 3. *K*-factor ranks the ability of a transformer to cope with harmonics, reduce skin-effect losses and reduce the possibility of core saturation [41]. *K*-factor is calculated by estimating the expected harmonic content and determining the load current *K*-factor based on that load. Expected harmonic content can either be measured or estimated from predetermined waveforms based on load type, *e.g.* variable frequency drives, switched-mode power supplies, and fluorescent lighting ballasts. Load *K*-factor is determined by equation 2.3.4 as follows:

$$K = \frac{\sum (I_h h)^2}{\sum h^2} \tag{2.3.4}$$

where, I_h = per unit load current (of h harmonic order)
h = harmonic order (1, 2, 3, etc.)

Once the calculation of the load *K*-factor is completed, a transformer with a *K*-factor rating that is greater than or equal to the load *K*-factor should be specified. Transformers are not constructed for every possible *K*-factor, but typical available dry-type ratings are 4, 7, and 13. Design modifications are implemented to achieve these *K*-factor ratings a number of ways including:

- Individually insulated conductors to reduce skin effect
- Larger secondary neutral conductor
- Individually insulated core laminations to reduce eddy currents in the core
- Electrostatic shield between primary and secondary windings

- Larger core with special steel to reduce hysteresis losses
- Cooling ducts
- Larger components/more material

Although a harmonic study might indicate the presence of a load *K*-factor the customer may not desire a *K*-factor rated transformer. In such cases it is still a recommended practice to derate standard transformers. This is accomplished by determining the eddy current loss factor and calculating the overall transformer derating percentage. Eddy current loss factor, a measure of the transformer's eddy current losses is generally acquired from transformer manufacturer testing or assumed based on transformer type and size [41]. Once obtained, overall derating can be calculated as follows:

$$I_{\max} = \sqrt{\frac{1+P_{EC-R}}{1+K\times P_{EC-R}}} \tag{2.3.5}$$

where, P_{EC-R} = eddy current loss factor under rated conditions for winding

The calculated value of I_{max} will be the percentage by which the transformer should be derated to account for the effects of the harmonic content.

Due to the limitations imposed by the operating natures of the core and coils and the materials they are made from, transformer structural design has seen little variation over recent years. Although optimization of the materials in use and design procedures does continue, manufacturers also consider efficiency based on transformer loading level. Loading level impacts losses and efficiency and does so differently for standard, low temperature-rise, and energy efficient transformer models.

2.4. Impact of Transformer Loading on Efficiency

Transformer no-load losses are not dependent on the size of the connected load and therefore are always present. The loaded losses on the other hand depend almost entirely on the amount of current being drawn and have a direct relationship with transformer loading amount. As loading increases, loaded losses also increase due to increased current flow and temperature rise. The increase is parabolic, since the losses are a function of the square of the current. However, this does not necessarily mean that the most efficient operating point is at the low end of the loading spectrum. A general rule of thumb is that the point of maximum efficiency for a transformer is when the no-load loss equals the loaded loss and the primary load losses equal the secondary load loss [27],[28]. The calculation for the load on the transformer (in kVA or amps) that corresponds to the maximum efficiency point for a standard temperature rise transformer is:

$$Load = \sqrt{\frac{No\,load\,loss}{Full\,load\,loaded\,loss}} \times Full\,load \qquad (2.4.1)$$

where, *Full load loaded loss* = the total loaded losses of the transformer at full load

It can thus be inferred that under-loading or overloading a transformer beyond the maximum efficiency point will result in more inefficient operation. An overview of transformer efficiency as well as the various types of transformer losses relative to transformer loading can be seen in Figure 2.6. Based on the values in the figure and using the above equation, it can be calculated that the maximum efficiency point would occur at a load of approximately 11 kVA or about 44.7 percent of the full load rating, which corresponds to the highest point on the efficiency curve.

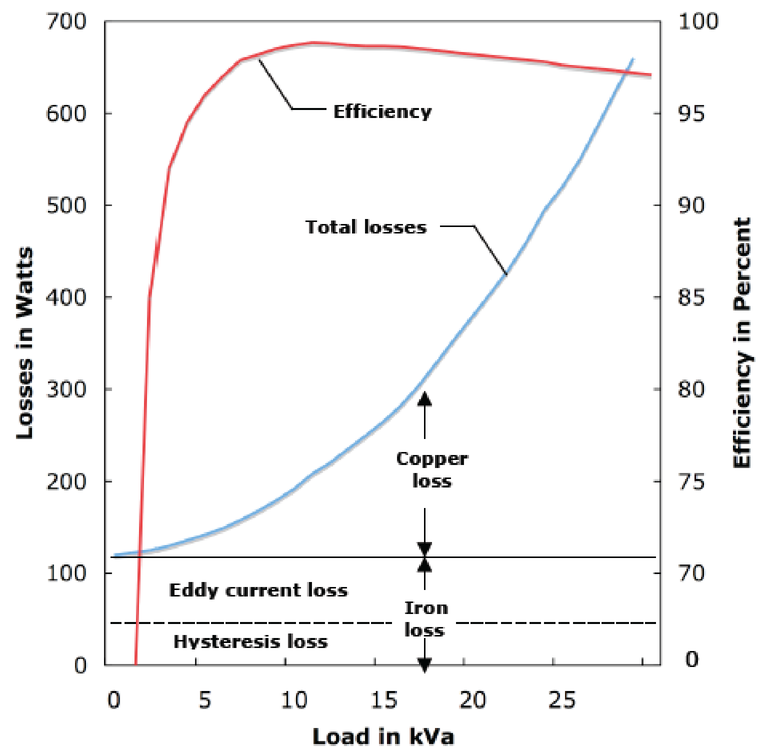


Figure 2.6 Losses versus load [27]

It is important to point out, that at about 3 kVA or 12 percent loading, the transformer efficiency relative to the maximum efficiency point, drops by approximately 5 percent, whereas at about 19 kVA or 77 percent loading it only drops by approximately 1 percent. This illustrates the concern for under-loading with respect to unnecessary energy consumption. The figure is one example of loss data and efficiency but individual transformers have values that vary. For example, a low temperature rise model would have different loss characteristics than a standard temperature rise unit, with an efficiency peak occurring at a higher loading level. The data can generally be obtained from most manufacturers and analyzed to assist with transformer specification. Prior to 2007, transformers in the United States had efficiency curves that peaked at various loading levels as efficiency standards were nonexistent [31]. However recent legislation has standardized the maximum efficiency point for all low and medium transformers manufactured and intended for installation in the fifty United States, the District of Columbia and Puerto Rico. This still allows manufacturers flexibility in how they structurally realize their designs but takes away the freedom in determining the most efficient loading level.

2.5. Impact of Energy Conservation Standards

As a result of the United States Energy Policy Act of 1992 – specifically *Title 1*, which sought to increase clean energy use, improve building energy conservation, and develop appliance standards – the US Department of Energy (DOE) began to analyze the energy usage of distribution transformers. The study was carried out by the DOE's largest science lab, Oak Ridge National Laboratories (ORNL) and began in 1995 [32]. The results and subsequent conclusions drawn by ORNL, published in 1996 were substantial. Transformers were responsible for the annual loss of approximately 140 billion kWh during power delivery [33]. The DOE/ORNL study helped to jumpstart the development of more stringent transformer efficiency standards.

Additionally, in 1995 the United States Environmental Protection Agency launched the *Energy Star* transformer specification program, which aimed to meet target efficiency goals that were co-devised with the National Electrical Manufacturers Association (NEMA) [31]. Utility companies and manufacturers were authorized to voluntarily participate in the program; however participation was not legally mandated.

Companies that partnered with the Energy Star program were entitled to legally advertise themselves as such, including display of the Energy Star name and mark on product literature and packaging.

While Energy Star partnering and specification remained in effect, in 1996 a new efficiency standard for transformers was developed and published by NEMA, called *NEMA TP-1-1996*. In 2002, NEMA TP-1-1996 would be updated to *NEMA TP-1-2002*. Over twenty transformer manufacturers, including many well established companies like General Electric, Siemens, and Square D came to a consensus on and developed the publication [34]. Although then optionally required, NEMA TP-1-2002 would later be the catalyst for major federal legislation changes. At that time, the standard sought to encourage the development of more efficient units at feasible manufacturing and sales costs, covering all single- and three-phase, liquid-filled and dry-type, medium (34.5 kV and below) and low (600 volts and below) voltage transformers. Some exceptions were included for small transformers, autotransformers, special applications transformers, etc. All existing applicable American National Standards Institute, Inc (ANSI) and NEMA standards were still required to be met. NEMA TP-1-2002 set the highest efficiency reference position at 0.35 per unit load for low voltage dry-type transformers with linear loads and outlined those minimum efficiencies as set forth in Table 2.2. Efficiency is defined as:

$$\%E = \frac{100 \times \left(P \times kVA \times 1000\right)}{P \times kVA \times 1000 + NL + LL \times P^2 \times T} \qquad (2.5.1)$$

Where:

P = Per unit load, 0.35 (or 0.50 for medium voltage)

kVA = nameplate kVA

NL = No load (core) loss at 20°C

LL = Load loss at its full load reference temperature consistent with ANSI C57.12.01 in watts

T = Load loss temperature correction factor to correct specified temperature of 75°C

Table 2.2 NEMA Class I efficiency levels [34]

NEMA CLASS I EFFICIENCY LEVELS FOR DRY-TYPE DISTRIBUTION TRANSFORMERS

Reference Condition	Temperature	% of Nameplate Load
Low Voltage	75°C	35%
Medium Voltage	75°C	50%

Single Phase Efficiency				Three Phase Efficiency			
kVA	Low Voltage	Medium Voltage ≤60 kV BIL	Medium Voltage >60 kV BIL	kVA	Low Voltage	Medium Voltage ≤60 kV BIL	Medium Voltage >60 kV BIL
15	97.7	97.6	97.6	15	97.0	96.8	96.8
25	98.0	97.9	97.9	30	97.5	97.3	97.3
37.5	98.2	98.1	98.1	45	97.7	97.6	97.6
50	98.3	98.2	98.2	75	98.0	97.9	97.9
75	98.5	98.4	98.4	112.5	98.2	98.1	98.1
100	98.6	98.5	98.5	150	98.3	98.2	98.2
167	98.7	98.8	98.7	225	98.5	98.4	98.4
250	98.8	98.9	98.8	300	98.6	98.6	98.5
333	98.9	99.0	98.9	500	98.7	98.8	98.7
500	—	99.1	99.0	750	98.8	98.9	98.8
667	—	99.2	99.0	1000	98.9	99.0	98.9
833	—	99.2	99.1	1500	—	99.1	99.0
				2000	—	99.2	99.0
				2500	—	99.2	99.1

Eventually on 8 August 2005 the Energy Policy Act of 2005 was signed into law, driving further support for reduced energy consumption in the US by including provisions within the act to direct the US DOE to promulgate new efficiency standards for commercial and industrial equipment. This included the adoption of the previously voluntary standards set forth in Table 4–2 of NEMA TP-1-2002 in the Code of Federal Regulations (CFR), thus mandating the efficiency within for low voltage dry-type transformers. The once optional standard became a US manufacturing code that would take effect for all non-exempt transformers built on or after 1 January 2007 [35]. For the first time in history, transformers were federally mandated to reduce unnecessary energy losses. As a result, the EPA decided that the Energy Star transformer specification program was no longer needed and suspended the program on 1 May 2007, discontinuing the use of the Energy Star name and mark on transformers at that time [36].

Although the TP-1-2002 standard has become an essential factor in transformer manufacturing since 2007, higher efficiency standards have been developed in search of even greater energy consumption savings. Specifically, the US DOE released an Advance Notice of Public Rulemaking (ANOPR), *10 CFR 430* "*Energy Conservation Program for Commercial and Industrial Equipment: Energy Conservation Standards for Distribution Transformers (Proposed Rule)"* on 29 July 2004. The ANOPR outlined different levels of transformer efficiency called *Candidate Standard Levels (CSL)*, with the NEMA TP-1 standard being the baseline or CSL-1 plus an additional four levels of proportionally increasing efficiencies to CSL-5 being the maximum technologically feasible level [37]. Each level would have 13 engineering design lines (DL) which allowed for a full range of transformer models. Low voltage design lines were DL 6 (single-phase, dry-type), DL 7 (three-phase, dry-type, 15-150kVA) and DL 8 (three-phase, dry-type, 225-100KVA). Again, these levels were determined at 35 percent, linear/resistive loading. Although the DOE only adopted the EPAct 2005 mandated TP-1 standards for transformer efficiency to take effect in 2007, NEMA and ten major transformer manufacturers considered the efficiencies set forth in the ANOPR. This led to the implementation of the NEMA Premium Efficiency Transformer Program. Similar to the Energy Star transformer program from the previous decade, this program was voluntary for manufacturers, allowing them to commit to saving even more energy than federally mandated, with their transformer designs. NEMA Premium Efficiency

Transformer designation requires that a transformer meet or exceed the DOE CSL-3 level efficiencies as set forth in 10 CFR 430, Table II.9, which equates to about a 30 percent reduction of losses from the TP-1 standard [38]. A summary can be seen in Table 2.3.

Table 2.3 NEMA Premium Efficiencies [38]

Single-phase		**Three-phase**	
kVA	**Efficiency (%)**	**kVA**	**Efficiency (%)**
15	98.39%	15	97.90%
25	98.60%	30	98.25%
37.5	98.74%	45	98.39%
50	98.81%	75	98.60%
75	98.95%	112.5	98.74%
100	99.02%	150	98.81%
167	99.09%	225	98.95%
250	99.16%	300	99.02%
333	99.23%	500	99.09%
		750	99.16%
		1000	99.23%

As efficiency standards continue to be developed through today and into the future, an important factor to note is that the current standards are improving but tend to only utilize a maximum efficiency point of 35 percent loading for a purely linear/resistive load. However since transformers are required to be sized per NFPA 70: National Electrical Code guidelines rarely are these specific requirements met for every commercial, higher education building. Furthermore, design demand calculations often differ from actual installed demand and each application may contain varying loading levels, phase imbalances and/or non-linear loads. Over time as building electrical use changes, these parameters can change even more drastically. This thesis will seek to examine how effective current transformer efficiency standards are in higher education building applications by comparing standard transformer performance under non-specified conditions.

CHAPTER 3

OPERATING THEORY AND CIRCUIT MODELING

3.1. Basic Principles

The basis of how a transformer works lies in Faraday's laws of electromagnetic induction, which describe the relationship between voltage and magnetic flux in two electrical circuits sharing a common path for magnetic flux. The first electrical circuit – or primary coil – when energized creates a magnetic flux that flows through the iron core, mutually inducing a voltage in the second circuit – or secondary coil. The secondary voltage created is defined by the equation:

$$e = M\frac{di}{dt} \tag{3.1.1}$$

where, e = induced EMF
M = mutual inductance

That induced secondary EMF, has a magnitude as expressed by the following equation:

$$e_2 = v_2 = N_2\frac{d\phi}{dt} \tag{3.1.2}$$

where, v_2 = instantaneous secondary voltage
N_2 = number of turns in secondary coil
ϕ = magnetic flux through one coil turn

And since in an ideal transformer the same flux flows through both coils, similarly the primary EMF has a magnitude of:

$$e_1 = v_1 = N_1\frac{d\phi}{dt} \tag{3.1.3}$$

where, v_1 = instantaneous primary voltage
N_1 = number of turns in secondary coil

Relating these equations together results in the equation:

$$\frac{v_2}{v_1} = \frac{N_2}{N_1} = K \qquad (3.1.4)$$

where, *K* (a constant) is know as the *voltage transformation* or *turns* ratio and implies whether the transformer is a step-up, step-down, or isolation transformer. In an ideal transformer, input power is equal to output power and thus:

$$v_1 \times i_1 = v_2 \times i_2 \qquad (3.1.5)$$

Relating both Equations 3.1.4 and 3.1.5 results the relationship between the turns ratio, the primary and secondary current, and the primary and secondary voltage:

$$\frac{v_2}{v_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K \qquad (3.1.6)$$

Additionally, for an applied sinusoidal voltage of a given frequency, *f*, the root mean square (rms) values of *v* (in volts) are:

$$V_1 = 4.44 \times 10^{-8} a_c B f N_1 \qquad (3.1.7)$$

$$V_2 = 4.44 \times 10^{-8} a_c B f N_2 \qquad (3.1.8)$$

where, a_c = square inches cross section of core
B = lines per square inch peak flux density
f = frequency in hertz

However, although these equations hold true for an ideal transformer with no losses, in reality all transformers have inherent impedance, *Z*, in the winding material. This impedance is generally listed on the transformer's nameplate, which gives a percentage of its rated secondary voltage at full load current [21]. Total coil impedance is made up of a resistance component, R, and an inductive reactance, X, with a relationship defined as:

$$Z = \sqrt{R^2 + X^2} \tag{3.1.9}$$

Each coil has separate impedance and combining both coil impedances, Z_1 and Z_2, results in the total impedance, Z. For each coil the resistance component originates from the natural resistance in the winding material, while the inductive reactance component originates from the leakage flux produced in that winding. These individual leakage fluxes differ from the mutual flux that couples the two windings. Coil impedance creates a voltage drop equal in magnitude to the current through the coil multiplied by the coil impedance. On the primary side coil, the total rms voltage will be the vector sum of the primary induced rms EMF and the voltage drop or:

$$V_1 = E_1 + I_1 Z_1 \tag{3.1.10}$$

On the secondary side coil, the secondary induced rms EMF will be the vector sum of the secondary side rms voltage and the voltage drop or:

$$E_2 = V_2 + I_2 Z_2 \tag{3.1.11}$$

From Equations 3.1.10 and 3.1.11, it can be seen that the voltage supplied to the transformer primary will not be the voltage supplied to the load, due to the voltage drop within the transformer material. An example would be a transformer designed for 208 V secondary voltage with a 3.6% impedance. At full load, the transformer secondary will output 3.6 percent less voltage (the voltage drop or I_2Z_2 component) which equates to 7.5 volts less or 200.5 volts. Although the impedance value impacts the secondary voltage, only the resistance component contributes to excess heat and thus transformer loss totals.

The inductance component does not restrict the flow of current, but rather prevents it from coming into being and can be neglected when calculating losses [21].

3.2. Equivalent Circuit and Losses

Based on the above information, an equivalent circuit can be drawn to represent the transformer, as seen in Figure 3.1, taking some other considerations in mind. Even when the transformer is unloaded (open circuit) it will have an excitation current component, I_e, of the primary current flowing through the primary coil. I_e is necessary to create the mutual flux required to induce an EMF on the secondary coil. This magnetizing current can be represented with a parallel R/L circuit, with the resistance, R_c, accounting for the no-load iron losses and the inductance, X_m, accounting for the inductive components of the transformer with an open secondary [39]. Knowing the correct no-load loss values, to specifically determine R_c is difficult. Generally, the core loss is calculated from empirical design curves of watts per pound of core steel, obtained from collected data from similar grade and type of transformers. Similar curves containing volt-amperes per pound of core steel are also used in determining the excitation current component values. For modeling purposes and since the main purpose of this thesis is to examine transformer load losses at different loading levels and conditions, no-load losses for simulated transformers will be assumed to be constant for each transformer regardless of conditions.

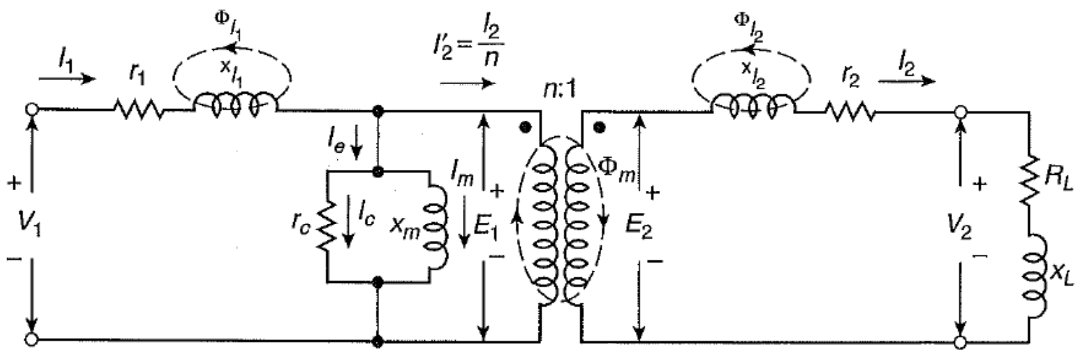


Figure 3.1 Transformer equivalent circuit with load [39]

For simplification in analyzing loaded transformer modeled circuits, all secondary side values can be referred to the primary side. This is due to the fact that the entirety of load current drawn from the transformer on the secondary side is directly supplied by the source on the primary side. Therefore, the values can be reflected to the primary side, eliminating the complexity of working with both sides of the transformer. The conversion is achieved by utilizing the turns ratio, *K* to equate the actual transformer to an equivalent 1:1 turn ratio transformer. Thus:

$$V_2' = V_2 K \tag{3.2.1}$$

$$I_2' = \frac{I_2}{K} \tag{3.2.2}$$

$$R_2' = R_2 K^2 \tag{3.2.3}$$

$$X_2' = X_2 K^2 \tag{3.2.4}$$

$$Z_L' = Z_L K^2 \tag{3.2.5}$$

The resulting equivalent circuit is shown in Figure 3.2. It should also be noted that values can be referenced to the secondary side as well, in a reverse process.

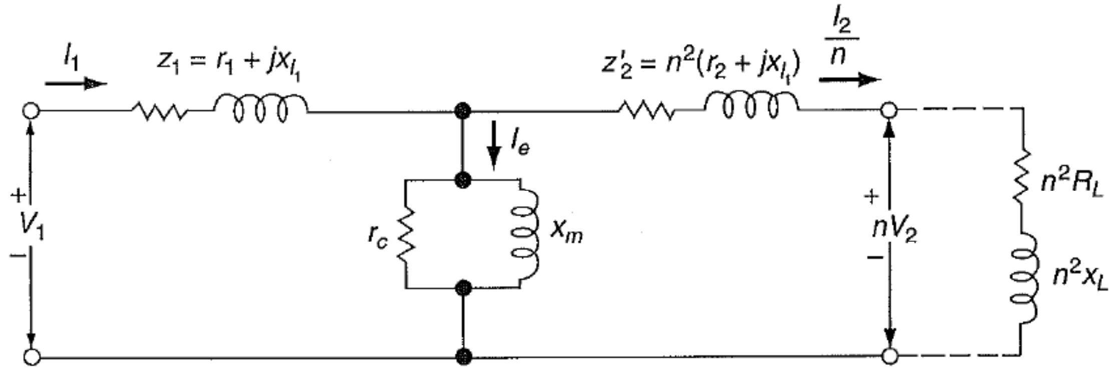


Figure 3.2 Transformer equivalent circuit, referenced to primary (where $K = n$) [39]

With given values for each coil's resistance, full load rated current and the turns ratio, an approximation of the transformer's total losses can be calculated. Load loss for this circuit at full, rated load is calculated as follows:

$$P_L = I_R^2\left(R_1 + R_2K^2\right) \tag{3.2.6}$$

where, P_L = watts load loss at rated current
I_R = rms amperes rated current

And load loss at any given load is calculated as follows:

$$P = \frac{P_L I^2}{I_R^2} \tag{3.2.7}$$

where, P = watts load loss
I = rms amperes

3.3. Three-phase Equivalent Circuit

In order to develop a foundation of transformer theory, the above equations and considerations have been in reference to a two winding, single-phase transformer. A more applicable model is now presented, the three-phase transformer, which has three sets of windings on a single core as seen in Figure 3.3.

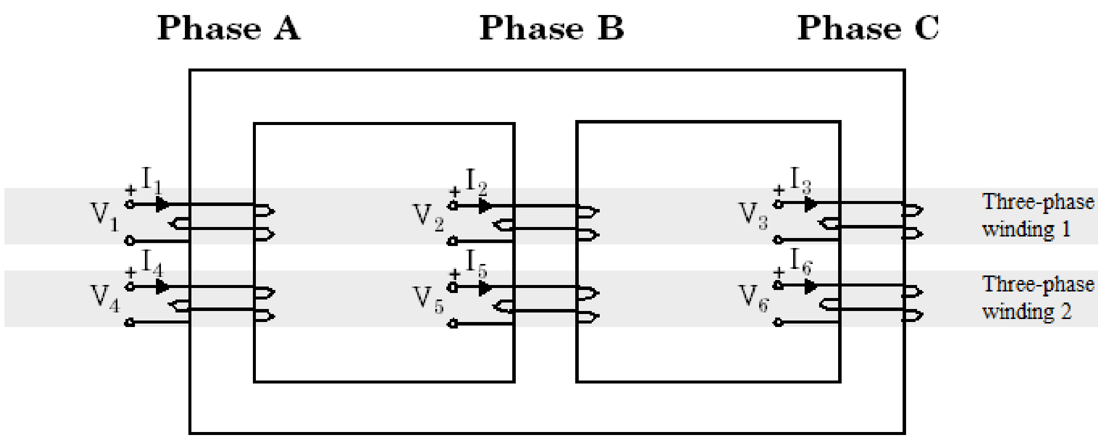


Figure 3.3 Three phase transformer winding configuration [40]

There are four main types of three-phase transformer coil configurations: delta-delta, delta-wye, wye-wye, and wye-delta. These configurations describe the nature of how both the primary and secondary side coils are connected to the phase and if applicable, neutral conductors, with the first term referring to the primary side and the second term to the secondary side. Of particular interest is the delta-wye transformer. As it is the most common configuration for the majority of transformers installed in higher education building applications, the delta-wye will be the standard model for this thesis. *Delta* indicates that each of the three coils is terminated on both sides of the coil with a phase conductor, in a manner such that each phase is used for only two of the coils. With primary phase conductors typically labeled as *A, B,* and C, the total phase-to-phase voltage will be applied across each coil, resulting in voltages V_{AB}, V_{BC}, V_{AC}. For the purpose of this thesis, V_{AB}, V_{BC}, V_{AC} equal 480V or 4160V (rms) and the phase-to-ground voltages equal 277V or 2400V (rms), respectively. *Wye* indicates that each of the three coils is terminated at only one side of the coil with a phase conductor, while the other sides of each coil share a common node that is connected to a grounded or neutral conductor. With secondary phase conductors labeled as *a, b,* and *c*, as well as the neutral conductor labeled as *n*, the total phase-to-phase voltage will be applied between coils, resulting in voltages V_{ab}, V_{bc}, V_{ca}, while a lower phase-to-neutral voltage will be applied across each coil, resulting in voltages V_{an}, V_{bn}, V_{cn}, For the purpose of this thesis, the V_{ab}, V_{bc}, V_{ca}, equal 208V or 480V (rms) and V_{an}, V_{bn}, V_{cn}, equal 120V or 277V (rms), respectively.

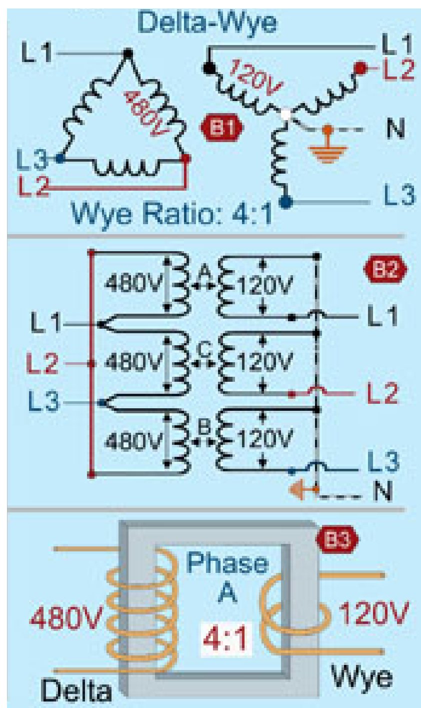


Figure 3.4 Delta-Wye transformer configuration [29]

Combining this with the information presented in Section 3.B allows for a complete circuit model of the three-phase transformer to be conceived. However, since the three-phase transformer is in a delta-wye configuration and cannot be directly translated to the simulation program an alternate model will need to be utilized. This will consist of each of the three phase conductors being separated individually, with three separate voltage sources and a shared neutral. On the primary side of the transformer circuit, each coil will be represented as a series impedance, similar to the single-phase model. However, instead of only having a single shunt impedance across one phase, there will be a parallel shunt impedance across each set of phase conductors to the common neutral, representing the excitation current in each coil and the core loss. Each secondary coil will also be represented as a series impedance and the load will be shown as in the single-phase model, dependant upon the load characteristics. This will provide for an accurate circuit representation (Figure 3.5) and as discussed in Section 3.2 referencing the secondary side component values to the primary side will allow for simpler analysis and modeling in Pspice.

Although a model has been generated, it is still necessary to assign values to the various components. While some of the component values are provided by the transformer manufacture or assumed based on operating conditions, others will need to be calculated or measured. The transformer primary voltage is assumed to be equal to the source voltage, since supply conductor voltage drop in a higher education building is typically negligible due to relatively short lengths. Some manufacturers provide the combined (primary and secondary) series impedance, often as a per unit (pu) value or percentage. With the pu values one can calculate the values in ohms as follows:

$$R_{base} = X_{base} = Z_{base} = \frac{V_1^2}{S_{base}} \tag{3.3.1}$$

$$R_{\Omega} = R_{pu} \times R_{base} \tag{3.3.2}$$

$$X_{\Omega} = X_{pu} \times X_{base} \tag{3.3.3}$$

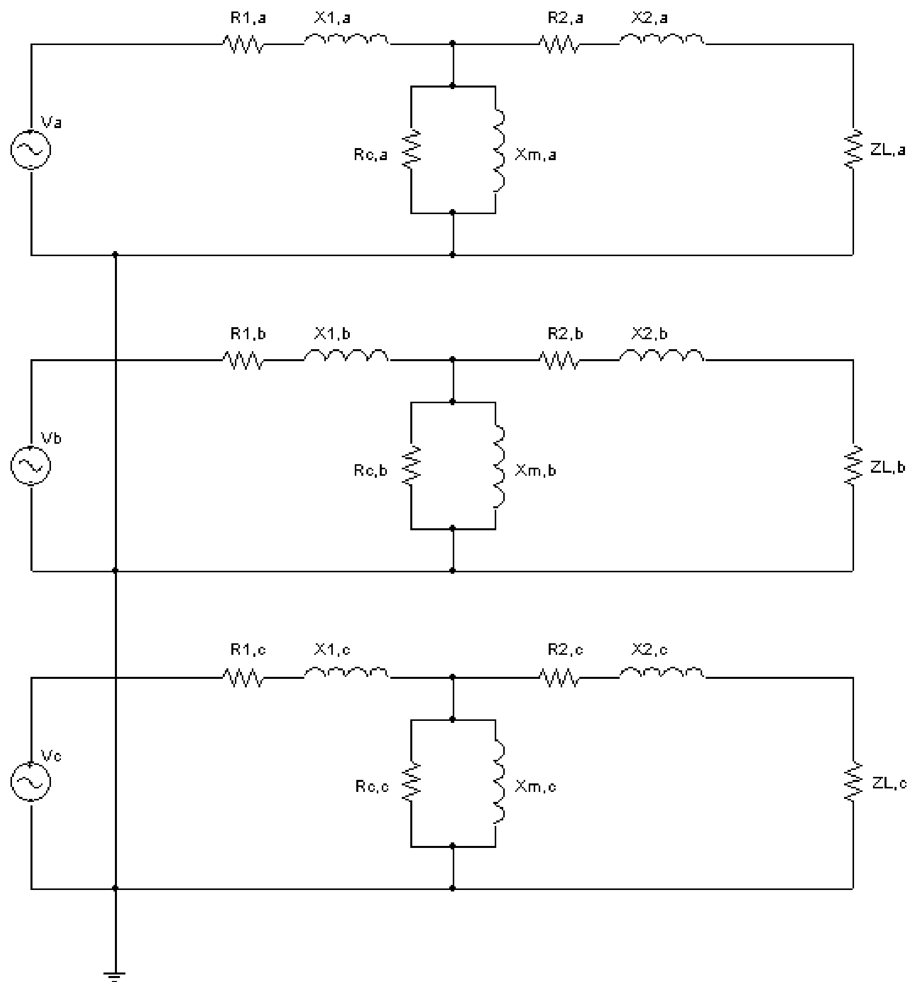


Figure 3.5 Pspice three-phase transformer model

However, since these provided values often represent the *combined* series impedance, it is possible to determine the value of each of the primary and secondary components separately. If not obtainable from the transformer manufacturer, another method for determining the primary and/or secondary series resistance for a single winding is through measurement with an ohmmeter. By measuring the secondary resistance of one phase's coil to ground, the primary resistance value can be determined by the relationship between the two as outlined in the following equation:

$$R_{\Omega} = R_1 + k^2 R_2 \tag{3.3.4}$$

With manufacturer provided total series resistance and measured secondary resistance known, primary winding resistance can be calculated. In the Pspice simulation, these values will be substituted in as values for R_1 and R_2 for each of the three phases, since it is assumed that each of the three phases have equivalent series resistance. It is important to take note that the R_2 in the simulation will not be the actual measured value, but rather the measured value referenced to the primary side, or multiplied by the turns ratio squared. Also, since more than 99 percent of the no-load resistance losses occur in the core however, it is safe to use any combination of values for R_1 and R_2 provided their sum equals the total series resistance. The same can be assumed for the series reactance values of X_1 and X_2, where related by:

$$X_{\Omega} = X_1 + k^2 X_2 \tag{3.3.5}$$

With all series impedance values known, it is now possible to estimate the core no-load iron resistance as well as the magnetizing inductance. If available, manufacturer provided excitation current and no-load loss can be used to approximate R_c and X_m through Pspice simulation. Generating a simple, energized unloaded transformer circuit as seen in Figure 3.6, with source voltage equal to 2400 or 277 V(rms), fundamental frequency of 60 Hz, known R_1 and X_1 and determining real power delivered to the shunt component can lead to an approximation for R_c. Real power is calculated by:

$$P = V_1 \times I_{1,1} \times \cos(\theta) \tag{3.3.6}$$

where, V_1 = phase-to-line voltage (rms)
$I_{1,1}$ = line amps (rms), at fundamental frequency
θ = displacement power factor (DPF)

Pspice will output the voltage, current and DPF for the user. These voltage and current magnitudes are shown in peak value and should be converted to rms by dividing by the square root of 2. Ultimately, considering that R_c and X_m values should be fairly high and also should be constrained by the relationship (determined by basic circuit analysis, assuming that the voltage drop across the series impedance is negligible):

$$\frac{V_1}{I_{ex}} \approx \sqrt{R_c^2 + X_m^2} \tag{3.3.7}$$

one can substitute properly related values for R_c and X_m until the manufacturer provided no-load loss is realized by equation 3.3.6. This is represented as when the power consumed by the transformer circuit with the only "load" being the shunt resistance equals the no-load loss. It is important to note that since the known no-load loss is for all three phases, that the no-load loss for the basic circuit should be one-third of the total known loss.

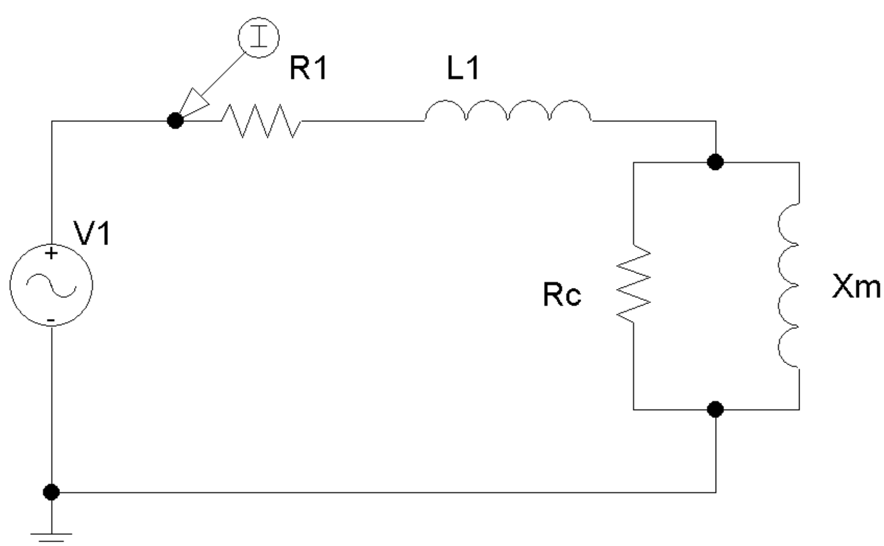


Figure 3.6 No-load transformer Pspice circuit

The final remaining part of the circuit that needs to be determined is the load impedance values. Load impedance values can be calculated from measurements or specifically selected to simulate a given scenario, *e.g.* 20% loading with 0.88 power factor. To utilize data from a real world transformer, measurements can be taken by using a 3-phase power analyzer to acquire snap-shot information, providing values for the current and voltage-to-ground present for each transformer secondary phase conductor as well as the real and reactive power amounts on each phase. Component values for the real and imaginary parts of the load can then be calculated using basic AC circuit analysis. With phase real power and current known, phase load resistance, R_L can be calculated by:

$$R_L = \frac{P}{I^2} \tag{3.3.8}$$

and used as the resistor value in the Pspice circuit. With phase reactive power and current known, phase load reactance, X_L can be calculated by:

$$X_L = \frac{Q}{I^2} \tag{3.3.9}$$

allowing for the actual inductor value to be calculated from load reactance being equal to ωL, and solving for L. Specific simulated load scenarios can also be created by using the same principles for determining values as in the measured case, but changing the power, current and/or power factor amounts to match desired conditions and re-solving for load resistor and inductor component values.

3.4. Effect of Load Imbalance

While most transformer manufacturers rate the units with the assumption that the load being supplied is equally balanced across all three phases, *i.e.* the phase currents I_a, I_b, I_c are all equal, in actuality these often differ. This is known as *load imbalance*. In such a scenario, when the impedances of each phase are unequal, these phase currents are calculated separately by dividing the individual phase-to-neutral voltage by the load impedance. Applying the basic Kirchhoff's current law, at the common node for the three phase conductors and the neutral conductor defines the value of the neutral current as:

$$\mathbf{I}_n = -(\mathbf{I}_a + \mathbf{I}_b + \mathbf{I}_c) \tag{3.4.1}$$

In the case of a balanced wye connected load, with each phase current 120 degrees apart, the sum will be zero and there will not be any additional neutral current flowing [42]. However, in an unbalanced wye where the phase currents have separate values, the neutral current will have a value, which will vary based on the amount of imbalance. This excess neutral current returns to the transformer via the neutral conductor where it will flow through the secondary windings and ultimately increase the I^2R losses, lowering overall system efficiency [43]. Although there are methods available to prevent or minimize phase imbalance, it is commonly an existing issue in higher education buildings. Therefore, while published transformer efficiency is rated for balanced loading, a study of transformer efficiency during a load imbalance situation will allow for a more accurate analysis of actual installed performance. The Pspice equivalent circuit will be similar to Figure 3.5, only with differing load impedance values based on sample measurements, which will achieve the measured or desired phase currents.

3.5. Effect of Harmonics

The prevalent application of power electronics in modern day electrical distribution systems introduces an additional influencing factor to the system operation. Computer switched mode power supplies (SMPS), variable frequency drives (VFD's), fluorescent lamp ballasts, photovoltaic array inverters and other devices that utilize high frequency switching and AC to DC or DC to AC conversion give rise to what are known as harmonic frequencies or harmonics. Harmonics are orders or multiples of the fundamental frequency that are generated by these types of loads, as briefly introduced in Chapter 2. In the U.S. for example, the 3rd harmonic would be equal to 60 Hz times 3, or 180 Hz. The individual frequency components are additives to the carrier frequency component, resulting in the overall rms value as defined by the following relationship:

$$I_s = \sqrt{I_{s1}^2 + \sum_{h \neq 1} I_{sh}^2} \quad (3.5.1)$$

Fourier analysis is needed to examine the individual component values of a voltage or current signal. Harmonic producing loads often draw line current that is distorted as compared to typical sinusoidal current waveforms for standard loads. These loads are often referred to as *non-linear loads.* The voltage or current distortion amount is measured by an index called *total harmonic distortion* (THD), given by the equation:

$$\%THDi = 100 \times \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} \quad (3.5.2)$$

Allotted amounts of current THD (THDi) and voltage THD (THDv) present in a distribution system are addressed in IEEE Std. 519-1992, depending upon system operating voltage [45].

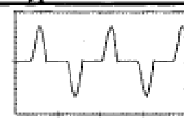
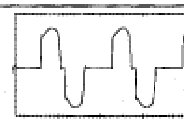
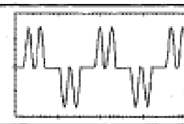
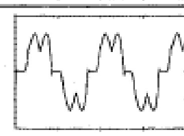
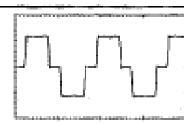
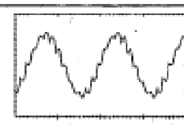
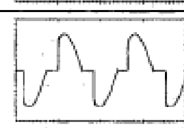
Type of Load	Typical Waveform	Typical Current Distortion
Single Phase Power Supply		80% (high 3rd)
Semiconverter		high 2nd,3rd, 4th at partial loads
6 Pulse Converter, capacitive smoothing, no series inductance		80%
6 Pulse Converter, capacitive smoothing with series inductance > 3%, or dc drive		40%
6 Pulse Converter with large inductor for current smoothing		28%
12 Pulse Converter		15%
ac Voltage Regulator		varies with firing angle

Figure 3.7 Nonlinear loads and their current waveforms [48]

THD limits are outside of the scope of this thesis, but it is important nonetheless to understand that increased harmonic content leads to greater waveform distortion and per equation 3.5.1, increased rms current. Although the increased rms current increases the overall system apparent power, the actual real power drawn from the load is unaffected by the presence of harmonic current values [46]. The average power for a load with a sinusoidal source voltage is defined by:

$$P = V_s I_{s1} \cos\phi_1 \qquad (3.5.3)$$

where, V_s = rms voltage
I_{s1} = rms current of fundamental frequency
ϕ_1 = angle between fundamental frequency current and voltage

For a non-sinusoidal source voltage, this equation will change slightly to:

$$P = \sum_{n=1}^{N} V_n I_n \cos(\phi_n) \qquad (3.5.4)$$

where, n = harmonic order

Equations 3.5.3 and 3.5.4 will be highly utilized in calculating transformer input and output powers in the various Pspice simulations. By measuring the rms voltage, current and angular difference between the two, power can quickly and easily be calculated.

As touched on in Chapter 2, harmonics impact the operating characteristics of power distribution transformers and resulting losses, requiring either transformer derating or specification of *K*-factor rated transformers based on calculated *K*-factor. Specifically, transformer losses due to the presence of harmonics will be impacted in the following ways, as described in IEEE C57.110-1998 [47]:

- Increased I^2R (heat) losses, due to increased rms current
- Increased effect on winding eddy current loss (P_{EC})
- Increased stray losses (P_{OSL}) in the core, clamps and structural parts

- Frequently, accompanying increased DC component, leading to slight increases in core loss and substantial increases in magnetizing current

Therefore, although increased amounts of system harmonics don't directly impact the power drawn by the load per equation 3.5.3, they *do* impact overall transformer losses. First, load losses are increased, since total transformer load loss, P_{LL} is equal to the sum of the I^2R , P_{EC} , and P_{OSL} all of which have been increased with the presence of harmonics. Furthermore, no-load losses are increased, since hysteresis effect is sensitive to the supply voltage distortion that occurs in the system [49]. Ultimately increased losses will result in poorer transformer efficiency, a hypothesis that is expected to be observed when simulating non-linear transformer loads.

