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LAPORAN PROJEK SARJANA MUDA

ANALYSIS OF FIVE PHASE TRANSFORMER

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Bachelor of Electrical Engineering (Power Electronic and Drive)

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"I hereby declare that I have read through this report entitle "Analysis of Five-Phase Transformer" and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Electrical Engineering (Power Electronic and Drive)"

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ANALYSIS OF FIVE-PHASE TRANSFORMER

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A report submitted in partial fulfilment of the requirements for degree of Bachelor of Electrical Engineering (Power Electronic and Drive)

Faculty of Electrical Engineering

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YEAR 2014

I declare that this report entitle "Analysis of Five-Phase Transformer" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …………………………………………..

Name : Lim Geok Yin

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ABSTRACT

Beginning in the late 1970s, the first five-phase induction motor drive system was proposed. Since then, there is large number of research has been in placed to develop the multiphase drive systems. Due to that, there is a need to develop a static phase transformation system in order to provide a multiphase output from the available three-phase supply. Three-phase supply are readily available in most area such as industrial premises, power generation and distribution station or from the grid. The study of five-phase transformer is not yet matured and the development of five-phase transformer is still in progress. In this study, the focus is to design and develop a transformer that able to convert a fixed voltage three-phase supply to a five-phase while maintaining its frequency. There are three single laminated cores are used to develop the five-phase transformer by manipulating the winding arrangement to produce five-phase output from three-phase source. Enameled wires are used in this research due to its thin layer of insulation for efficiency and ability to operate at high temperature. Besides, in this study, the performance of the transformer has been analyzed in term of efficiency and voltage regulation. There are two other parameters that has been analyze are the phase shifts of the output waveform and the voltage ratio from primary to secondary windings. To achieve the objectives, the output voltage should close to sinusoidal in shape and the phase shift for five-phase system is approximately 72°. In addition, total harmonic distortion of five-phase transformer also has been analysed and presented in this report. Thus, this proposed five phase transformer connections, is able to run the five-phase induction motor in the laboratory.

ABSTRAK

Bermula pada lewat tahun 1970-an, sistem pemacu motor aruhan lima fasa yang pertama telah dicadangkan. Sejak itu, terdapat banyak penyelidikan telah dilaksanakan dalam membangunkan sistem pemacu berbilang fasa. Lanjutan dari itu, terdapat keperluan untuk membangunkan system penukar fasa statik bagi mendapatkan bekalan berbilang fasa dari bekalan tiga fasa yang sedia. Bekalan tiga fasa boleh didapati di kebanyakan tempat seperti di premis industri, stesen penjanaan dan pengagihan atau *grid*. Kajian tentang pengubah lima fasa masih belum matang dan pembangunan berkaitan dengannya masih dijalankan. Dalam kajian ini, tumpuan adalah dalam merekabentuk dan seterusnya membangunkan sebuah pengubah yang boleh menukar bekalan kuasa tiga fasa kepada bekalan kuasa lima fasa dengan mengekalkan frekuesi yang sama. Tiga teras pengubah berlapis digunakan untuk membangunkan pengubah lima fasa dengan memanipulasi susunan belitan bagi menghasilkan keluaran lima fasa dari sumber kuasa tiga fasa. Wayar enamel dipilih untuk digunakan dalam kajian ini kerana mempunyai lapisan penebat yang nipis bagi meningkatkan kecekapan dan juga mampu beroperasi pasa suhu yang tinggi. Selain itu, tumpuan kajian ini adalah juga untuk menganalisis prestasi pengubah yang dibina dari segi kecekapan dan regulasi voltan. Terdapat dua parameter lain yang perlu dianalisiskan iaitu anjakan fasa pada keluaran dan nisbah voltan antara belitan utama dan belitan sekunder. Untuk mencapai objektif kajian, voltan keluaran perlu hampir kepada bentuk sinus dan anjakan fasa bagi keluaran lima fasa adalah hampir 72°. Di samping itu, jumlah herotan yang disebabkan oleh harmonik bagi pengubah lima fasa juga akan dianalisis dan diterangkan dalam laporan ini. Dengan itu, pengubah lima fasa yang di hasilkan ini berjaya memacu motor aruhan lima fasa yang terdapat di makmal.

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A_{core}	-	Cross-sectional Area of the core material
AC	-	Alternating Current
B_{max}	-	Maximum Flux Density in the Core
DC	-	Direct Current
E	-	Rated Coil Voltage
E.M.F	-	Electro-Motive Force
F	-	Operating Frequency
HVAC	-	Heating, Ventilation and Air-conditioning
N	-	Number of turn in winding
N_P	-	Number of turn in Primary winding
N_S	-	Number of turn in Secondary winding
V_P	-	Primary Voltage
V_S	-	Secondary Voltage
P	-	Power
S	-	Rated power
TH	-	Total Harmonic
THD	-	Total Harmonic Distortion
TR	-	Turn Ratio

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

In the early 19th century, there is rapid development in the power system application in many areas such as transmission, distribution and power system appliances. In the year 1970s, there is rapidly growth in the sector of machines [2]. Therefore, there is an interest on five-phase motor drive system increased over years. Recently, multiphase systems are the focus of research due to their inherent advantages compared to the three-phase counterparts [1].

Multiphase transformer that provide precisely controlled multiphase output resulting in low harmonic currents over a wide range of load currents without requiring resistive and inductive tuning when applied to a rectifier system and provide specified output voltage for a given input voltage [3]. Therefore, multiphase transformer system can improve the phasor balance and reduce total harmonic distortion. There are many electrical system require direct current power. Those direct current (DC) is typically produced by rectifying three-phase alternating current (AC) voltage. The rectifiers, yet, induce harmonic distortion in the input line [4].

In the ac-dc rectifier system, multiphase such as 6-phase and 12-phase system is found to be fewer ripples with a high frequency of ripple. The purpose of choosing a 6-, 12-, or 24-phase system is because these numbers are multiple of three. Besides, the design for this kind of system is simple and straightforward. The increase number of phases definitely enhances the complexity of the system. However, there are none of these designs are available for odd number of phases like 5, 7, 11 etc [1].

1.2 PROBLEM STATEMENT

In the past decade, the sector of machines has growth rapidly. The interest of study five-phase motor drive system has increased over years. The advantages of five-phase transformer over three-phase transformer are low harmonic distortion and the rated current per phase is small. However, the study of five-phase transformer is not yet matured and it is not widely available in industry.

1.3 OBJECTIVE(S) OF THE PROJECT

The objectives of this project are:

- To design and develop a five-phase transformer by converting the three-phase grid supply to a five-phase fixed voltage by maintaining the constant frequency supply
- To analyze the performance of the transformer base on the efficiency and voltage regulation, the phase shift of the output waveform and the voltage ratio (primary winding to secondary winding)
- To analyse total harmonic distortion for five-phase transformer

1.4 PROJECT SCOPE

This project is focus on design and develops a transformer that able to produce five-phase output from three-phase input. Besides, this project is also focus on analyze the performance of a five-phase transformer based on the efficiency and voltage regulation, the phase shift of the output waveform and the voltage ratio (primary winding to secondary winding). This project is only focus on five-phase transformer and other phases like four-phase, six-phase, seven-phase etc. are not covered. The frequency is fixed to 50Hz. The stability of five-phase transformer is not considered in this project because it is only focused on the phase shift of the waveform and more sinusoidal waveform. Base on the available core; a step-down and 1-to-1 transformers will be designed and developed to test the consistency. The supply voltage per phase on primary side for this transformer is 86.97V due to number of turns on the primary side, estimated rated current is 2.2A and the estimated rated power per phase is 191VA.

1.5 CONTRIBUTION OF RESEARCH

- To gain new knowledge on five-phase transformer since there is not widely used in industries
- To extend the knowledge of five-phase transformer based on the performance analysis of the five-phase transformer

1.6 REPORT OUTLINES

This report consists of five chapters. Chapter one is the ‘Introduction’. This chapter will explain about the conceptual and theoretical information regarding the five-phase transformer. It includes the project background, problem statement, objectives of the project, scope of the project, contribution of this research and report outlines.

Chapter two is the ‘Literature Review’. This chapter describe about background theory of the transformer and three-phase transformer. Besides, related previous work for this project also included in this chapter.

In this chapter three, it is described about the methodology of the project. It is included the basic design of the project, hardware development, testing and measurement.

Chapter four is the ‘Result and Analysis’. The performance of hardware are important to validate the findings accordingly to the objectives of the project and analysis of the hardware and theoretical estimation.

Chapter five is the ‘Conclusion and Recommendation’. This chapter is important to conclude the major result of the research. Besides, the recommendations are to improve the project in future.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter introduces and explains the source of idea for design, concept, specification and other information that related to the project. It is found base on the product that have been developed or research by institutions before this project. From this study is to analyze the performance of the transformer which converts the three-phase grid supply to a five-phase fixed voltage by maintaining the constant frequency supply as proposed in [1] as well as achieving the desired objectives.

A literature review is to summarize all the information which is related to the selected area of study. From the literature review, we can reuse or develop the design and also reduce the troubleshooting on hardware by referring to the previous journals.

2.2 THEORY

2.2.1 TRANSFORMER

Since 1830s, transformers have been an essential component in electrical and electronic circuits. Although there are new technologies in some electronic circuits have reduced the need for transformer, but they are still important in many applications [6]. A transformer is a static device to convert the electric power in one circuit to electric power in another circuit with same frequency. A transformer consists of two or more coils of wire wrapped around a common ferromagnetic core. These coils are not directly connected. The only connection between the coils is the common magnetic flux present within the core [5]. One of the transformer windings is connected to a source of ac electric power, and the second (and perhaps third) transformer winding supplies electric power to the load. The transformer winding connected to the power source is called the primary winding or input winding, and the winding connected to the load is called the secondary winding or output winding. If there is a third winding on the transformer, it is called the tertiary winding [5]. The working principle of the transformer is shown in Figure 2.1.

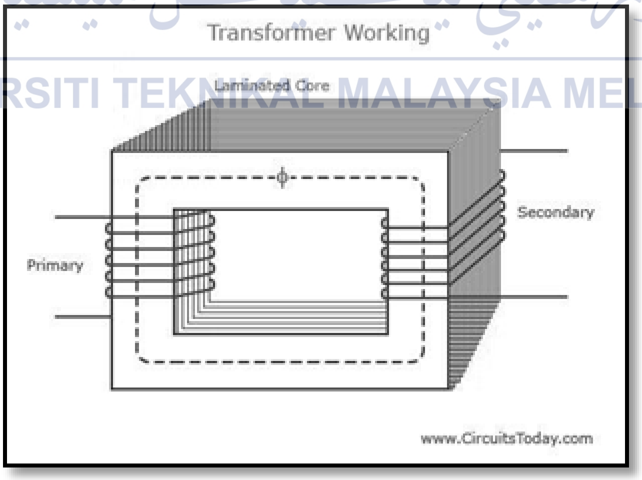

Figure 2.1: Transformer working [7]

In Figure 2.1, it is shown that transformer has primary and secondary windings. The core laminations are joined in the form of strips in between the strips that there are some narrow gaps right through the cross-section of the core. These staggered joints are said to be 'imbricated'. There have high mutual inductance in both coils. A mutual electro-motive force is induced in the transformer from the alternating flux that is set up in the laminated core, due to the coil that is connected to a source of alternating voltage [7].

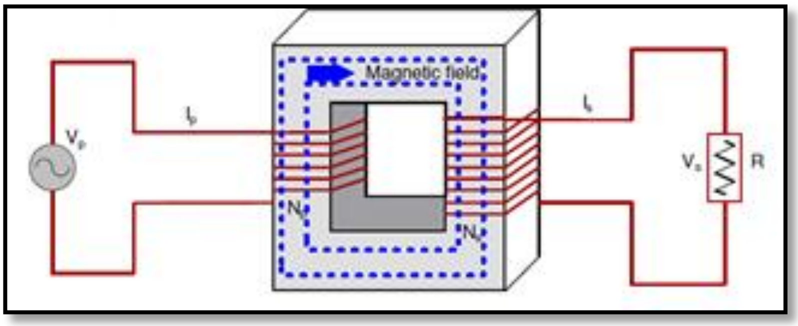

Figure 2.2: Transformer schematic [8]

When an alternating voltage is applied to the primary winding, the back electro-motive force (E.M.F) generated by primary is given by Faraday's law:

$$EMF = V_p = -N_p A \frac{\Delta B}{\Delta t} \tag{2.1}$$

A current in the primary winding produces a magnetic field in the core. The magnetic field is almost totally confined in the iron core and couples around through the secondary coil. The induced voltage in the secondary winding is also given by Faraday's law:

$$V_s = -N_s A \frac{\Delta B}{\Delta t} \tag{2.2}$$

The rate of change of flux is same as in primary winding. Therefore, diving the equation (2.1) by (2.2) gives:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \tag{2.3}$$

Figure 2.2 show the magnetic circuit has the primary and secondary coils on separate legs. In fact, half of the primary and secondary coils are wound on the two legs, with sufficient insulation between the two coils and the core to properly insulate from each winding and the core. A transformer wound will greatly reduce the effectiveness of the operation due to magnetic leakage as shown in Figure 2.2. Magnetic leakage is the part of the magnetic flux that passes through either one of the coils, however, not through both. The further the distance between primary and secondary windings, the longer the magnetic circuit and the larger the leakage. Figure below shows the construction of a single phase transformer [8].

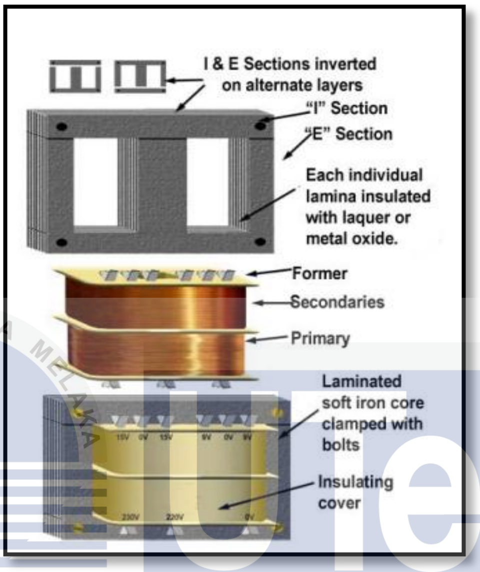

Figure 2.3: The construction of the transformer [8]

The voltage developed by transformer action is:

$$E = \sqrt{2} \times \pi \times f \times N \times B_{max} \times A_{core}$$

$$E = 4.44 \times f \times N \times B_{max} \times A_{core} \tag{2.4}$$

Where E = rated coil voltage (V),

f = operating frequency (Hz),

N = number of turn in the winding,

B_{max} = maximum flux density in the core (tesla),

A_{core} = cross-sectional area of the core material (m^2)

Furthermore, for the voltage equation, a power equation expressing the volt-ampere (VA) rating in terms of the other input parameters is also used in transformer design [8]. The form of the equation is

$$VA = 4.44 \times f \times N \times B_{max} \times A_{core} \times J \times A_{cond} \quad (2.5)$$

Where, N, B_{max}, A_{core} and f had defined on above,

J = current density $\left(\frac{A}{mm^2}\right)$,

A_{cond} = coil cross-sectional area (mm^2) in the core window,

J depends upon heat dissipation and cooling.

2.2.2 THREE-PHASETRANSFORMER

Transformer for three-phase circuits can be constructed in one of two ways. One approach is simply to take three single-phase transformers and connect them in a three-phase bank. An alternating approach is to make a three-phase transformer consisting of three sets of winding wrapped on a common core. These two possible types of transformer construction are shown in Figure 2.4 and Figure 2.5. A single three-phase transformer is lighter, smaller, cheaper, and slightly more efficient, but using three separate single-phase transformers has the advantage that each unit in the bank could be replaced individually in the event of trouble. A utility wound only need to stock a single spare single-phase transformer to back up all three phases, potentially saving money [5].

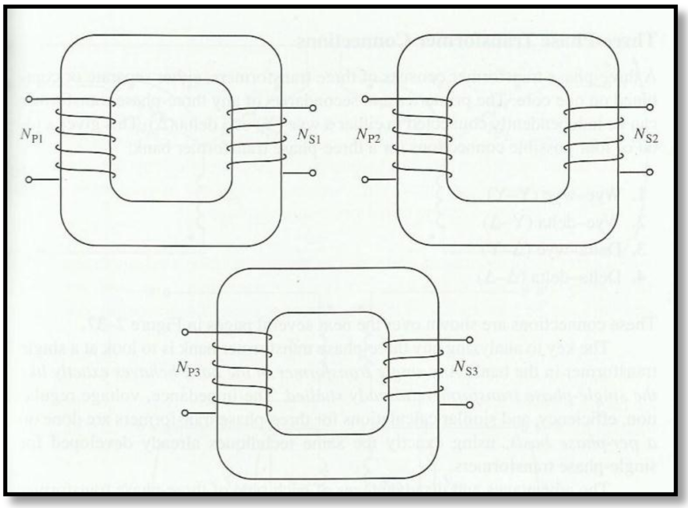

Figure 2.4: A three-phase transformer bank composed of independent transformers [5]

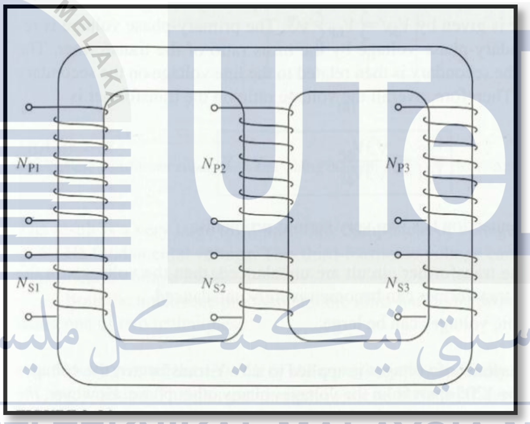

Figure 2.5: A three-phase transformer wound on a single three-legged core [5]

A three-phase transformer consists of three transformers, either separate or combined on one core. The primaries and secondaries of any three-phase transformer can be independently connected in either wye (Y) or a delta (Δ) [5]. The common three-phase transformer connection which listing primary winding first are:

- wye-wye is commonly used for interior wiring systems
- wye-delta is used to step-down utilities high line voltages
- delta-wye is often used for industrial applications
- delta-delta is often used for industrial applications

In addition, three-phase supplies have many electrical advantages over single-phase power and when considering three-phase transformers need to deal with three alternating voltages and currents differing in phase-time by 120 degrees as shown in Figure 2.5 [9].