Another issue associated with harmonic producing loads is neutral conductor loading. Section 4 of this chapter discussed the impact of neutral conductor current flow as a result of balanced and unbalanced phase loading. As described in that section, for a balanced, linear load profile the neutral conductor current will be zero. However, the presence of power electronics and other harmonic producing, non-linear loads will have a different impact on neutral conductor loading for balanced loads. For an individual phase, current can be expressed as a summation of its components, the fundamental frequency current and the harmonic current [50]. Since even harmonics are generally zero, the summation of current components can be further simplified to only the fundamental frequency current and the odd harmonics. This resulting equation is shown in equation 3.5.5.

$$i_a = i_{a1} + \sum_{h=2k+1}^{\infty} i_{ah} \tag{3.5.5}$$

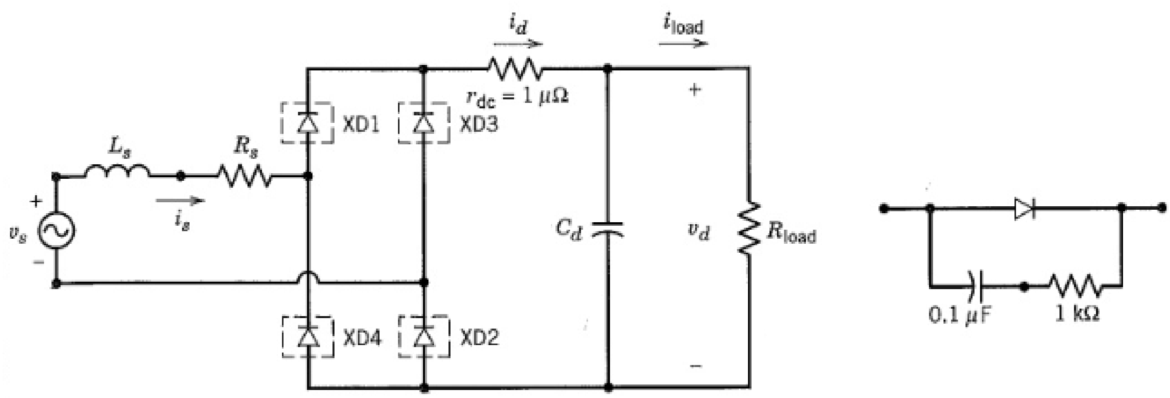
where, k = 1, 2, 3, …

Assuming all phases are balanced and thus $i_a = i_b = i_c$, using equation 3.4.1 it can be determined that the summation of the fundamental frequency components and all nontriplen harmonics (harmonics with orders not divisible by three) is zero. The total neutral current is therefore limited to the summation of the triplen harmonics, which when all phases are balanced is equal to three times their individual values or expressed in terms of the rms values as:

$$I_n = 3 \times \sqrt{\sum_{h=3(2k-1)}^{\infty} I_{sh}} \qquad (3.5.6)$$

This equation shows that the neutral current rms value can be three times the triplen harmonic current rms value in the phase conductors. Neutral rms current can be as high as 1.732 times the phase rms currents [50], which has led to changes in electrical code sizing requirements for neutral conductors and the application of "double neutrals" (using two neutral conductors or a single neutral conductor sized at 200 percent, along with twice as many termination points at transformers and panelboards) by design engineers in distribution systems with large amounts of triplen harmonics. The additional neutral current contributes to increased transformers losses, as described previously in this section and Section 4.

Due to the large presence and use of SMPS's in higher education buildings, harmonic content is often dominated by the 180 Hz or 3rd harmonic component [51]. Although methods may be employed to mitigate the effect of these currents, such as filters, they are rarely employed in typical higher education environments and their installation will not be considered within the scope of this thesis. Taking this into consideration, for the purpose of examining the effect of harmonic currents on transformer losses, a simulation load model that duplicates SMPS behavior is needed. In order to properly simulate 3rd harmonic producing SMPS's in Pspice, the diode full-bridge rectifier model will be utilized. The rectifier is seen in Figure 3.8, where L_s and R_s represent the transformer secondary winding circuit equivalent. The diode/snubber subcircuit substitutes each of the diode symbols in the main circuit. The component values for both the main and sub circuits have been previously determined and verified to produce predominantly 180 Hz current components and these values will remain static throughout the simulation. The resistance and/or reactance values of the load will be varied as necessary to achieve proper conditions, similar to the previously discussed circuit model in Section 3 that does not include the full-bridge rectifier. Development of this model will allow for power consumption, efficiency and transformer losses to be calculated when supplying a non-linear load.



(a) (b)

Figure 3.8 (a) Pspice Circuit for Diode Full-Bridge Rectifer, (b) Pspice subcircuit for Diode with Snubber [52]

3.6. Efficiency and Loss Calculations

Combining the efficiency background information from Chapter 2, Section 3 with the power calculation methods from Section 3 of this chapter will allow for transformer overall efficiency to be calculated. After developing a proper transformer model with the desired no-load losses as shown in Section 3 of this chapter, a load can be added in the form of one of the various methods discussed. Through Pspice readings, power supplied to the transformer and power supplied to the load can be calculated, allowing for derivation of the total transformer losses, *i.e.* the difference between the two power amounts. Additionally, transformer efficiency can be determined.

It is important to point out that although transformer efficiency is a critical parameter when comparing two or more units of the same capacity rating, it can lead to deceiving inferences when comparing units of different capacity rating. With transformers of the same capacity, the percentage of full load will be the same for both transformers. Therefore, whichever one is operating at a higher efficiency level, will have fewer losses and thus lower operating cost. Clearly specifying the higher efficiency unit is the better choice from an energy savings standpoint. However, using two differently sized transformers to supply the same size load will result in each transformer having a different loading level. For example, 30 percent load on a 30 kVA transformer would be the equivalent of a 20 percent load on a 45 kVA transformer. Although the efficiency of the 30 kVA transformer would most likely be higher than that of the 45 kVA model, there is still the possibility that the total losses of the 45 kVA model are actually *less*. If that were the case, since amount of energy waste – not transformer efficiency – is what can be translated to end-user savings, it is possible that although more “inefficient” the 45 kVA transformer would actually be a better selection from an energy savings standpoint. Therefore it is vital that one consider not only the overall efficiency, but the total losses as well, especially when comparing transformers of varying capacity ratings.

CHAPTER 4

DATA COLLECTION AND SIMULATIONS

4.1. Data Collection

4.1.1. Higher Education Building Loading Data

The main purpose of this thesis is to perform a comparison of transformer energy efficiency performance with optimal loading under ideal, design conditions and transformer energy efficiency performance with varying loading levels and non-ideal load characteristics. Since NEMA TP-1 establishes an optimal loading percentage of 35 per cent (50 per cent for medium voltage units) it is important to gather data that will determine a more realistic loading percentage for higher education buildings. In 1999, a study was completed by the United States Department of Energy to determine average load factor, or the ratio of average load to peak load, for buildings of different types. The results of that study are shown in Figure 4.1. From the figure, it can be discerned that schools have an average transformer load factor of about 16-17 per cent, making the actual transformer loading percentage even lower. Both the load factor and actual loading percentage are much less than the NEMA TP-1 established efficiency points.

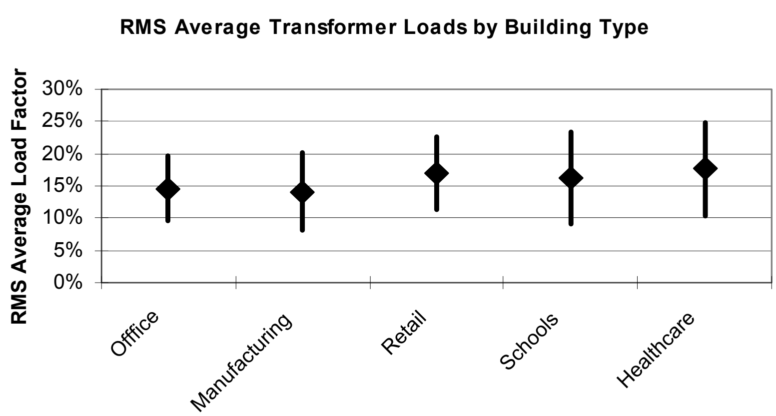


Figure 4.1 1999 DOE Transformer load factor study [53]

Going a step further than the somewhat dated DOE study involves conducting an updated study of higher education building loads, which will account for the higher efficiency implementations that have been implemented in the first part of the 21st century and determine actual transformer loading as a percentage of full load rating.

In 2011, in an effort to investigate the efficacy of National Electrical Code demand factor calculations and transformer sizing requirements, the APPA (formerly known as the Association of Higher Education Facilities Officers) Code Advocacy Task Force (CATF) conducted a "call for transformer loading data" from various college campuses throughout the United States [54]. This entailed requesting voluntary transformer loading data from interested participants with the intention of examining if there is a potential need for changes to the current code based upon the summary of collected data. These changes/considerations could then be proposed through the National Electrical Code Committee for upcoming code cycles. A number of colleges and universities responded with loading data, including:

- Coppin State University
- De Anza College
- Foothill College
- Dixie State College of Utah
- Delta College
- Lamar Community College
- Kentucky Community & Technical College
- Mt. San Antonio College
- Virginia Wesleyan College
- Long Beach City College
- University of Nevada, Las Vegas
- University of Michigan
- University of California, Berkeley
- University of Notre Dame

Each of the schools was asked to provide average and peak loading data for as many building distribution transformers as possible. Although transformers are required to be adequately sized to provide for peak demand, the majority of buildings only operate at that peak demand for very short intervals of time and usually for only a few days out of the year. Therefore, the average loading is a more accurate figure for calculating transformer losses and efficiency, since this is the range the transformer is operating at most of the time. However, one must still be cognizant of the peak demand, in order to ensure that the transformer is not overloaded at any point.

Load data was generally acquired through customer-owned, permanently installed Building Management Systems (BMS) and/or temporarily installed current transformer (CT) type metering/monitoring devices. Individual monitoring devices from school to school were from varying manufacturers, but each device serves the purpose of collecting consumption and peak demand data for customer assessment. The monitoring system used specifically for the UNLV transformers was the Square D *PowerLogic®* system, along with a combination of permanently installed PM800 and CM4000 series power meters, which meet ANSI 12.20 Class 0.2 and IEC 62053-22 Class 05S standards for accuracy.

(a) (b)

Figure 4.2 (a) PM800 Power Meter, (b) CM4000 Power Meter

The data was then compiled for all of the participating colleges and averaged in order to determine an overall peak load and average load that could serve as a more recent update to the 1999 U.S. DOE study. The results of the APPA "call for transformer loading data" are summarized in Table 4.1 and data for each individual school can be seen in Appendix I. Information from over 500 monitored transformers is included.

Table 4.1 Higher Education Average and Peak Loading Summary

Entity	Average Loading (%)	Peak Loading (%)
University of Nevada, Las Vegas	15.11	34.35
Coppin State University	10.92	15.15
Dixie State College of Utah	15.72	18.30
De Anza College	8.05	N/A
Foothill College	10.40	N/A
Long Beach City College	7.23	N/A
Mt. San Antonio College	5.55	N/A
Delta College	4.47	N/A
Kentucky Community College	11.57	13.69
Lamar Community College	4.49	13.80
Wesleyan Virginia College	13.38	16.88
UC Berkeley	25.82	40.19
University of Michigan	19.60	40.13
University of Notre Dame	25.91	36.24
TOTAL	**12.73**	**25.41**

These results establish the estimated overall transformer average load for higher education buildings in 2011 of 12.73 per cent that will be used as a comparison to the NEMA TP-1 specified load values for energy consumption simulations in Pspice. Additionally, Table 4.1 establishes the overall transformer peak load for higher education buildings of 25.41 percent, which can be useful in determining if transformer overloading will be of concern during potential sizing considerations.

4.1.2. Individual Transformer Field Measurements

In order to further substantiate loading data, field measurements were taken on a few randomly selected 480V-208/120V transformers located on the UNLV campus. The only criterion for selection was that the transformers were manufactured after 1 January 2007, to ensure that they meet TP-1 design standards. Measurements were taken with a Powersmiths Cyberhawk 300 power management meter with the following specifications:

Type – EP 300
Power – 85-250 VAC 1ϕ: 47-65 Hz: 60VA
Meter Voltage Inputs – 50-600 VAC 50/60 Hz:L-L, L-N
CT Inputs – 1 or 5 Amp (input selected) 50/60 Hz

Proper installation of the meter only requires voltage probes placed on the secondary side phase A, B, C and neutral terminals in addition to CT's placed on the secondary side phase A, B, C and neutral wires. Finally, two CT's are placed on any two phases on the primary side. With all devices in place, the meter can instantly calculate loading levels, estimated losses and efficiencies of the transformer. A summary of the collected instantaneous data is shown in Table 4.2, including loading percentage, estimated efficiency and total measured transformer losses. Since the monitored transformers are from different manufacturers and have varying construction materials and *K*-factors, total transformer losses and efficiencies may differ from the results of the simulations. However, the data in the table supports the theory established in Section 4.1.1 that the majority of transformers installed on higher education campuses are significantly lightly loaded. From the measured loading percentages, an average loading of approximately 6 per cent will be utilized in one of the simulation cases following in Section 4.2.

Table 4.2 UNLV Field Installed Transformer Loading Summary

Unit	Loading (%)	Total Losses (W)	Efficiency (%)
Hammond 150 kVA	5.6	861	90.4
Siemens 30 kVA (1)	3.0	173	79.7
Siemens 30 kVA	5.9	174	90.9
Siemens 75 kVA	8.4	403	93.2

4.2. Pspice Transformer Simulations

With estimated average loading and basic load parameters for higher education transformers now defined, it is possible to move into the next step of the analysis, power consumption comparison. As previously mentioned, efficiency and watt losses are often provided by many transformer manufactures, however this information does not usually cover the full spectrum of installed conditions. The first step in the simulation process will be to correctly develop a default Pspice model that reflects an actual, real-world TP-

1 transformer and successfully exhibits similar power loss characteristics under no load. Varying load types and sizes can then be added to the default model. There are three loading cases that will be examined in this thesis, each with four sub-cases. The three cases are: (1) phases balanced, linear load; (2) phases unbalanced, linear load; (3) phases unbalanced, non-linear load. Within each main case, the results will be presented for: (a) NEMA maximum efficiency point of 35 percent loading; (b) higher education building average of 12.73 percent loading; (c) field measured transformer with 6 per cent loading; and (d) a smaller standard size transformer supplying equivalent loads as in sub-cases "b" and "c" (which will therefore have a higher loading percentage on the smaller unit). Each sub-case will be presented and discussed in a separate section of this chapter. The Pspice circuit schematics can be found in Appendix III.

4.2.1. Default Model

As previously discussed, transformers can be purchased with a number of varying specifications, from materials to *K*-factor rating to temperature rise. For the purpose of this thesis, the transformer being examined is the General Electric, copper winding, 150^{o}C temperature rise TP-1 unit, as it meets specifications commonly prescribed for installation at UNLV. The manufacturer provided typical performance data, obtained from the GE website, can be seen on page 1 of Appendix II. Other lines of GE transformers' performance data is available from the manufacturer for comparison but will not be examined in this thesis.

For the default model, a unit with a 225 kVA rating has been selected, having approximately 400 watts of no-load losses, series R(pu) of 3.7% and X(pu) of 4.6%.

Application of the circuit shown in Figure 3.6 will allow for proper simulation of the no-load losses for a single phase, after calculating values for R_c and R_m (from manufacturer provided excitation current and equation 3.3.7) and R_1 and X_1 (from equations 3.3.1 and 3.3.2). Using one circuit for each phase produces the proper three-phase model. With the proper component values assigned, it is only a matter of changing the R_c and R_m values to maintain the correct relationship for given excitation current, in this case 1.507 A total, while deriving a total watt loss equaling 400 watts. After running the simulation, Figure 4.3 shows a screen shot of the excitation current values (peak) after adjusting for (eliminating) the DC component. Each phase current has a steady-state, rms magnitude of about 0.602 A. Using Equation 3.3.6 to calculate real power supplied to the each phase of the transformer during no-load conditions, with a Pspice given DPF of -37^{o} per phase, results in a single phase loss of 133.2 watts, or 399.6 watts total. The results show that this represents an acceptable default model for the real-world transformer with the same characteristics. The design procedure can also be repeated, ensuring that component values are changed, in order to create other transformer models.

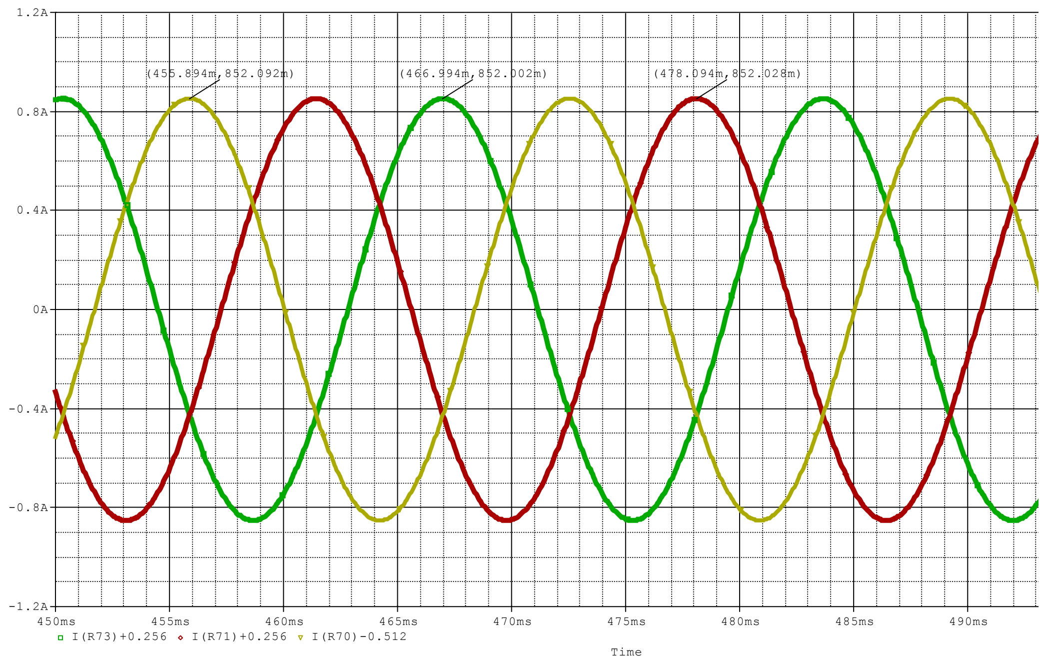


Figure 4.3 Default Model No-load Excitation (peak)

DC COMPONENT = 5.119609E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	8.520E-01	1.000E+00	-3.706E+01	0.000E+00
2	1.200E+02	1.325E-04	1.555E-04	-5.618E+01	1.794E+01
3	1.800E+02	1.410E-04	1.655E-04	-5.645E+00	1.055E+02

Figure 4.4 Default Model Phase 'A' Current Magnitude and Phase

4.2.2. Case 1a – Phases Balanced, Linear Loading of 35%

Now that the default model for a 225 kVA transformer has been produced, it is time to "load" the transformer and examine the efficiency and total losses of the simulation. Case 1a will start with purely sinusoidal current drawing loads that are equally balanced across all three phases. Load resistance values will be calculated to produce the NEMA TP-1 maximum efficiency load that draws 35 per cent of rated full load current from the transformer. For the 225 kVA transformer, each coil is rated for 75 kVA total. 35 per cent of 75 kVA is 26.25 kVA. At rated voltage of 277 V per phase (rms), the transformer should draw approximately 94.76 A (rms). Since manufacturer efficiency listings are for linear loading, the load will be purely resistive. Figures 4.5 – 4.8 show the results of the simulation. Note that for all secondary current figures, secondary currents are being referenced to the primary current by dividing by the turns ratio. Actual secondary currents would be approximately 2.3 times as large.

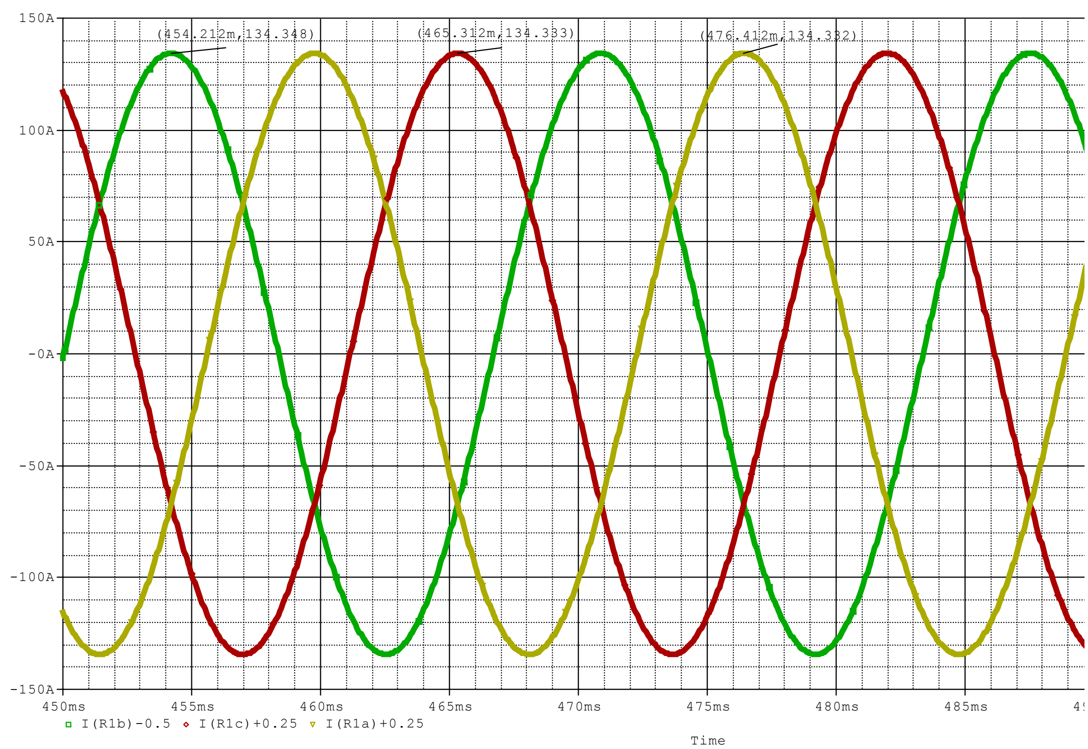


Figure 4.5 Balanced, Linear 35% Loading, 225 kVA – Primary Currents (peak)

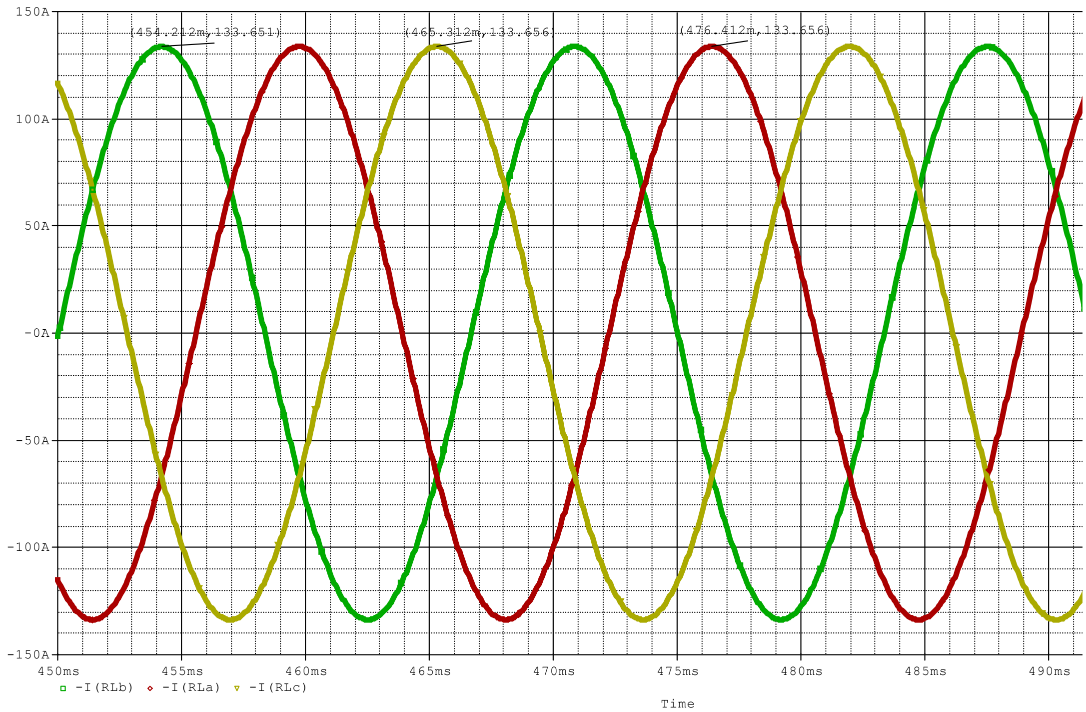


Figure 4.6 Balanced, Linear 35% Loading, 225 kVA – Secondary Currents (peak)

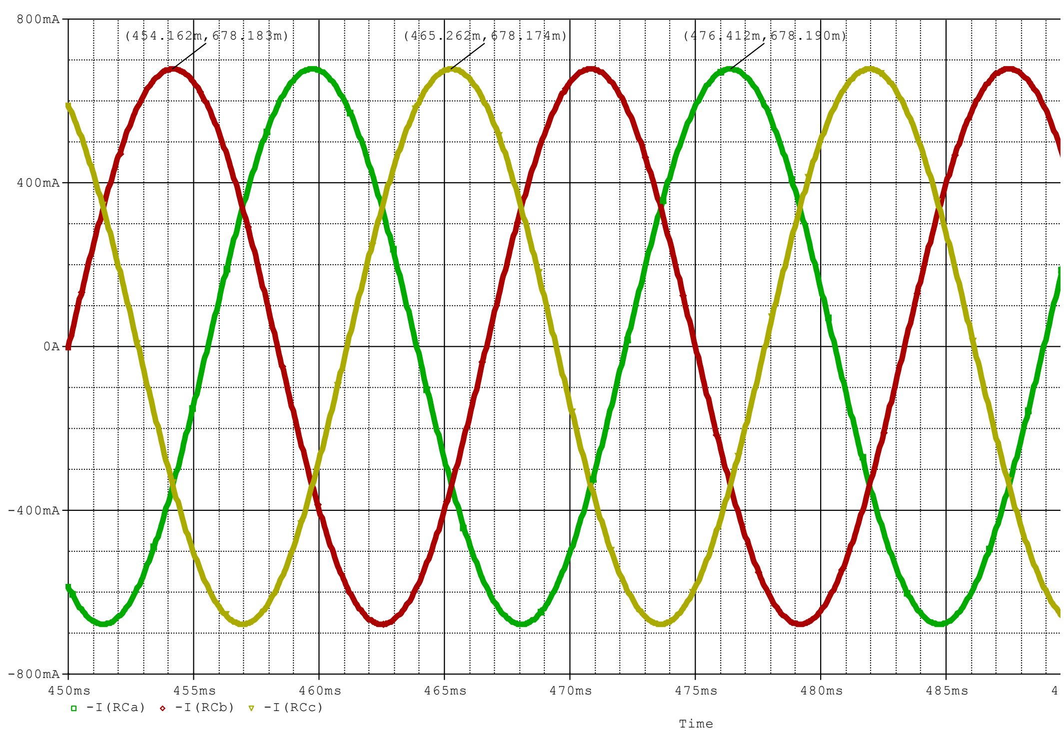


Figure 4.7 Balanced, Linear 35% Loading, 225 kVA – Current through *Rc* (peak)

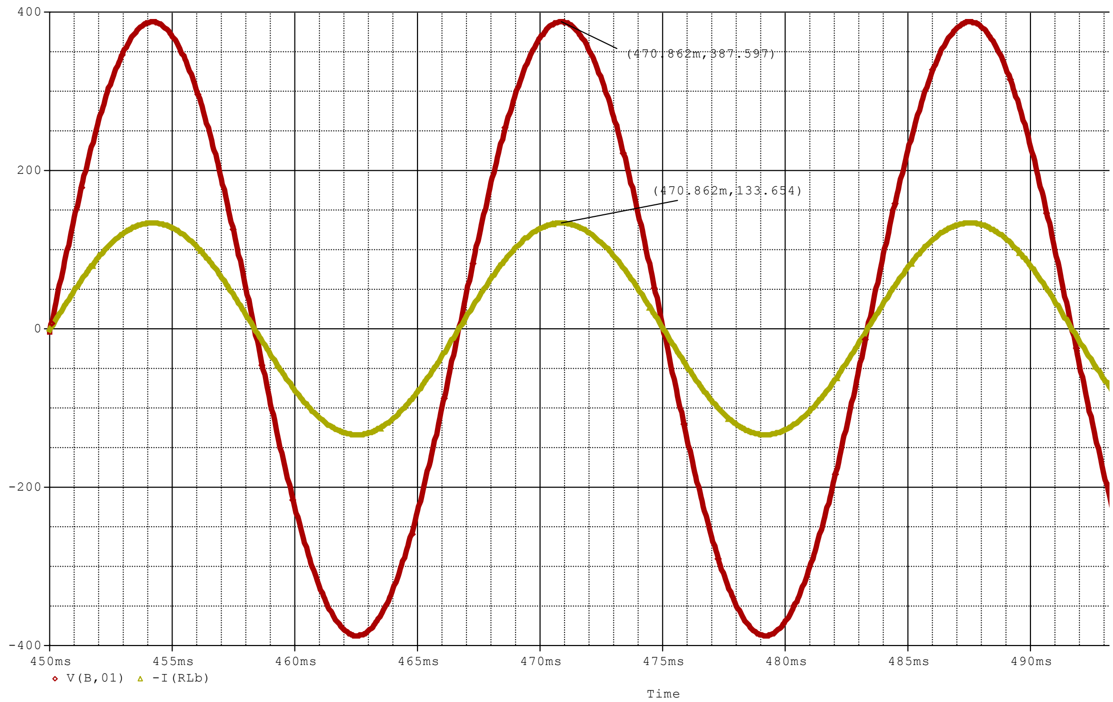


Figure 4.8 Balanced, Linear 35% Loading, 225 kVA – Load Phase Angle

From the figures above it can be determined that there is an rms primary current of 95 A, secondary current of 94.46 A, and a transformer “core loss” current of 0.48 A, per phase. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 69 watts in each primary coil, 157 watts in each secondary coil, and 396 watts in the transformer core, with a load consuming approximately 25,897 watts per phase. Therefore the total transformer loss is 1,076 watts, with an efficiency of 98.6 per cent for this load, which matches the manufacturer advertised efficiency for this loading level. Also it can be observed that the load current and voltage are in phase, which is expected.

4.2.3. Case 1b – Phases Balanced, Linear Loading of 12.73%

Utilizing the same default transformer and power factor from Case 1a, this case will examine a transformer with the higher education average loading of 12.73 per cent. For this case, a load is needed that draws 12.73 percent of 75 kVA per phase at rated primary voltage, or approximately equal to 34.5 A (rms) per phase. Figures 4.9 – 4.12 show the results of the simulation. From the figures below it can be determined that there is an rms primary current of 33.9 A, secondary current of 33.4 A, and a transformer "core loss" current of 0.48 A, per phase. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 9 watts in each primary coil, 20 watts in each secondary coil, and 396 watts in the transformer core, with a load consuming approximately 9,203 watts per phase. Therefore the total transformer loss is 483 watts, with an efficiency of 98.2 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

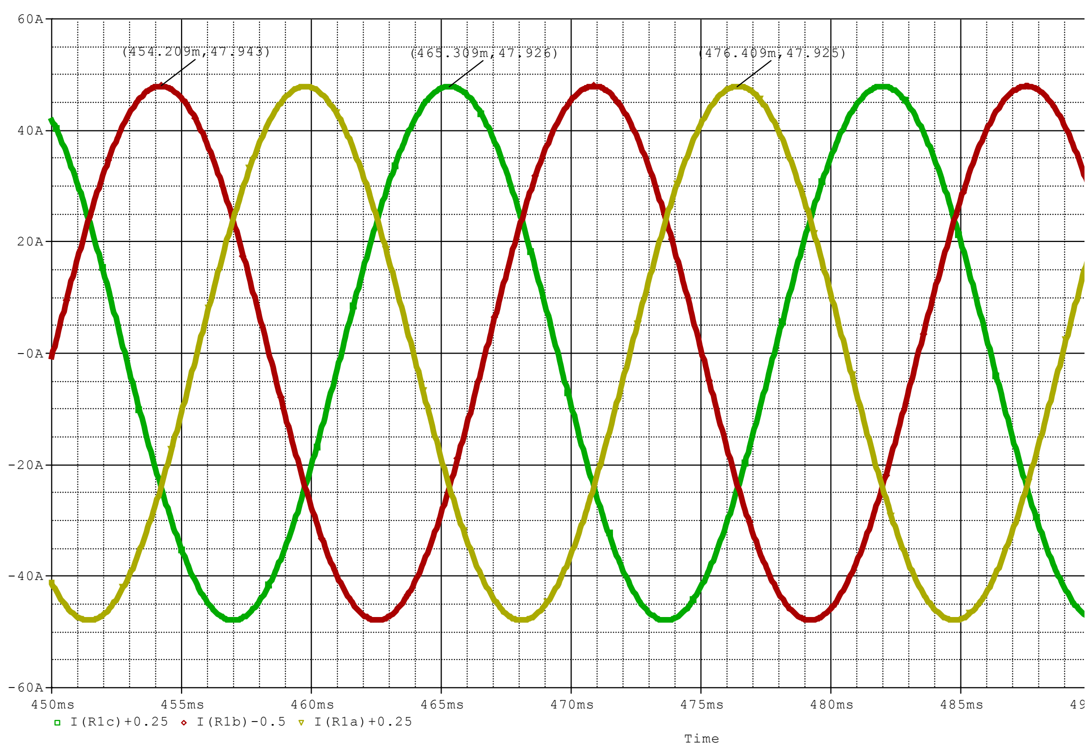


Figure 4.9 Balanced, Linear 12.73% Loading, 225 kVA – Primary Currents (peak)

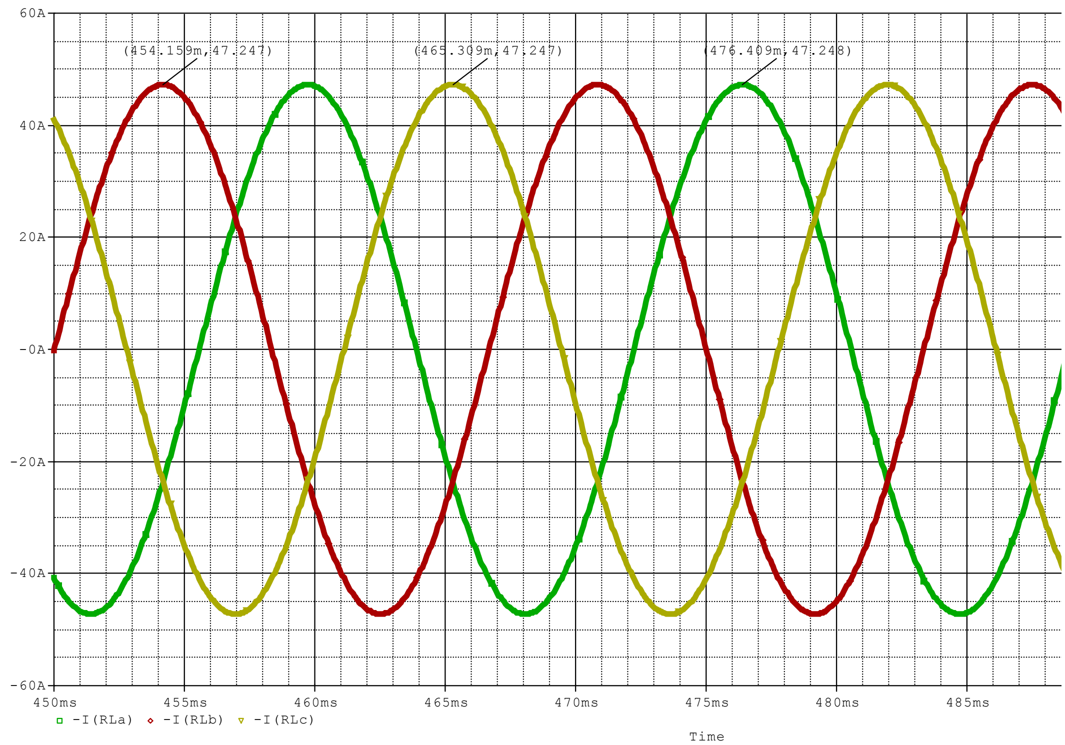


Figure 4.10 Balanced, Linear 12.73% Loading, 225 kVA – Secondary Currents (peak)

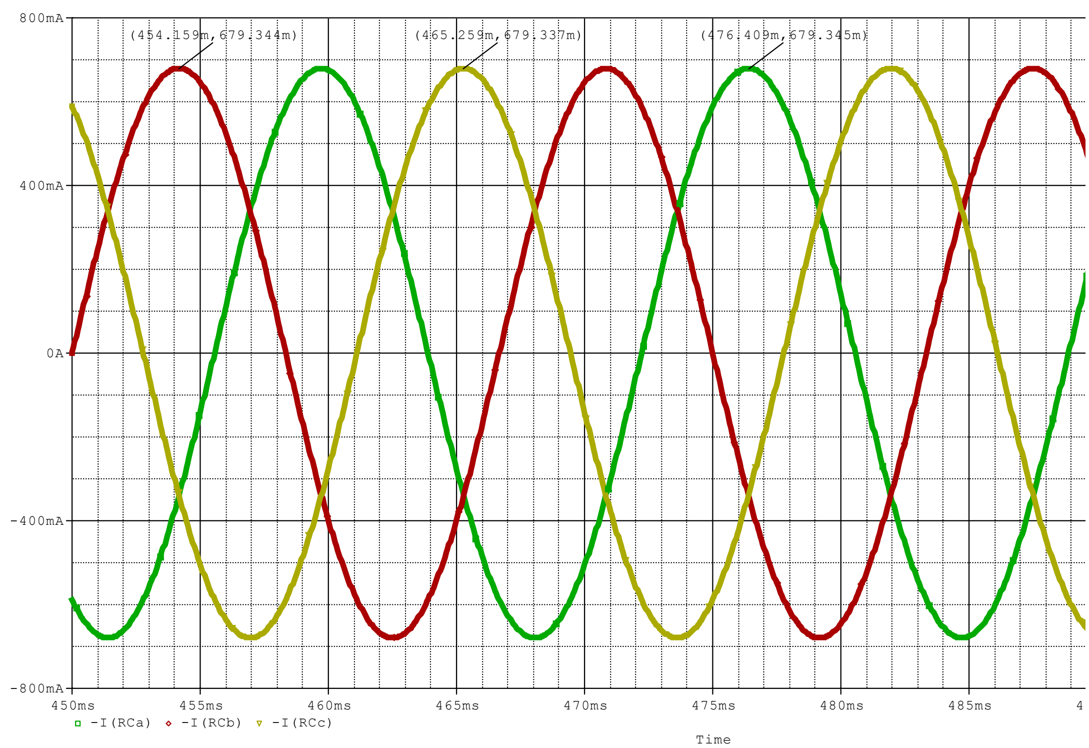


Figure 4.11 Balanced, Linear 12.73% Loading, 225 kVA – Current through *Rc* (peak)

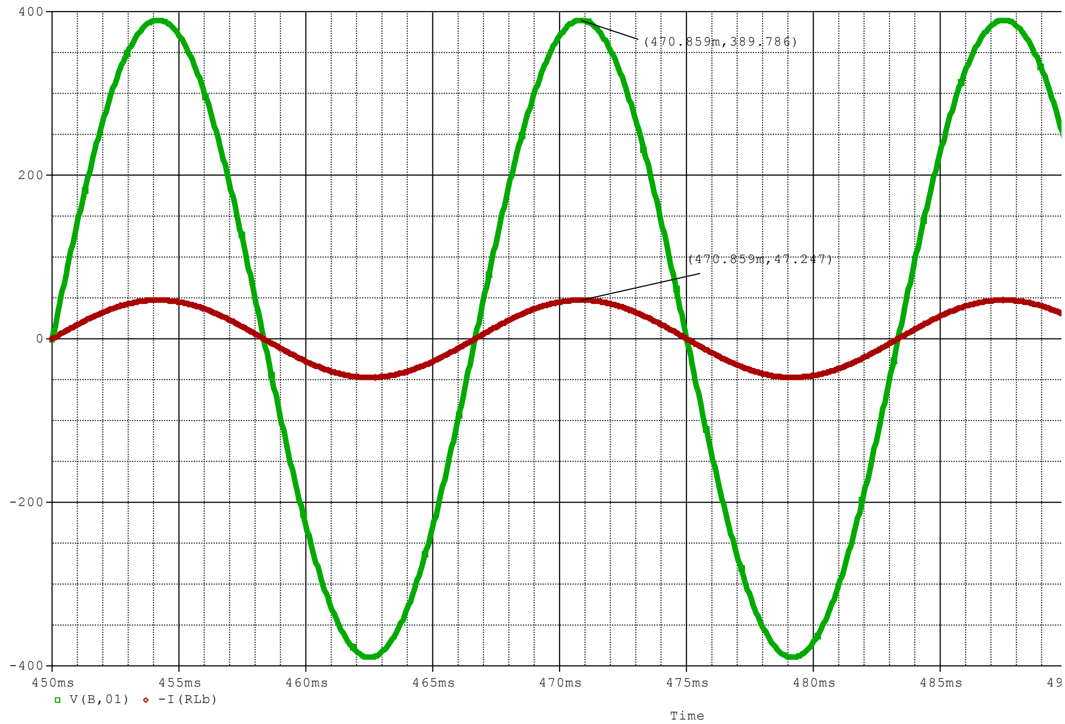


Figure 4.12 Balanced, Linear 12.73% Loading, 225 kVA – Load Phase Angle

4.2.4. Case 1c – Phases Balanced, Linear Loading of 6%

Utilizing the same default transformer and power factor from Case 1a, this case will examine a transformer with the field measured loading of 6 per cent. For this case, a load is needed that draws 6 percent of 225 kVA per phase at rated primary voltage, or approximately equal to 16.2 A (rms) per phase. Figures 4.13 – 4.16 show the results of the simulation. From the figures below it can be determined that there is an rms primary current of 16.26 A, secondary current of 15.8 A, and a transformer "core loss" current of 0.48 A, per phase. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 2 watts in each primary coil, 4 watts in each secondary coil, and 396 watts in the transformer core, with a load consuming approximately 4,369 watts per phase. Therefore the total transformer loss is 414 watts, with an efficiency of 96.9 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are noticeably lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