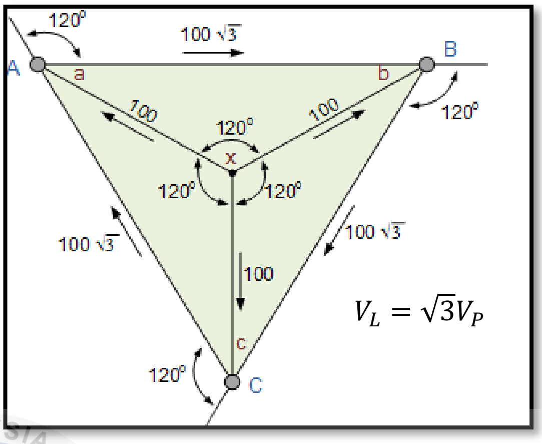

Figure 2.6: Three-phase voltages and currents [9]

2.2.2.1 WYE-WYE CONNECTION

In wye-wye connection, the primary voltage on each phase of the transformer is given by $V_{\emptyset P} = \frac{V_{LP}}{\sqrt{3}}$. The primary-phase voltage is related to the secondary-phase voltage by the turn ratio of the transformer [5]. Therefore, the turn ratio (TR) for wye-wye connection is:

$$TR = \frac{N_P}{N_S} = \frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}V_{\emptyset P}}{\sqrt{3}V_{\emptyset S}} \qquad (2.6)$$

However, the wye-wye connection has two very serious problems:

- If loads on the transformer circuit are unbalanced, then the voltages on the phases of the transformer can become severely unbalanced.
- Third-harmonic voltage can be large.

If a three-phase set of voltages is applied to a wye-wye transformer, the voltages in any phase will be 120° apart from the voltages in any other phase. However, the third-harmonic components of each of the three phases will be in phase with each other, since there are three cycles in the third harmonic for each cycle of the fundamental frequency [5].

The wye-wye connection is illustrated in Figure 2.7

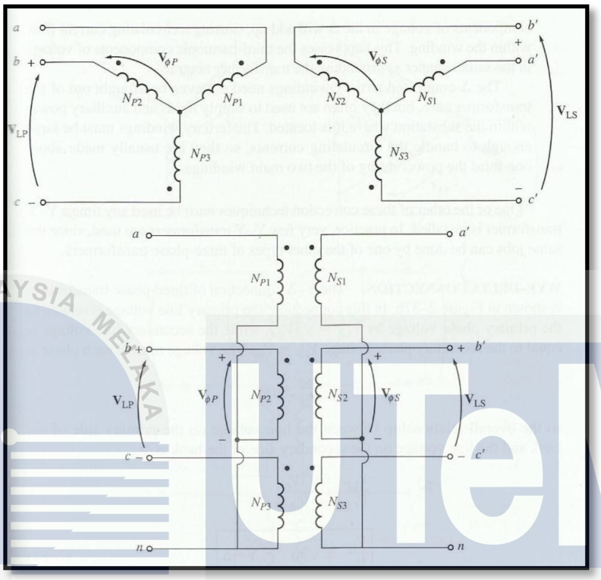

Figure 2.7: Wye-wye connection [5]

2.2.2.2 WYE-DELTA CONNECTION

In wye-delta connection, the primary line voltage is related to the primary phase voltage by $V_{LP} = \sqrt{3}V_{\emptyset P}$, while the secondary line voltage is equal to the secondary phase voltage $V_{LS} = V_{\emptyset S}$ [5]. Therefore, the turn ratio (TR) for wye-delta connection is:

$$TR = \frac{N_P}{N_S} = \frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}V_{\emptyset P}}{V_{\emptyset S}} \quad (2.7)$$

Delta-wye connection introduces a 30°, 150°, 270°, or 330° phase shift. Therefore, they cannot be paralleled with wye-wye or delta-delta connection. The phase angles of transformer secondaries must be equal if they are to be paralleled, which means that attention must be paid to the direction of the 30° phase shift occurring in each transformer bank to be paralleled together [5].

The wye-delta connection is illustrated in Figure 2.8.

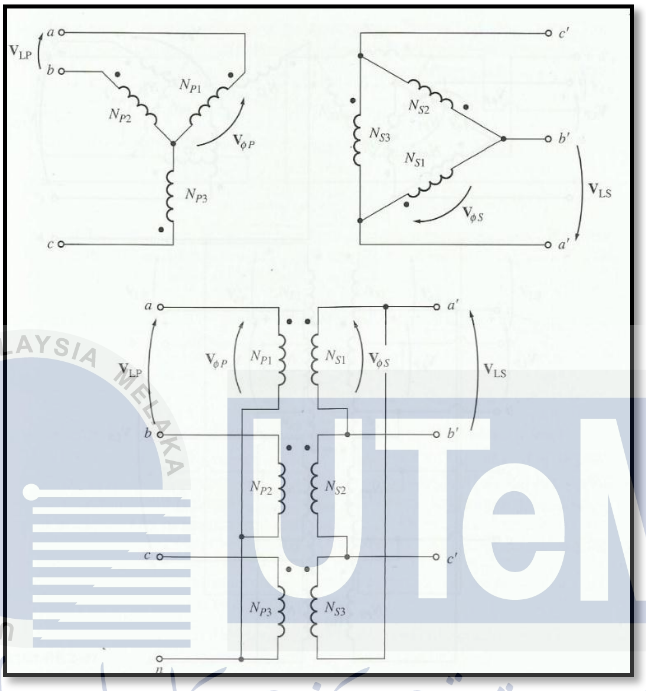

Figure 2.8: Wye-delta connection [5]

2.2.2.3 DELTA-WYE CONNECTION

In delta-wye connection, the primary line voltage is equal to the primary-phase voltage, $V_{LP} = V_{\emptyset P}$, while the secondary voltages are related by $V_{LS} = \sqrt{3}V_{\emptyset S}$ [5]. Therefore, the turn ratio (TR) for delta-wye connection is:

$$TR = \frac{N_P}{N_S} = \frac{V_{LP}}{V_{LS}} = \frac{V_{\emptyset P}}{\sqrt{3}V_{\emptyset S}} \tag{2.8}$$

This connection has the same phase shift as the wye-delta transformer [5].

The connection of delta-wye is illustrated in Figure 2.9.

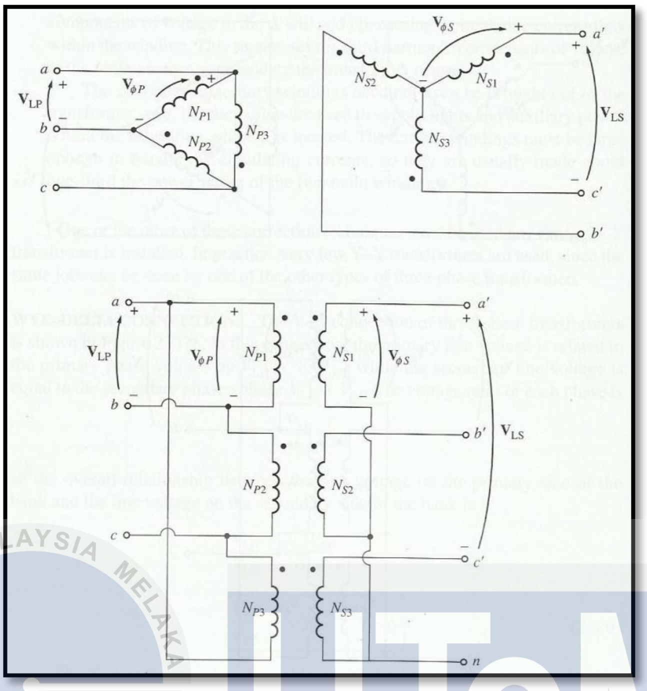

Figure 2.9: Delta-wye connection [5]

2.2.2.4 DELTA-DELTA CONNECTION

In delta-delta connection, $V_{LP} = V_{\emptyset P}$ and $V_{LS} = V_{\emptyset S}$ [5]. Therefore, the turn ratio (TR) for delta-delta connection is:

$$TR = \frac{N_P}{N_S} = \frac{V_{LP}}{V_{LS}} = \frac{V_{\emptyset P}}{V_{\emptyset S}} \tag{2.9}$$

This transformer has no phase shift associated with it and no problems with unbalanced loads or harmonics [5].

The connection of delta-delta is illustrated in Figure 2.10.

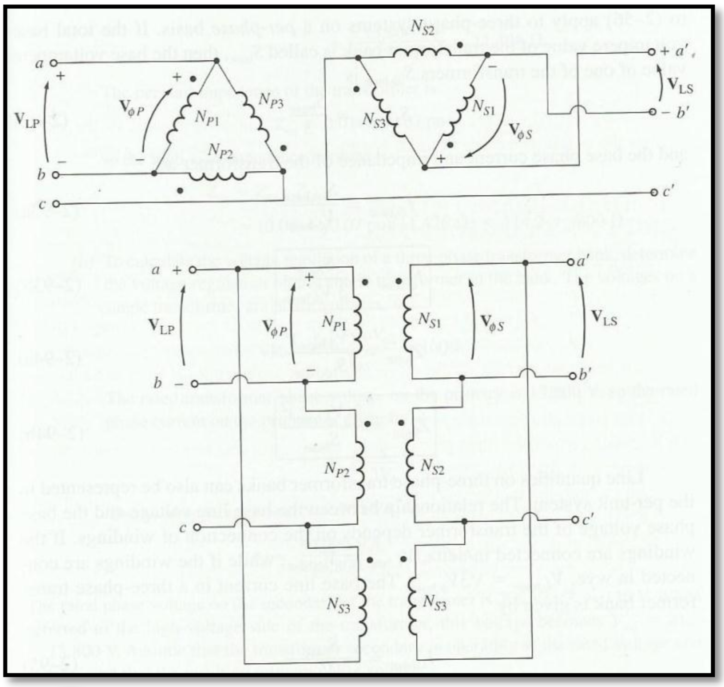

Figure 2.10: Delta-delta connection [5]

2.2.2.5 SUMMARY OF THREE-PHASE TRANSFORMER

Table 2.1 shows the overall of the three-phase transformer line voltage and current.

Table 2.1: Overall of three-phase transformer

Primary-Secondary Configuration	**Line Voltage**	**Line Current**
Wye-Wye	$V_{LP} = aV_{LS}$	$I_{LP} = \frac{I_{LS}}{a}$
Wye-Delta	$V_{LP} = \sqrt{3}aV_{LS}$	$I_{LP} = \frac{I_{LS}}{\sqrt{3}a}$
Delta-Wye	$V_{LP} = \frac{aV_{LS}}{\sqrt{3}}$	$I_{LP} = \frac{\sqrt{3}I_{LS}}{a}$
Delta-Delta	$V_{LP} = aV_{LS}$	$I_{LP} = \frac{I_{LS}}{a}$

Where: *a* equals the transformers "turns ratio" (TR) of the number of primary windings N_P, divided by the number of secondary windings N_S, $\left(\frac{N_P}{N_S}\right)$.

2.2.3 TOTAL HARMONIC DISTORTION

Total harmonic distortion (THD) is another term used to quantify the non-sinusoidal property of a waveform. THD is the ratio of the rms value of all the nonfundamental frequency terms to the rms value of the fundamental frequency term [22].

$$TH = \sqrt{\frac{\sum_{n\neq 1} I_{n,rms}^2}{I_{1,rms}^2}} \tag{2.10}$$

Assume no dc component in the output,

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,rms})^2}}{V_{1,rms}} = \frac{\sqrt{V_{rms}^2 - V_{1,rms}^2}}{V_{1,rms}} \tag{2.11}$$

2.3 RELATED PREVIOUS WORK (FIVE-PHASE TRANSFORMER)

Multiphase system is the system that has more than three-phase system. The application of multiphase system is discovered in electric power generation, transmission and utilization. Multiphase system such as six-phase transmission lines can deliver the same power capacity with a lower phase-to-phase voltage and smaller. Besides, it is more compact towers when compared to a standard double-circuit three-phase line. With this six-phase compact towers may also help in the reduction of magnetic field [14].

In the beginning of this century, the research about multiphase drive system has expanded momentum because of the availability of cheap reliable semiconductor devices and digital signal processors [15].

From the research [1], the author proposed a novel phase transformation system which converts an available three-phase source to an output five-phase source. Little effort is made for developing any static transformer system to convert the phase number from three to n-phase where n must be more than 3 or odd.

Multiphase such as 6- and 12-phase transformers are designed to feed a multipulse rectifier system and the technology has matured. With 6- and 12-phase system, there is found to produce less ripple with high frequency of ripple in an ac-dc rectifier system. Lately, a 24-phase and 36-phase transformer system has been proposed for supplying a multiphase rectifier [16]-[19]. The reason of choosing 6-, 12- or24-phase system is that these numbers are multiple of 3. Besides, designing this type of system is simple and straightforward. By increasing the number of phases certainly enhances the complexity of the system [1]. Due to the research [1], it stated that none of these design are available for an odd number of phases such as 5-, 7-, 11- etc. as far as the authors know.

According to [1], a special transformer connection scheme to obtain a balanced five-phase supply with the input as balanced three-phase was proposed. The block diagram, Figure 2.11, shows the proposed system.

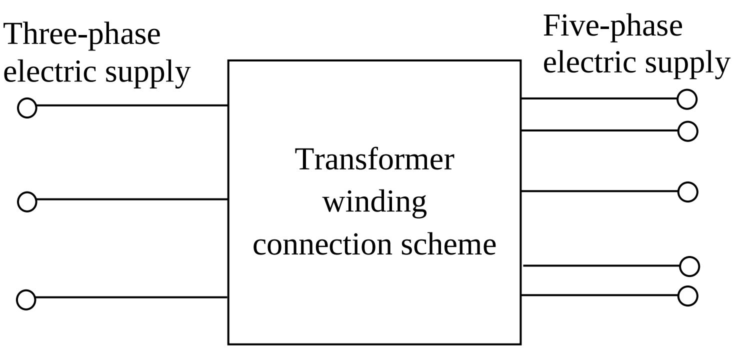

Figure 2.11: Block representation of the proposed system [1]

The fixed voltage and fixed frequency available grid supply can be transformed to the fixed voltage and fixed frequency five-phase output supply [1]. The input and output can be arranged as follow:

- Input wye, output wye;
- Input wye, output polygon;
- Input delta, output wye;
- Input delta, output polygon.

Since input is a three-phase system, then the winding are connected in a usual way [1].

The advantage of multiphase transformer is it can reduce the total harmonic distortion and improve the phasor diagram. There are many electrical system require direct current power. Those direct current (DC) is typically produced by rectifying three-phase alternating current (AC) voltage. The rectifiers, yet, induce harmonic distortion in the input line [4].

2.4 SUMMARY OF REVIEW

The research on a transformer that able to produce five-phase source from the available three-phase source is limited. There are few references are available [1][2][20][21]. However, reference [2], [20] and [21], the method they build the hardware are same as [1]. Therefore, in this project, the method in [1] will be applied to design and develop the five-phase transformer with different knowledge. The turn ratio of the transformer will be different and the size of wire used will be different too. Besides, the size of core will also change.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The purpose of this chapter is to give detail on the project about the methodology that is used. Methodology is one of the parts that explain about the project flow from the beginning until it is done. Every choice and decision that has been taken throughout the project must be explained briefly in stages.

3.2 METHODOLOGY OF THE PROJECT

3.2.1 BASIC DESIGN

Figure 3.1 shows the flow chart of the project activities.

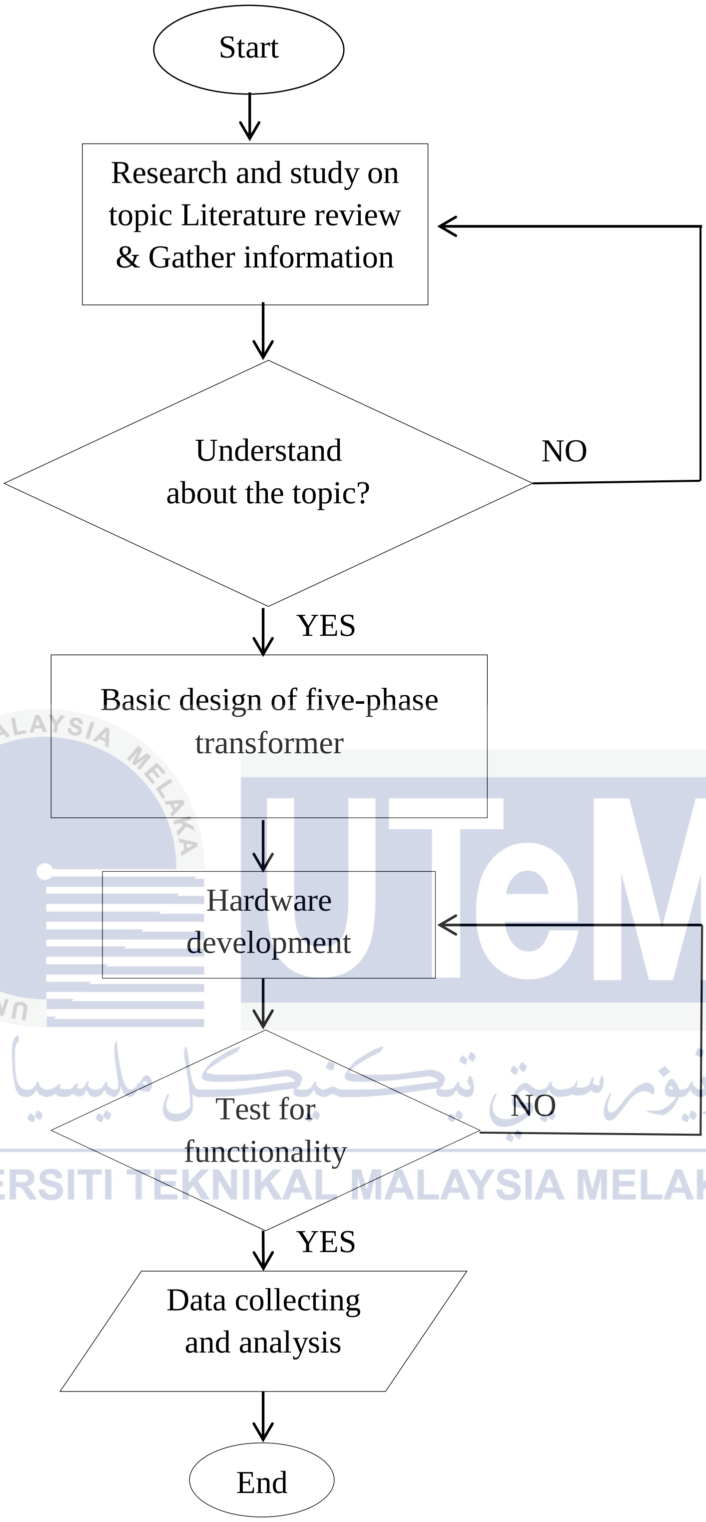

Figure 3.1: Flow chart of the project activities

There are few ways or methods to be used to achieve the objectives that had listed. First is to work on the literature review about this topic. Next is to draft out the basic design of the five-phase transformer. Then, need to choose the components that are suitable for this project which can reduce the cost and at the same time, not complicated. Since this project is about to build a five-phase transformer, so the components or equipment can be taken from the laboratory in UTeM. After the hardware is finished develop, then the transformer need to go for testing. If the hardware is functioning well, then the data and result is recorded and analysed. Finally discussion and conclusion are made for this project.

3.2.1.1 WINDING ARRANGEMENT FOR FIVE-PHASE TRANSFORMER

The method that used to design these five-phase transformers was followed the method in [1]. Wye-wye connection was used to design the five-phase transformer because it was easy to do the connection and all the other ends were joined together especially for five-phase transformer, it was difficult to do the connection by using delta connection. Three separate cores were used to develop the transformer. Each of it was carrying one primary and three secondary coils, except in one core where only two secondary coils were used. There were six terminals of primaries which connected in a proper way resulting star connection and the other 16 terminals of secondaries were connected in a different way which resulting in star output. Figure 3.2(a) and Figure 3.2(b) show the transformer winding arrangement was in wye-wye connection.