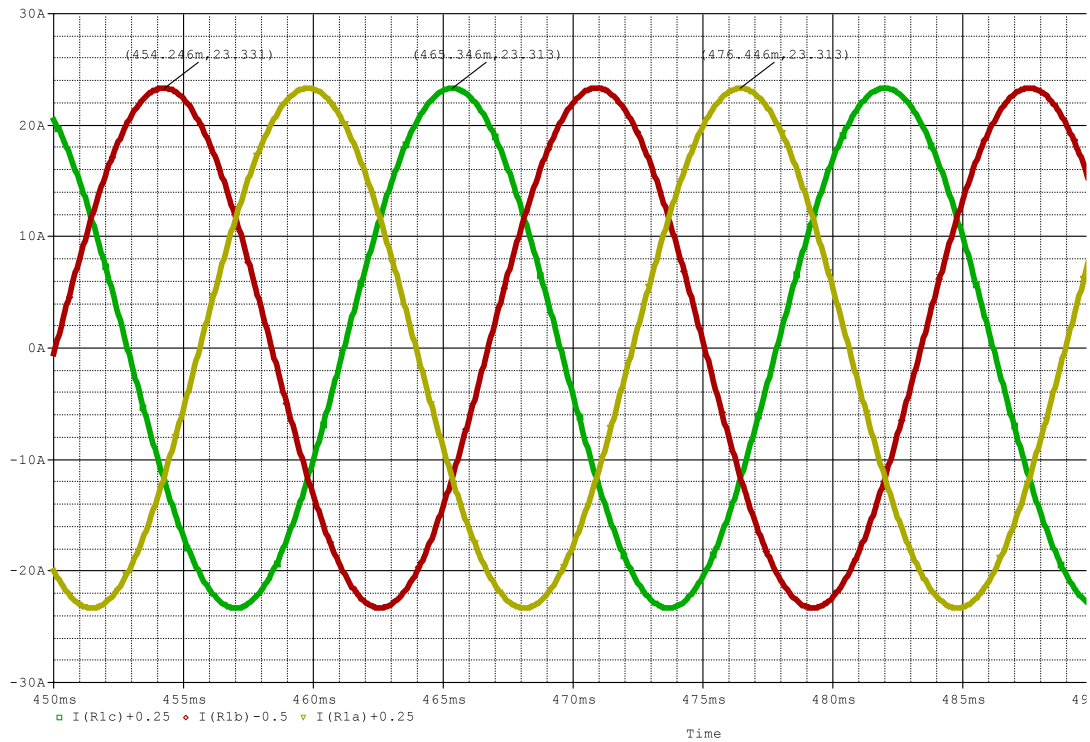


Figure 4.13 Balanced, Linear 6% Loading, 225 kVA – Primary Currents (peak)

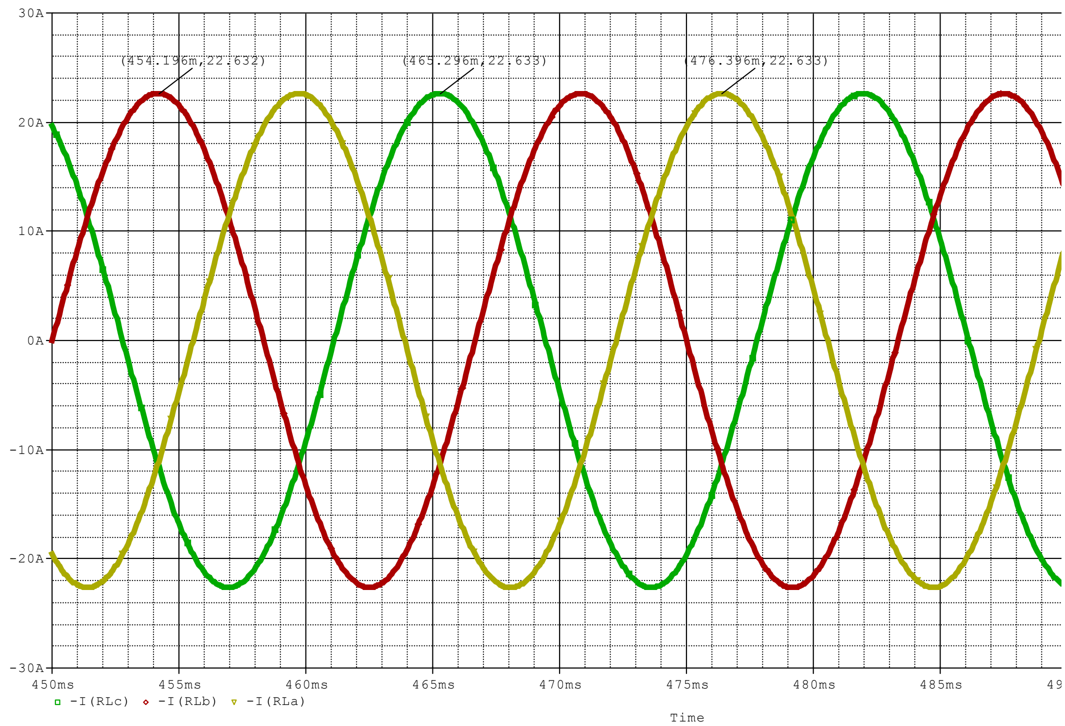


Figure 4.14 Balanced, Linear 6% Loading, 225 kVA – Secondary Currents (peak)

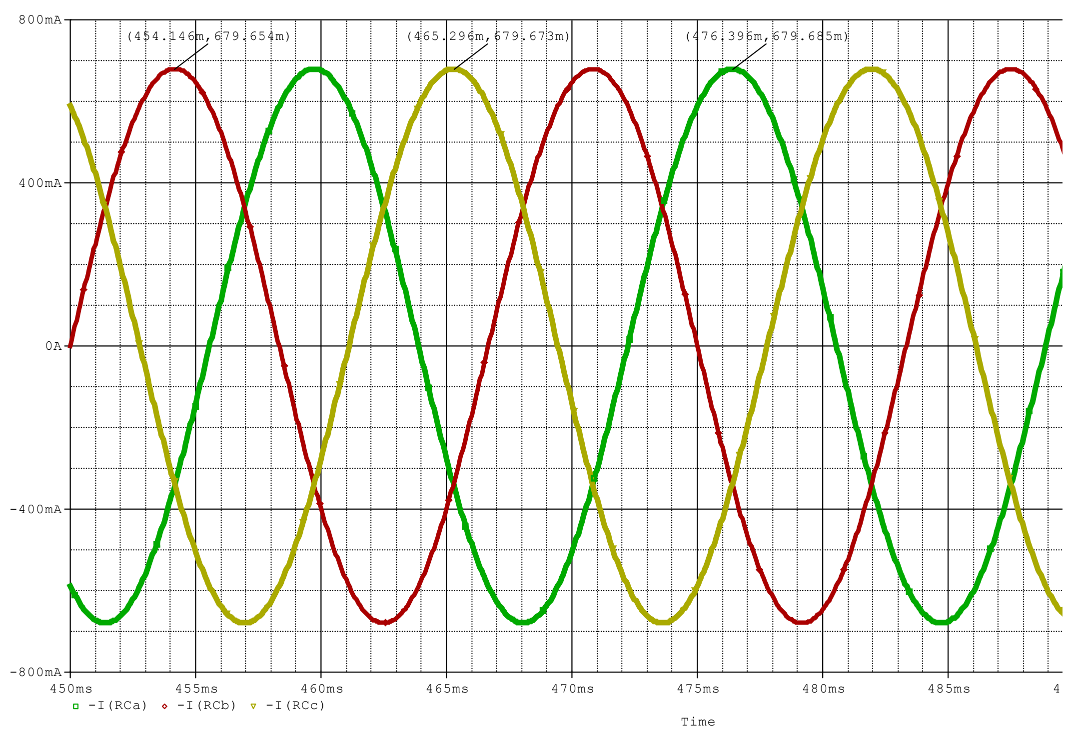


Figure 4.15 Balanced, Linear 6% Loading, 225 kVA – Current through *Rc* (peak)

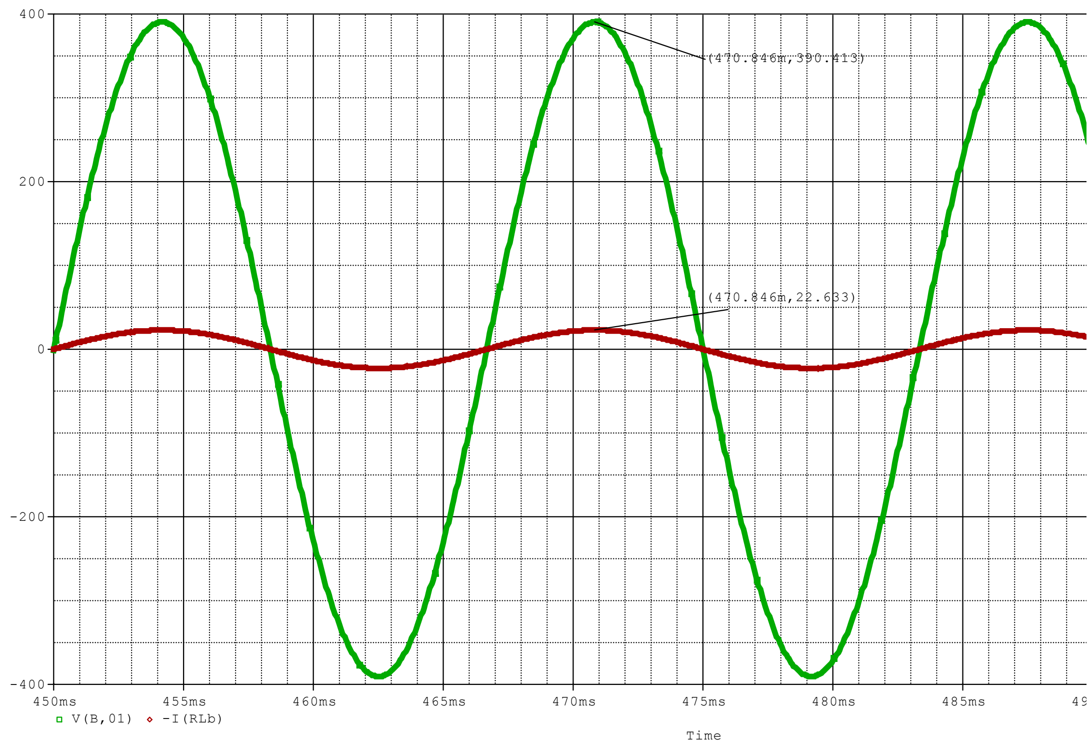


Figure 4.16 Balanced, Linear 6% Loading, 225 kVA – Load Phase Angle

4.2.5. Case 1d – Phases Balanced, Linear Loading of 38.19% and 18%

Case 1c will use a transformer that is rated for less power to supply the same loads as in Case 1b and 1c. A 12.73 per cent load and a 6 per cent load on the 225 kVA transformer translate to approximately a 38.19 per cent load and a 18 per cent load when supplied by a 75 kVA transformer, respectively. This case will represent the use of a transformer that is about one-third of the size of the original to power the same load. Using the same design process as outlined in Section 4.2.1, a separate default model was developed for a 75 kVA, based on manufacturer provided specifications. Figures 4.17 – 4.21 show the results of the simulation.

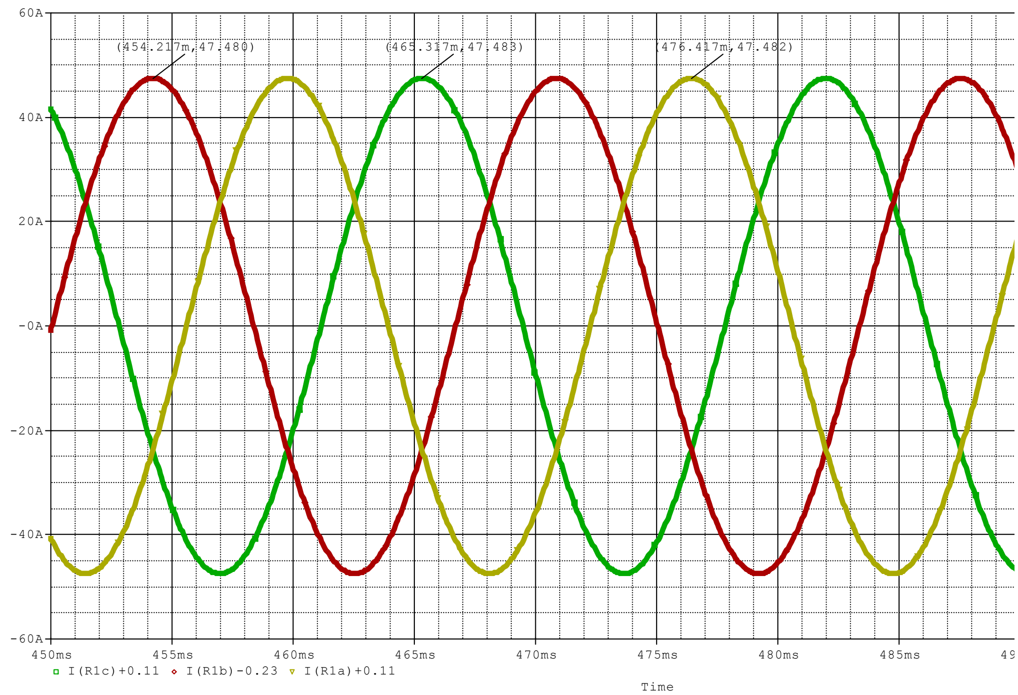


Figure 4.17 Balanced, Linear 38.19% Loading, 75 kVA – Primary Currents (peak)

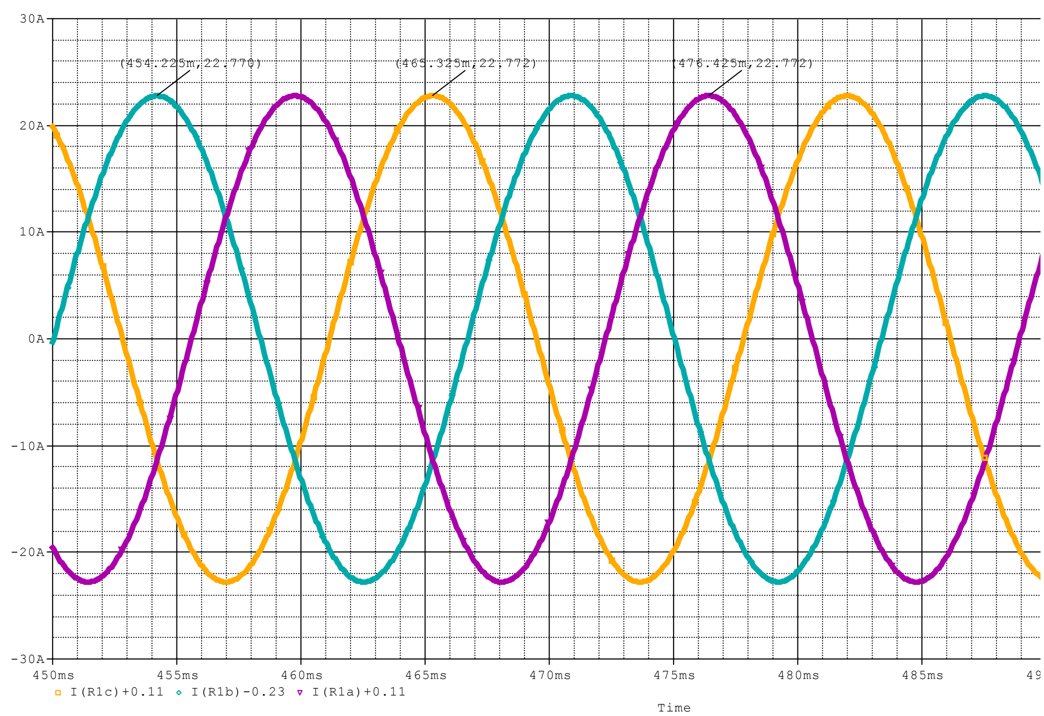


Figure 4.18 Balanced, Linear 18% Loading, 75 kVA – Primary Currents (peak)

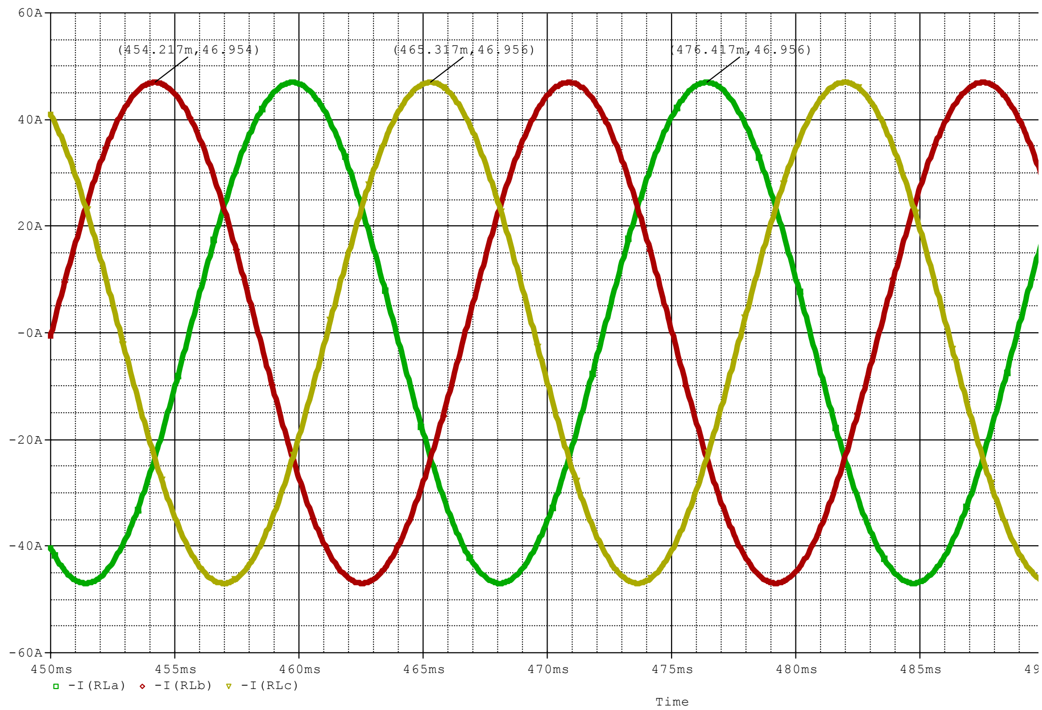


Figure 4.19 Balanced, Linear 38.19% Loading, 75 kVA – Secondary Currents (peak)

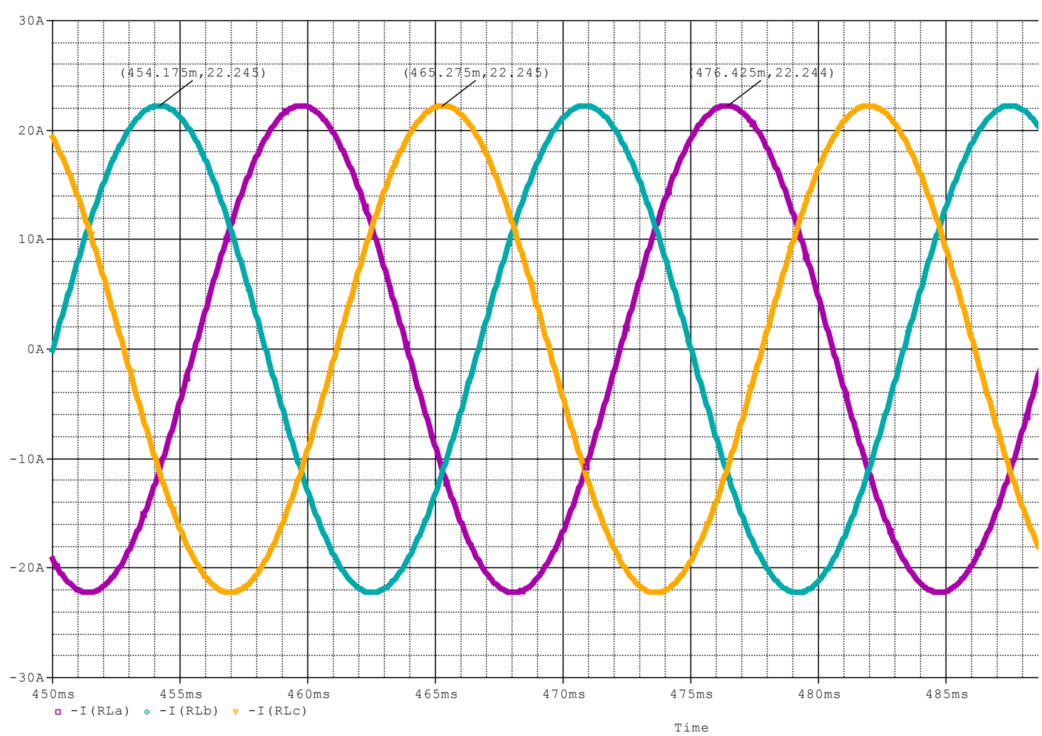


Figure 4.20 Balanced, Linear 18% Loading, 75 kVA – Secondary Currents (peak)

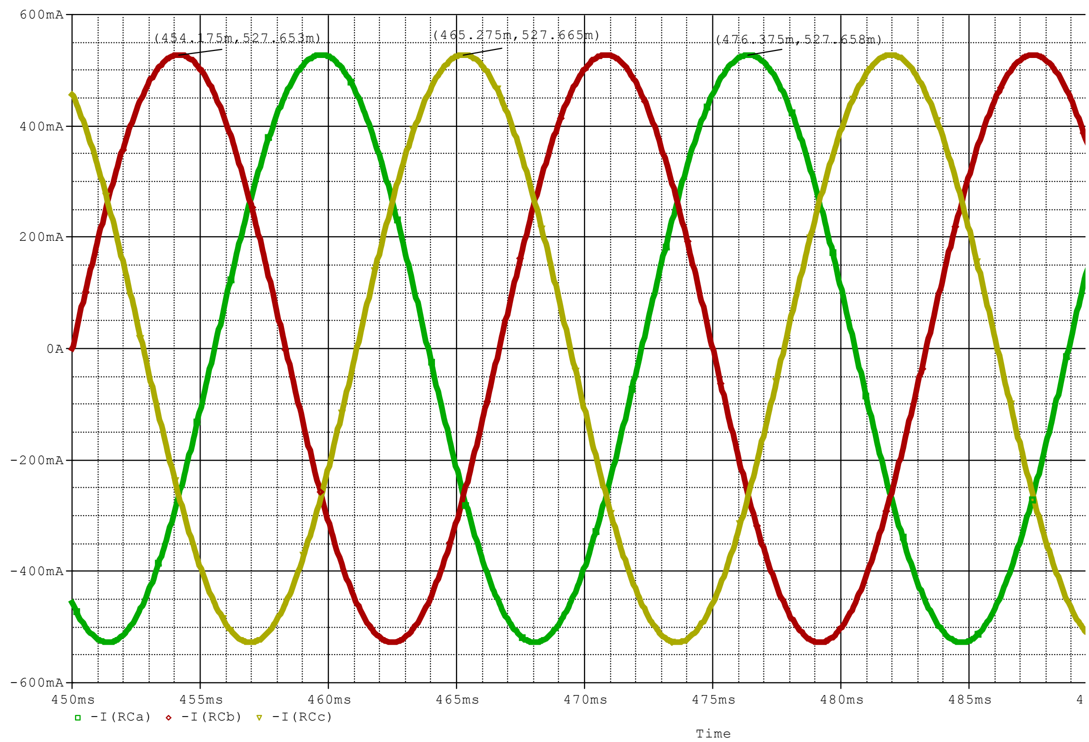


Figure 4.21 Balanced, Linear 38.19% and 15% Loading, 75 kVA – Current through *Rc*

From the figures above it can be determined that:

For 38.19% loading:

There is an rms primary current of 33.6 A, secondary current of 33.2 A, and a transformer "core loss" current of 0.37 A, per phase. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 26 watts in each primary coil, 58 watts in each secondary coil, and 306 watts in the transformer core, with a load consuming approximately 9,093 watts. Therefore the total transformer loss is 558 watts, with an efficiency of 98.0 per cent for this load, which matches the manufacturer advertised efficiency for this loading range.

For 18 % loading:

There is an rms primary current of 16 A, secondary current of 15.7 A, and a transformer "core loss" current of 0.37 A, per phase. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 6 watts in each primary coil, 13 watts in each secondary coil, and 306 watts in the transformer core, with a load consuming approximately 4,313 watts. Therefore the total transformer loss is 363 watts, with an efficiency of 97.3 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are slightly lower than the 97.8 per cent advertised efficiency at the 25 per cent loading level.

4.2.6. Case 2a – Phases Unbalanced, Linear Loading of 35%

This case will examine load conditions similar to Case 1a, however in this case the loads across the three phases will be unbalanced, and draw different amounts of current. This is a more realistic load profile in higher education commercial buildings than that of Case 1. One phase load will be set to 35 per cent of rated transformer power, while each of the other two phases will be set to approximately +20 per cent and -20 per cent of the default load, respectively. Additionally, a resistor with the same value as a single phase secondary coil will be inserted into the neutral conductor, allowing for observation of the neutral current and to simulate this additional current flowing through the three transformer secondary coils. As in Case 1, since this case is for linear loading, the load will be purely resistive. Figures 4.22 – 4.24 show the results of the simulation.

From the figures below it can be determined that there are rms primary currents of 95 A, 79.5 A, and 118 A; secondary currents of 94.5 A, 79 A, and 117.6 A; and a transformer "core loss" current of 0.48 A, per phase. Additionally, there is a neutral current of 33.4 A, which is equal to the sum of the unbalanced current from the three phases. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 223 watts in the three primary coils, 530 watts in the three secondary coils (including the additional value due to the unbalanced neutral current that circulates), and 396 watts in the transformer core, with a load consuming approximately 79,702 watts total. Therefore the total transformer loss is 1,149 watts, with an efficiency of 98.5 per cent for this load, which is only very slightly lower than the manufacturer advertised efficiency for this loading level.

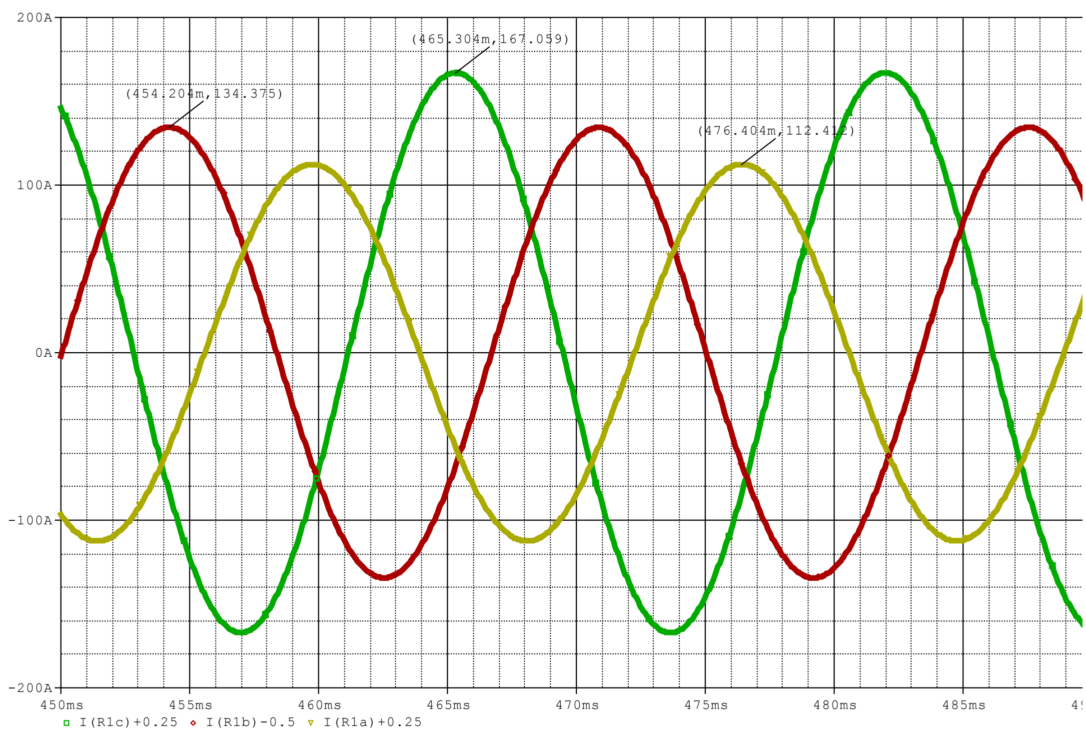


Figure 4.22 Unbalanced, Linear 35% Loading, 225 kVA – Primary Currents (peak)

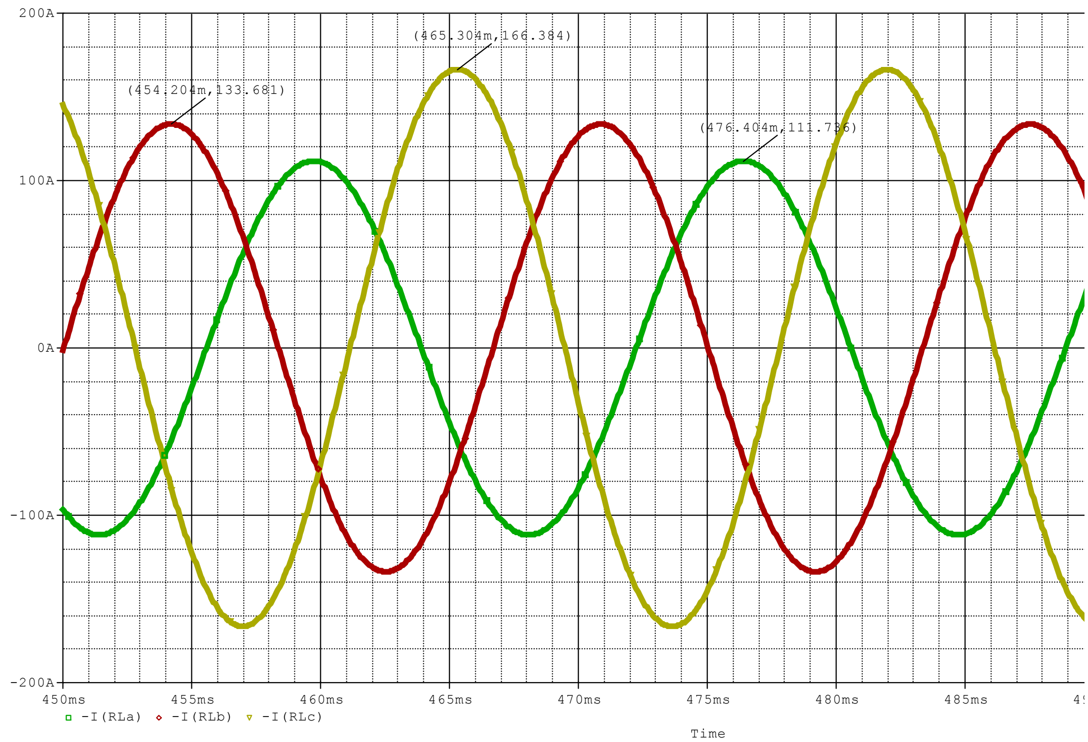


Figure 4.23 Unbalanced, Linear 35% Loading, 225 kVA – Secondary Currents (peak)

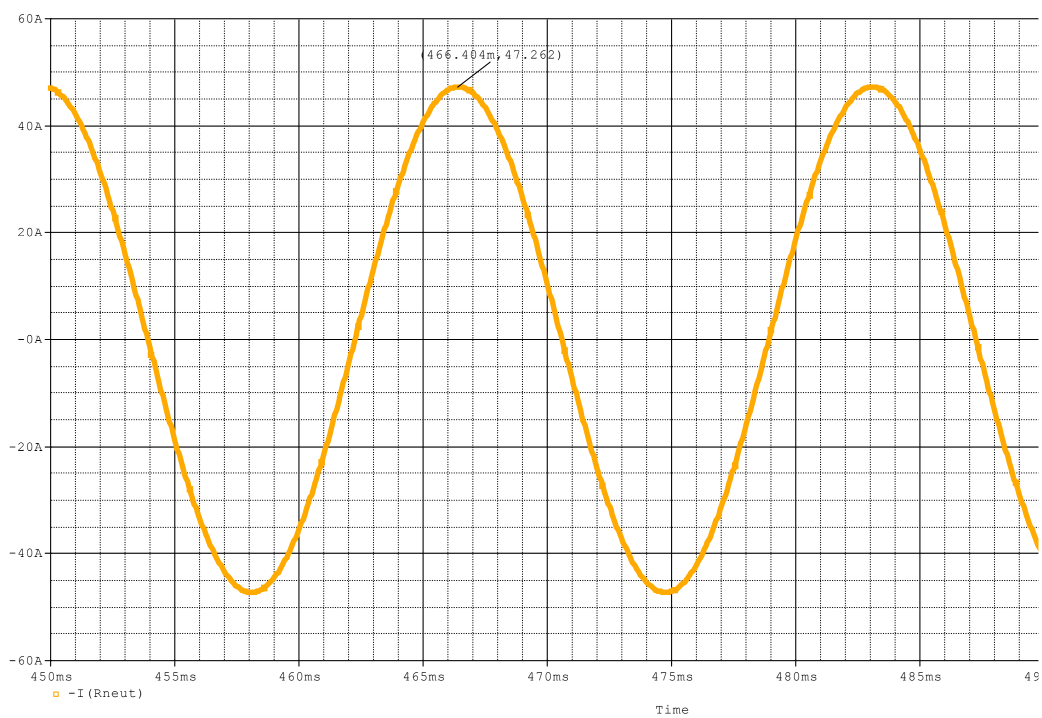


Figure 4.24 Unbalanced, Linear 35% Loading, 225 kVA – Neutral Current (peak)

4.2.7. Case 2b – Phases Unbalanced, Linear Loading of 12.73%

This case will be mostly the same as Case 2a, however the default load will be adjusted to approximately 12.73 per cent while each of the other two phases will be set to approximately +20 per cent and -20 per cent of the default load, respectively. Additionally, a resistor with the same value as a single phase secondary coil will be inserted into the neutral conductor, allowing for observation of the neutral current and to simulate this additional current flowing through the three transformer secondary coils. Figures 4.25 – 4.27 show the results of the simulation.

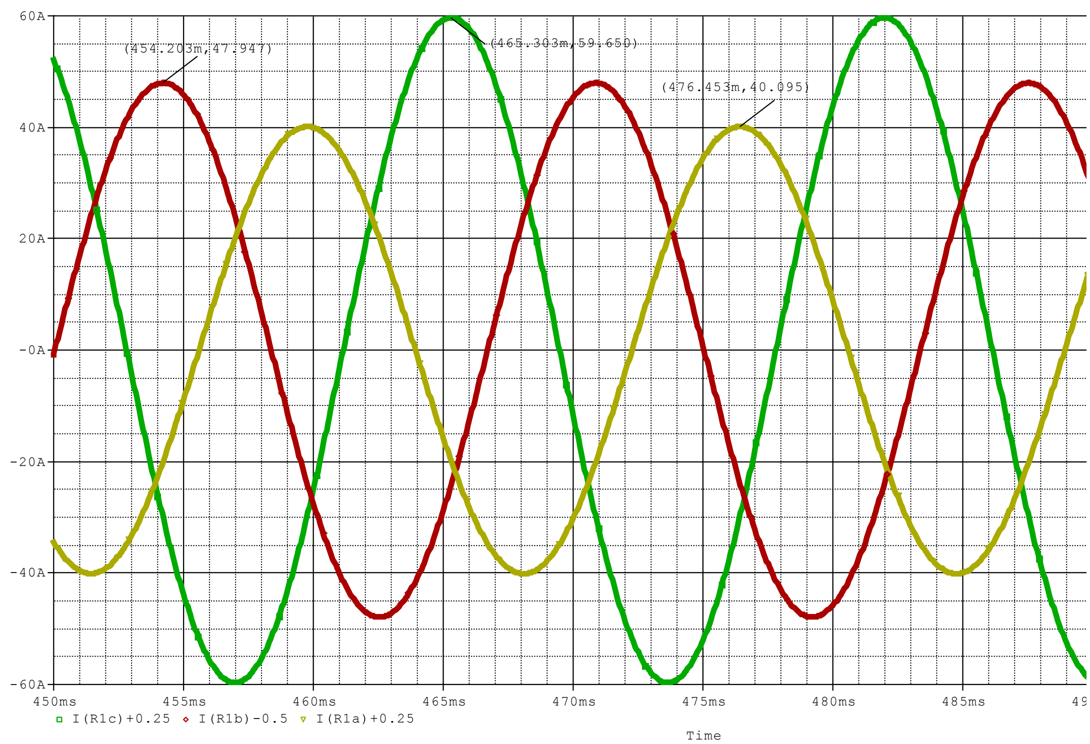


Figure 4.25 Unbalanced, Linear 12.73% Loading, 225 kVA – Primary Currents (peak)

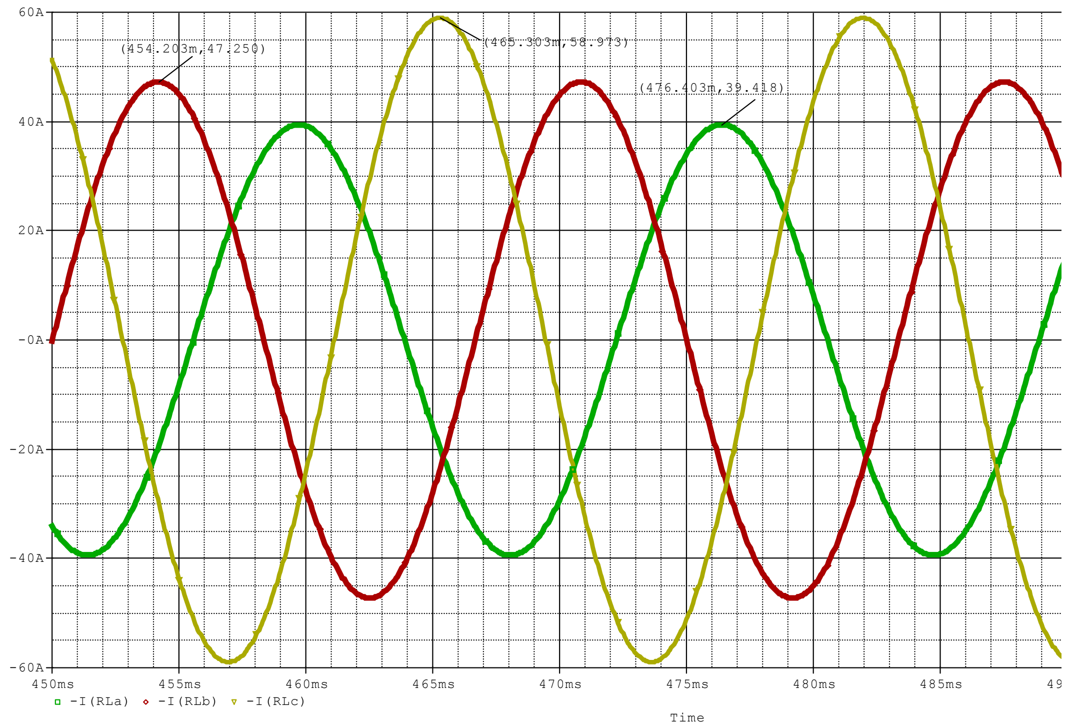


Figure 4.26 Unbalanced, Linear 12.73% Loading, 225 kVA – Secondary Currents (peak)

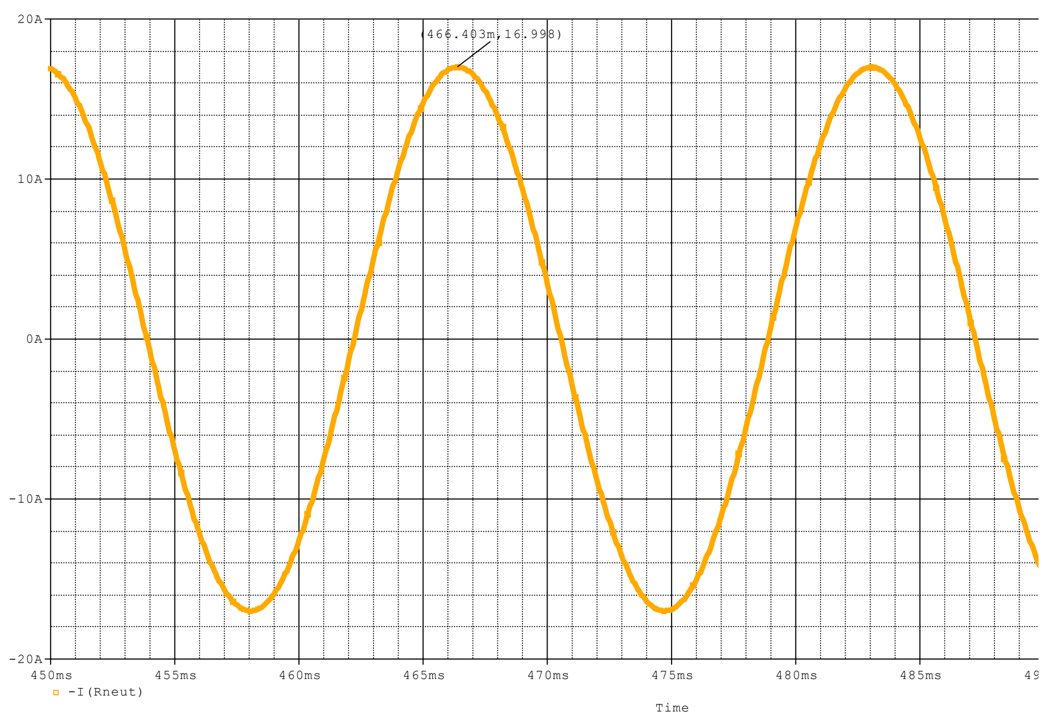


Figure 4.27 Unbalanced, Linear 12.73% Loading, 225 kVA – Neutral Current (peak)

From the figures above it can be determined that there are rms primary currents of 33.9 A, 28.3 A, and 42.1 A; secondary currents of 33.2 A, 27.9 A, and 41.6 A; and a transformer "core loss" current of 0.48 A, per phase. Additionally, there is a neutral current of 12 A, which is equal to the sum of the unbalanced current from the three phases. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 28 watts in the three primary coils, 66 watts in the three secondary coils (including the additional value due to the unbalanced neutral current that circulates), and 396 watts in the transformer core, with a load consuming approximately 28,220 watts total. Therefore the total transformer loss is 490 watts, with an efficiency of 98.2 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

4.2.8. Case 2c – Phases Unbalanced, Linear Loading of 6%

This case will be mostly the same as Case 2a, however the default load will be adjusted to approximately 6 per cent while each of the other two phases will be set to approximately +20 per cent and -20 per cent of the default load, respectively. Again, a resistor with the same value as a single phase secondary coil will be inserted into the neutral conductor, allowing for observation of the neutral current and to simulate this additional current flowing through the three transformer secondary coils. Figures 4.28 – 4.30 show the results of the simulation.