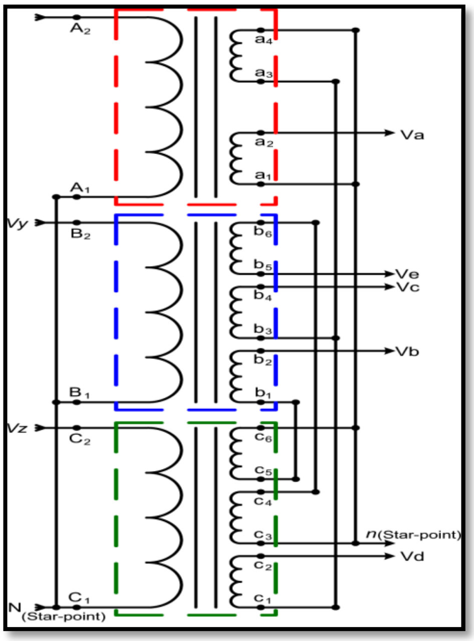

Figure 3.2(a): Transformer winding arrangement in wye-wye connection [1]

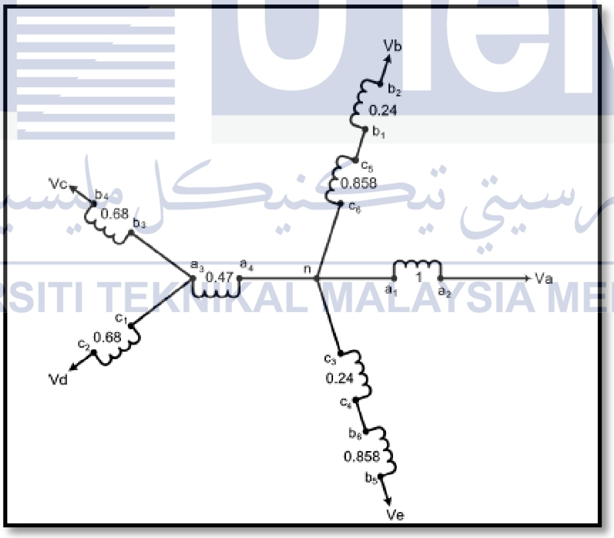

Figure 3.2(b): Transformer winding arrangement in wye connection [1]

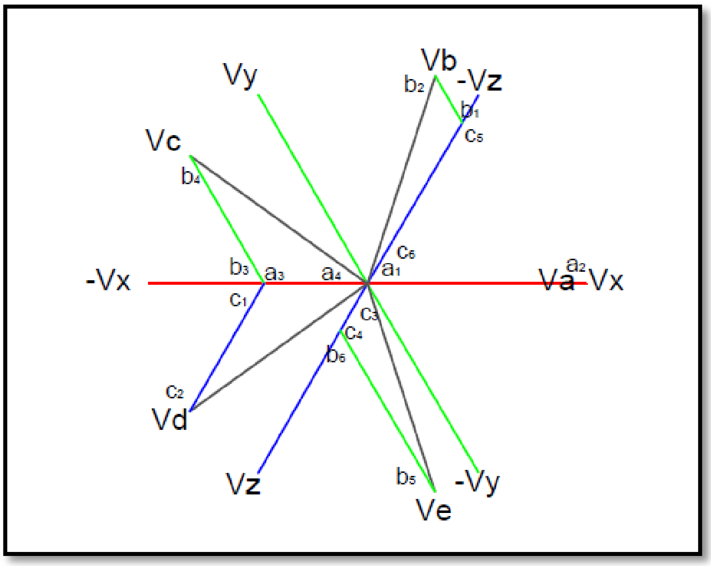

Figure 3.3: Phasor diagram of the transformer connection in wye-wye connection [1]

The phase shift for each output is about 72° and it was obtained by using appropriate turn ratios. The turn ratios were different in each phase. The letters “X”, “Y”, and “Z” were represented the input phases while the letters “A”, “B”, “C”, “D”, and “E” were represented the output. Figure 3.2(a) and Figure 3.2(b) were transformed into phasor diagram as shown in Figure 3.3. The detail of Figure 3.3 explanation as below:

- The output phase A was along the input phase X.
- The output phase B was resulted from the phasor sum of winding voltage “c_5c_6” and “b_1b_2”.
- The output phase C was resulted from the phasor sum of winding voltage “a_4a_3” and “b_3b_4”.
- The output phase D was resulted from the phasor sum of winding voltage “a_4a_3” and “C_1C_2”.
- The output phase E was resulted from the phasor sum of winding voltage “C_4C_3” and “b_6b_5”.

From [1], the turn ratio to design the proposed transformer was shown in Table 3.1. The designed transformation system was a 1:1, input: output ratio.

Table 3.1: Design of the five phase transformer [1]

Primary	Secondary	Turn ratio, $\frac{N_P}{N_S}$
Phase X	a_1a_2	1
	a_4a_3	0.47
Phase Y	b_1b_2	0.68
	b_4b_3	0.858
	b_5b_6	0.24
Phase Z	c_1c_2	0.68
	c_4c_3	0.858
	c_5c_6	0.24

However, the turn ratio which stated in Table 3.1 is not reflected in Figure 3.2(b) and Figure 3.3. The phase shift for each phase is not 72° (see Appendix C). Therefore, the alternative way that used to design the transformer was followed Table 3.2.

Table 3.2: Design of the five phase transformer follows phasor diagram

Primary	Secondary	Turn ratio, $\frac{N_P}{N_S}$
Phase X	a_1a_2	1
	a_4a_3	0.47
Phase Y	b_1b_2	0.24
	b_4b_3	0.68
	b_5b_6	0.858
Phase Z	c_1c_2	0.68
	c_4c_3	0.24
	c_5c_6	0.858

In this project is to develop a 1-to-1 transformer and step down transformer, therefore the ratio that was chosen is 1:1 and 1:0.7. The number of turns that was chosen for the primary winding is 200.

Figure 3.4 shows the transformer winding arrangement in wye connection which follows the method in Figure 3.2(b) but with different turn ratio. Figure 3.5 is the phasor diagram of the transformer connection in wye-wye connection with different turn ratio.

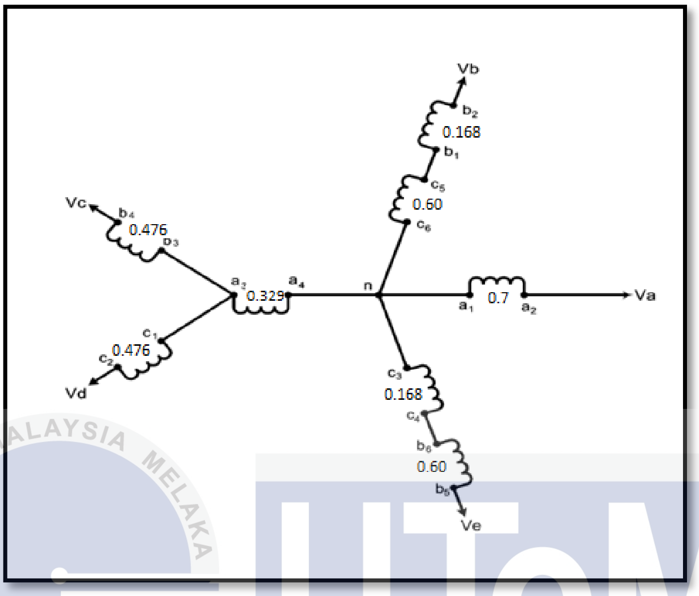

Figure 3.4: Transformer winding arrangement in wye connection with different turn ratio

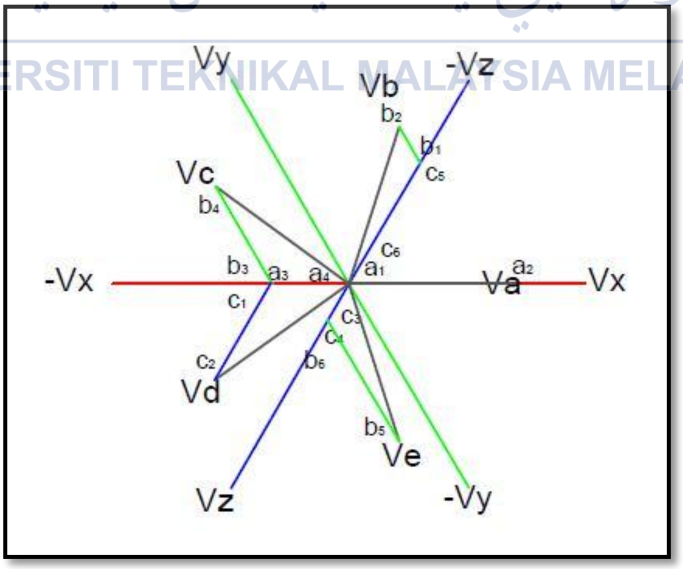

Figure 3.5: Phasor diagram of the transformer connection in wye-wye connection with different turn ratio

As follow Table 3.2, to get the step-down transformer turn ratio for each terminal;

Phase X,

a_1a_2, $1 \times 0.7 = 0.7$

a_4a_3, $0.47 \times 0.7 = 0.329$

Phase Y,

b_1b_2, $0.24 \times 0.7 = 0.168$

b_4b_3, $0.68 \times 0.7 = 0.476$

b_5b_6, $0.858 \times 0.7 = 0.60$

Phase Z,

c_1c_2, $0.68 \times 0.7 = 0.476$

c_4c_3, $0.24 \times 0.7 = 0.168$

c_5c_6, $0.858 \times 0.7 = 0.60$

Table 3.3 shows the overall of turn ratio which the calculation was using the turn ratio showed in Table 3.2 that needed to use to develop a step-down transformer.