From the figures below it can be determined that there are rms primary currents of 16.3 A, 13.6 A, and 20.2 A; secondary currents of 15.8 A, 13.2 A, and 19.7 A; and a transformer “core loss” current of 0.48 A, per phase. Additionally, there is a neutral current of 5.6 A, which is equal to the sum of the unbalanced current from the three phases. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 7 watts in the three primary coils, 15 watts in the three secondary coils (including the additional value due to the unbalanced neutral current that circulates), and 396 watts in the transformer core, with a load consuming approximately 13,460 watts total. Therefore the total transformer loss is 418 watts, with an efficiency of 96.9 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

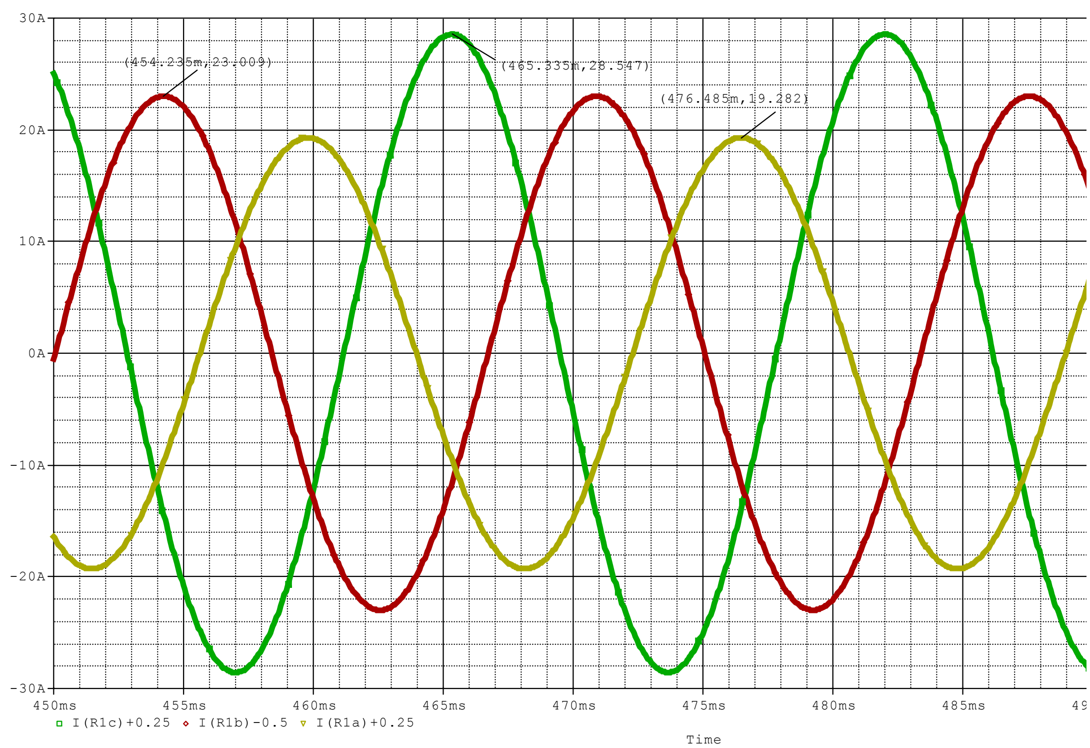


Figure 4.28 Unbalanced, Linear 6% Loading, 225 kVA – Primary Currents (peak)

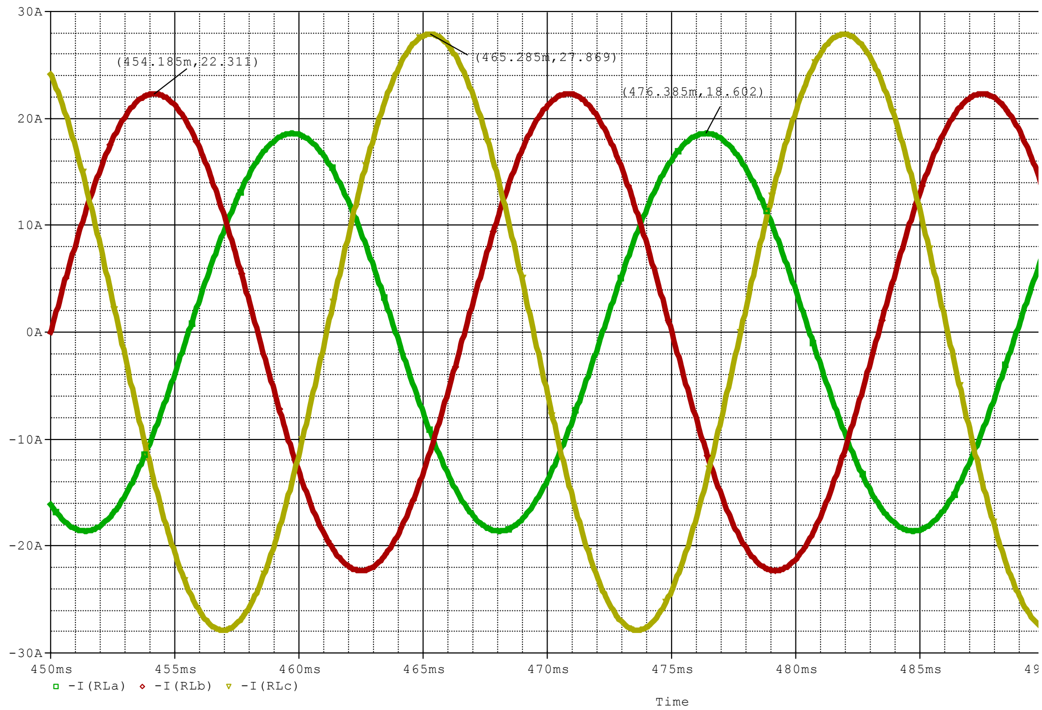


Figure 4.29 Unbalanced, Linear 6% Loading, 225 kVA – Secondary Currents (peak)

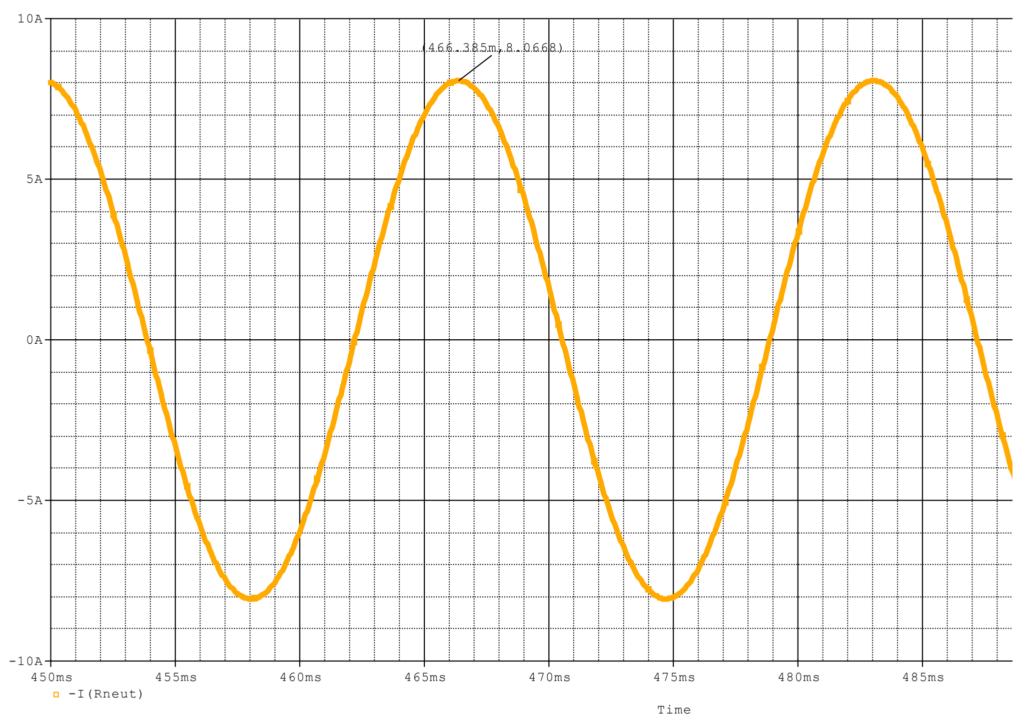


Figure 4.30 Unbalanced, Linear 6% Loading, 225 kVA – Neutral Current (peak)

4.2.9. Case 2d – Phases Unbalanced, Linear Loading of 38.19% and 18%

This case uses the same methodology as outlined in Case 1d, with the inclusion of a variation in loading per phase by 20 per cent, similar to the other sub-cases in this set. Again, a 75 kVA transformer will be used in this simulation, with both 38.19 percent and 18 per cent loading, representing reductions for previous loading of 12.73 per cent and 6 per cent, respectively. Figures 4.31 – 4.36 show the results of the simulation.

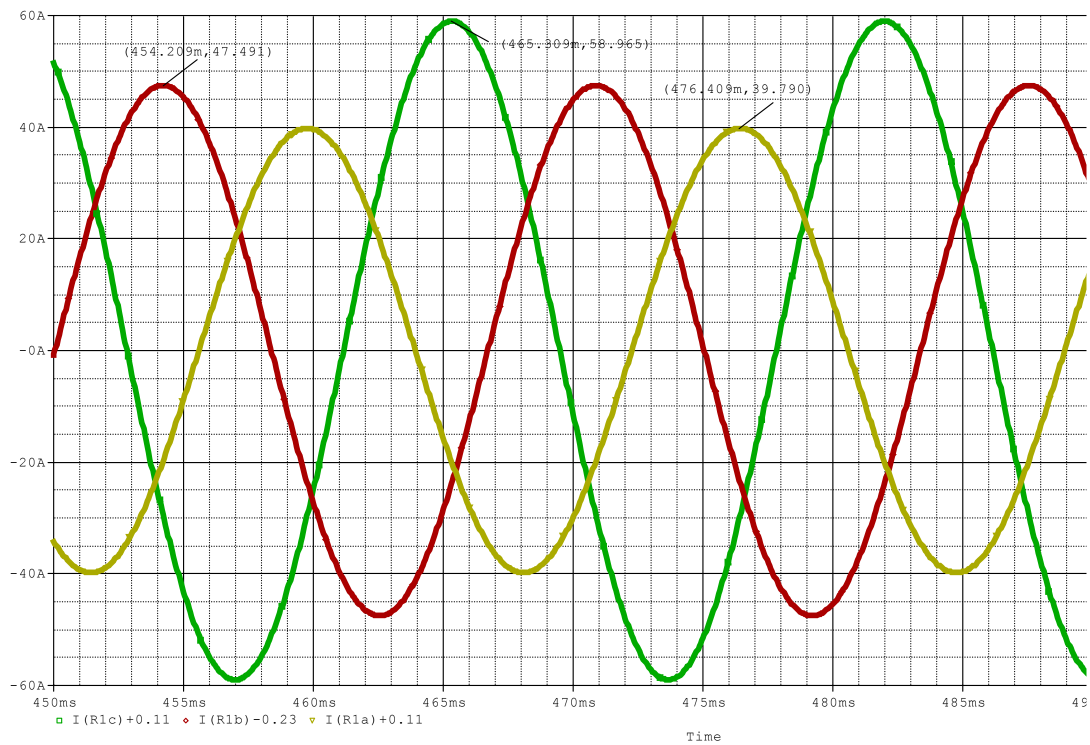


Figure 4.31 Unbalanced, Linear 38.19% Loading, 75 kVA – Primary Currents (peak)

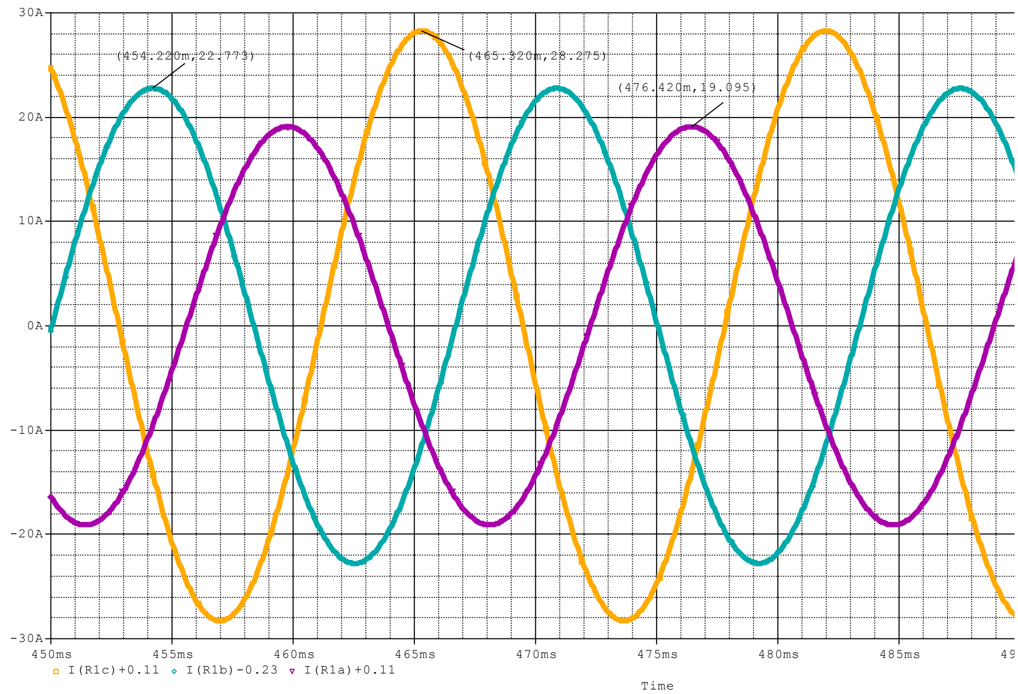


Figure 4.32 Unbalanced, Linear 18% Loading, 75 kVA – Primary Currents (peak)

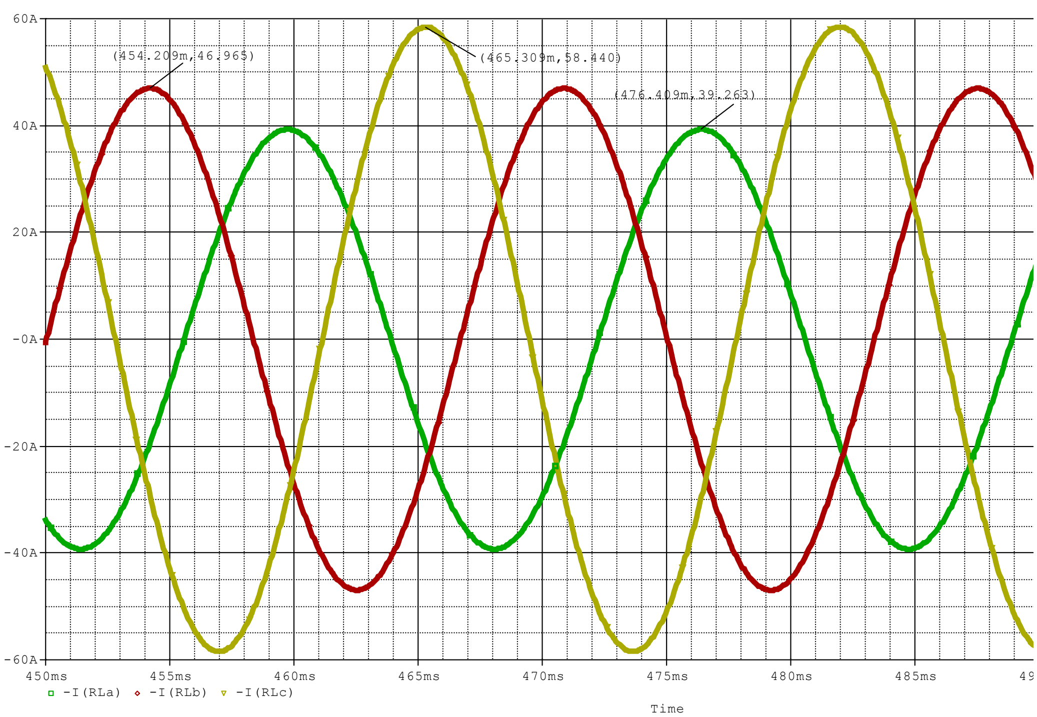


Figure 4.33 Unbalanced, Linear 38.19% Loading, 75 kVA – Secondary Currents (peak)

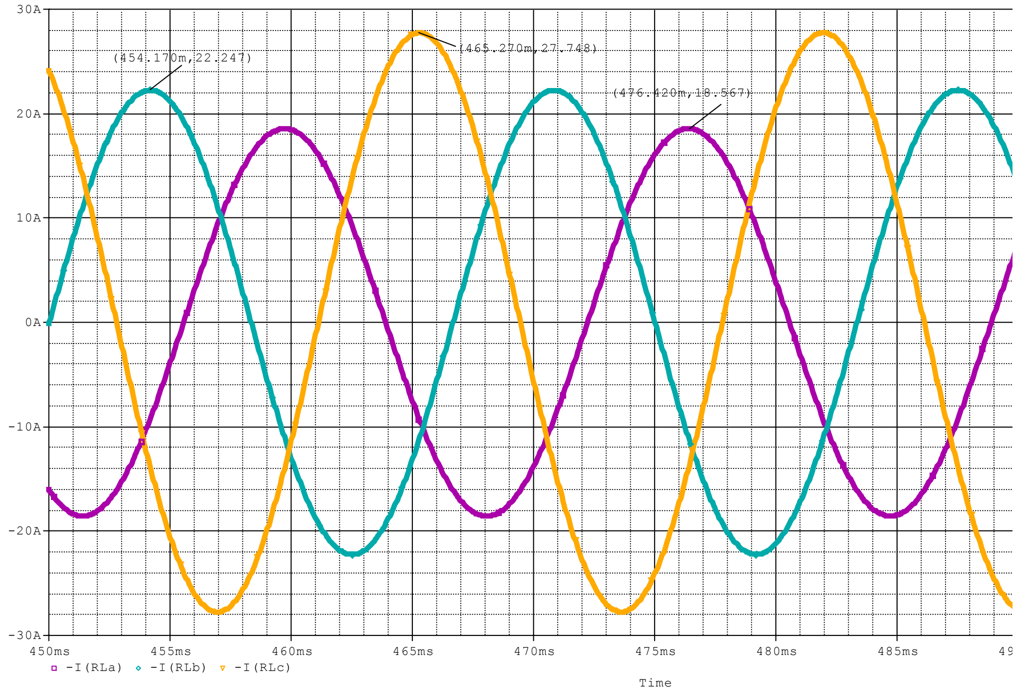


Figure 4.34 Unbalanced, Linear 18% Loading, 75 kVA – Secondary Currents (peak)

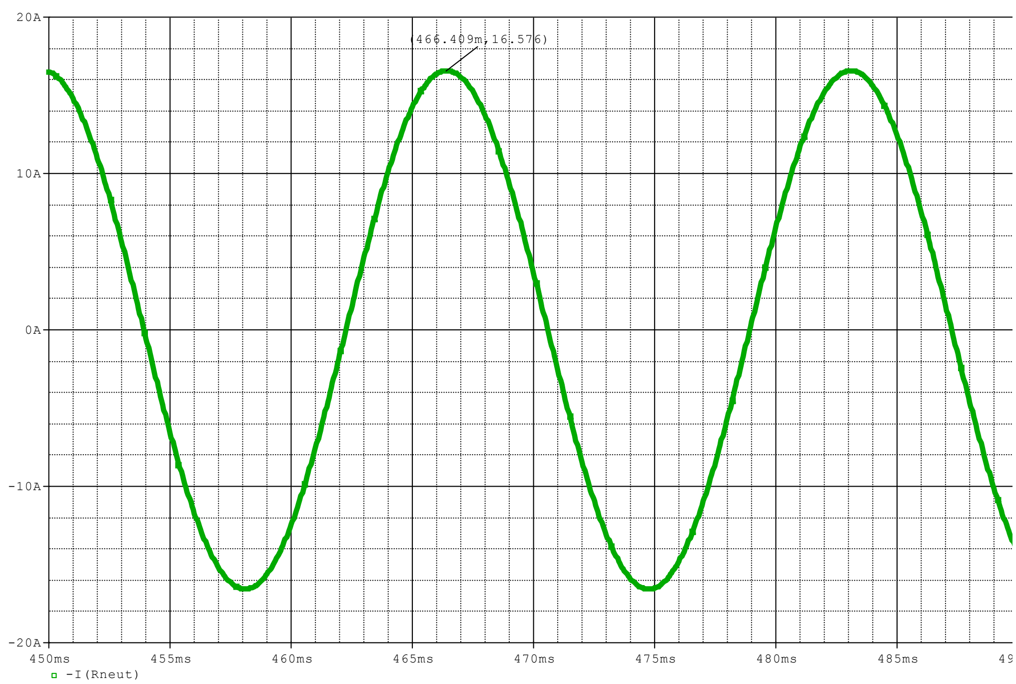


Figure 4.35 Unbalanced, Linear 38.17% Loading, 75 kVA – Neutral Current (peak)

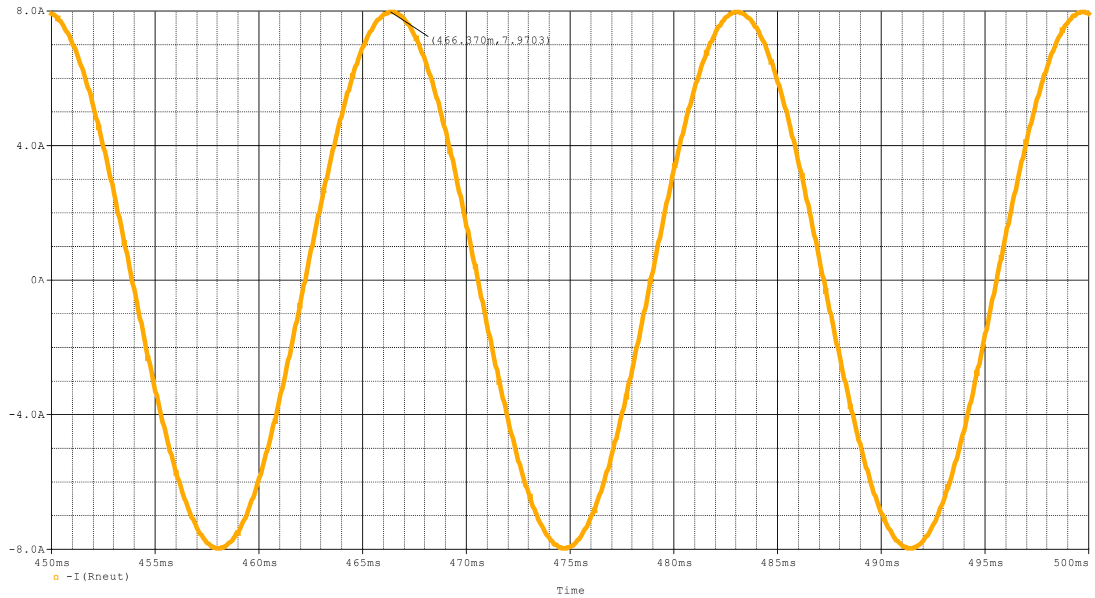


Figure 4.36 Unbalanced, Linear 18% Loading, 75 kVA – Neutral Current (peak)

From the figures above it can be determined that:

For 38.19% loading:

There are rms primary currents of 33.6 A, 28.1 A, and 41.7 A; secondary currents of 33.2 A, 27.8 A, and 41.3 A; and a transformer "core loss" current of 0.37 A, per phase. Additionally, there is a neutral current of 11.7 A, which is equal to the sum of the unbalanced current from the three phases. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 85 watts in the three primary coils, 197 watts in the three secondary coils (including the additional value due to the unbalanced neutral current that circulates), and 306 watts in the transformer core, with a load consuming approximately 21,102 watts total. Therefore the total transformer loss is 588 watts, with an efficiency of 97.3 per cent for this load, which is lower than the manufacturer advertised efficiency for this loading range.

For 18% loading:

There are rms primary currents of 16.1 A, 13.3 A, and 19.9 A; secondary currents of 15.73 A, 13 A, and 19.6 A; and a transformer "core loss" current of 0.37 A, per phase. Additionally, there is a neutral current of 5.6 A, which is equal to the sum of the unbalanced current from the three phases. From these currents and the various resistor values, one can determine the loss through each of the circuit components. There is a loss of 19 watts in the three primary coils, 44 watts in the three secondary coils (including the additional value due to the unbalanced neutral current that circulates), and 306 watts in the transformer core, with a load consuming approximately 13,257 watts total. Therefore the total transformer loss is 369 watts, with an efficiency of 97.3 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

4.2.10. Case 3a – Phases Unbalanced, Non-linear Loading of 35%

The next set of cases will address a common higher education load profile where the three phases are not only unbalanced, but also supplying non-linear current drawing loads like single phase SMPS. These types of loads tend to draw high amounts of 3^{rd} harmonics, leading to increased losses as discussed in Chapter 3. The neutral conductor in this case will not only carry the unbalanced fundamental frequency current but also the 3rd and other triplen harmonics, which will circulate through the transformer secondary, leading to a further increase in losses. The full-bridge rectifier shown in Figure 3.8 will be used in Pspice to simulate the non-linear load for each phase. For this first case, a single phase load of 35 per cent will be used. The other two phases will be varied by +20 and -20 per cent to simulate the imbalance. Figures 4.37 – 4.42 show the results of the simulation.

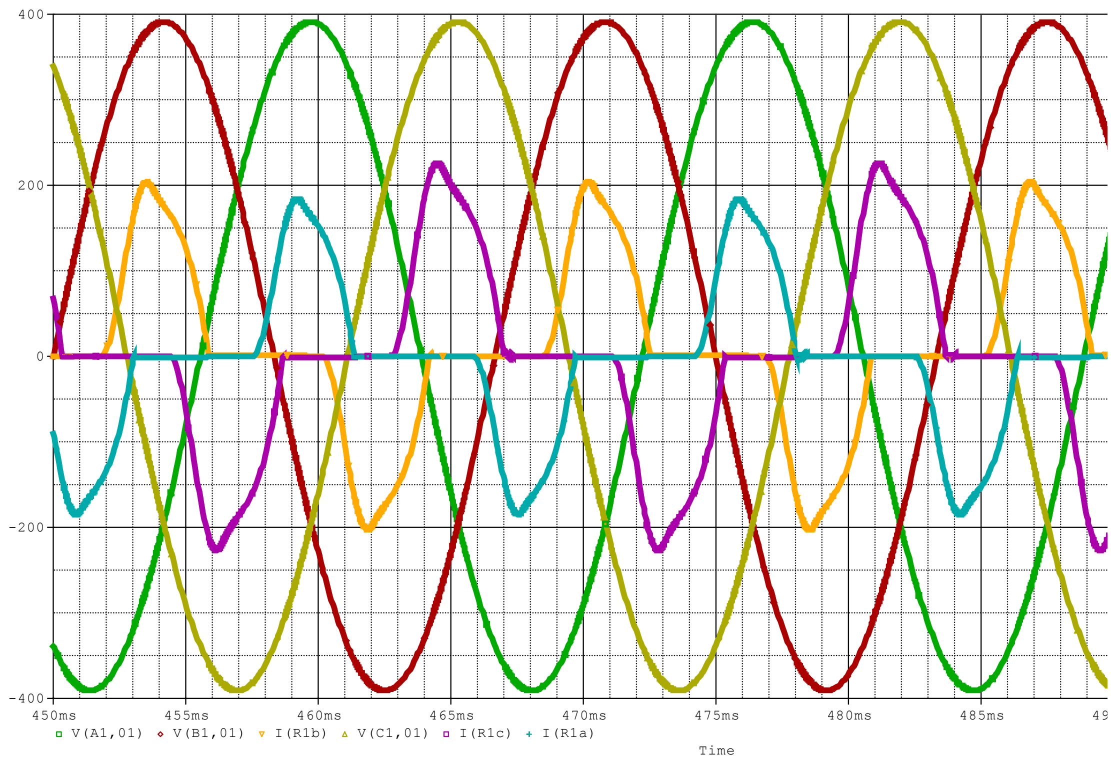


Figure 4.37 Unbalanced, Non-Linear 35% Loading, 225 kVA – Primary Phase-to-Ground Voltages and Currents (peak)

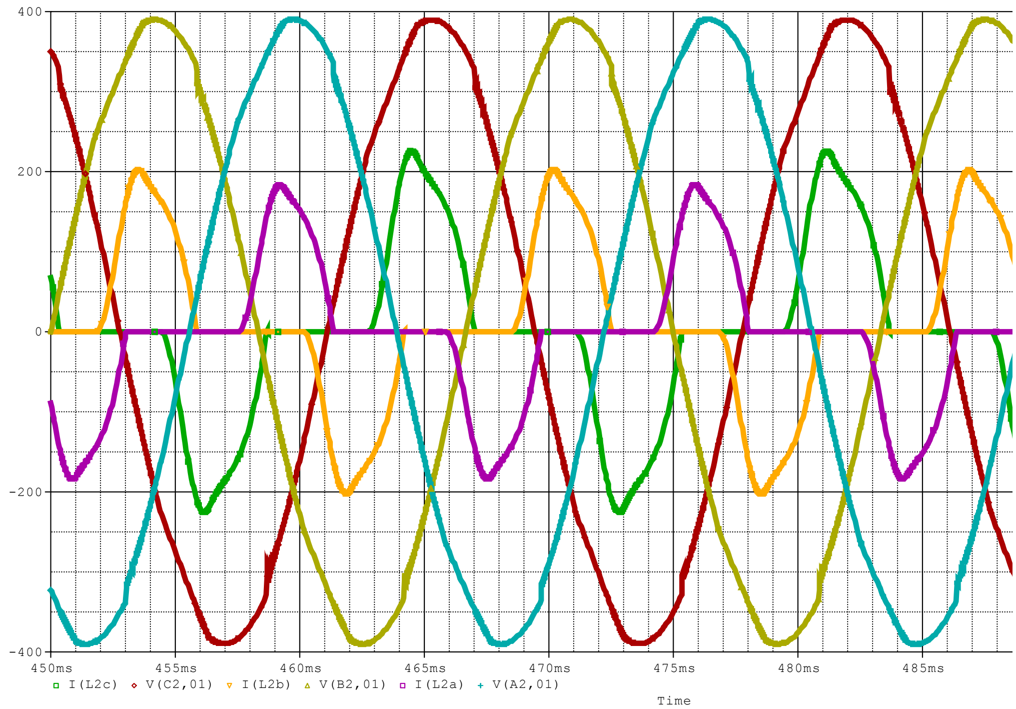


Figure 4.38 Unbalanced, Non-Linear 35% Loading, 225 kVA – Secondary Phase-to-Ground Voltages and Currents (peak)

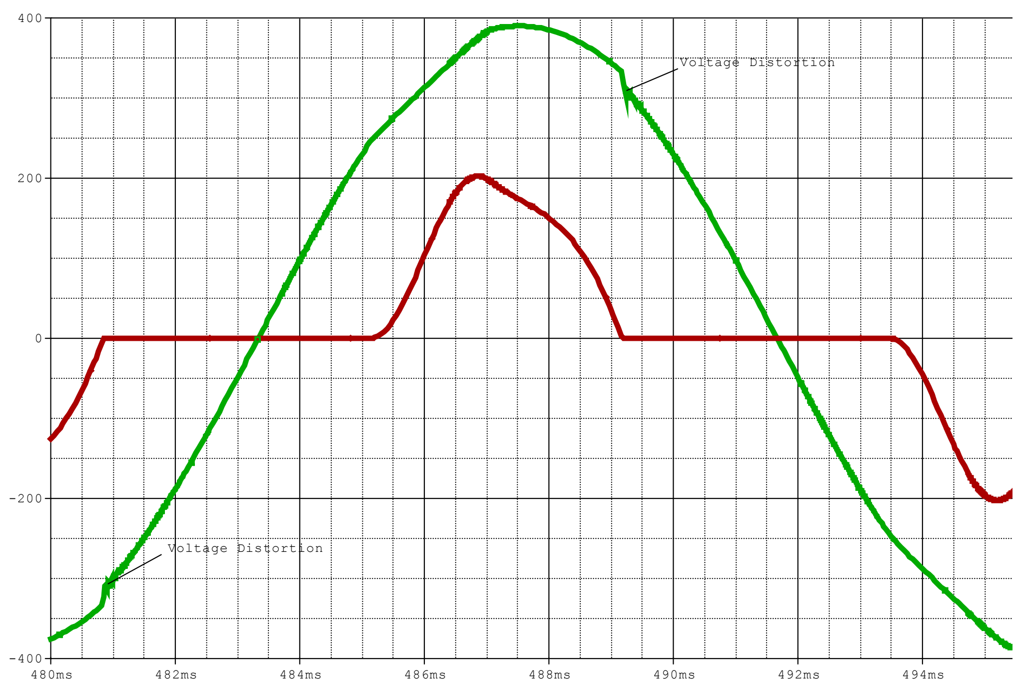


Figure 4.39 Unbalanced, Non-Linear 35% Loading, 225 kVA – Single Phase-to-Ground Secondary Voltage Distortion (peak)

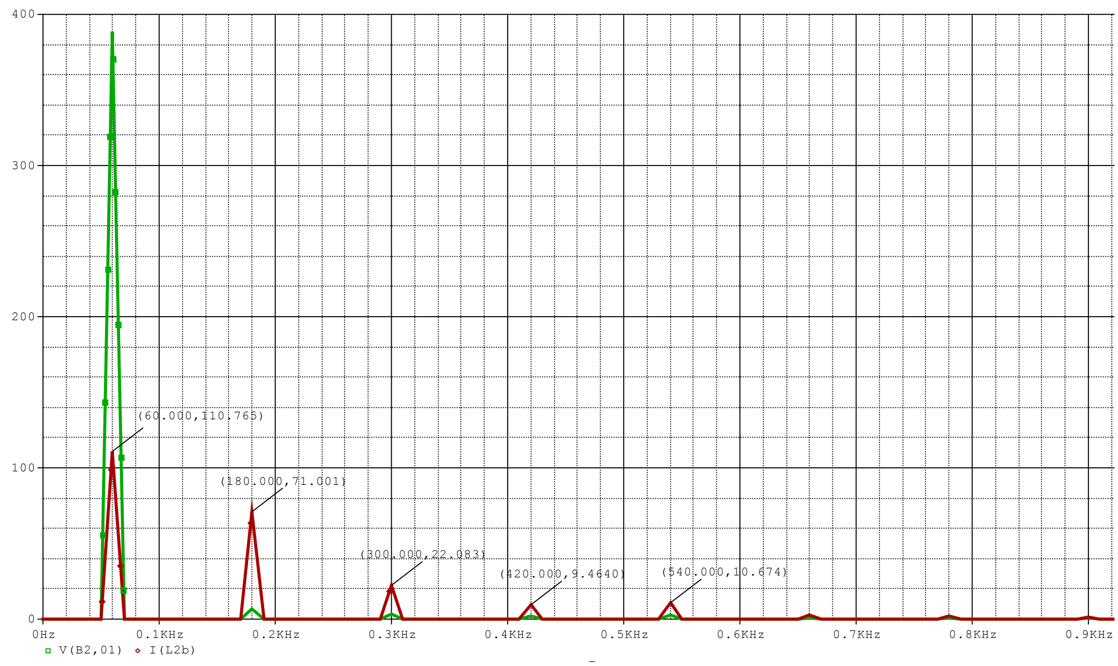


Figure 4.40 Unbalanced, Non-Linear 35% Loading, 225 kVA – Secondary Single Phase-to-Ground Voltage and Current Frequency Content (peak)

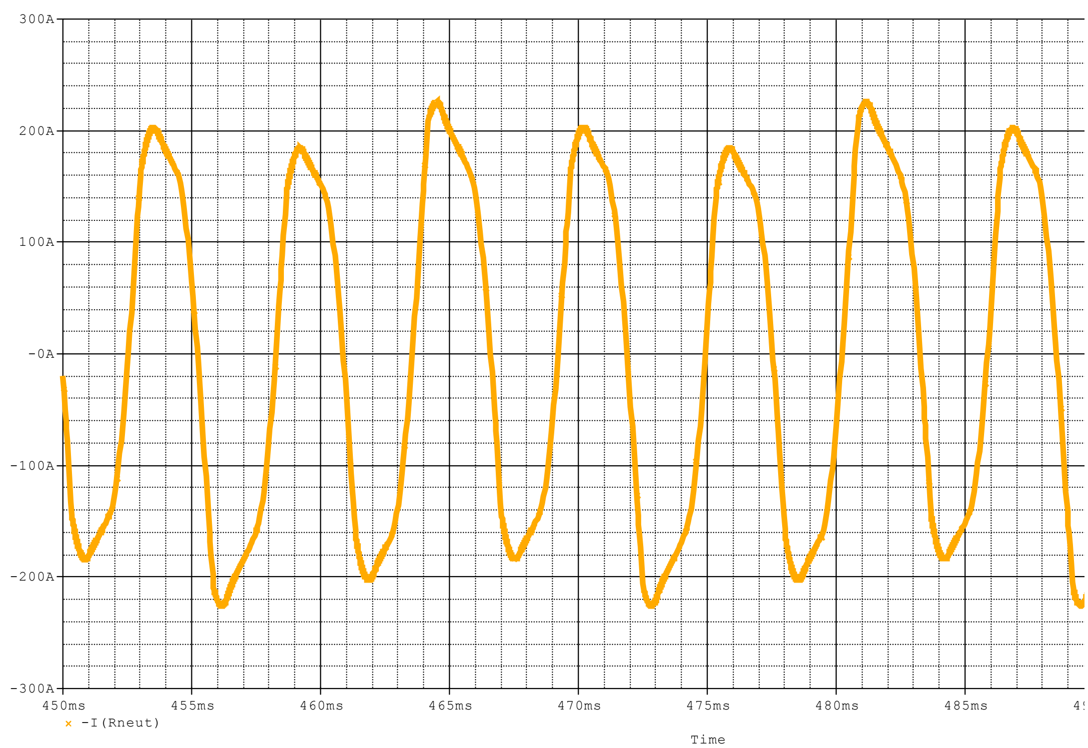


Figure 4.41 Unbalanced, Non-Linear 35% Loading, 225 kVA – Neutral Current (peak)

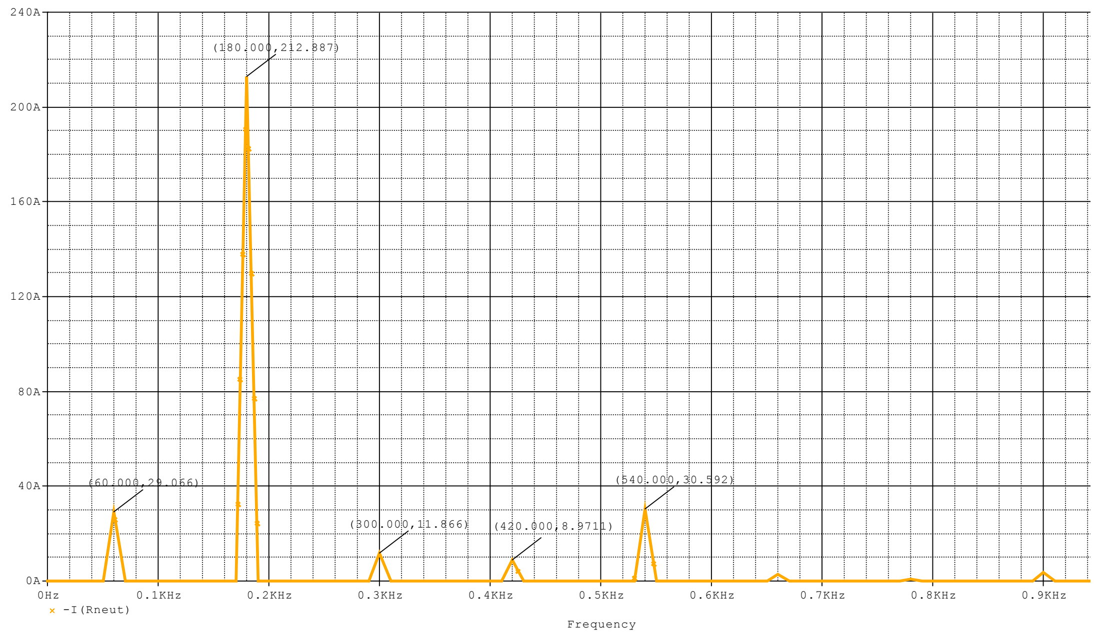


Figure 4.42 Unbalanced, Non-Linear 35% Loading, 225 kVA – Neutral Current Frequency Content (peak)

From Figures 4.37 – 4.39 it is clear that significant THD is existent in both the primary and secondary transformer currents. For the primary currents, the Pspice output file displays a THD of 67.99%, 72.57%, and 62.9% and rms values calculated using equation 3.5.2 of 95.17 A, 84.5 A, and 108.89 A. Primary voltages-to-ground have such small amounts of THD that it can be considered negligible, as seen by the sinusoidal waveform in Figure 4.37. For the secondary currents, the Pspice output file displays a THD of 68.42%, 73.06%, and 63.27% and rms values calculated using equation 3.5.2 of 94.83 A, 84.14 A, and 108.52 A. Secondary phase-to-ground voltages, as evident from one phase example in Figure 4.39, contain small amounts of distortion, with THD's of 2.15%, 2.02%, and 2.33%. Both the secondary currents and phase-to-ground voltages are dominated by the 3rd Harmonic, with smaller amounts coming from 5th, 7th, and 9th.

Losses due to neutral current flow must also be considered. Neutral current magnitude and frequency content is shown in Figures 4.41 and 4.42, with a THD of 738.7% and an rms value of 153.56 A. The unbalanced current from the three phases is only contributing about 20.64 A, while the majority of the rest comes from the triplen harmonics generated by the load. As previously stated, the neutral rms current will return to and circulate through the transformer secondary, increasing the losses. Using equations 3.5.3 to determine the transformer input power equation 3.5.4 to determine the output power to the load, transformer efficiency can be calculated. The input powers for each phase are 21,710 watts, 18,904 watts, and 25,326 watts, plus an additional 415 watts accounting for the loss due to the excess neutral current, for a total of 66,355 watts. The powers to the loads for each phase are 21,288 watts, 18,517 watts, and 24,780 watts, for a total of 64,585 watts. Total transformer losses are 1,770 watts with an efficiency of 97.3 per cent for this load. This is noticeably lower than the advertised efficiency of 98.6 per cent that is advertised and was realized through simulation in Cases 1a and 2a.

4.2.11. Case 3b – Phases Unbalanced, Non-linear Loading of 12.73%

This case will be the same as Case 3a, with the exception of the default load being adjusted to the higher education average of 12.73 per cent and the other two phases being increased/decreased by 20 per cent. Figures 4.43 – 4.45 show the results of the simulation.

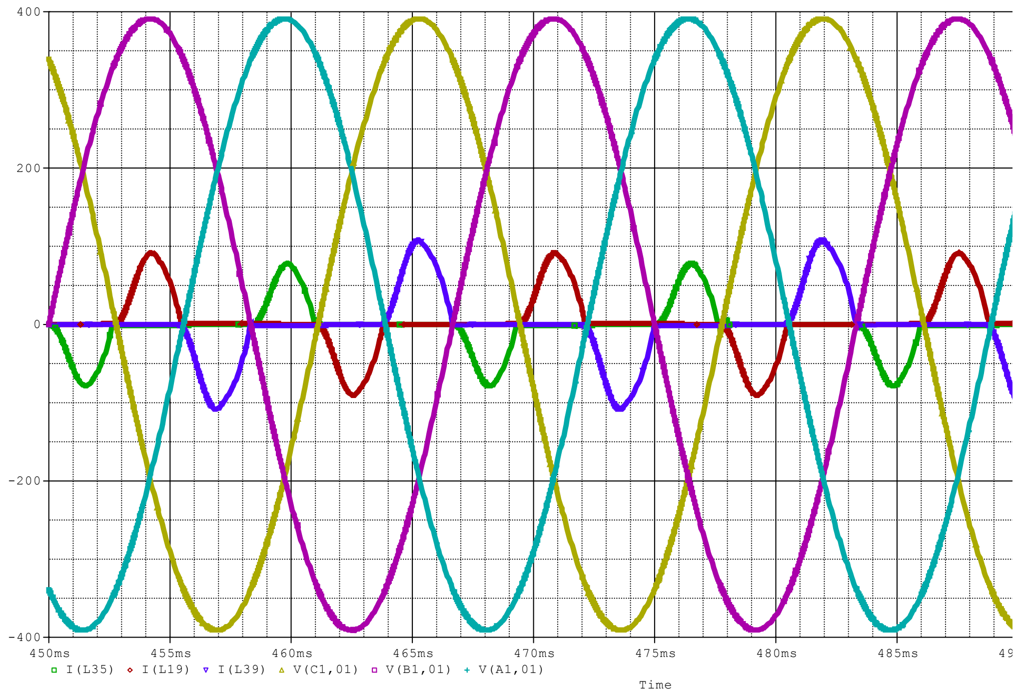


Figure 4.43 Unbalanced, Non-Linear 12.73% Loading, 225 kVA – Primary Phase-to-Ground Voltages and Currents (peak)

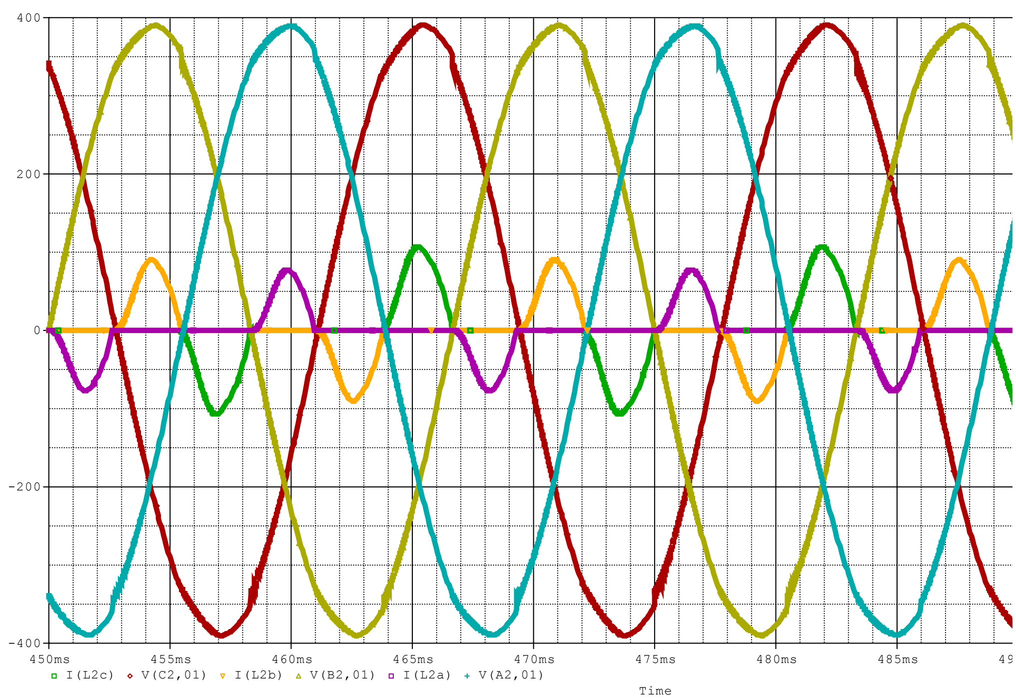


Figure 4.44 Unbalanced, Non-Linear 12.73% Loading, 225 kVA – Secondary Phase-to-Ground Voltages and Currents (peak)

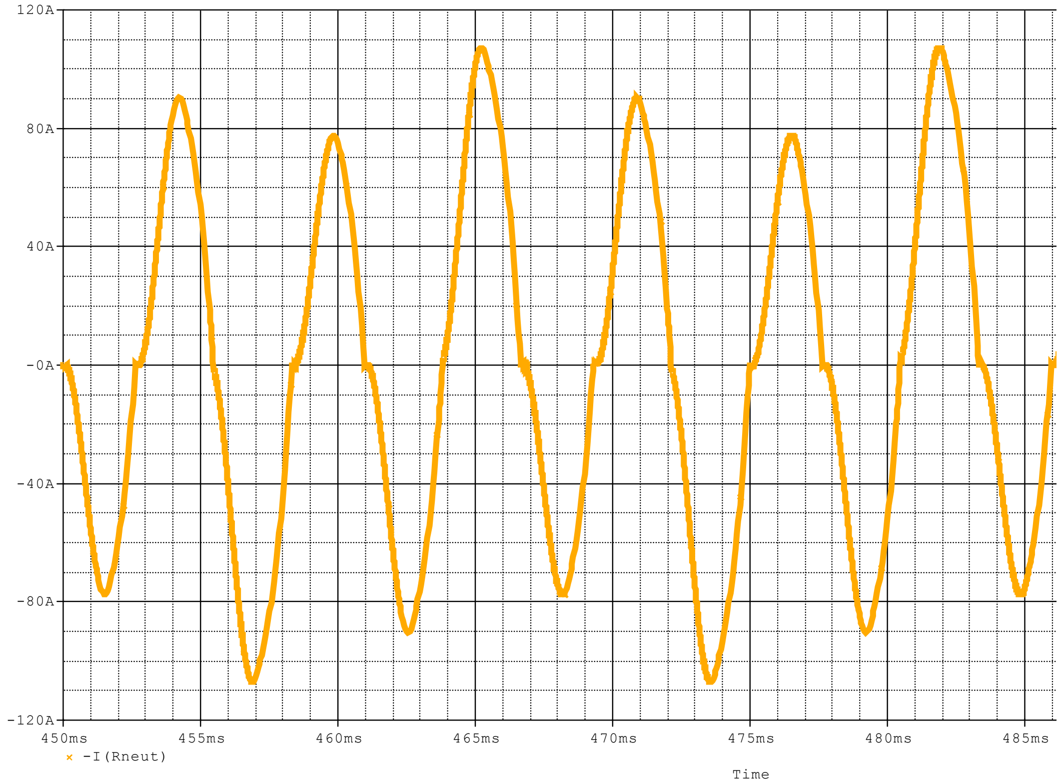


Figure 4.45 Unbalanced, Non-Linear 12.73% Loading, 225 kVA – Neutral Current (peak)

From Figures 4.43 and 4.44 it is clear that significant THD is existent in both the primary and secondary transformer currents. For the primary currents, the Pspice output file displays a THD of 104.27%, 110.43%, and 96.99% and rms values calculated using equation 3.5.2 of 34.3 A, 28.42 A, and 42.6 A. Primary voltages-to-ground have such small amounts of THD that it can be considered negligible, as seen by the sinusoidal waveform in Figure 4.43. For the secondary currents, the Pspice output file displays a THD of 106.5%, 113.4%, and 98.56% and rms values calculated using equation 3.5.2 of 33.9 A, 28.1 A, and 42.26 A. Secondary phase-to-ground voltages contain small amounts of distortion, with THD's of 1.18%, 1.06%, and 1.33%.

Losses due to neutral current flow must also be considered. Neutral current magnitude is shown in Figure 4.45, with a THD of 604.42% and an rms value of 61.1 A. The unbalanced current from the three phases is only contributing about 9.97 A, while the majority of the rest comes from the triplen harmonics generated by the load. Using equations 3.5.3 to determine the transformer input power equation 3.5.4 to determine the output power to the load, transformer efficiency can be calculated. The input powers for each phase are 6,574 watts, 5,276 watts, and 8,465 watts, plus an additional 66 watts accounting for the loss due to the excess neutral current, for a total of 20,381 watts. The powers to the loads for each phase are 6,406 watts, 5,122 watts, and 8,275 watts, for a total of 19,803 watts. Total transformer losses are 578 watts with an efficiency of 97.1 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are noticeably lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

4.2.12. Case 3c – Phases Unbalanced, Non-linear Loading of 6%

This case will be the same as Case 3a, with the exception of the default load being adjusted to 6 per cent and the other two phases being increased/decreased by 20 per cent. Figures 4.46 – 4.47 show the results of the simulation.

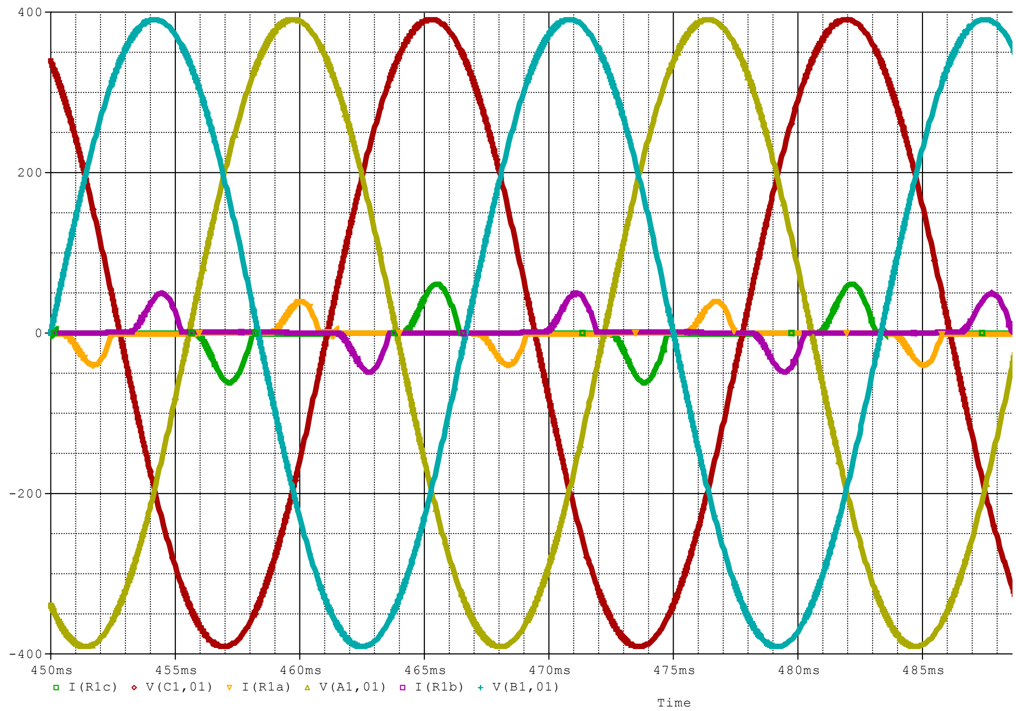


Figure 4.46 Unbalanced, Non-Linear 6% Loading, 225 kVA – Primary Phase-to-Ground Voltages and Currents (peak)

Figure 4.47 Unbalanced, Non-Linear 6% Loading, 225 kVA – Secondary Phase-to-Ground Voltages and Currents (peak)

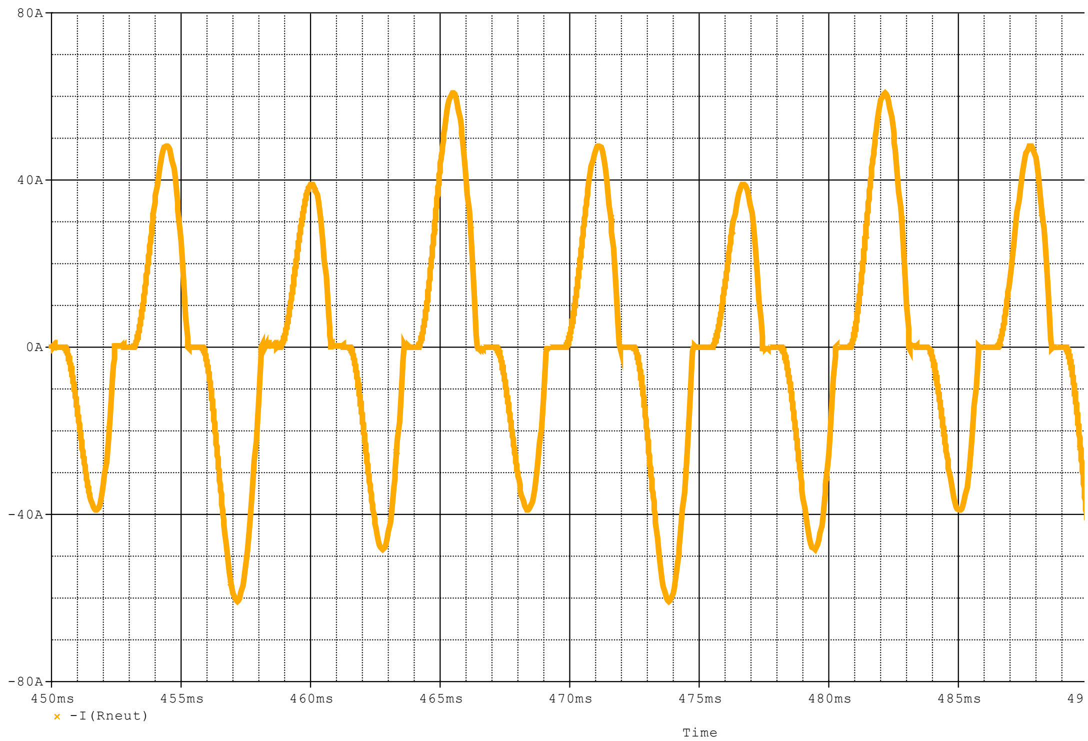


Figure 4.48 Unbalanced, Non-Linear 6% Loading, 225 kVA – Neutral Current (peak)

From Figures 4.43 and 4.44 it is clear that significant THD is existent in both the primary and secondary transformer currents. For the primary currents, the Pspice output file displays a THD of 125.94%, 130.25%, and 119.26% and rms values calculated using equation 3.5.2 of 16.23 A, 12.78 A, and 21.2 A. Primary voltages-to-ground have such small amounts of THD that it can be considered negligible, as seen by the sinusoidal waveform in Figure 4.46. For the secondary currents, the Pspice output file displays a THD of 132.67%, 139.54%, and 123.85% and rms values calculated using equation 3.5.2 of 33.9 A, 12.44 A, and 20.9 A. Secondary phase-to-ground voltages contain very small amounts of distortion, with THD's of 0.72%, 0.62%, and 0.88%.

Losses due to neutral current flow must also be considered. Neutral current magnitude is shown in Figure 4.48, with a THD of 559.33% and an rms value of 28.98 A. The unbalanced current from the three phases is only contributing about 5.12 A, while the majority of the rest comes from the triplen harmonics generated by the load. Using equations 3.5.3 to determine the transformer input power equation 3.5.4 to determine the output power to the load, transformer efficiency can be calculated. The input powers for each phase are 2,779 watts, 2,135 watts, and 3,766 watts, plus an additional 15 watts accounting for the loss due to the excess neutral current, for a total of 8,695 watts. The powers to the loads for each phase are 2,628 watts, 1,993 watts, and 3,603 watts, for a total of 8,224 watts. Total transformer losses are 471 watts with an efficiency of 94.6 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are much lower than the 98.7 per cent advertised efficiency at the 25 per cent loading level.

4.2.13. Case 3d – Phases Unbalanced, Non-linear Loading of 38.19% and 18%

This case uses the same methodology as outlined in Case 1d and 2d, with the inclusion of a variation in loading per phase by 20 per cent as well as the non-linear full-bridge rectifier load, similar to the other sub-cases in this set. Again, a 75 kVA transformer will be used in this simulation, with both 38.19 percent and 18 per cent loading, representing reductions for previous loading of 12.73 per cent and 6 per cent, respectively. Figures 4.49 – 4.54 show the results of the simulation.

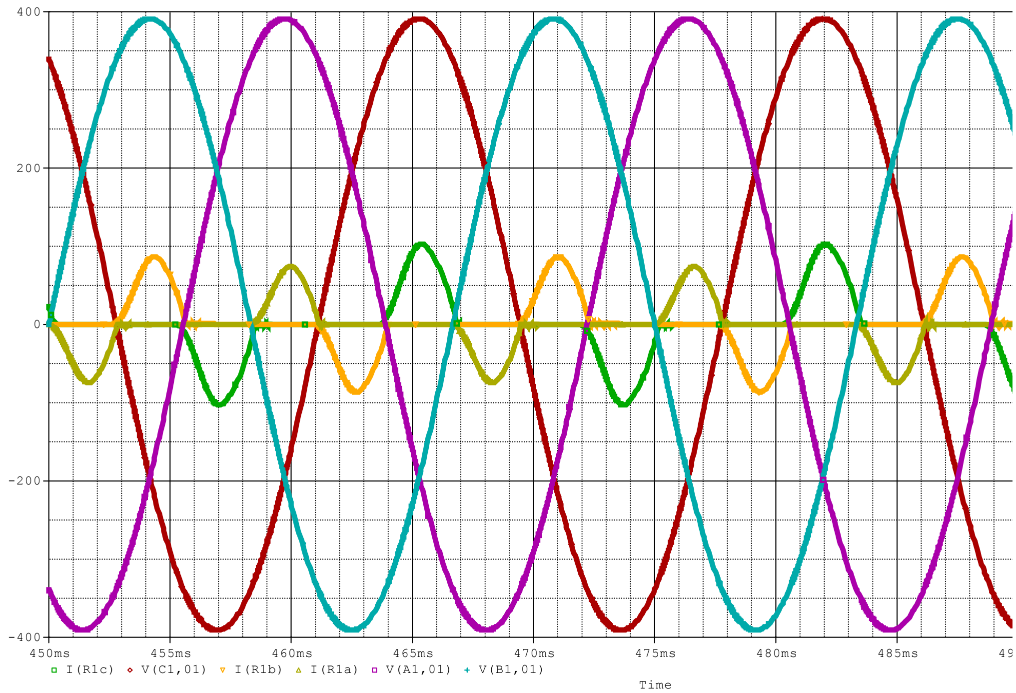


Figure 4.49 Unbalanced, Non-Linear 38.19% Loading, 75 kVA – Primary Phase-to-Ground Voltages and Currents (peak)

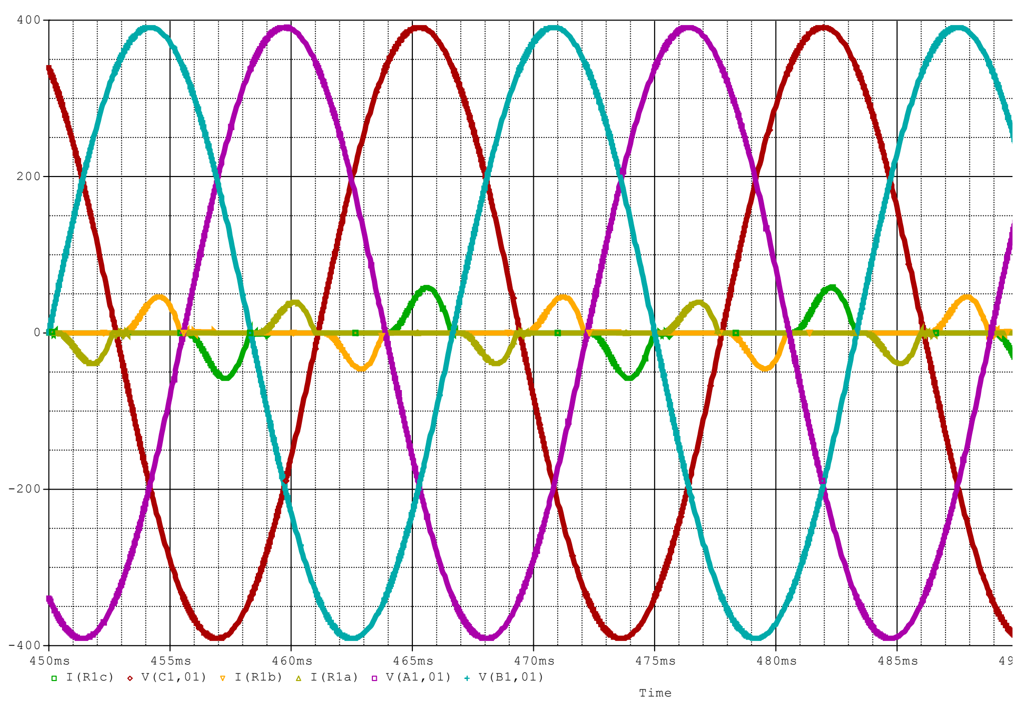


Figure 4.50 Unbalanced, Non-Linear 18% Loading, 75 kVA – Primary Phase-to-Ground Voltages and Currents (peak)

Figure 4.51 Unbalanced, Non-Linear 38.19% Loading, 75 kVA – Secondary Phase-to-Ground Voltages and Currents (peak)

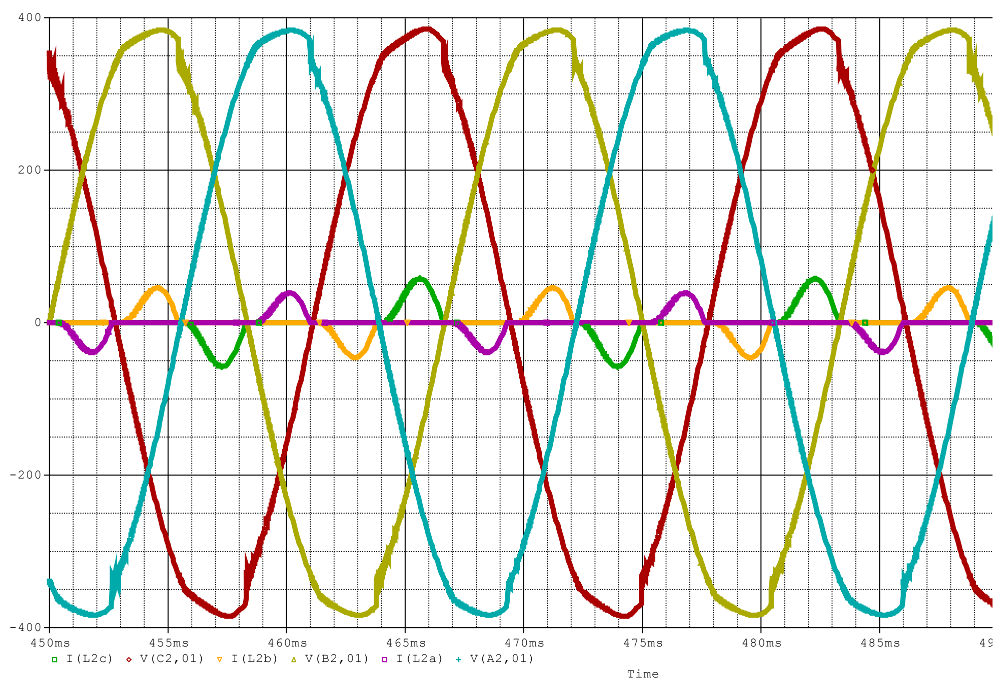


Figure 4.52 Unbalanced, Non-Linear 18% Loading, 75 kVA – Secondary Phase-to-Ground Voltages and Currents (peak)

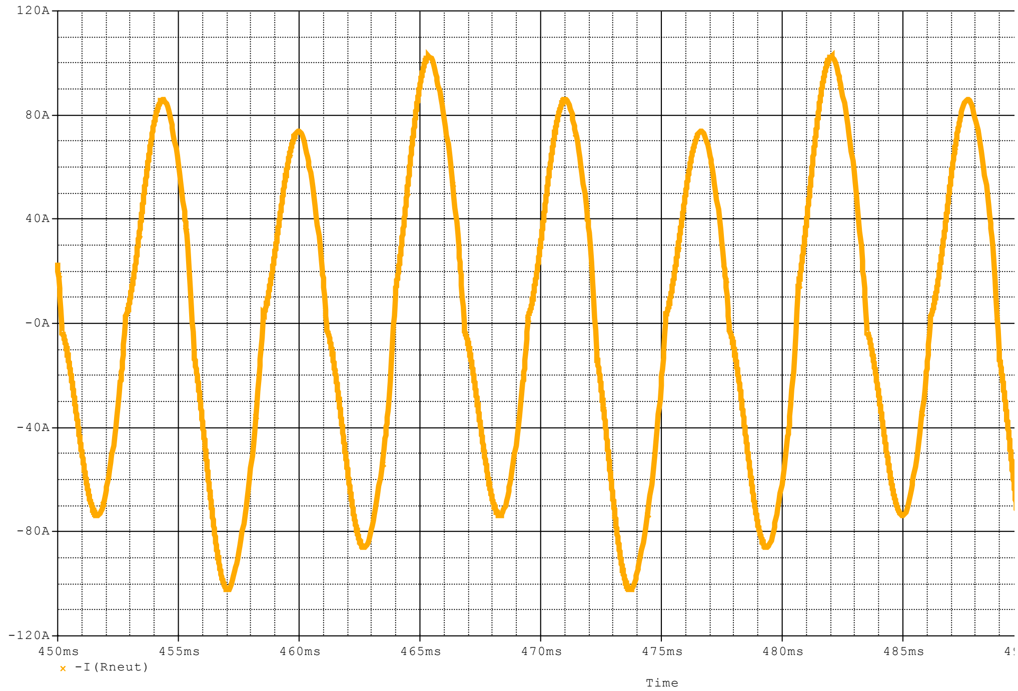


Figure 4.53 Unbalanced, Non-Linear 38.19% Loading, 75 kVA – Neutral Current (peak)

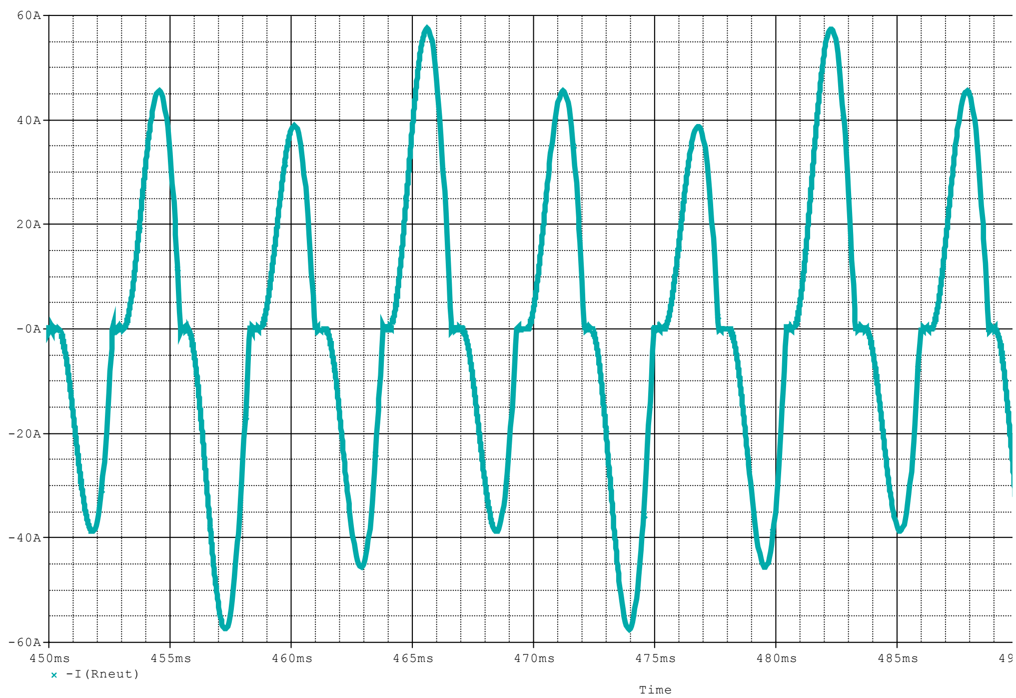


Figure 4.54 Unbalanced, Non-Linear 18% Loading, 75 kVA – Neutral Current (peak)

From the figures above it can be determined that:

For 38.19% loading:

For the primary currents, the Pspice output file displays a THD of 97.14%, 102.78%, and 90.41% and rms values calculated using equation 3.5.2 of 34.1 A, 28.3 A, and 42.17 A. Primary voltages-to-ground have such small amounts of THD that it can be considered negligible. For the secondary currents, the Pspice output file displays a THD of 98.69%, 104.82%, and 91.52% and rms values calculated using equation 3.5.2 of 33.9 A, 28.1 A, and 41.9 A. Secondary phase-to-ground voltages contain very small amounts of distortion, with THD's of 3.25%, 2.94%, and 3.73%.

Losses due to neutral current flow must also be considered. Neutral current magnitude is shown in Figure 4.53, with a THD of 599.76% and an rms value of 60.7 A. The unbalanced current from the three phases is only contributing about 9.98 A, while the majority of the rest comes from the triplen harmonics generated by the load. Using equations 3.5.3 to determine the transformer input power equation 3.5.4 to determine the output power to the load, transformer efficiency can be calculated. The input powers for each phase are 6,761 watts, 5,457 watts, and 8,654 watts, plus an additional 195 watts accounting for the loss due to the excess neutral current, for a total of 21,067 watts. The powers to the loads for each phase are 6,562 watts, 5,287 watts, and 8,400 watts, for a total of 20,249 watts. Total transformer losses are 818 watts with an efficiency of 96.1 per cent for this load. This is much lower than the 98.0 per cent advertised efficiency for this loading range.

For 18% loading:

For the primary currents, the Pspice output file displays a THD of 117.12%, 120.26%, and 111.03% and rms values calculated using equation 3.5.2 of 16.2 A, 13.5 A, and 21.16 A. Primary voltages-to-ground have such small amounts of THD that it can be considered negligible. For the secondary currents, the Pspice output file displays a THD of 121.6%, 125.93%, and 114.15% and rms values calculated using equation 3.5.2 of 16.06 A, 13.3 A, and 20.94 A. Secondary phase-to-ground voltages contain very small amounts of distortion, with THD's of 2.05%, 1.77%, and 2.43%.

Losses due to neutral current flow must also be considered. Neutral current magnitude is shown in Figure 4.54, with a THD of 603.65% and an rms value of 29.37 A. The unbalanced current from the three phases is only contributing about 4.8 A, while the majority of the rest comes from the triplen harmonics generated by the load. Using equations 3.5.3 to determine the transformer input power equation 3.5.4 to determine the output power to the load, transformer efficiency can be calculated. The input powers for each phase are 2,900 watts, 2,380 watts, and 3,901 watts, plus an additional 45 watts accounting for the loss due to the excess neutral current, for a total of 9,226 watts. The powers to the loads for each phase are 2,785 watts, 2,227 watts, and 3,766 watts, for a total of 8,778 watts. Total transformer losses are 448 watts with an efficiency of 95.1 per cent for this load. There is no manufacturer provided efficiency for this size load, but the simulation results are much lower than the 97.8 per cent advertised efficiency at the 25 per cent loading level.

4.3. Summary of Results and Discussion

Compilation of the results from Section 4.2 results in a conclusive presentation shown in Table 4.3. The table is not organized in the order of the simulations in the preceding section, but rather the cases are grouped by loading percentage to allow for easier comparison. Further, the data for the re-calculated loads of the down-sized units (sub-case 'd' for all cases) are grouped with their original respective transformers.

Table 4.3 Summary of Transformer Simulation Data

Case	Rating (kVA)	Loading (%)	Losses (W)	Efficiency (%)
Balanced, linear	225	35	1,076	98.6
Unbalanced, linear	225	35	1,149	98.5
Unbalanced, nonlinear	225	35	1,770	97.3
Balanced, linear	225	12.73	483	98.2
Balanced, linear	75	38.19	558	98
Unbalanced, linear	225	12.73	490	98.2
Unbalanced, linear	75	38.19	588	97.3
Unbalanced, nonlinear	225	12.73	578	97.1
Unbalanced, nonlinear	75	38.19	818	96.1
Balanced, linear	225	6	414	96.9
Balanced, linear	75	18	363	97.3
Unbalanced, linear	225	6	418	96.9
Unbalanced, linear	75	18	369	97.3
Unbalanced, nonlinear	225	6	471	94.6
Unbalanced, nonlinear	75	18	448	95.1

From the table, some general observations can be made. For transformers loaded at the TP-1 “optimal” loading level of 35 per cent, efficiency and total losses were true to manufacturer claims for balanced, linear loads. As the load shifted to an unbalanced profile efficiency decreased as losses increased, which were even more pronounced as the load became non-linear. These results are expected, due to excess currents flowing through the transformer secondary coils.

For the transformers loaded at the higher education average, efficiencies dropped moderately but noticeably for all of the load profiles compared to the 35 per cent default case, following the “typical” transformer efficiency curve, while decreasing further for an unbalanced linear load and even further for an unbalanced non-linear load. When simulating the same load on the smaller size transformer, in order to make an accurate comparison to the larger unit watt loss must also be examined. Efficiencies among the smaller sized units decreased relative to the load profile similar to the other cases, while additionally the total watts lost were more than the same load on the larger transformer, especially in the case with the non-linear load. This data indicates that down-sizing to the smaller transformer would actually slightly increase energy waste by about 25.6 per cent (average for the three load profiles) and thus operating costs at the higher education average, particularly in distribution systems with a large amount of non-linear loads.

For the transformers loaded at the field measured average, efficiencies dropped substantially by an average of approximately 2 per cent for all of the load profiles compared to the default case, with the unbalanced non-linear load having the biggest contribution to raising the average. Again, efficiencies among the smaller sized units decreased relative to the load profile, but the total watts lost were less than the same load on the larger transformer, even in the case with the non-linear load. This data indicates that down-sizing to the smaller transformer would slightly decrease energy waste by about 10.4 per cent (average for the three load profiles) and thus operating costs at the field measured average or in systems with extremely lightly loaded transformers. These general observations were with respect to transformer power usage only and will be related to other factors in Chapter 5 of this thesis.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

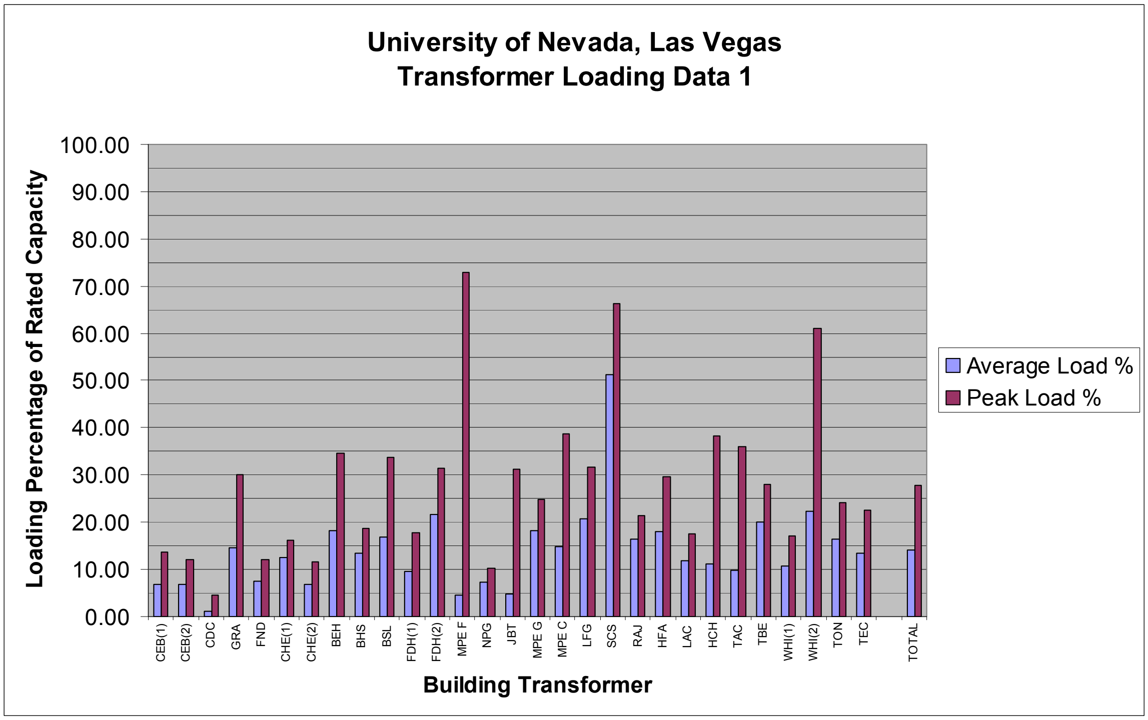
Through this research work, an assessment of distribution transformer design standards and code-required sizing requirements was carried out. With regards to energy efficiency, it could be seen from the results of the simulations that transformers do indeed operate as advertised for a balanced linear load. These efficiencies worsen as the nature of the load varies to a more realistic field load profile where phases are not balanced and harmonics are present in the system. In general, transformer efficiencies only drop by a few per cent at most for smaller differences in loading percentage compared to the TP-1 design point of 35 per cent. This would indicate that transformer efficiency standards are currently effective and clearly a step in the right direction. It would be more beneficial to the end user if the manufacturer not only shared efficiencies and watt loss for an ideal load, but also for non-linear loads. Further, for true optimization the synergy between the manufacturers design and how the transformer is installed should exist and there still remains the issue of code required load calculations and the impact they have on transformer loading.