Table 3.3: Turn ratio for step-down transformer

Primary	**Secondary**	**Turn ratio, $\frac{N_P}{N_S}$**	**Number of turns, N_S**
Phase X	a_1a_2	0.7	140
	a_4a_3	0.329	66
Phase Y	b_1b_2	0.168	34
	b_4b_3	0.476	95
	b_5b_6	0.60	120
Phase Z	c_1c_2	0.476	95
	c_4c_3	0.168	34
	c_5c_6	0.60	120

3.2.1.2 CALCULATE THE RATED VOLTAGE AND POWER

This step was to calculate the rated voltage that needed to use when during testing hardware. The rated voltage for the transformer was:

$$E = \sqrt{2} \times \pi \times f \times N \times B_{max} \times A_{core} \tag{3.1}$$

$$E = 4.44 \times f \times N \times B_{max} \times A_{core} \tag{3.2}$$

Where E = rated coil voltage (V),

F = operating frequency (Hz),

N = number of turn in the winding,

B_{max} = maximum flux density in the core (tesla),

A_{core} = cross-sectional area of the core material (m^2)

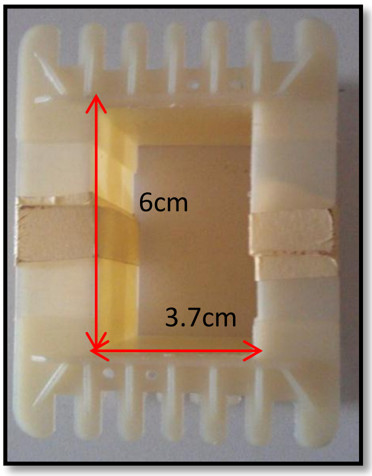

Figure 3.6: Transformer bobbin

From Figure 3.6, the cross-sectional area of the core material was

$$A_{core} = 0.06m \times 0.037m = 0.00222m^2$$

Frequency is fixed, $f = 50Hz$

$$B_{max} = 1.25\, web/m^2$$

Number of turns, $N = 200$

$$E = 4.44 \times f \times N \times B_{max} \times A_{core}$$

$$E = 4.44 \times 50 \times 200 \times 1.25 \times 0.00222$$

$$E = 123.21V \approx 123V$$

$$E_{rms} = \frac{E}{\sqrt{2}} = \frac{123}{\sqrt{2}} = 86.97V$$

Therefore, the rated voltage is 86.97V.

$$E_{3\emptyset} = 86.97 \times \sqrt{3} = 150.6V$$

In this project, the size of enamelled wire chosen was 0.7mm (22SWG) as shown in Appendix E. The current rating for this wire size is about 4.5A [24]. However in this project, for the safety purpose, the rated current chosen is about 2.2A.

Therefore, the rated power, S for the transformer was:

$$S = VI = 86.97 \times 2.2 = 191VA$$

Assume that the power factor was 0.8, the power:

$$P = Scos\theta \quad (3.3)$$

$$P = 191 \times 0.8 = 153W$$

Therefore, this transformer can only carry the loads that less than 153W.

3.2.1.3 EXPECTED RESULTS

- **CALCULATED RESULTS FOR 1-TO-1 VOLTAGE**

  The 1-to-1 input voltage (3 phase input) for per phase was

  Equation:

$$V_{\Phi P} = \frac{V_{LP}}{\sqrt{3}} \quad (3.4)$$

  Output voltage per phase for 5-phase was

  Equation:

$$\frac{N_P}{N_S} = \frac{1}{1} = \frac{V_{\Phi P}}{V_{\Phi S}} \quad (3.5)$$

$$V_{\Phi S} = V_{\Phi P}$$

  Output voltage (Line-to-Line) for 5-phase was

  Equation:

$$V_{LS} = \frac{\sqrt{5}V_{\phi S}}{\sqrt{3}} \quad (3.6)$$

By using the equation (3.4), (3.5), (3.6), the 1-to-1 voltages 2 were calculated and shown in Table 3.4.

Table 3.4: Calculated 1-to-1 output voltage

V_{LP}, (V)	$V_{ØP}$, (V)	V_{LS}, (V)	$V_{øS}$, (V)
10	5.8	7.5	5.8
20	11.5	14.8	11.5
30	17.3	22.3	17.3
40	23.1	29.8	23.1
50	28.9	37.3	28.9
60	34.6	44.7	34.6
70	40.4	52.2	40.4
80	46.2	59.6	46.2
90	52	67.1	52
100	57.7	74.5	57.7
110	63.5	82	63.5
120	69.3	89.5	69.3
130	75.1	96.9	75.1
140	80.8	104.4	80.8
150	86.6	136.9	86.6

- **CALCULATED RESULTS FOR STEP-DOWN VOLTAGE**

The equation use to calculate step down input voltage (3 phase input) for per phase was same as in equation (3.4).

Output voltage per phase for 5-phase is given by

$$\frac{N_P}{N_S} = \frac{1}{0.7} = \frac{V_{\Phi P}}{V_{\Phi S}}$$
$$V_{\Phi S} = 0.7 V_{\Phi P} \quad (3.7)$$

The equation used to calculate the output voltage (Line-to-Line) for step down 5-phases was same as equation (3.6).

By using the equation (3.4), (3.6), (3.7), the step-down voltages are calculated and shown in Table 3.5.

Table 3.5: Calculated step down output voltage

V_{LP}	$V_{øP}$	V_{LS}	$V_{øS}$
10	5.8	5.2	4.04
20	11.5	10.4	8.08
30	17.3	15.7	12.1
40	23.1	20.9	16.2
50	28.9	26.1	20.2
60	34.6	31.3	24.3
70	40.4	36.5	28.3
80	46.2	41.7	32.3
90	52	46.9	36.4
100	57.7	52.2	40.4
110	63.5	57.4	44.5
120	69.3	62.6	48.5
130	75.1	67.8	52.5
140	80.8	73	56.6
150	86.6	78.3	60.6

- **PHASE SHIFT OF THE OUTPUT WAVEFORM**

The output waveform for each phases in secondary need to have a phase shift 72° between each phases. The waveform was tested by using the oscilloscope with 2 channels. Therefore, V_a was act as a reference voltage. Table 3.6 shows the expected results of the five-phase transformer.

Table 3.6: Phase shift for each phases

Reference Voltage	Phase Voltage	Phase Shift (°)
V_a	V_b	72
	V_c	144
	V_d	216
	V_e	288

3.2.2 HARDWARE DEVOLOPMENT

3.2.2.1 COMPONENT USED

This project is basically to develop a transformer that can produce five-phase transformer from three-phase source. The components that need to use to develop the hardware are enamelled copper wire, transformer bobbin and E-I laminated core.

- **ENAMELLED COPPER WIRE**

Enameled copper wire also known as magnet wire is chosen for this project is because it is an insulated copper electrical conductor. It is normally used in motors, transformers and other electromagnetic equipment. Magnet wire creates an electromagnetic field when it wound into a coil and energized.

Besides, magnet wire plays a critical role in three areas of energy transformation which are:

- Electrical to electrical
- Electrical to mechanical
- Mechanical to electrical

Electrical to electrical transformation includes transformers, which are used to transfer power. Electrical to mechanical transformation normally used in motorized appliances, automobiles, industrial machinery, and residential and commercial HVAC systems. Whereas mechanical to electrical transformation happens when machine power is converted into electricity [10].

In this project, it is act as an electrical to electrical transformation. The size of the wire that is chosen for this project is 0.7mm (22SWG). The Figure 3.7 is the enamelled copper wire.

Figure 3.7: 0.7mm enamelled copper wire

- **TRANSFORMER BOBBIN**

Bobbin is selected to use to develop the transformer is because it is a permanent container for the wire, acting to the form the shape of the coil and ease assembly of the windings into or onto the magnetic core [11]. Figure below is the transformer bobbin:

Figure 3.8: Transformer bobbin

- **E-I LAMINATED CORE**

The function of an E-I lamination core is to discharge the energy of the primary winding of transformer to the secondary winding. This laminated core is selected is because normally silicon steel lamination is used for low frequency transformer of the electrical and electronic equipment [12]. Figure 3.9 shows the E-I lamination core.

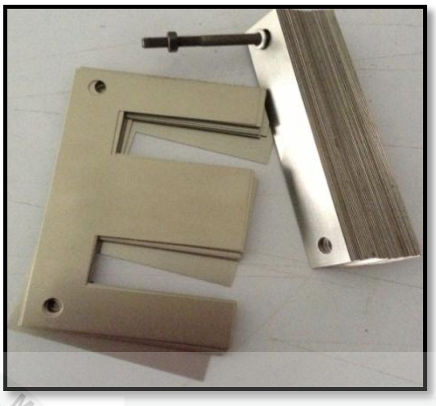

Figure 3.9: E-I laminated core

- **INSULATING PAPER**

The use of insulating paper is to cover the winding wires, insulate the turn from each other and from the core. Figure 3.10 is the insulating paper.