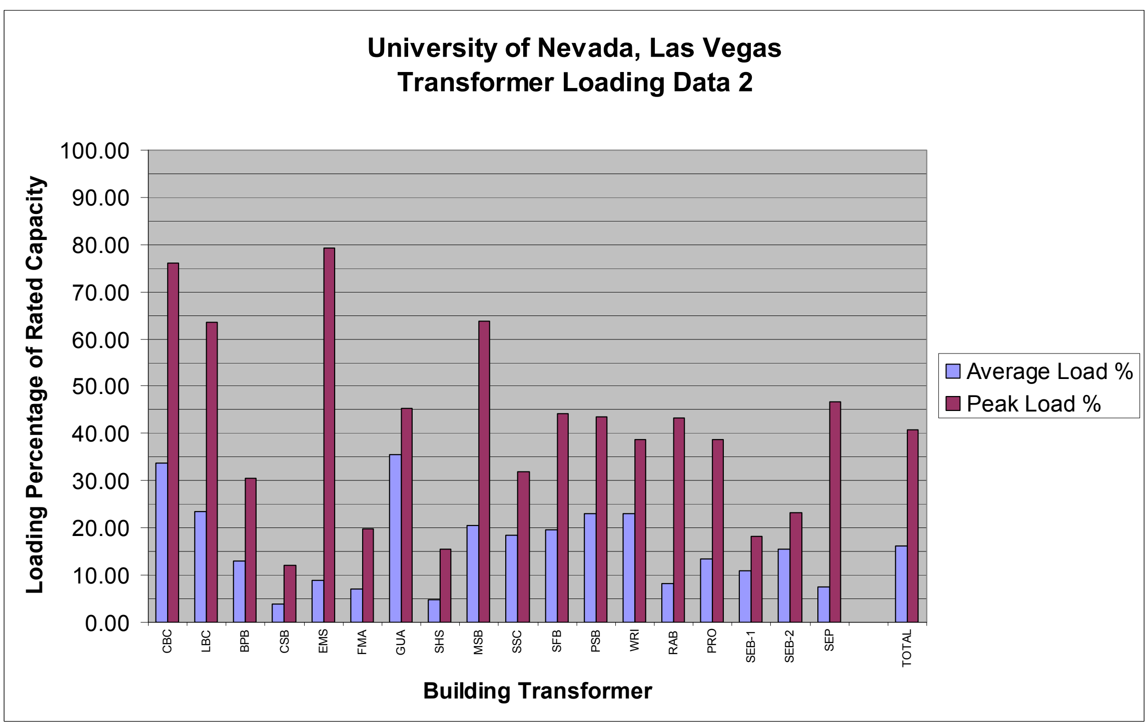
A poll of numerous higher education campuses showed that the average annual loading was merely 12.73 per cent. A random sampling of recently installed transformers at UNLV showed an instantaneous average loading of only 6 per cent. Clearly the building loads these transformers were designed to power are much less than originally calculated through the NEC. Proposals to change the Code are considered often, with NEC updates being released every three years. If it were possible to make changes in how loads were calculated, thus downsizing the size of installed transformers, how would it impact efficiency? In the case of downsizing to a unit one-third the size of the original design transformer for the 12.73 per cent load, energy consumption would actually worsen, whereas in the 6 per cent load case it would improve. This is due to the fact that in general the smaller the transformer, the lower the overall efficiencies. However, one must consider other factors than efficiency alone and the trade off between efficiency and these other factors. Smaller transformers generally cost less upfront and would have less fault current available, allowing for lower rated distribution and panelboards and overcurrent protective devices, smaller cable and conduit. There would be more room available in electrical rooms due to decreased footprint of installed equipment, allowing for smaller electrical rooms and re-allocation of that square footage for other building uses, which is always a premium. Safety would be improved with less available power and thus lowered fire and arc-flash risks. In order to determine if these trade offs carry the possibility of a slight increase in energy consumption, more detailed load studies should be conducted or ideally required by NEC for new construction as well as existing installations. These load studies will allow for the building owner to assess the increased lifetime energy cost versus the many benefits of having smaller sized transformers. Further research may include:

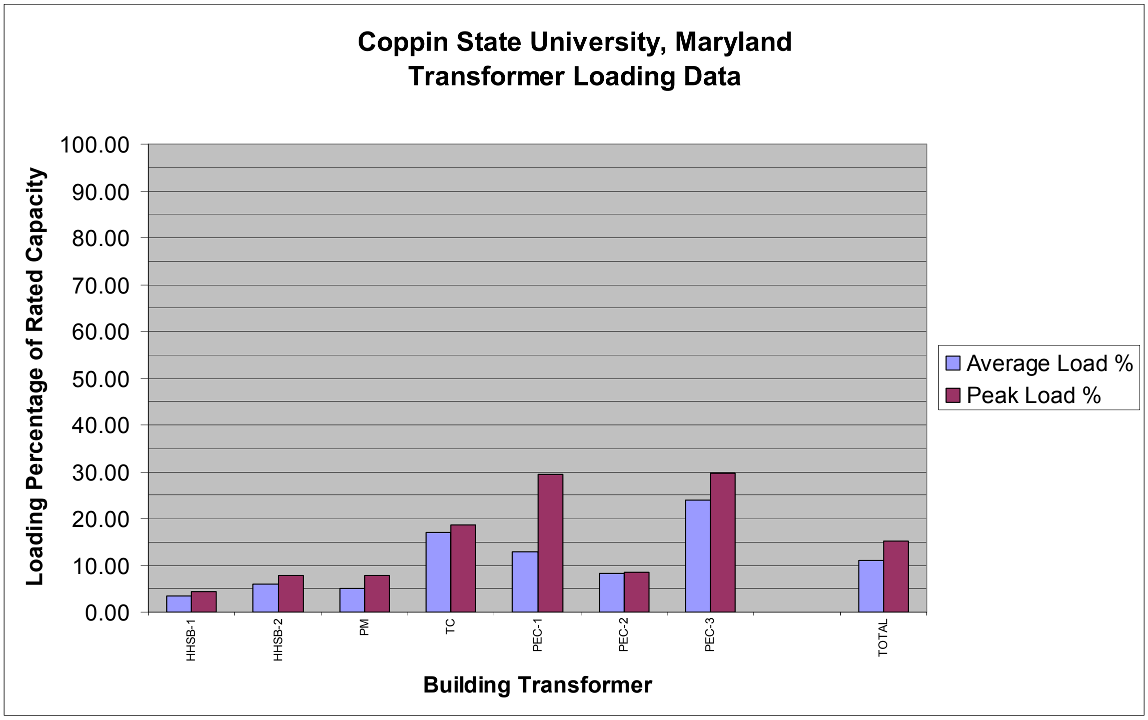
- Gathering more loading data from a larger number of higher education campuses
- Assessing various units from other manufacturers, including CSL-3 compliant, *K*-factor rated, and aluminum material models
- Impact of loading percentage on internal temperatures and thus life expectancy
- Examination of NEC load calculations and identification of possible areas for improvement

APPENDIX I

INDIVIDUAL COLLEGE LOADING DATA






Coppin State University, Maryland
Transformer Loading Data
Loading Percentage of Rated Capacity
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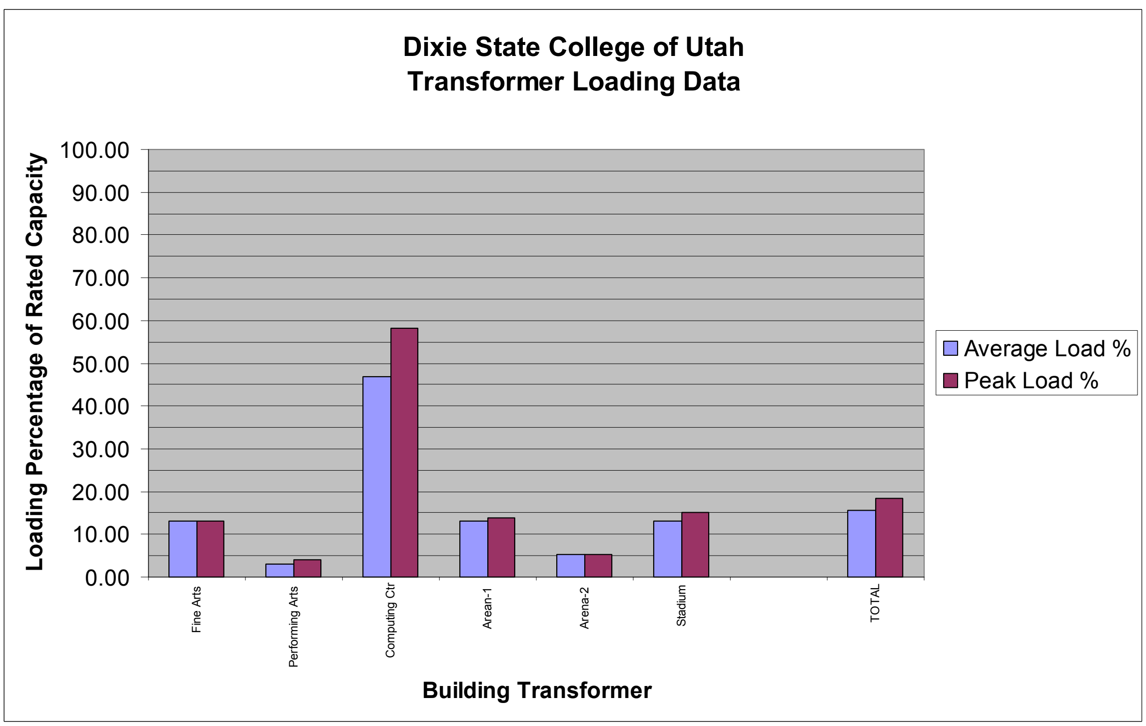
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
HHSB-1
HHSB-2
PM
TC
PEC-1
PEC-2
PEC-3
TOTAL
Building Transformer
Average Load %
Peak Load %


Dixie State College of Utah
Transformer Loading Data
Loading Percentage of Rated Capacity
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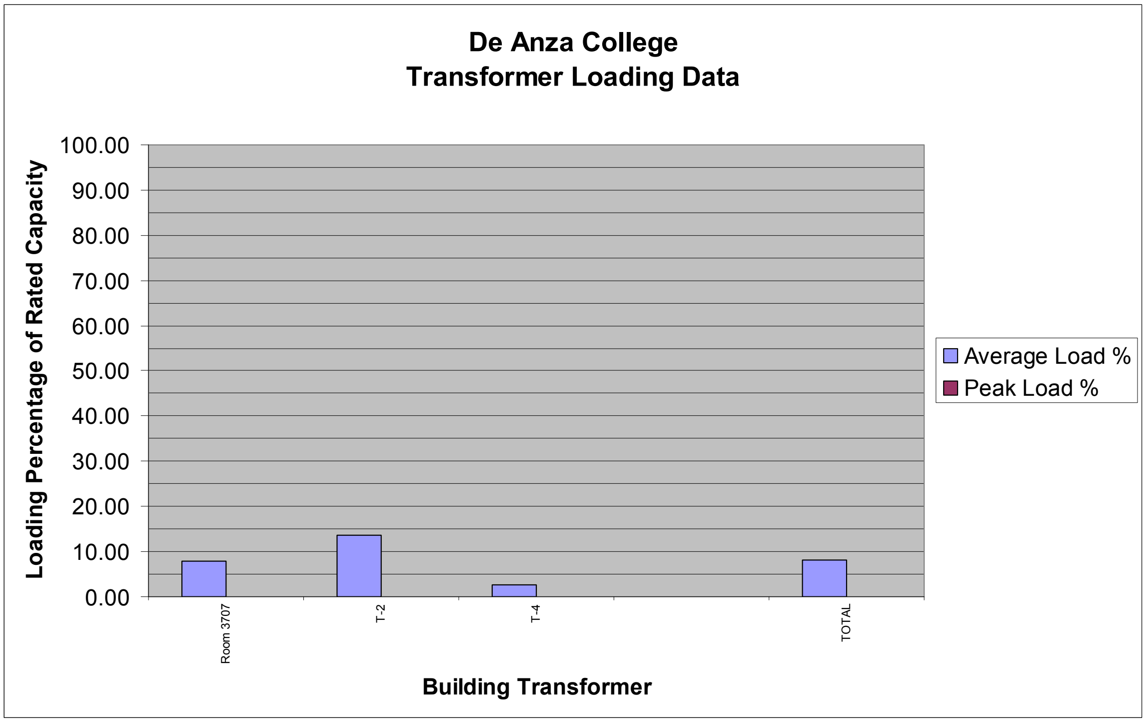
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Fine Arts
Performing Arts
Computing Ctr
Arean-1
Arena-2
Stadium
TOTAL
Building Transformer
Average Load %
Peak Load %


De Anza College
Transformer Loading Data
Loading Percentage of Rated Capacity
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60.00
50.00
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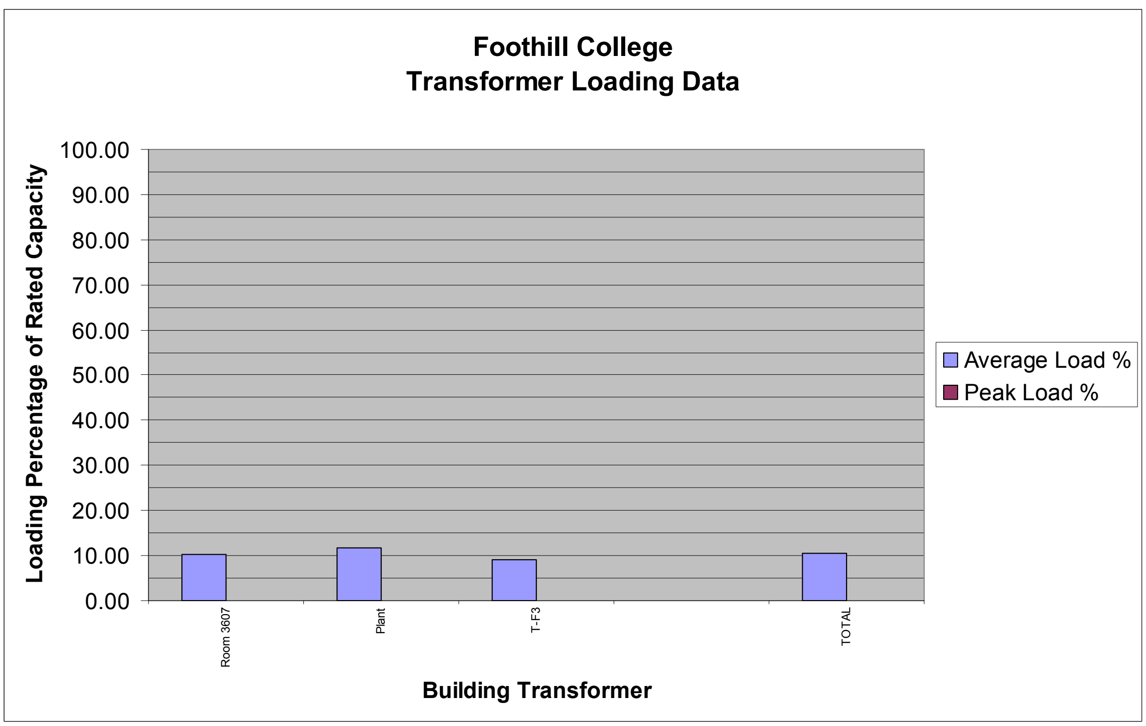
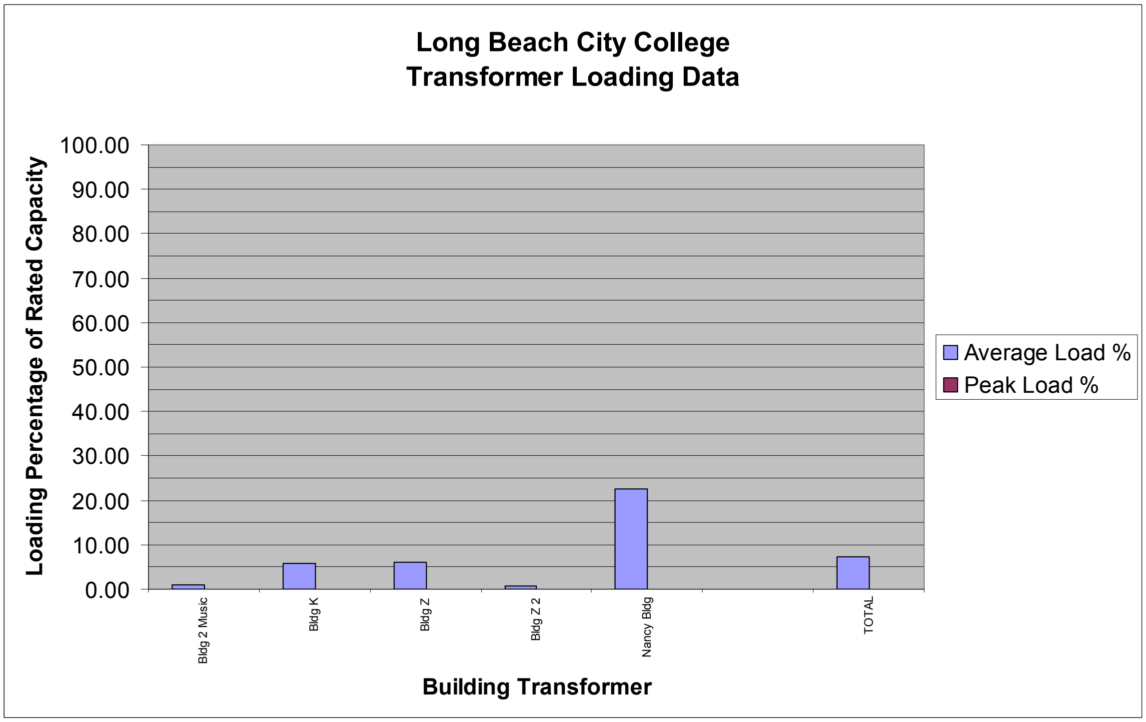
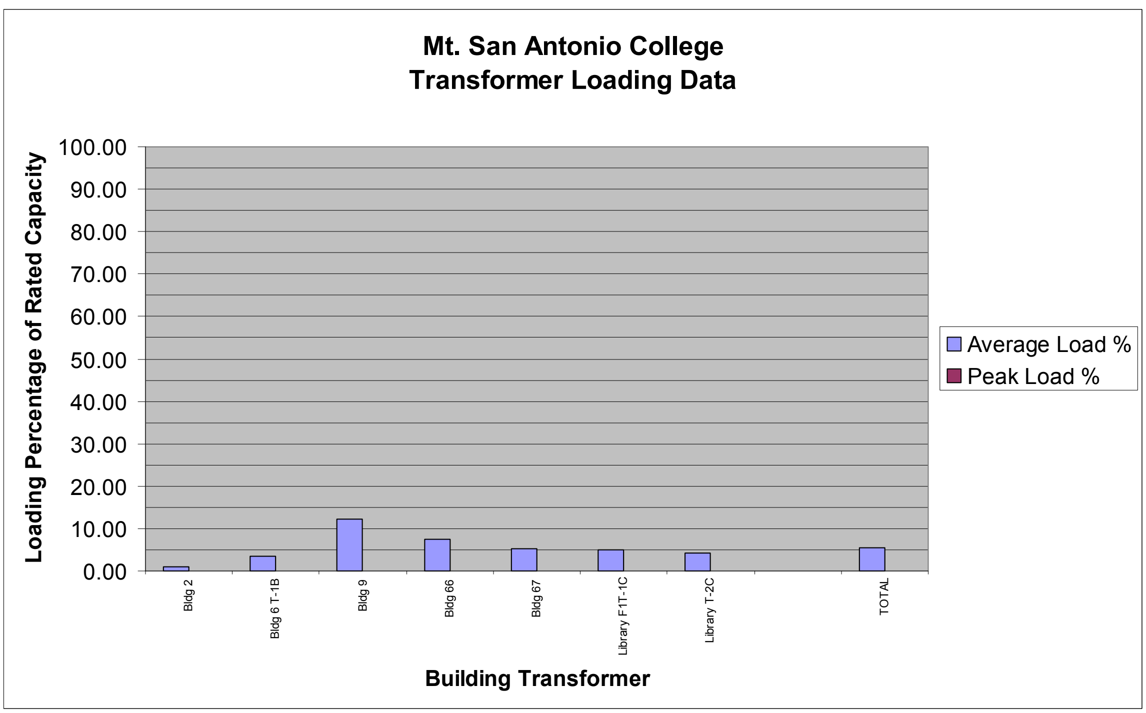
20.00
10.00
0.00
Room 3707
T-2
T-4
TOTAL
Building Transformer
Average Load %
Peak Load %


Foothill College
Transformer Loading Data
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Room 3607
Plant
T-F3
TOTAL
Building Transformer
Average Load %
Peak Load %


Long Beach City College
Transformer Loading Data
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Bldg 2 Music
Bldg K
Bldg Z
Bldg Z 2
Nancy Bldg
TOTAL
Building Transformer
Average Load %
Peak Load %


Mt. San Antonio College
Transformer Loading Data
Loading Percentage of Rated Capacity
100.00
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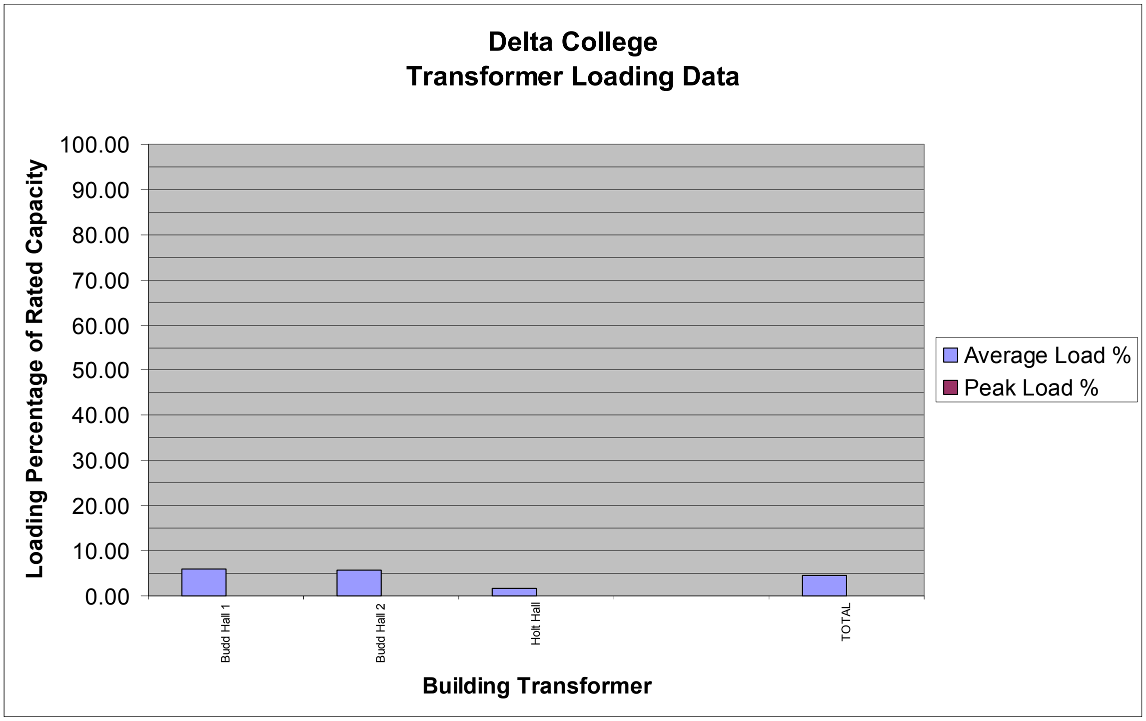
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Bldg 2
Bldg 6 T-1B
Bldg 9
Bldg 66
Bldg 67
Library F1T-1C
Library T-2C
TOTAL
Building Transformer
Average Load %
Peak Load %


Delta College
Transformer Loading Data
Loading Percentage of Rated Capacity
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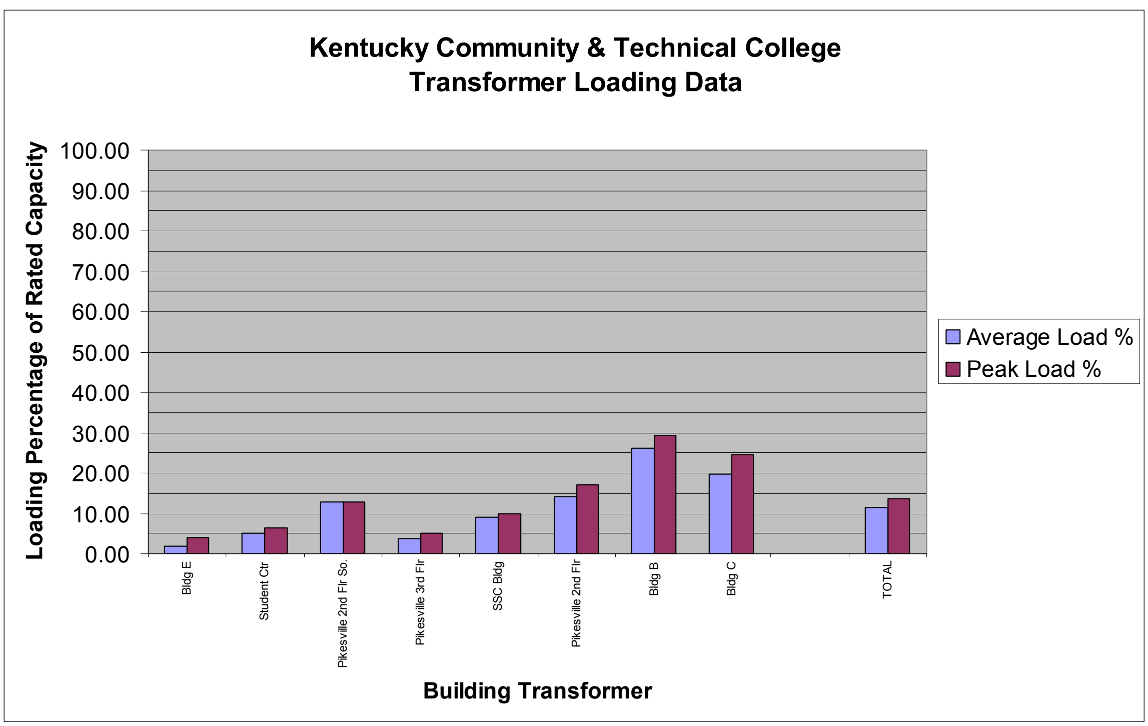
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Budd Hall 1
Budd Hall 2
Holt Hall
TOTAL
Building Transformer
Average Load %
Peak Load %


Kentucky Community & Technical College
Transformer Loading Data
Loading Percentage of Rated Capacity
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80.00
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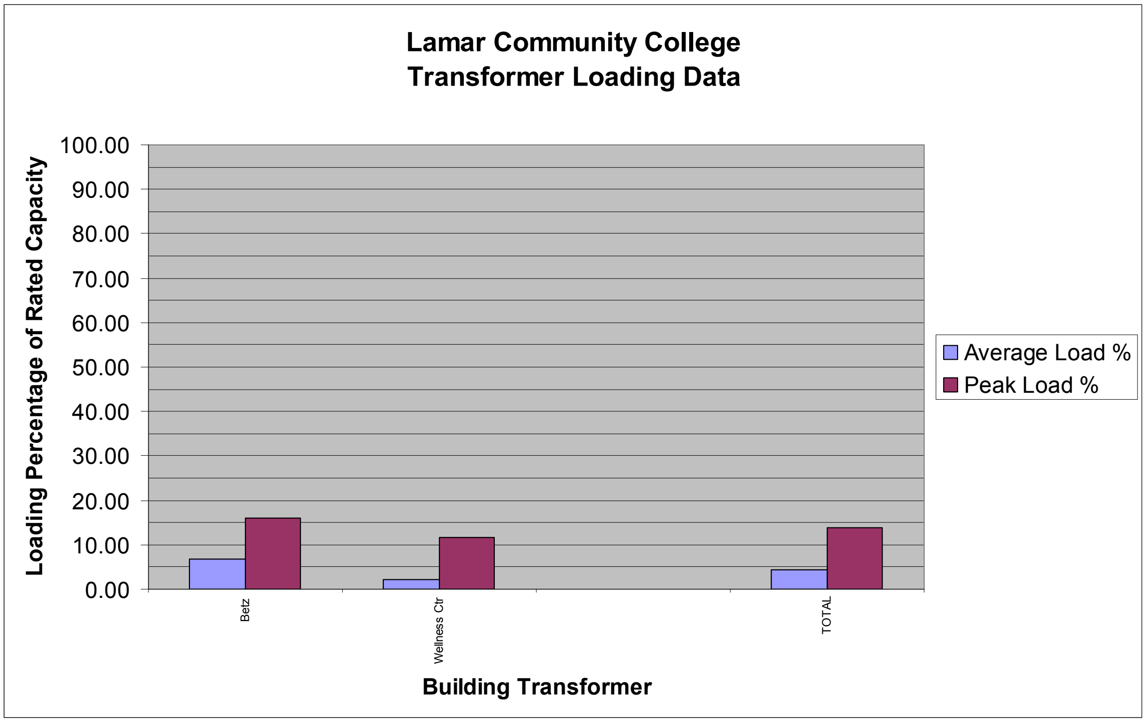
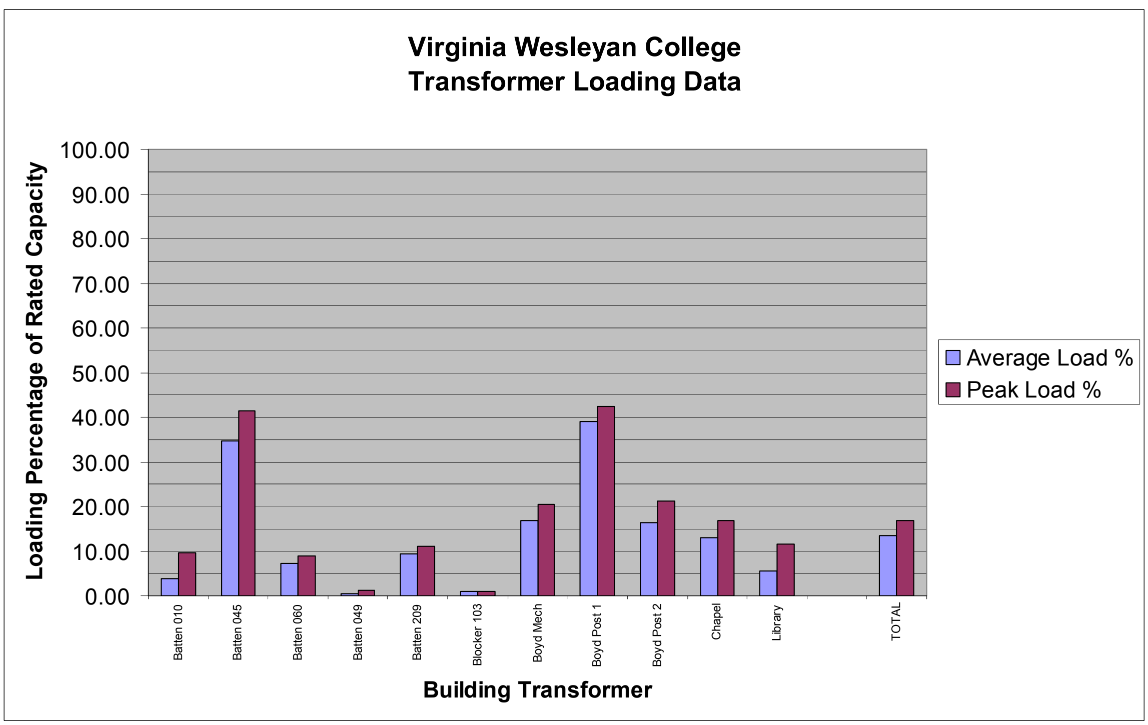
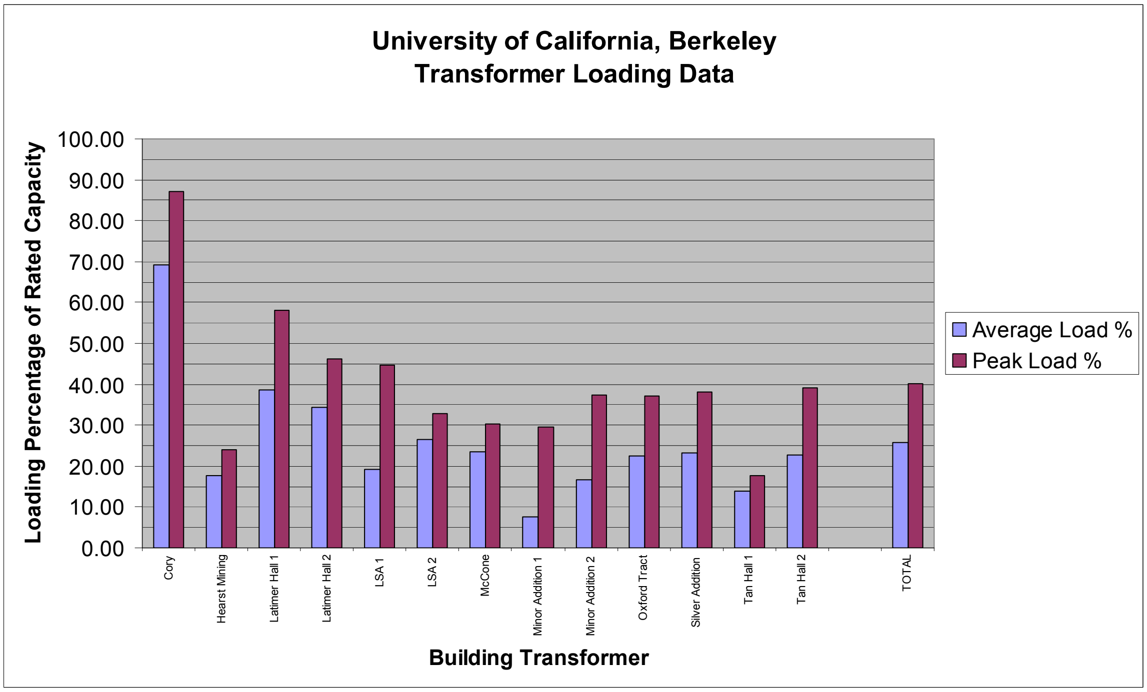
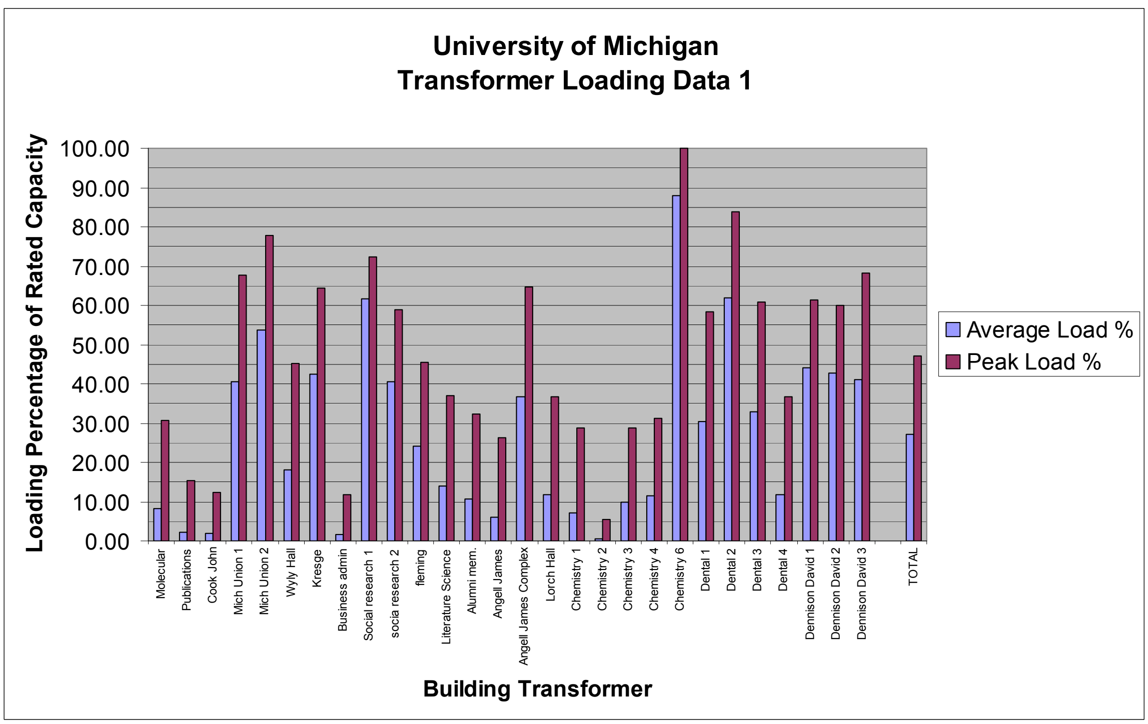
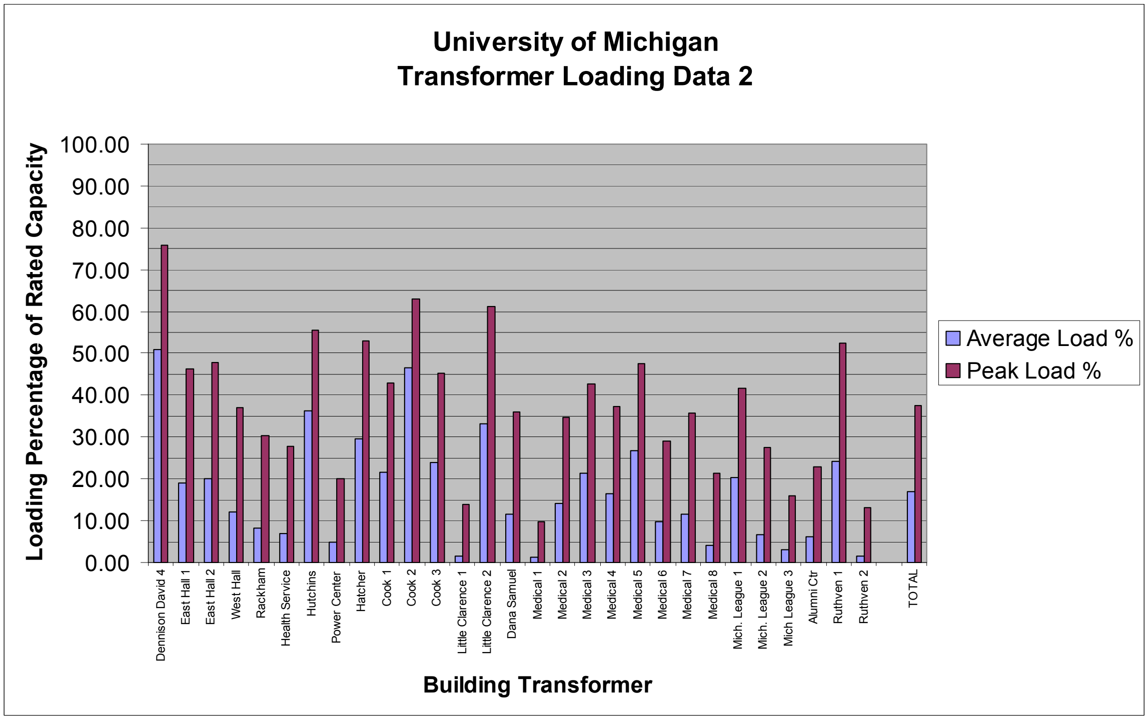
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Bldg E
Student Ctr
Pikesville 2nd Flr So.
Pikesville 3rd Flr
SSC Bldg
Pikesville 2nd Flr
Bldg B
Bldg C
TOTAL
Building Transformer
Average Load %
Peak Load %

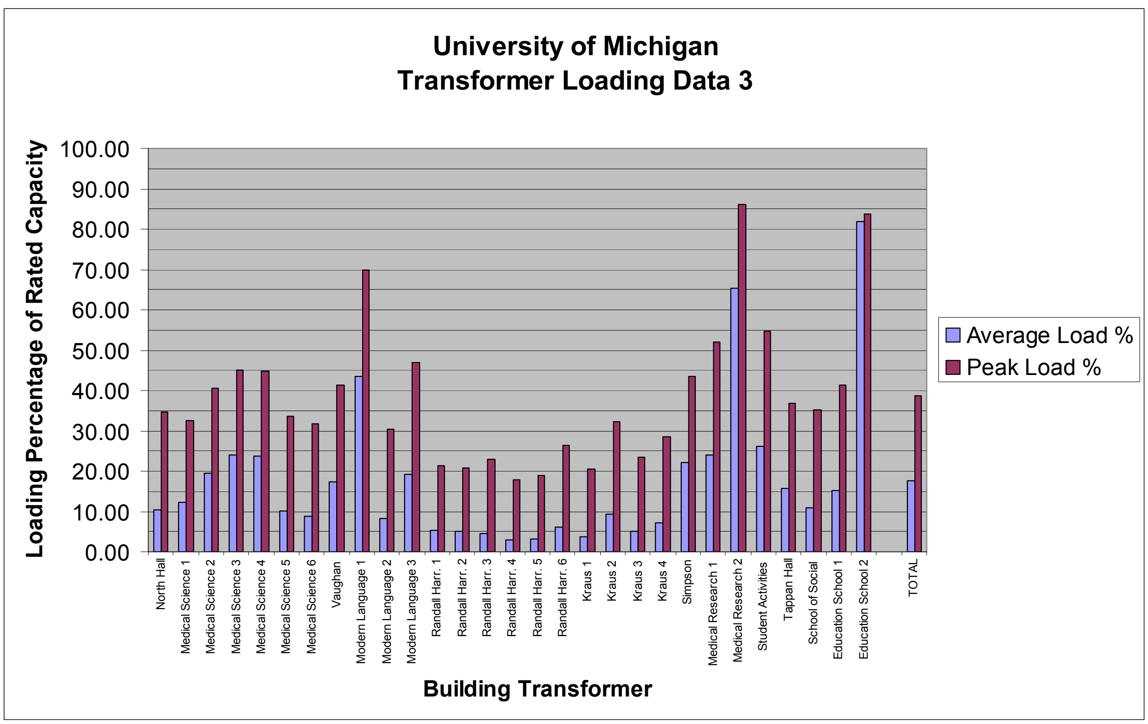

Lamar Community College
Transformer Loading Data
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Betz
Wellness Ctr
TOTAL
Building Transformer
Average Load %
Peak Load %

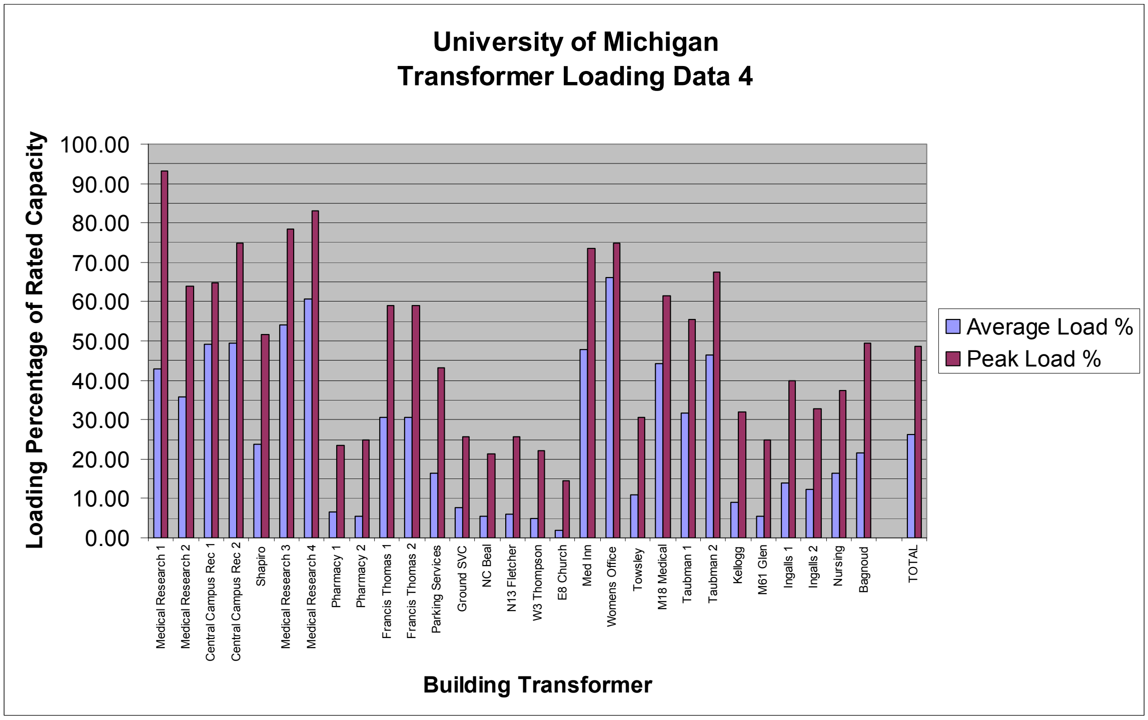

Virginia Wesleyan College
Transformer Loading Data
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Batten 010
Batten 045
Batten 060
Batten 049
Batten 209
Blocker 103
Boyd Mech
Boyd Post 1
Boyd Post 2
Chapel
Library
TOTAL
Building Transformer
Average Load %
Peak Load %

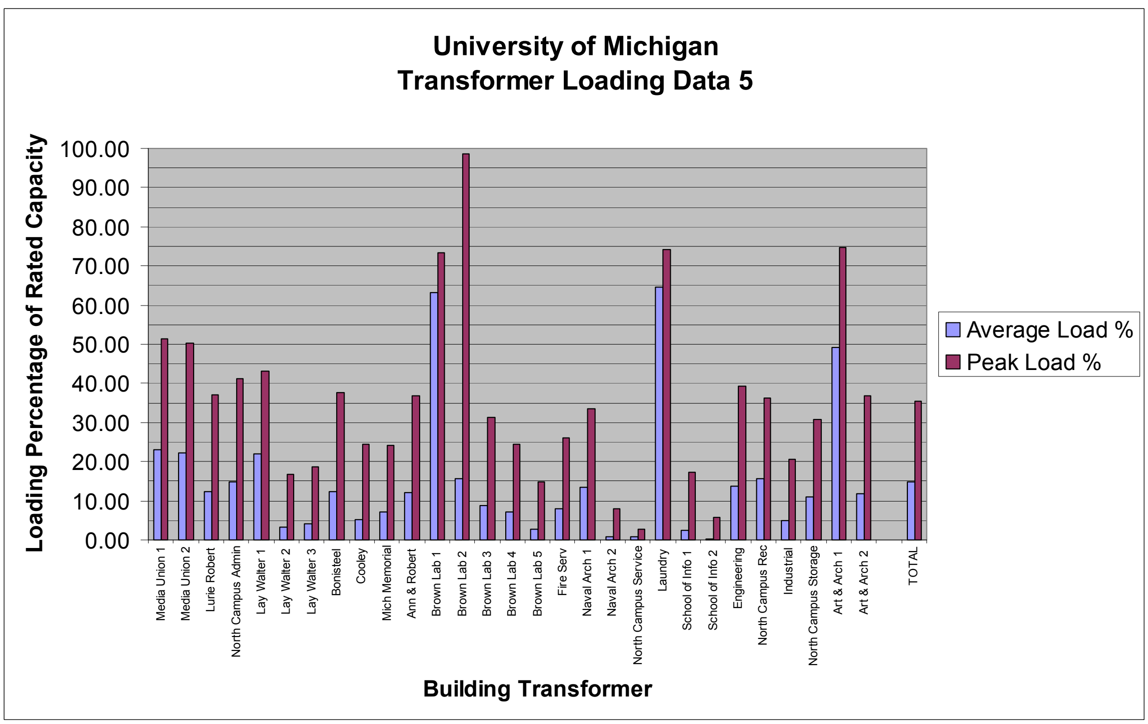

University of California, Berkeley
Transformer Loading Data
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Cory
Hearst Mining
Latimer Hall 1
Latimer Hall 2
LSA 1
LSA 2
McCone
Minor Addition 1
Minor Addition 2
Oxford Tract
Silver Addition
Tan Hall 1
Tan Hall 2
TOTAL
Building Transformer
Average Load %
Peak Load %

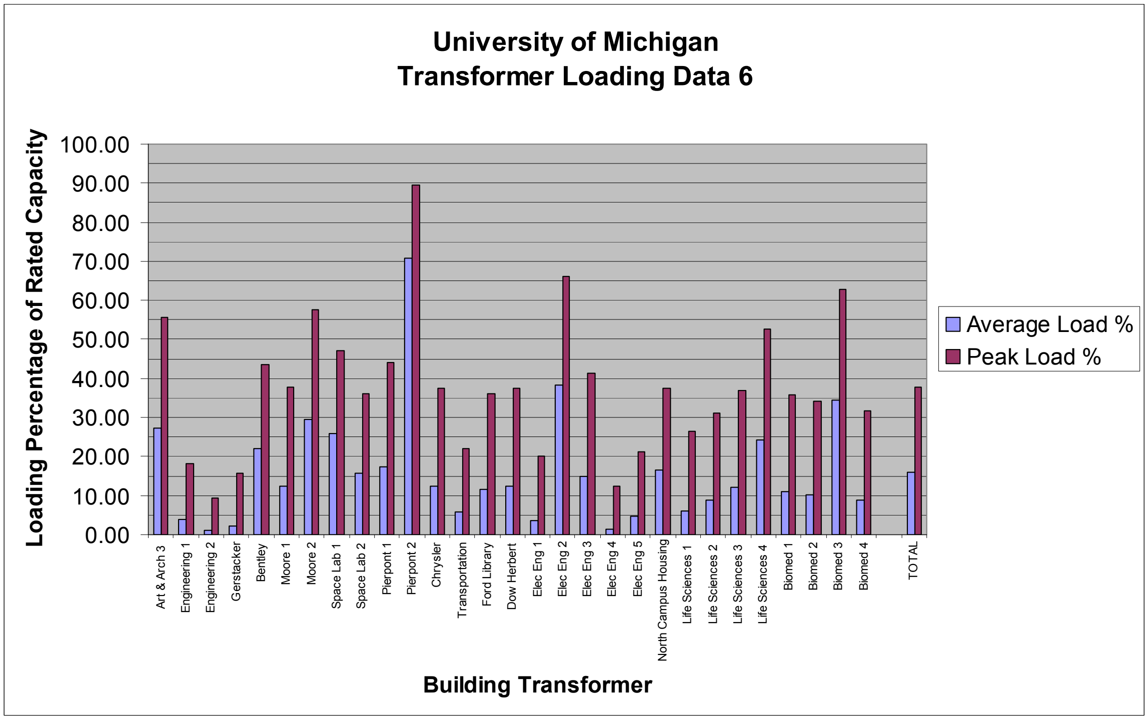

University of Michigan
Transformer Loading Data 1
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Molecular
Publications
Cook John
Mich Union 1
Mich Union 2
Wyly Hall
Kresge
Business admin
Social research 1
socia research 2
fleming
Literature Science
Alumni mem.
Angell James
Angell James Complex
Lorch Hall
Chemistry 1
Chemistry 2
Chemistry 3
Chemistry 4
Chemistry 6
Dental 1
Dental 2
Dental 3
Dental 4
Dennison David 1
Dennison David 2
Dennison David 3
TOTAL
Building Transformer
Average Load %
Peak Load %

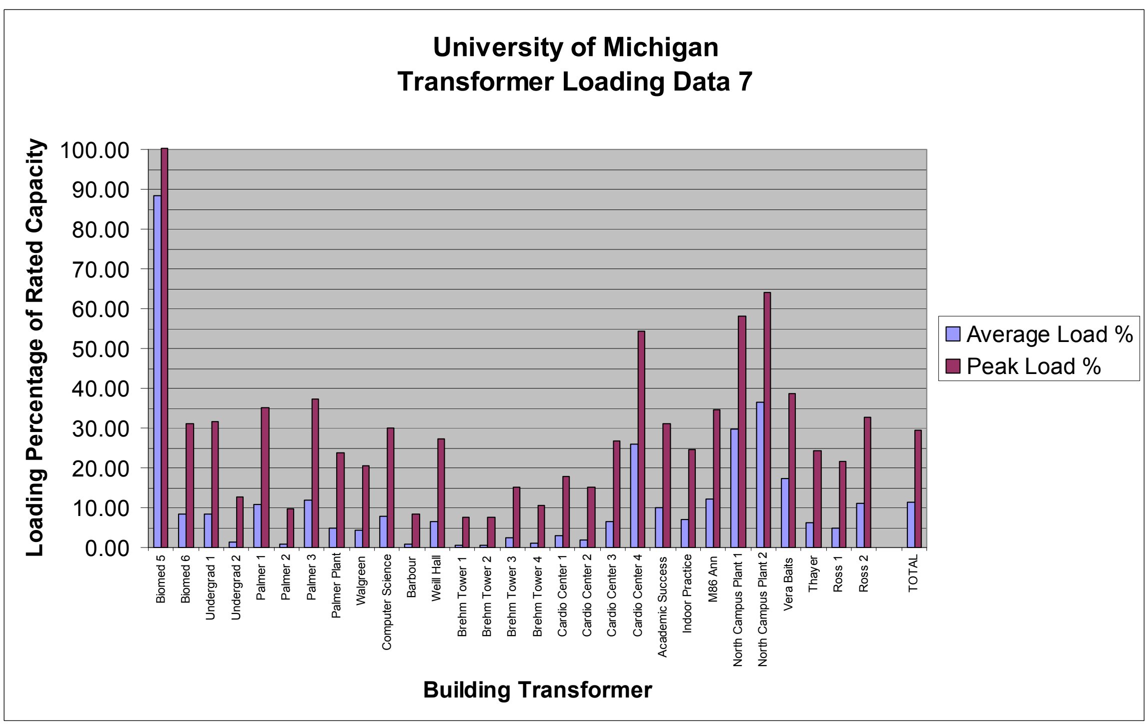

University of Michigan
Transformer Loading Data 2
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Average Load %
Peak Load %
Dennison David 4
East Hall 1
East Hall 2
West Hall
Rackham
Health Service
Hutchins
Power Center
Hatcher
Cook 1
Cook 2
Cook 3
Little Clarence 1
Little Clarence 2
Dana Samuel
Medical 1
Medical 2
Medical 3
Medical 4
Medical 5
Medical 6
Medical 7
Medical 8
Mich. League 1
Mich. League 2
Mich League 3
Alumni Ctr
Ruthven 1
Ruthven 2
TOTAL
Building Transformer

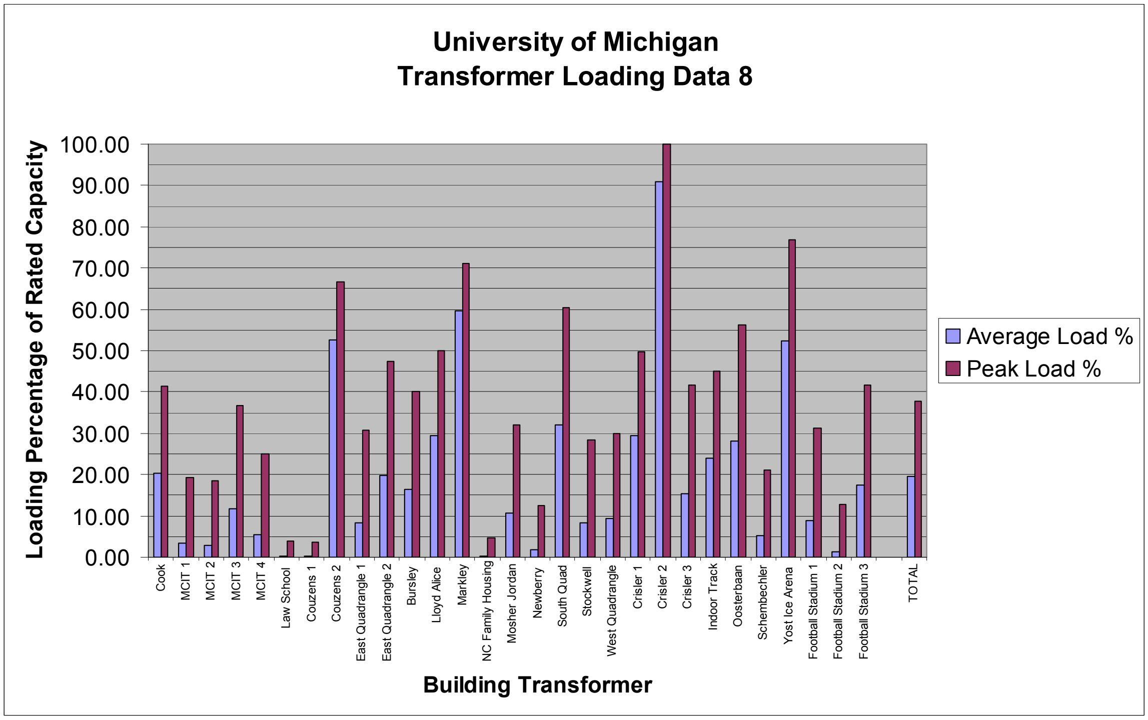

University of Michigan
Transformer Loading Data 3
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Average Load %
Peak Load %
North Hall
Medical Science 1
Medical Science 2
Medical Science 3
Medical Science 4
Medical Science 5
Medical Science 6
Vaughan
Modern Language 1
Modern Language 2
Modern Language 3
Randall Harr. 1
Randall Harr. 2
Randall Harr. 3
Randall Harr. 4
Randall Harr. 5
Randall Harr. 6
Kraus 1
Kraus 2
Kraus 3
Kraus 4
Simpson
Medical Research 1
Medical Research 2
Student Activities
Tappan Hall
School of Social
Education School 1
Education School 2
TOTAL
Building Transformer

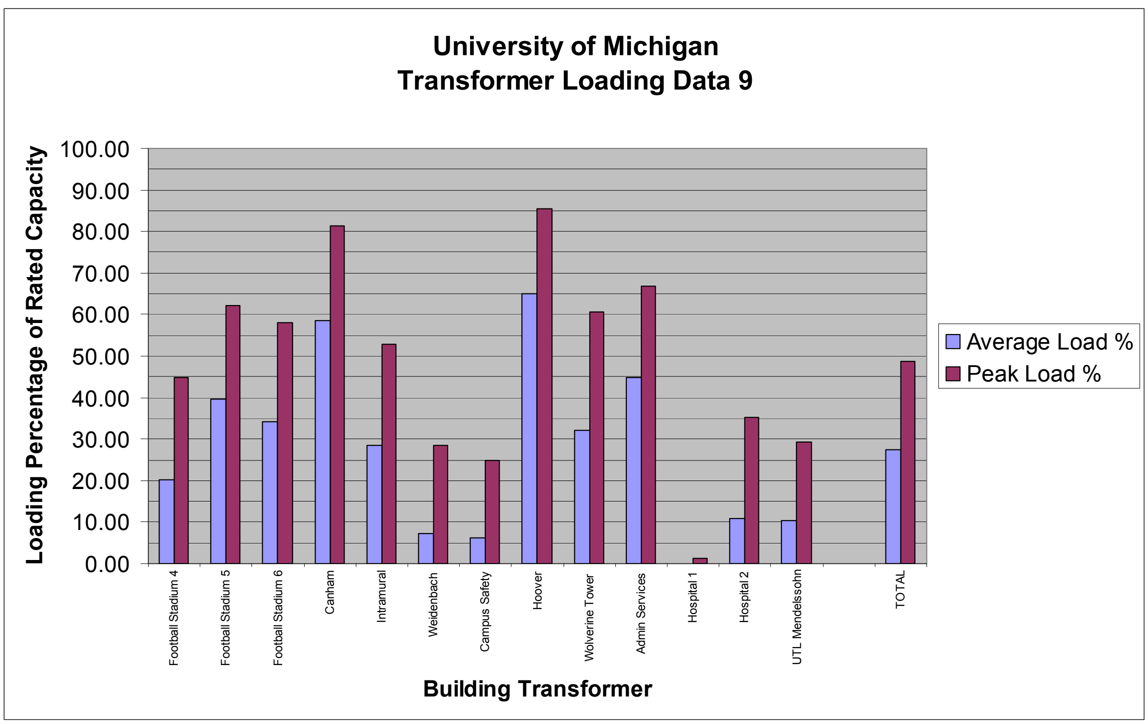

University of Michigan
Transformer Loading Data 4
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Medical Research 1
Medical Research 2
Central Campus Rec 1
Central Campus Rec 2
Shapiro
Medical Research 3
Medical Research 4
Pharmacy 1
Pharmacy 2
Francis Thomas 1
Francis Thomas 2
Parking Services
Ground SVC
NC Beal
N13 Fletcher
W3 Thompson
E8 Church
Med Inn
Womens Office
Towsley
M18 Medical
Taubman 1
Taubman 2
Kellogg
M61 Glen
Ingalls 1
Ingalls 2
Nursing
Bagnoud
TOTAL
Building Transformer
Average Load %
Peak Load %

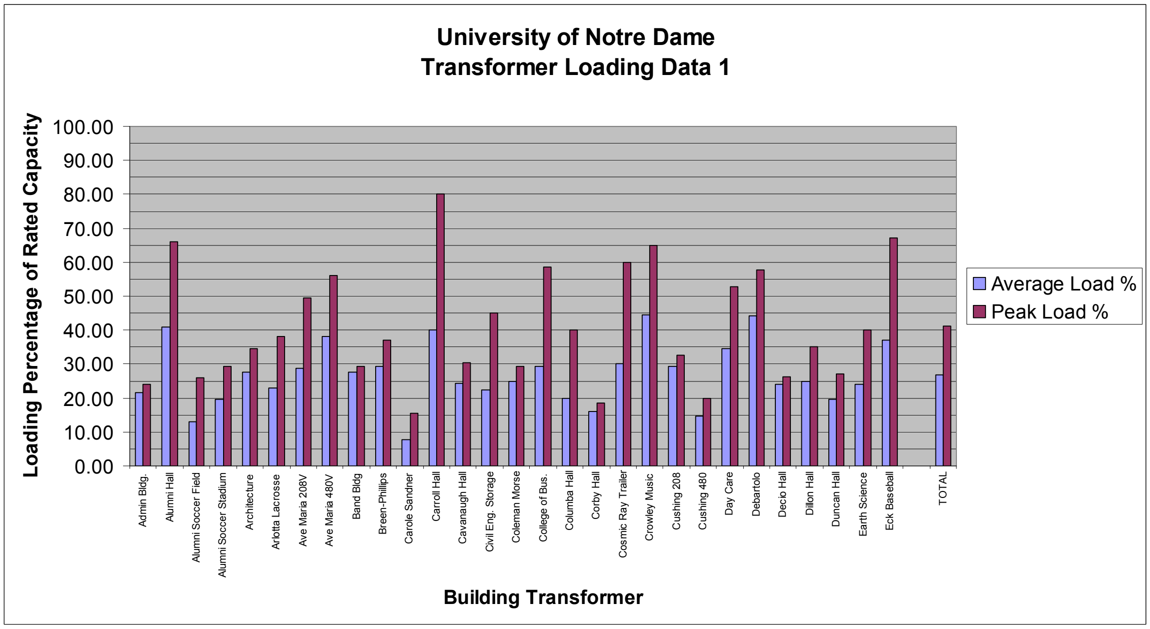

University of Michigan
Transformer Loading Data 5
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Media Union 1
Media Union 2
Lurie Robert
North Campus Admin
Lay Walter 1
Lay Walter 2
Lay Walter 3
Bonisteel
Cooley
Mich Memorial
Ann & Robert
Brown Lab 1
Brown Lab 2
Brown Lab 3
Brown Lab 4
Brown Lab 5
Fire Serv
Naval Arch 1
Naval Arch 2
North Campus Service
Laundry
School of Info 1
School of Info 2
Engineering
North Campus Rec
Industrial
North Campus Storage
Art & Arch 1
Art & Arch 2
TOTAL
Building Transformer
Average Load %
Peak Load %

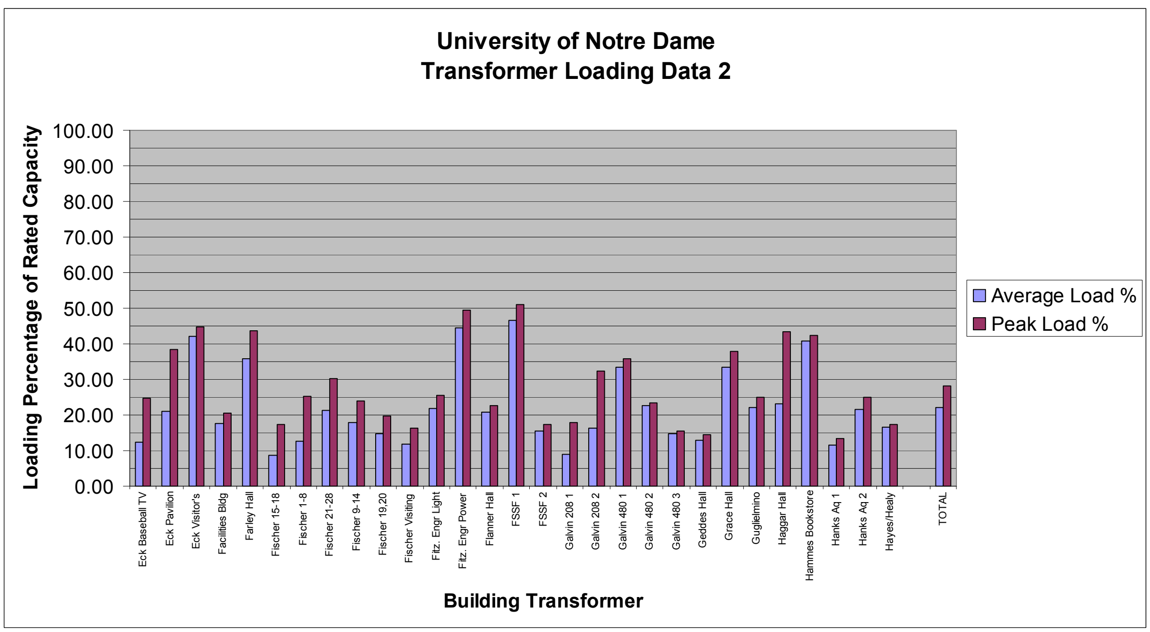

University of Michigan
Transformer Loading Data 6
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Art & Arch 3
Engineering 1
Engineering 2
Gerstacker
Bentley
Moore 1
Moore 2
Space Lab 1
Space Lab 2
Pierpont 1
Pierpont 2
Chrysler
Transportation
Ford Library
Dow Herbert
Elec Eng 1
Elec Eng 2
Elec Eng 3
Elec Eng 4
Elec Eng 5
North Campus Housing
Life Sciences 1
Life Sciences 2
Life Sciences 3
Life Sciences 4
Biomed 1
Biomed 2
Biomed 3
Biomed 4
TOTAL
Building Transformer
Average Load %
Peak Load %

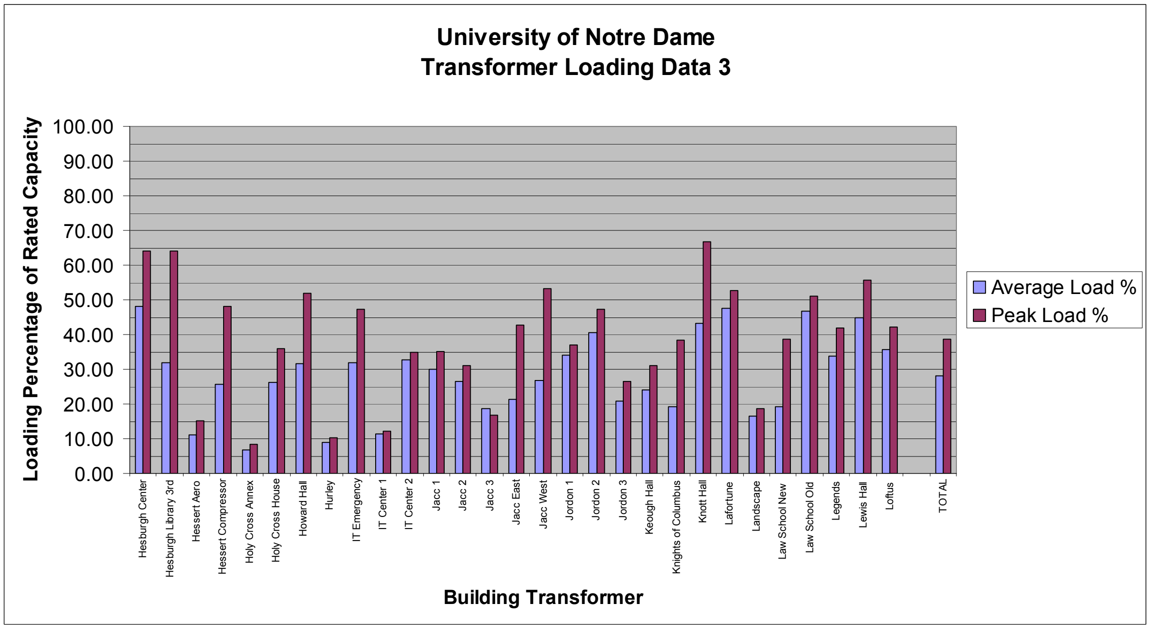

University of Michigan
Transformer Loading Data 7
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Biomed 5
Biomed 6
Undergrad 1
Undergrad 2
Palmer 1
Palmer 2
Palmer 3
Palmer Plant
Walgreen
Computer Science
Barbour
Weill Hall
Brehm Tower 1
Brehm Tower 2
Brehm Tower 3
Brehm Tower 4
Cardio Center 1
Cardio Center 2
Cardio Center 3
Cardio Center 4
Academic Success
Indoor Practice
M86 Ann
North Campus Plant 1
North Campus Plant 2
Vera Baits
Thayer
Ross 1
Ross 2
TOTAL
Building Transformer
Average Load %
Peak Load %

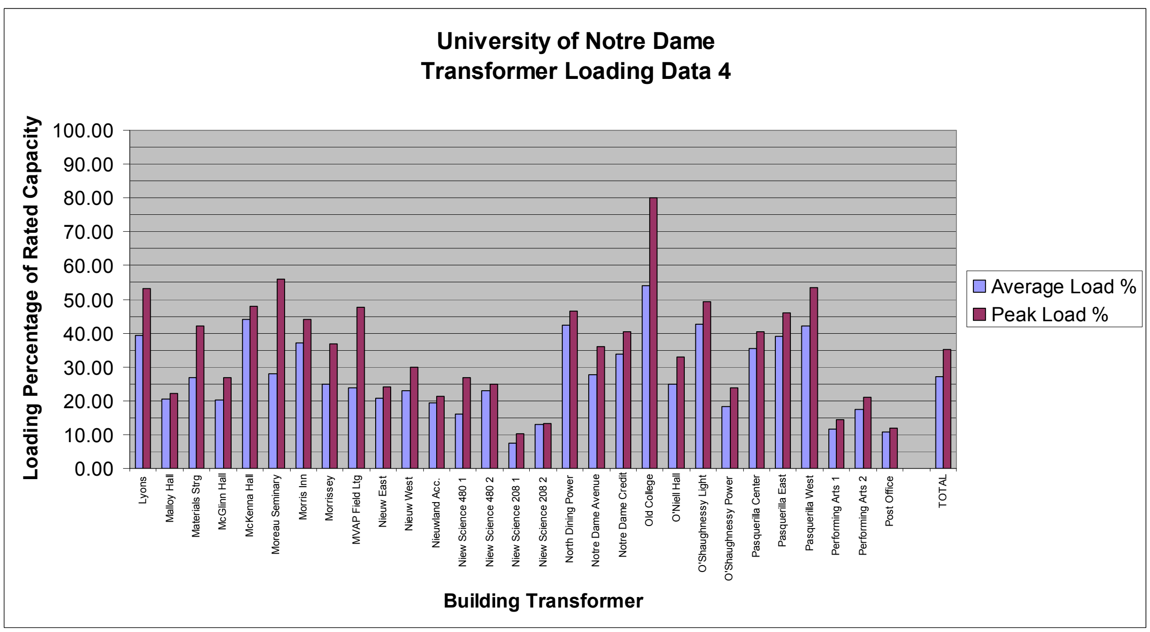

University of Michigan
Transformer Loading Data 8
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Cook
MCIT 1
MCIT 2
MCIT 3
MCIT 4
Law School
Couzens 1
Couzens 2
East Quadrangle 1
East Quadrangle 2
Bursley
Lloyd Alice
Markley
NC Family Housing
Mosher Jordan
Newberry
South Quad
Stockwell
West Quadrangle
Crisler 1
Crisler 2
Crisler 3
Indoor Track
Oosterbaan
Schembechler
Yost Ice Arena
Football Stadium 1
Football Stadium 2
Football Stadium 3
TOTAL
Building Transformer
Average Load %
Peak Load %

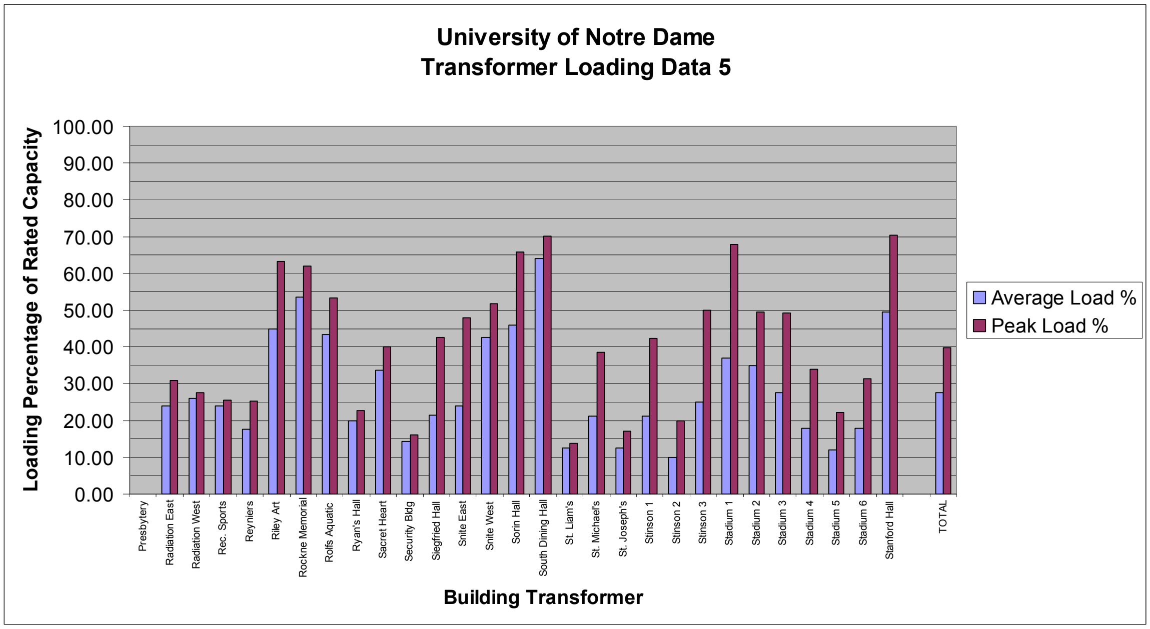

University of Michigan
Transformer Loading Data 9
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Football Stadium 4
Football Stadium 5
Football Stadium 6
Canham
Intramural
Weidenbach
Campus Safety
Hoover
Wolverine Tower
Admin Services
Hospital 1
Hospital 2
UTL Mendelssohn
TOTAL
Building Transformer
Average Load %
Peak Load %

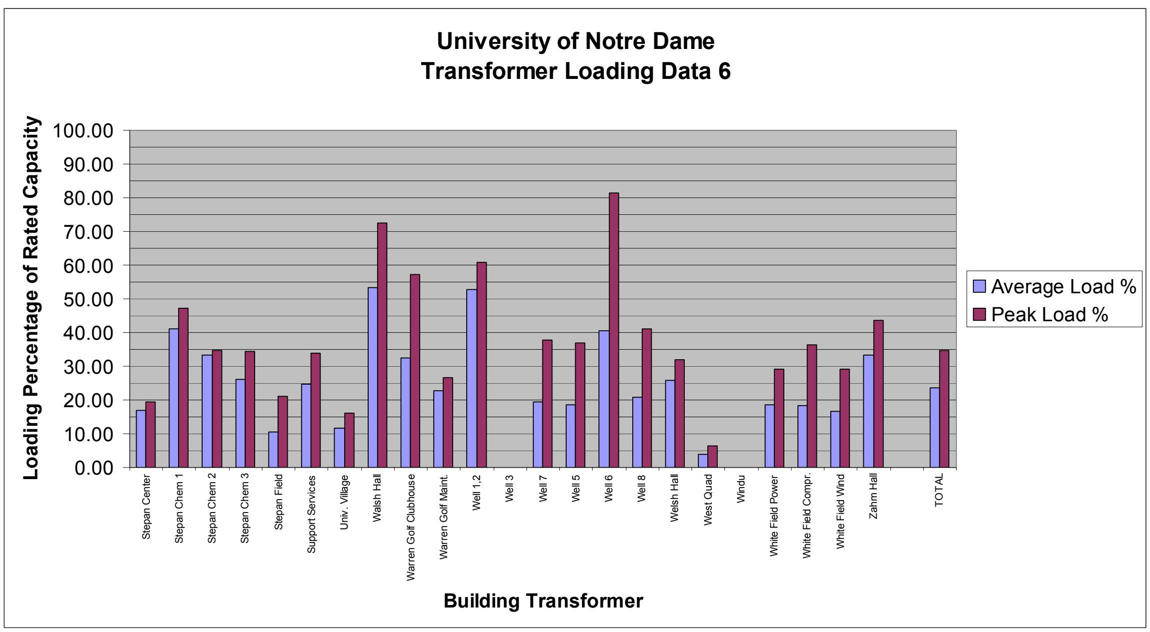

University of Notre Dame
Transformer Loading Data 1
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Admin Bldg.
Alumni Hall
Alumni Soccer Field
Alumni Soccer Stadium
Architecture
Arlotta Lacrosse
Ave Maria 208V
Ave Maria 480V
Band Bldg
Breen-Phillips
Carole Sandner
Carroll Hall
Cavanaugh Hall
Civil Eng. Storage
Coleman Morse
College of Bus.
Columba Hall
Corby Hall
Cosmic Ray Trailer
Crowley Music
Cushing 208
Cushing 480
Day Care
Debartolo
Decio Hall
Dillon Hall
Duncan Hall
Earth Science
Eck Baseball
TOTAL
Building Transformer
Average Load %
Peak Load %


University of Notre Dame
Transformer Loading Data 2
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Eck Baseball TV
Eck Pavilion
Eck Visitor's
Facilities Bldg
Farley Hall
Fischer 15-18
Fischer 1-8
Fischer 21-28
Fischer 9-14
Fischer 19,20
Fischer Visiting
Fitz. Engr Light
Fitz. Engr Power
Flanner Hall
FSSF 1
FSSF 2
Galvin 208 1
Galvin 208 2
Galvin 480 1
Galvin 480 2
Galvin 480 3
Geddes Hall
Grace Hall
Guglielmino
Haggar Hall
Hammes Bookstore
Hanks Aq 1
Hanks Aq 2
Hayes/Healy
TOTAL
Building Transformer
Average Load %
Peak Load %


University of Notre Dame
Transformer Loading Data 3
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Hesburgh Center
Hesburgh Library 3rd
Hessert Aero
Hessert Compressor
Holy Cross Annex
Holy Cross House
Howard Hall
Hurley
IT Emergency
IT Center 1
IT Center 2
Jacc 1
Jacc 2
Jacc 3
Jacc East
Jacc West
Jordon 1
Jordon 2
Jordon 3
Keough Hall
Knights of Columbus
Knott Hall
Lafortune
Landscape
Law School New
Law School Old
Legends
Lewis Hall
Loftus
TOTAL
Building Transformer
Average Load %
Peak Load %


University of Notre Dame
Transformer Loading Data 4
Loading Percentage of Rated Capacity
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Lyons
Malloy Hall
Materials Strg
McGlinn Hall
McKenna Hall
Moreau Seminary
Morris Inn
Morrissey
MVAP Field Ltg
Nieuw East
Nieuw West
Nieuwland Acc.
New Science 480 1
New Science 480 2
New Science 208 1
New Science 208 2
North Dining Power
Notre Dame Avenue
Notre Dame Credit
Old College
O'Niell Hall
O'Shaughnessy Light
O'Shaughnessy Power
Pasquerilla Center
Pasquerilla East
Pasquerilla West
Performing Arts 1
Performing Arts 2
Post Office
TOTAL
Building Transformer
Average Load %
Peak Load %





Note: University of Notre Dame average loading was calculated by taking average of provided values for minimum and maximum demand.

APPENDIX II

MANUFACTURER PROVIDED TYPICAL PERFORMANCE DATA

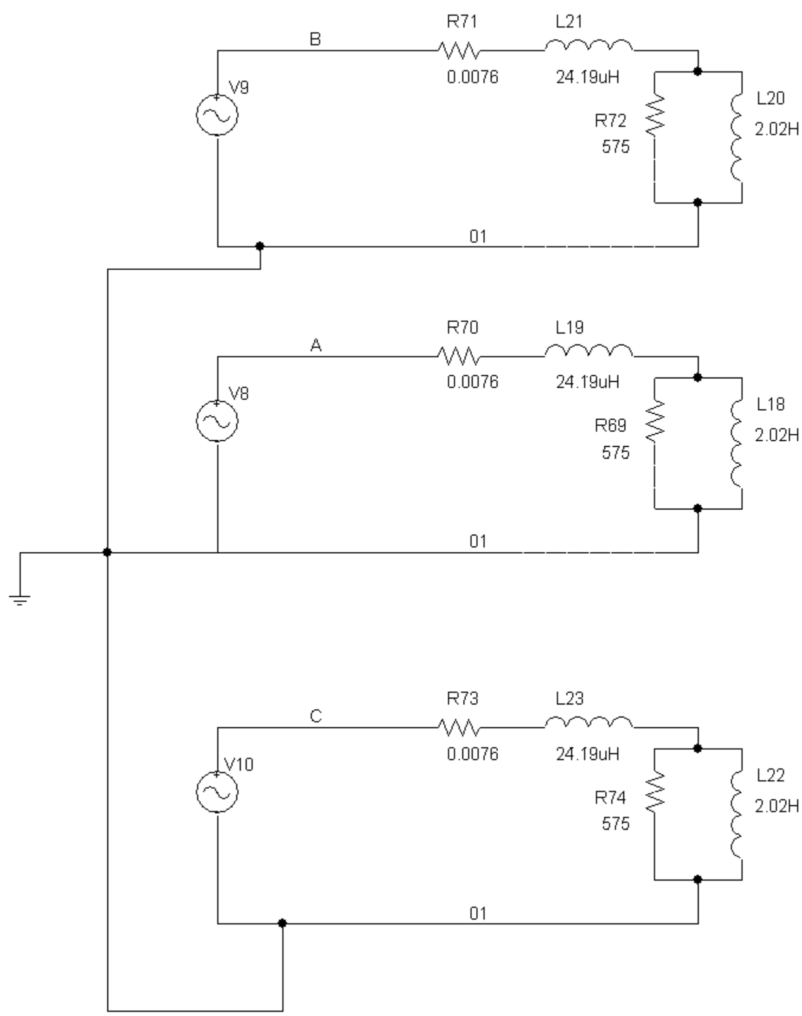
TYPICAL TRANSFORMER PERFORMANCE DATA
Copper 480V DELTA TO 208/120V WYE
TP1 TRANSFORMERS

KVA	DEG C RISE	CAT NO	LOSSES IN WATTS		EFFICIENCY					% REGULATION		%R	%X	% Z	X/R	DIMENSIONS			WT.	dB	OUTLINE
			N.L.	TOTAL	.25L	.35L	.50L	.75L	FULL	1.0 PF	.8 PF					HT	W	D	LBS.		DRAWING
15	150	9T83C9871	167	912	96.8	97.0	97.2	96.7	95.9	4.4	4.8	4.3	2.2	4.8	0.5	27.3	18.7	16.9	290	45.0	303B401AAP071
	115	9T83C9871G15	167	848	96.8	97.0	97.2	96.7	95.9	4.4	4.8	4.3	2.2	4.8	0.5	27.3	18.7	16.9	290	45.0	303B401AAP071
	80	9T83C9871G80	131	419	96.2	97.0	97.4	97.6	97.4	1.0	2.2	1.0	2.3	2.5	2.3	32.1	23.8	18.4	370	45.0	303B401AAP072
30	150	9T83C9872	138	1495	97.3	97.5	97.3	96.8	96.1	4.5	5.7	4.4	3.5	5.7	0.8	32.1	23.8	18.4	370	45.0	303B401AAP072
	115	9T83C9872G15	138	1398	97.3	97.5	97.3	96.8	96.1	4.5	5.7	4.4	3.5	5.7	0.8	32.1	23.8	18.4	370	45.0	303B401AAP072
	80	9T83C9872G80	196	844	97.0	97.5	97.7	97.7	97.4	1.5	2.8	1.5	2.6	3.0	1.7	32.1	23.8	18.4	460	45.0	303B401AAP073
45	150	9T83C9873	199	1930	97.5	97.7	97.6	97.2	96.6	4.1	5.3	4.1	3.4	5.3	0.8	32.1	23.8	18.4	460	45.0	303B401AAP073
	115	9T83C9873G15	211	1596	97.5	97.8	97.8	97.4	97.0	3.3	4.7	3.2	3.6	4.8	1.1	32.1	23.8	18.4	480	45.0	303B401AAP073
	80	9T83C9873G80	305	1036	97.1	97.7	98.0	98.1	98.0	1.0	2.3	1.0	2.5	2.7	2.5	35.7	31.8	24	673	50.0	303B401AAP074
75	150	9T83C9874	305	2719	97.8	98.0	98.0	97.6	97.1	3.5	5.1	3.4	4.0	5.2	1.2	35.7	31.8	24	673	50.0	303B401AAP074
	115	9T83C9874G15	329	2228	97.7	98.0	98.1	97.8	97.4	2.7	4.2	2.7	3.5	4.4	1.3	35.7	31.8	24	710	50.0	303B401AAP074
	80	9T83C9874G80	422	1475	97.5	98.0	98.3	98.3	98.2	1.0	2.4	1.0	2.6	2.8	2.6	39.9	31.8	24	940	50.0	303B401AAP075
112.5	150	9T83C9875	422	3237	98.0	98.2	98.3	98.0	97.6	2.7	4.4	2.7	3.8	4.6	1.4	39.9	31.8	24	940	50.0	303B401AAP075
	115	9T83C9875G15	422	3126	98.0	98.2	98.2	98.0	97.6	2.6	4.9	2.5	4.8	5.4	1.9	39.9	31.8	24	940	50.0	303B401AAP075
	80	9T45G0005G81	400	2100	98.3	98.5	98.5	98.5	98.2	1.5	2.3	1.5	1.9	2.4	1.3	37.3	29.5	28.5	976	54.0	303B899AAP077
150	150	9T45G0006	400	3430	98.5	98.7	98.5	98.3	97.8	2.0	3.5	2.0	3.1	3.7	1.6	0	0	0	976	54.0	303B899AAP077
	115	9T45G0006G51	400	3430	98.5	98.7	98.5	98.3	97.8	2.0	3.5	2.0	3.1	3.7	1.6	37.3	29.5	28.5	976	54.0	303B899AAP077
	80	9T45G0006G81	400	3425	98.5	98.7	98.5	98.3	97.8	2.0	3.5	2.0	3.1	3.7	1.6	37.3	29.5	28.5	976	54.0	303B899AAP077
225	150	9T45G0007	400	8770	98.7	98.6	98.2	97.5	96.3	3.7	5.7	3.7	4.6	5.9	1.2	37.3	34.8	28.5	976	54.0	303B899AAP077
	115	9T45G0007G51	500	4970	98.7	98.8	98.6	98.4	97.9	2.0	3.8	2.0	3.8	4.3	1.9	40.9	34.8	25.6	1160	54.0	303B899AAP078
	80	9T45G0007G81	500	4970	98.7	98.8	98.6	98.4	97.9	2.0	3.8	2.0	3.8	4.3	1.9	40.9	34.8	25.6	1160	54.0	303B899AAP078
300	150	9T45G0008	500	10270	98.8	98.7	98.3	97.8	96.7	3.3	5.3	3.3	4.6	5.7	1.4	40.9	34.8	25.6	1160	54.0	303B899AAP078
	115	9T45G0008G51	740	5540	98.7	98.8	98.7	98.6	98.2	1.6	3.2	1.6	3.2	3.5	2.0	45.4	38.5	33.6	1700	54.0	303B899AAP079
	80	9T45G0008G81	740	5540	98.7	98.8	98.7	98.6	98.2	1.6	3.2	1.6	3.2	3.5	2.0	45.4	38.5	33.6	1700	54.0	303B899AAP079
500	150	9T45G0009	740	14150	98.9	98.9	98.6	98.1	97.3	2.7	5.4	2.7	5.2	5.8	1.9	45.4	38.5	33.6	1700	54.0	303B899AAP079
	115	9T45G0009G51	740	14150	98.9	98.9	98.6	98.1	97.3	2.7	5.4	2.7	5.2	5.8	1.9	45.4	38.5	33.6	1700	54.0	303B899AAP079
	80	9T45G0009G81	1395	5950	98.7	98.8	99.0	99.0	98.8	0.9	2.0	0.9	2.1	2.3	2.3	57.5	47.5	40	4030	56.0	303B899AAP067
750	150	9T45G0010	1395	11300	99.0	99.1	99.0	98.9	98.5	1.3	3.7	1.3	4.4	4.6	3.4	57.5	47.5	40	4030	56.0	303B899AAP067
	115	9T45G0010G51	1395	11300	99.0	99.1	99.0	98.9	98.5	1.3	3.7	1.3	4.4	4.6	3.4	57.5	47.5	40	4030	56.0	303B899AAP067
	80	9T45G0010G81	1395	11300	99.0	99.1	99.0	98.9	98.5	1.3	3.7	1.3	4.4	4.6	3.4	57.5	47.5	40	4030	56.0	303B899AAP067
1000	150	9T45G0011	1395	22500	99.1	99.1	98.9	98.5	97.8	2.1	6.1	2.1	7.3	7.6	3.5	57.5	47.5	40	4030	56.0	303B899AAP068