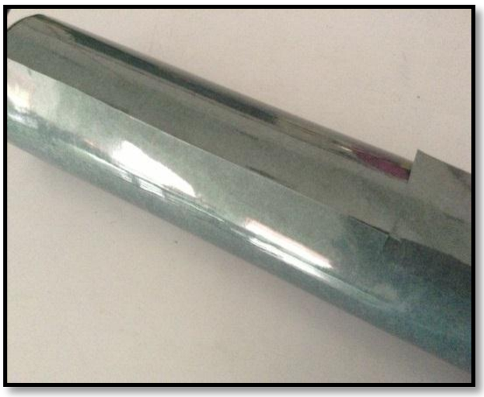

Figure 3.10: Insulating paper

3.2.2.2 PROCEDURES OF BUILD HARDWARE

3.2.2.2.1 THE 1-TO-1 RATIO TRANSFORMER

- **PHASE X HARDWARE BUILDED**

  The steps to construct a step-down transformer for phase X were as below:

1. The first transformer bobbin for phase X was installed on the winding machine.
2. 0.70mm copper wire was used and inserted into the transformer bobbin and the winding machine was being rotated manually.
3. The copper wire was arranged neatly and fitted to each other; this step was repeated until 200 turns were made.
4. Separator was used on primary coil (phase X) after 200 turns were made.
5. For the phase X, it carried 2 secondary coils. Then for the secondary parts, the steps needed to repeat twice but with different number of turns.
6. The step was repeated but it was until 200 turns for the a_1a_2 of the secondary winding.
7. Separator was used on a_1a_2 after 200 turns were made.
8. The step was repeated but it was until 94 turns for the a_4a_3 of the secondary winding.
9. Separator was used on a_4a_3 after 94 turns were made.
10. E-I lamination plates were inserted on the coil case one by one.
11. The complete E-I lamination plates was screwed after the whole coil case was fully filled.

- **PHASE Y HARDWARE BUILDED**

  The steps to construct a step-down transformer for phase Y were as below:

1. The second transformer bobbin for phase Y was installed on the winding machine.
2. 0.70mm copper wire was used and inserted into the transformer bobbin and the winding machine was being rotated manually.
3. The copper wire was arranged neatly and fitted to each other; this step was repeated until 200 turns were made.
4. Separator was used on primary coil (phase Y) after 200 turns were made.

5. For the phase Y, it carried 3 secondary coils. Then for the secondary parts, the steps needed to repeat three times but with different number of turns.
6. The step was repeated but it was until 48 turns for the b_1b_2 of the secondary winding.
7. Separator was used on b_1b_2 after 48 turns were made.
8. The step was repeated but it was until 136 turns for the b_4b_3 of the secondary winding.
9. Separator was used on b_4b_3 after 136 turns were made.
10. Then, the step was repeated again but it was until 172 turns for the b_5b_6 of the secondary winding.
11. Separator was used on b_5b_6 after 172 turns were made.
12. E-I lamination plates were inserted on the coil case one by one.
13. The complete E-I lamination plates was screwed after the whole coil case was fully filled.

- **PHASE Z HARDWARE BUILDED**

The steps to construct a step-down transformer for phase Z were as below:

1. The second transformer bobbin for phase Z was installed on the winding machine.
2. 0.70mm copper wire was used and inserted into the transformer bobbin and the winding machine was being rotated manually.
3. The copper wire was arranged neatly and fitted to each other; this step was repeated until 200 turns were made.
4. Separator was used on primary coil (phase Y) after 200 turns were made.
5. For the phase Z, it was also carried 3 secondary coils. Then for the secondary parts, the steps also needed to repeat three times but with different number of turns.
6. The step was repeated but it was until 136 turns for the c_1c_2 of the secondary winding.
7. Separator was used on c_1c_2 after 136 turns were made.
8. The step was repeated but it was until 48 turns for the c_4c_3 of the secondary winding.
9. Separator was used on c_4c_3 after 48 turns were made.
10. Then, the step was repeated again but it was until 172 turns for the c_5c_6 of the secondary winding.
11. Separator was used on c_5c_6 after 172 turns were made.

12. E-I lamination plates were inserted on the coil case one by one.
13. The complete E-I lamination plates was screwed after the whole coil case was fully filled.

    Figure 3.11 showed the transformers that had done.

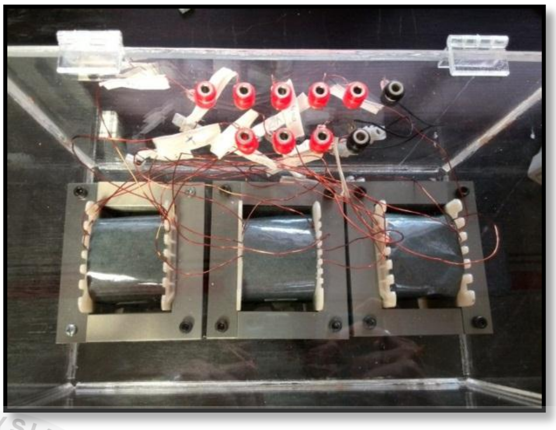

Figure 3.11: Five-phase transformers

3.2.2.2.2 STEP-DOWN TRANSFORMER

For step-by –step procedure on development of step-down five phase transformer, please see Appendix D.

3.3 TESTING AND MEASUREMENT

3.3.1 NO LOAD TEST

After the basic design and the hardware was finished build, then the transformers can go for testing. The equipment that needed to use to test and measured the hardware was three-phase power supply, 4 multimeters and 2 channels oscilloscope. Figure 3.12 showed the circuit connection of the five-phase transformer for no load test.

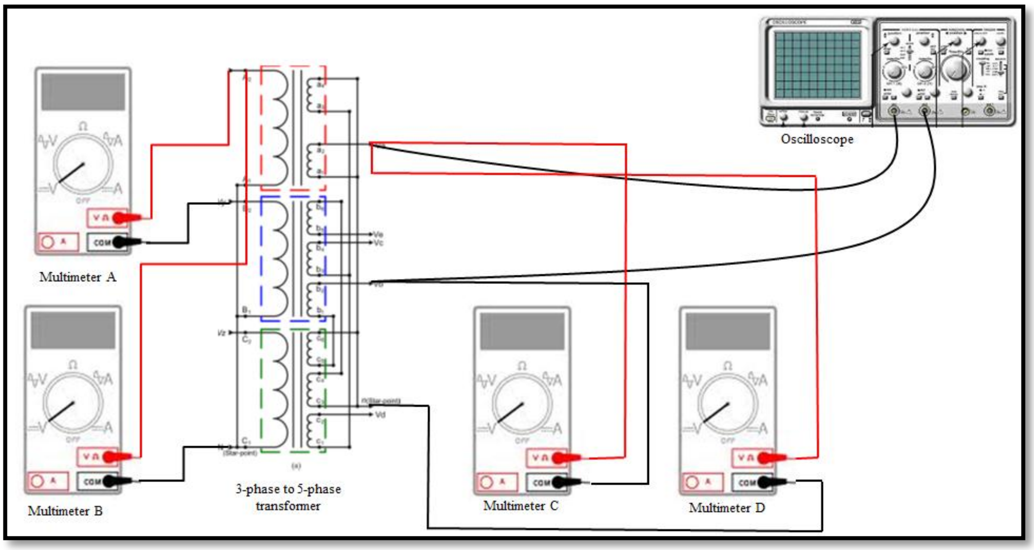

Figure 3.12: Circuit connection for no load test

The multimeter *A* was placed between V_X and V_Y for measuring the input voltage line to line, V_{LP}. The multimeter *B* was placed between V_x and *n* for measuring the input voltage per-phase, $V_{\emptyset P}$. While the multimeter *C* was placed between V_a and V_b for measuring the output voltage line to line, V_{LS} and the multimeter *D* is placed between V_a and *n* for measuring the output voltage per-phase, $V_{\emptyset S}$. The oscilloscope was used to measure the phase shift of the output waveform for each phases. V_a act as a reference voltage and it was used to observe the performance of the phase shift between V_a and V_b, V_a and V_c, V_a and V_d, V_a and V_e.

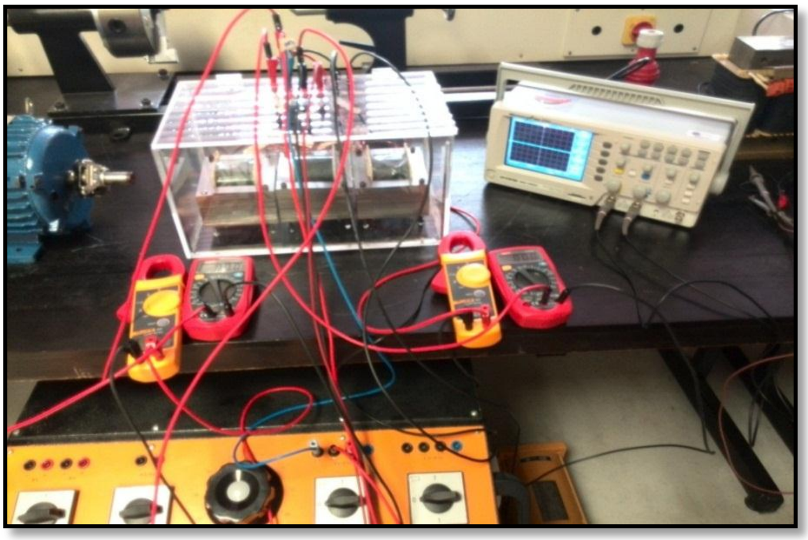

Figure 3.13: Hardware setup for no load testing

Figure 3.13 shows the hardware setup for no load testing. It was shown the connection from power supply to the transformer and the input/output voltages were measured using multimeters.

3.3.2 RESISTIVE LOAD TEST

After the no load test was complete, then the experiment with resistive load is performed. The resistive load test is used to determine the regulation and the efficiency of the developed transformer. The equipment that required for testing and measurement of the hardware is three-phase power supply, 4 multimeters and resistive load station. Figure 3.14 shows the circuit connection of the five-phase transformer for resistive load test.