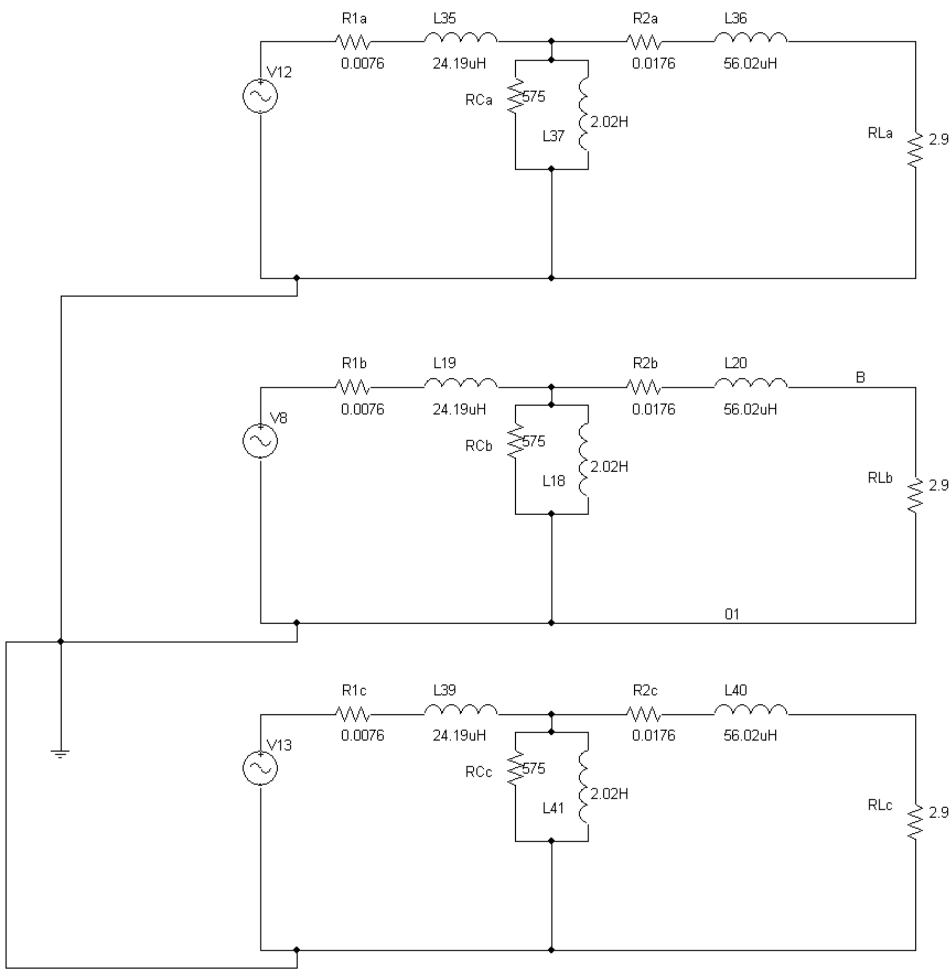
Source: http://www.ge.com/

APPENDIX III

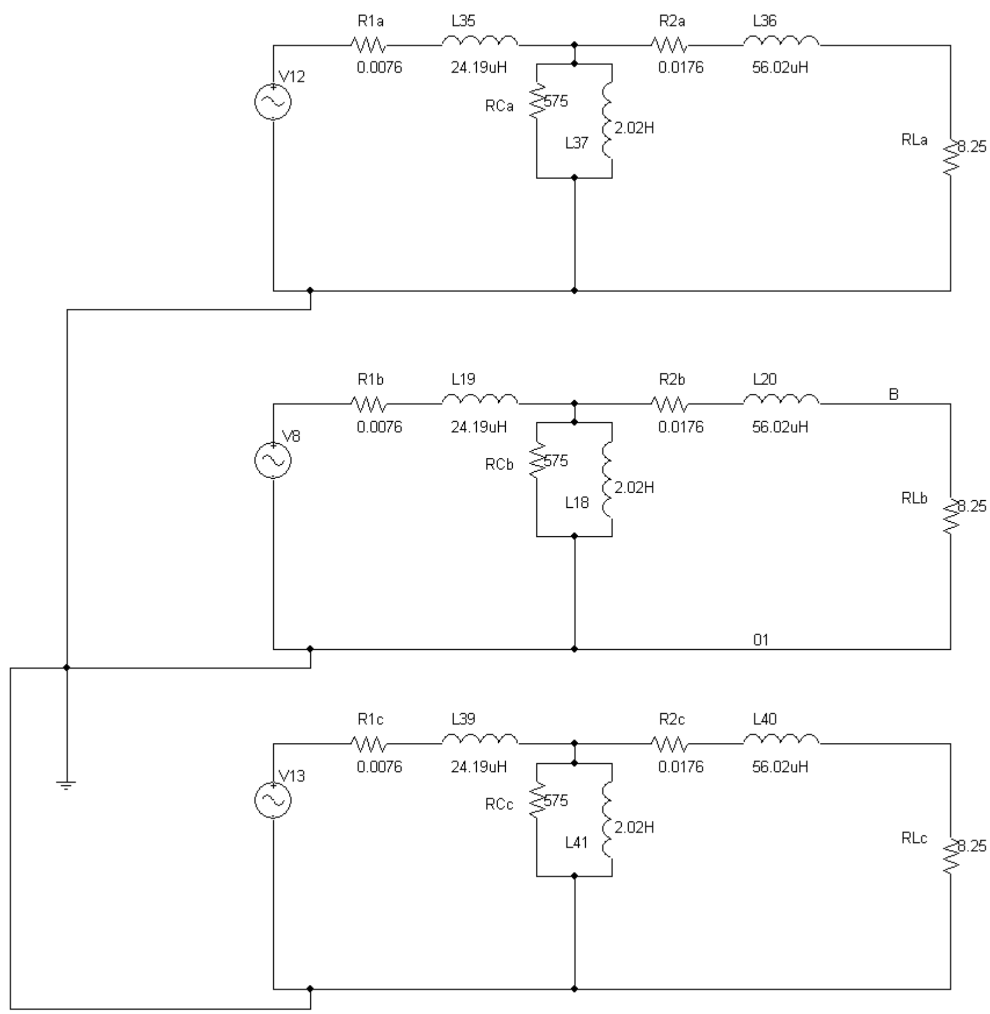
PSPICE SCHEMATICS



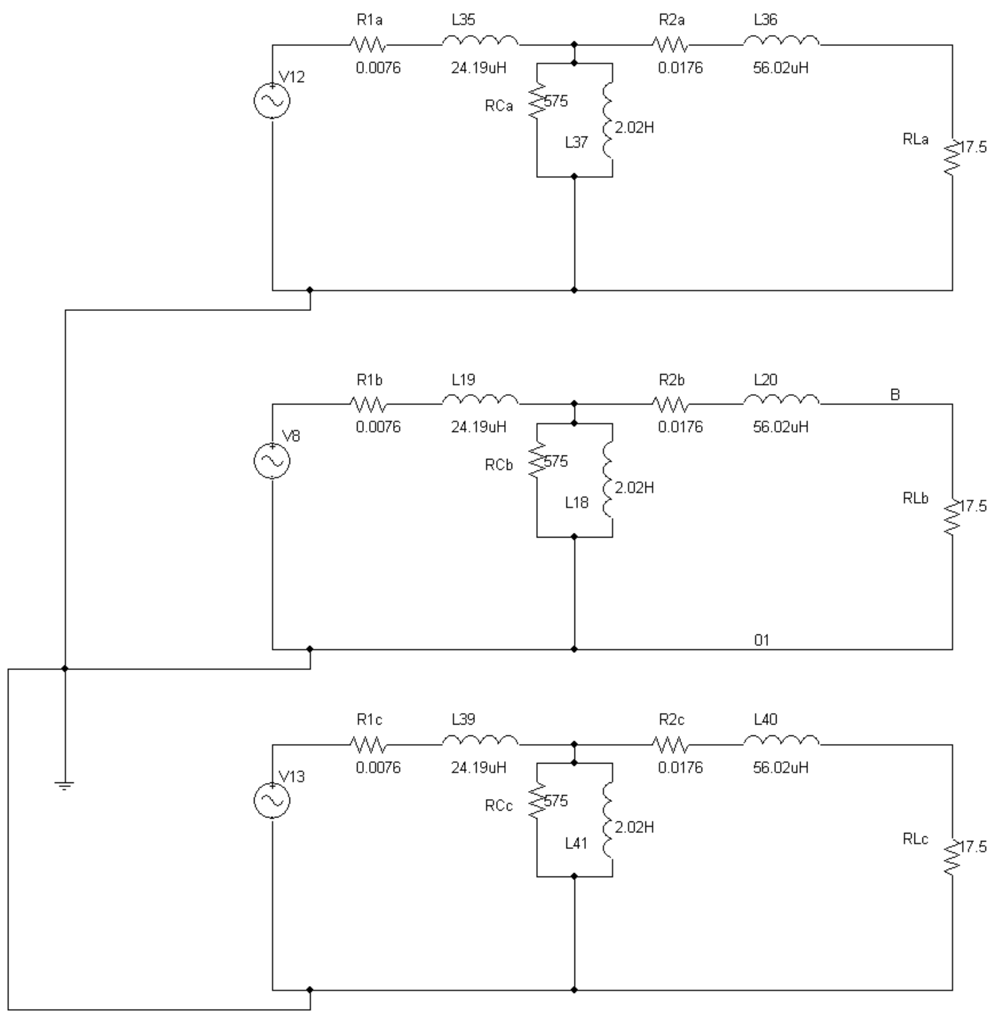
Default Model - 225 kVA Transformer No-Load



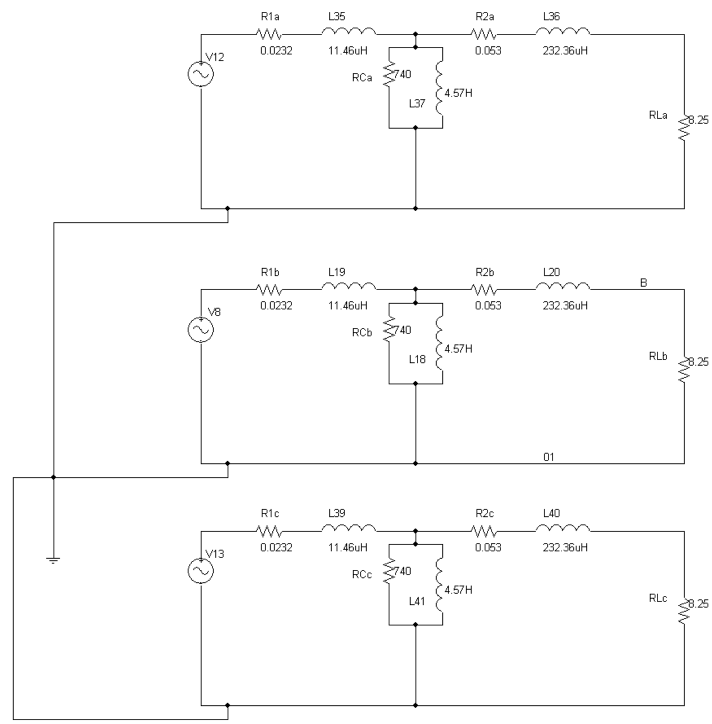
Case 1a Model - 225 kVA Transformer 35% Load

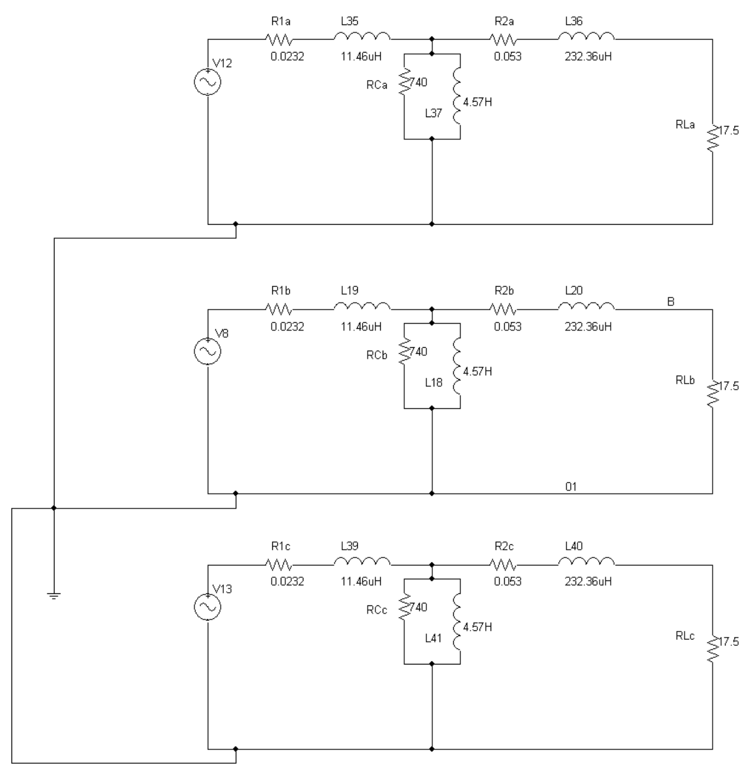


Case 1b Model - 225 kVA Transformer 12.73% Load

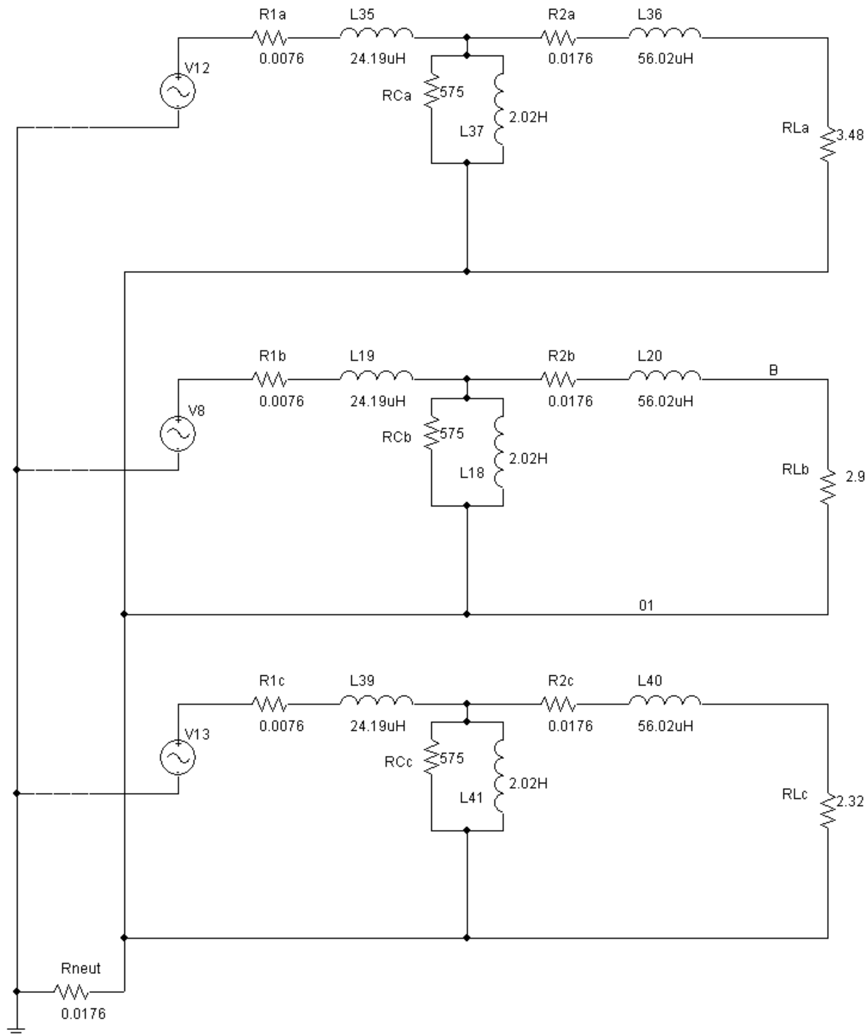


Case 1c Model - 225 kVA Transformer 6% Load

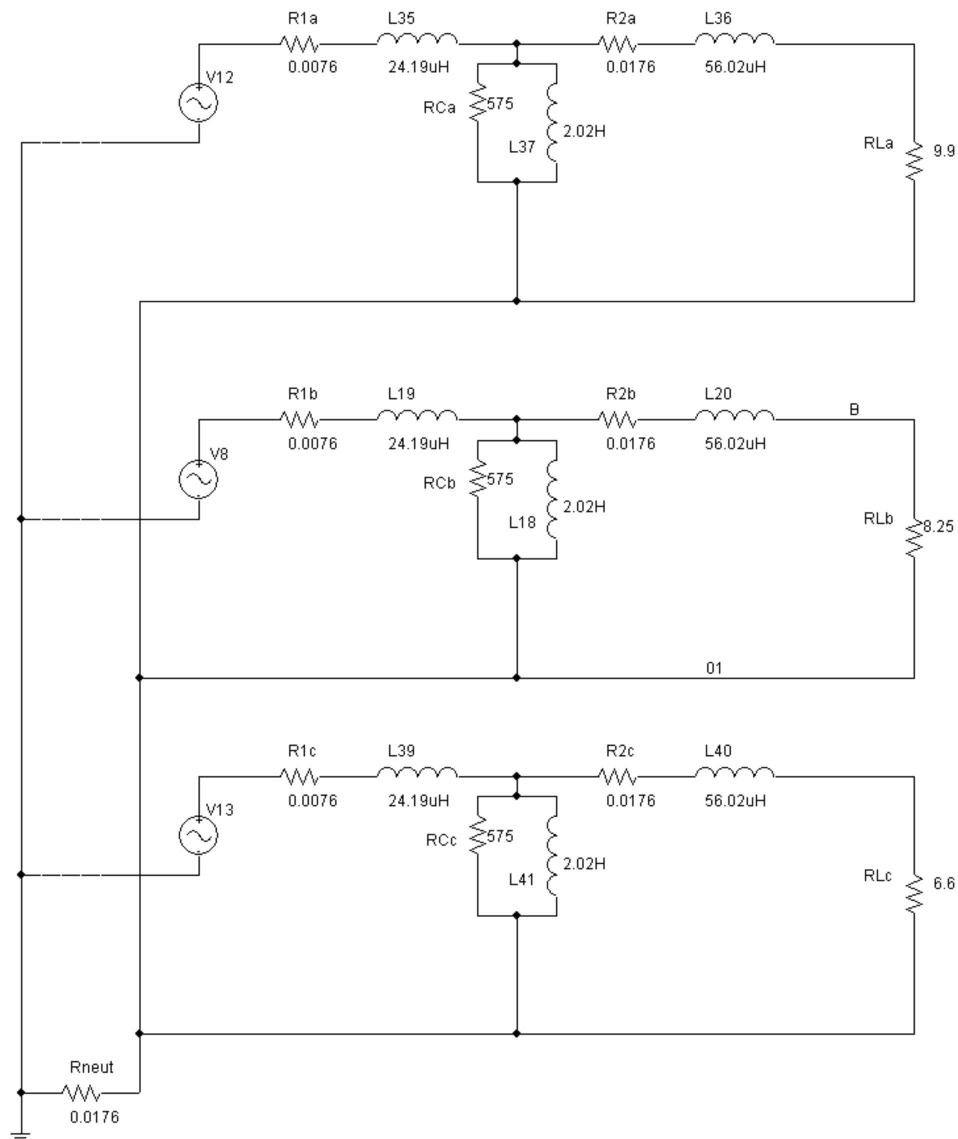




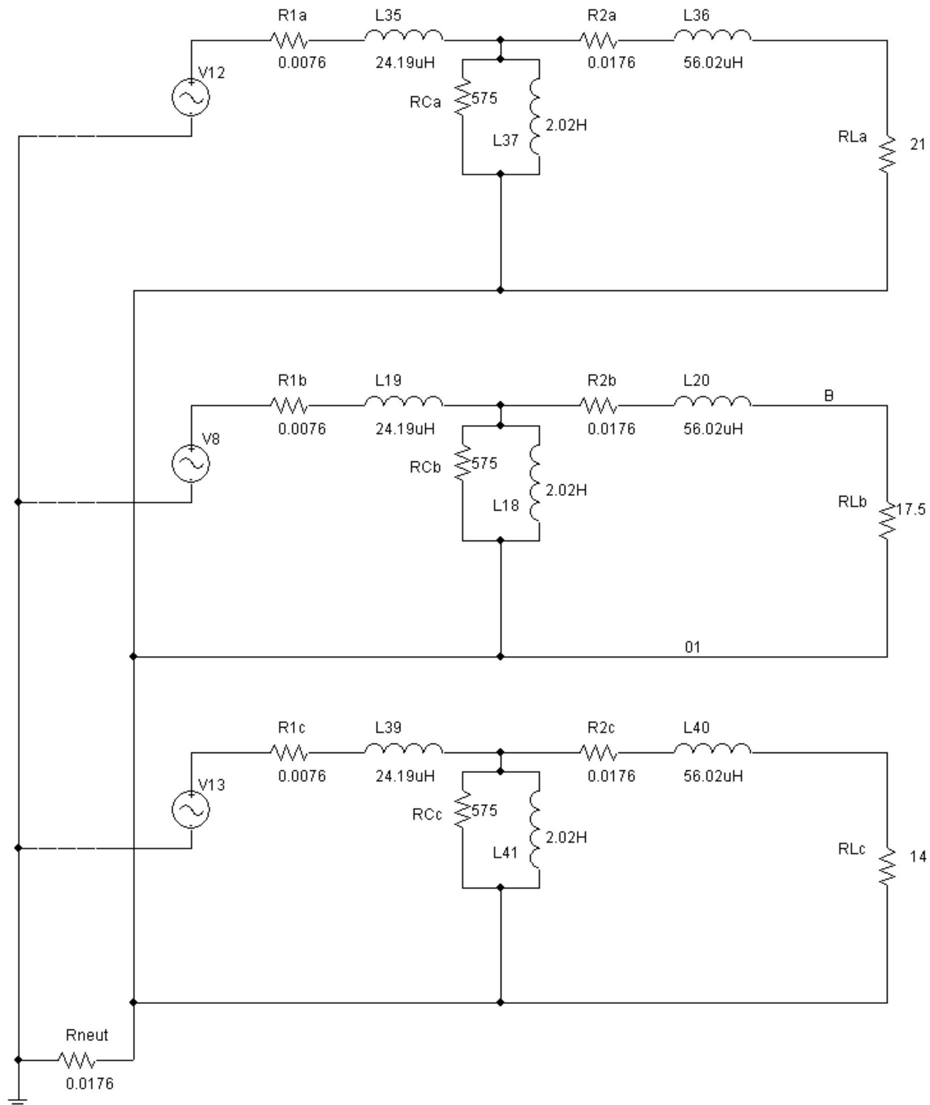
Case 1d Models - 75 kVA Transformer 38.19% and 18% Loads



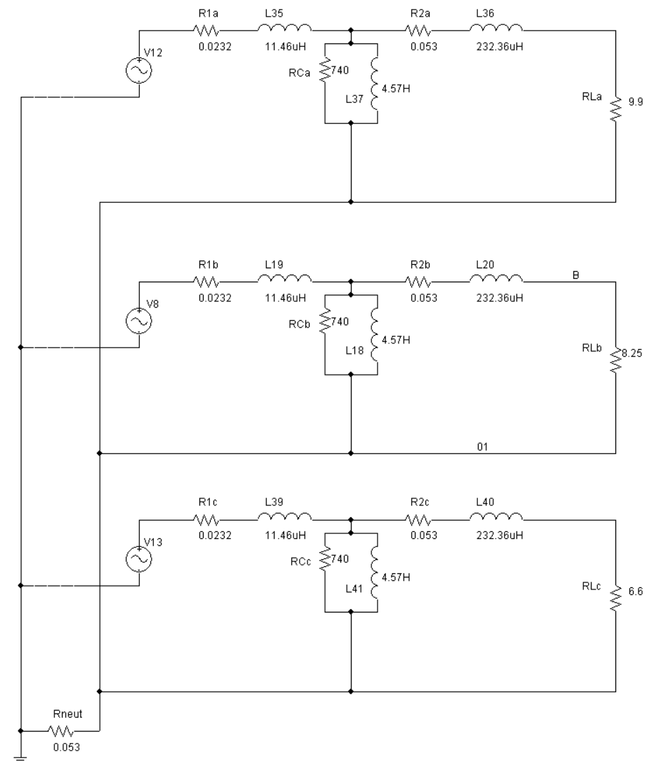
Case 2a Model 225 kVA Transformer 35% Load, Unbalanced

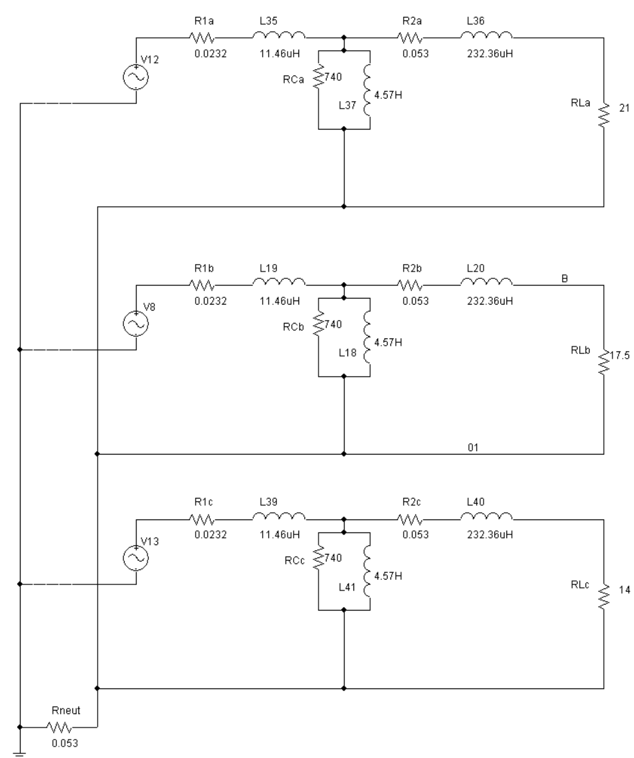


Case 2b Model 225 kVA Transformer 12.73% Load, Unbalanced

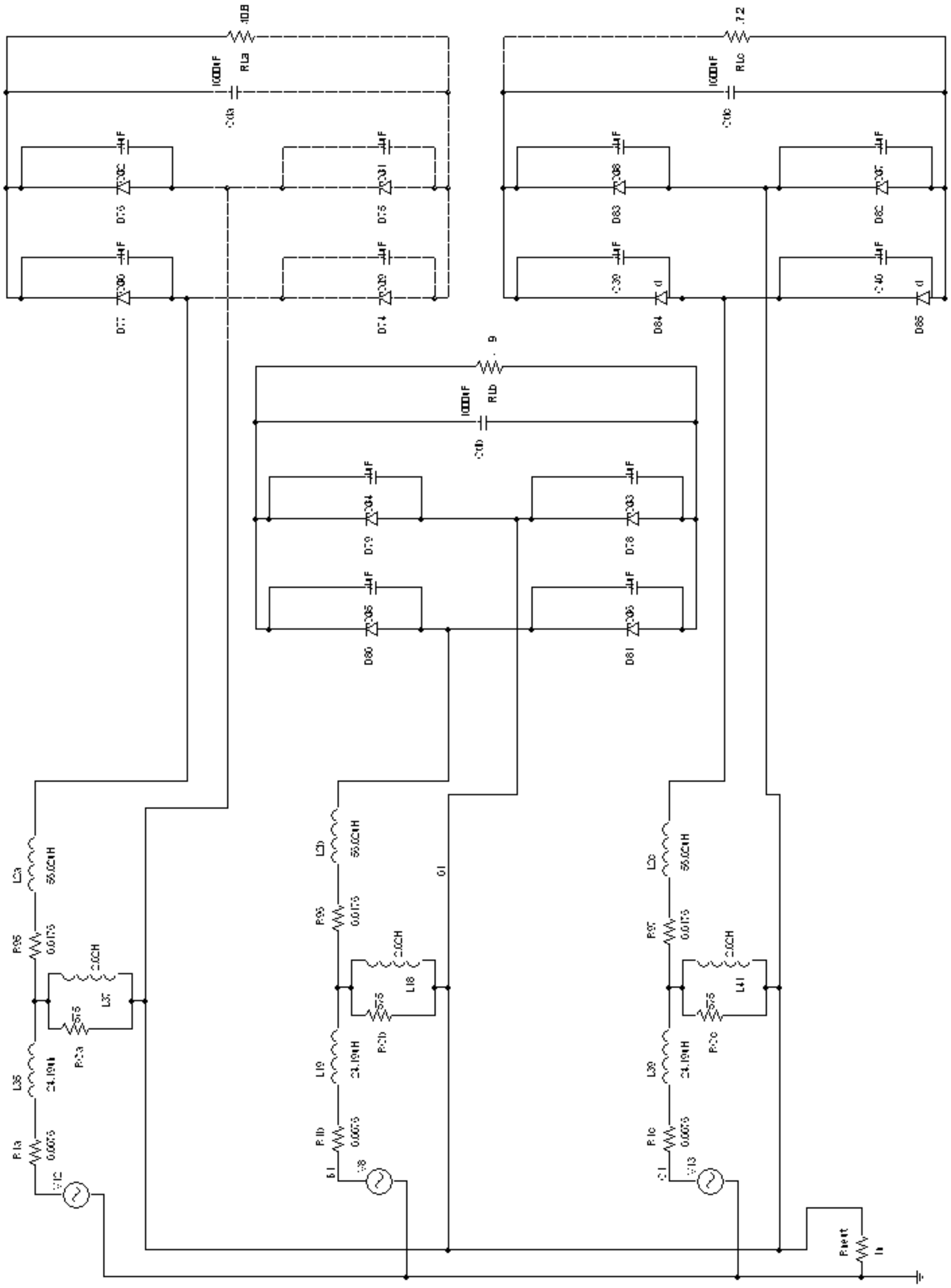


Case 2c Model 225 kVA Transformer 6% Load, Unbalanced

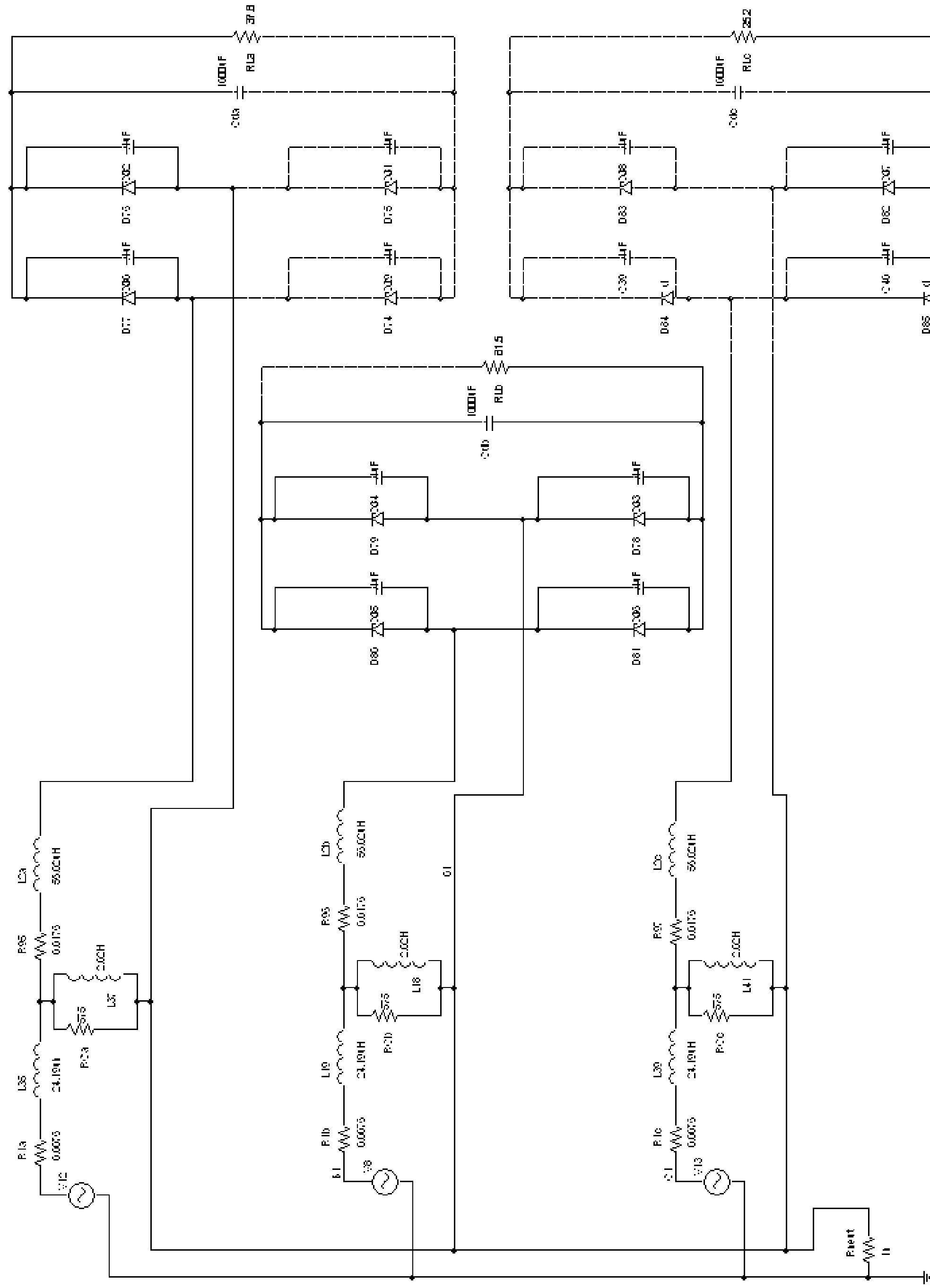




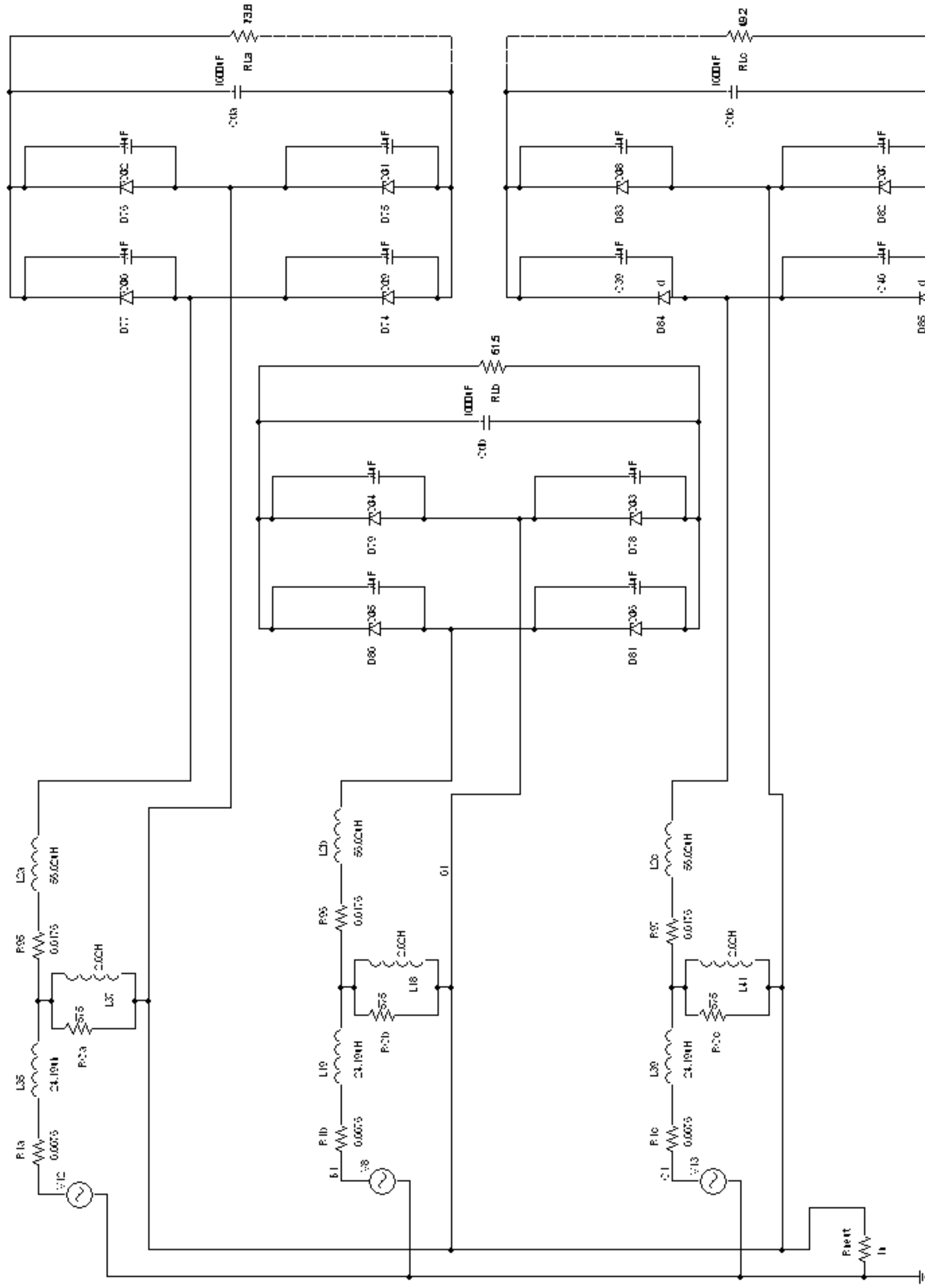
Case 2d Model 75 kVA Transformer 38.19% and 18% Loads, Unbalanced



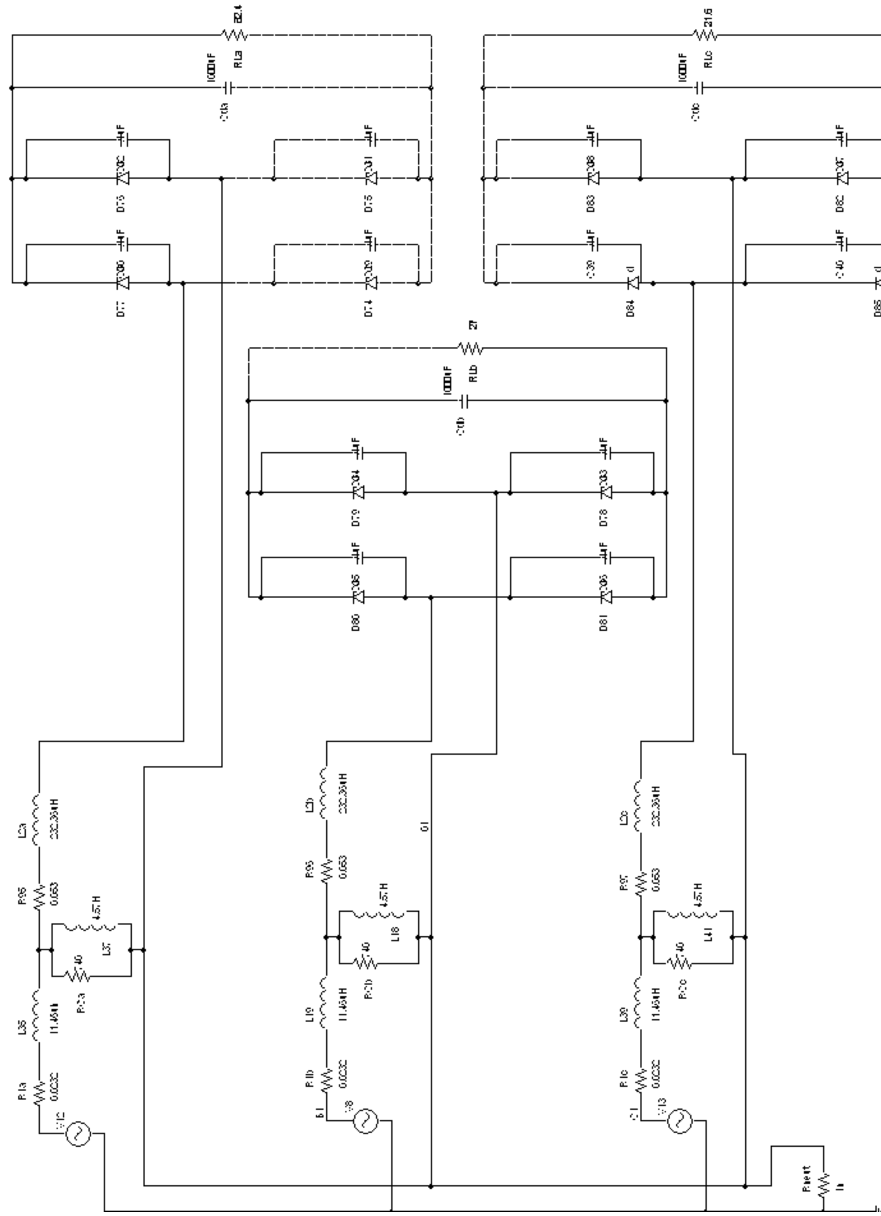
Case 3a Model 225 kVA Transformer 35% Load, Unbalanced, Non-linear



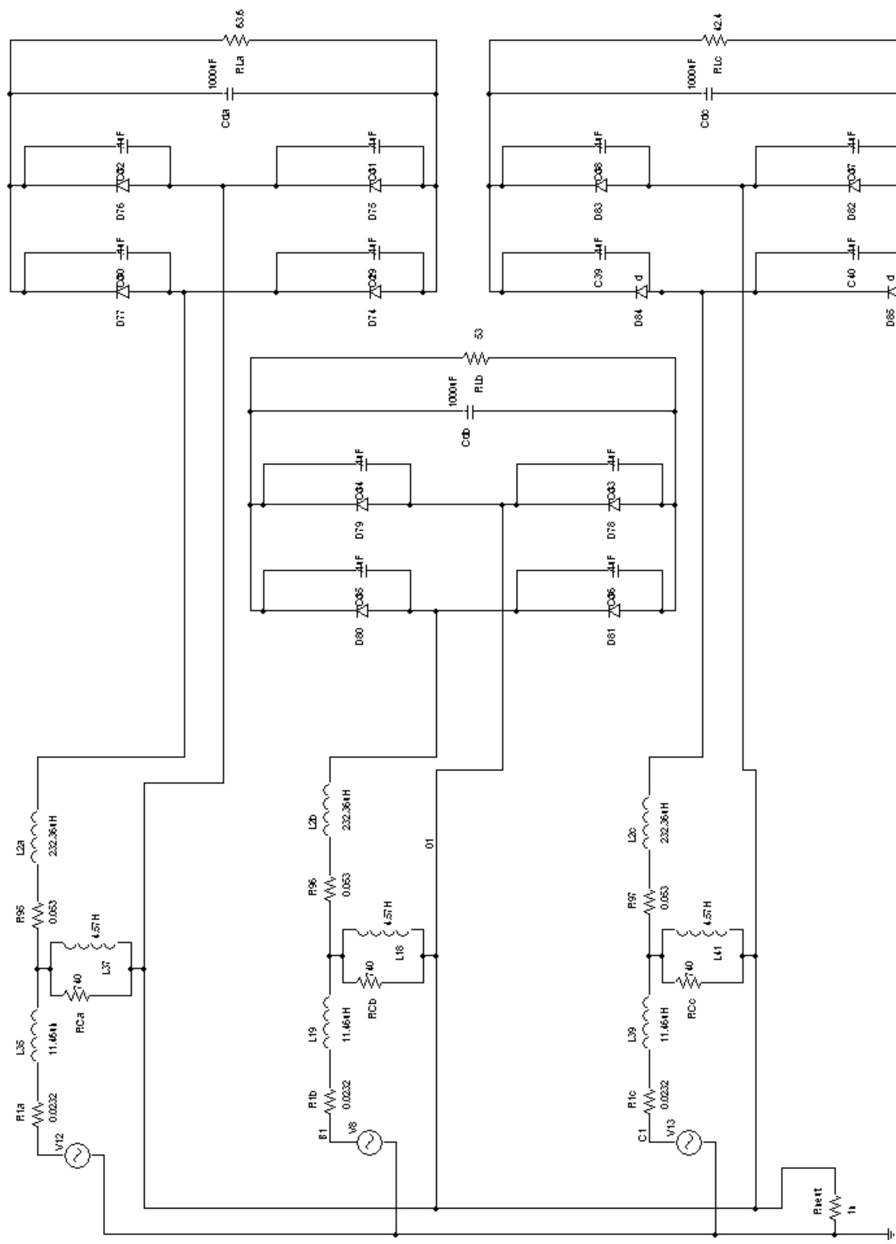
Case 3b Model 225 kVA Transformer 12.73% Load, Unbalanced, Non-linear



Case 3c Model 225 kVA Transformer 6% Load, Unbalanced, Non-linear



Case 3d Model 75 kVA Transformer 38.19% Load, Unbalanced, Non-linear



Case 3d Model 75 kVA Transformer 18% Load, Unbalanced, Non-linear

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