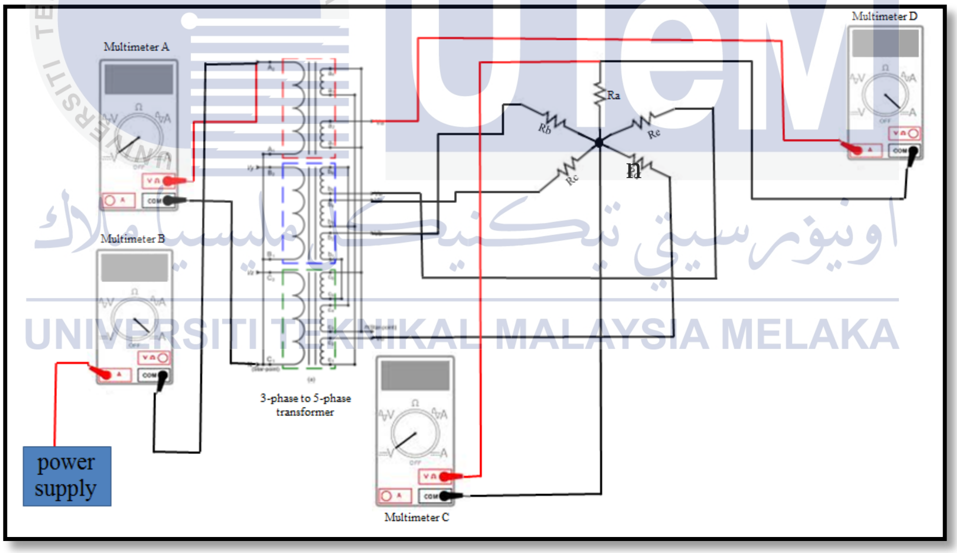

Figure 3.14: Circuit connection for resistive load testing

The multimeter *A* was placed between V_X and *N* for measuring the input voltage per phase, $V_{\emptyset P}$. The multimeter *B* was placed between power supply and V_X for measuring the input current per-phase, $I_{\emptyset P}$. While the multimeter *C* was placed between R_a and *n* for measuring the output voltage per phase, $V_{\emptyset S}$ and the multimeter *D* is placed between V_a and Ra for measuring the output current per-phase, $I_{\emptyset S}$.

Figure 3.15: Hardware setup for resistive load testing

Figure 3.15 shows the hardware setup for resistive load testing. It shows the connection from the power supply to the transformer and then to the resistive load. The input/output voltages were measured by using multimeters.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 INTRODUCTION

This chapter will discuss about the result of hardware and analysis of the hardware and theoretical estimation.

4.2 NO LOAD TEST

4.2.1 EXPERIMENTAL RESULTS FOR OUTPUT VOLTAGE

4.2.1.1 RESULTS FOR 1-TO-1 TRANSFORMER

In this test, phase X was taken to measure for primary voltage while phase A was taken to measure for secondary voltage. Table 4.1 shows the output voltage for 1-to-1 transformer. In this section, a percentage error between the input voltage and output voltage was calculated due to it was a 1-to-1 transformer.

$$\text{Percentage of error} = \left|\frac{V_{\emptyset P} - V_{\emptyset S}}{V_{\emptyset P}}\right| \times 100\% \quad (4.1)$$

Where V_{LP} is primary line-to-line voltage

$V_{øP}$ is primary voltage per phase

V_{LS} is secondary line-to-line voltage

$V_{øS}$ is secondary voltage per phase

Due to the number of turns, the maximum voltage for testing the transformer was $150V_{L\text{-}L}$, while the minimum voltage was chosen to test the transformer is $10V_{L\text{-}L}$.

Table 4.1: Output voltage for 1-to-1 ratio transformer

V_{LP}, (V)	$V_{øP}$, (V)	V_{LS}, (V)	$V_{øS}$, (V)	Percentage error for $V_{øP}$ and $V_{øS}$, (%)
10	5.50	7.20	5.50	0.00
20	11.20	14.50	11.20	0.00
30	17.00	22.00	17.00	0.00
40	22.60	29.80	22.60	0.00
50	28.10	37.60	28.00	0.36
60	33.70	45.60	33.60	0.30
70	38.90	53.50	38.80	0.26
80	44.10	61.60	44.00	0.23
90	49.50	69.80	49.40	0.20
100	54.40	78.00	54.30	0.18
110	59.50	86.60	59.40	0.17
120	64.60	95.40	64.50	0.15
130	69.10	104.40	69.20	0.14
140	73.90	114.60	73.90	0.00
150	79.60	125.00	79.60	0.00

From Table 4.1, the experimental results showed that the secondary per phase voltage is almost the same as the primary per phase voltage. In this section, the experimental setup and the results obtained by using the three-phase to five-phase transformer system will be explained. For this transformer system that has a 1:1, input: output ratio, hence, the output voltage almost same as input voltage. The biggest percentage error between the primary and secondary voltage was only 0.36%. Therefore, it shows that this transformer had fulfilled the requirement of a 1-to-1 ratio.

- **COMPARISON BETWEEN CALCULATED RESULTS AND EXPERIMENTAL RESULTS FOR 1-TO-1 TRANSFORMER**

Table 4.2 shows the comparison between the calculated and experimental results for voltage per phase at primary and the percentages of error.

$$\text{Percentage of error} = \left|\frac{V_{\emptyset P(calc)} - V_{\emptyset P(exp)}}{V_{\emptyset P(exp)}}\right| \times 100\% \quad (4.2)$$

Table 4.2: Comparison between calculated and experimental results for primary voltage per phase (1-to-1 ratio)

Input voltage, V_{LP} (V)	**Calculated primary voltage per phase, $V_{\emptyset P(CALC)}$ (V)**	**Experimental primary voltage per phase, $V_{\emptyset P(EXP)}$ (V)**	**Percentage error (%)**
10	5.8	5.5	5.45
20	11.5	11.2	2.68
30	17.3	17.0	1.76
40	23.1	22.6	2.21
50	28.9	28.1	2.85
60	34.6	33.7	2.67
70	40.4	38.9	3.86
80	46.2	44.1	4.76
90	52.0	49.5	5.05
100	57.7	54.4	6.07
110	63.5	59.5	6.72
120	69.3	64.6	7.28
130	75.1	69.1	8.68
140	80.8	73.9	9.34
150	86.6	79.6	8.79

Table 4.3 shows the comparison between the calculated and experimental results for line-to-line secondary voltages and the percentages of error.

$$\text{Percentage of error} = \left|\frac{V_{LS(calc)} - V_{LS(exp)}}{V_{LS(exp)}}\right| \times 100\% \quad (4.3)$$

Table 4.3: Comparison between calculated and experimental results for line-to-line secondary voltages (1-to-1 ratio)

Input voltage, V_{LP} (V)	**Calculated secondary voltage line-to-line, $V_{LS\ (CALC)}$**	**Experimental secondary voltage line-to-line, $V_{LS\ (EXP)}$**	**Percentage error, %**
10	7.5	7.2	4.17
20	14.8	14.5	2.07
30	22.3	22.0	1.36
40	29.8	29.8	0.00
50	37.3	37.6	0.80
60	44.7	45.6	1.97
70	52.2	53.5	2.43
80	59.6	61.6	3.25
90	67.1	69.8	3.87
100	74.5	78.0	4.49
110	82.0	86.6	5.31
120	89.5	95.4	6.18
130	96.9	104.4	7.18
140	104.4	114.6	8.90
150	136.9	125.0	9.52

Table 4.4 shows the comparison between the calculated and experimental results for line-to-line secondary voltages and the percentages of error.

$$\text{Percentage of error is, } \left|\frac{V_{\emptyset S(calc)}-V_{\emptyset S(exp)}}{V_{\emptyset S(exp)}}\right| \times 100\% \qquad (4.4)$$

Table 4.4: Comparison of calculated and experimental results for secondary voltage per phase (1-to1 ratio)

Input voltage, V_{LP} (V)	**Calculated secondary voltage per phase, $V_{\emptyset S(CALC)}$ (V)**	**Experimental secondary voltage per phase, $V_{\emptyset S(EXP)}$ (V)**	**Percentage error, %**
10	5.8	5.5	5.45
20	11.5	11.2	2.68
30	17.3	17.0	1.76
40	23.1	22.6	2.21
50	28.9	28.0	3.21
60	34.6	33.6	2.98
70	40.4	38.8	4.12
80	46.2	44.0	5.00
90	52.0	49.4	5.26
100	57.7	54.3	6.26
110	63.5	59.4	6.90
120	69.3	64.5	7.44
130	75.1	69.2	8.53
140	80.8	73.9	9.34
150	86.6	79.6	8.79

Although the 1-to-1 transformer had successfully developed, however, from the Table 4.2 to Table 4.4, it shows that there was still had some percentage error between the calculation and the experimental results. The main reason is because an ideal condition is considered in the calculation with no losses. However in experimental the result, the output voltage is affected by all the possible losses of the transformer.

4.2.1.2 RESULTS FOR STEP-DOWN TRANSFORMER

In this test, phase X was also taken to measure for primary voltage while phase A was also taken to measure for secondary voltage. Table 4.5 shows the output voltage for step-down transformer.

Where V_{LP} is primary line-to-line voltage
$V_{øP}$ is primary voltage per phase
V_{LS} is secondary line-to-line voltage
$V_{øS}$ is secondary voltage per phase

Table 4.5: Output voltage for step-down transformer

V_{LP}, (V)	$V_{øP}$, (V)	V_{LS}, (V)	$V_{øS}$, (V)
10	5.50	4.80	3.80
20	11.50	10.00	7.90
30	17.20	15.10	11.90
40	22.90	20.40	15.90
50	28.30	25.90	19.70
60	33.80	31.20	23.50
70	38.70	36.80	26.90
80	43.80	42.40	30.50
90	48.80	48.00	34.00
100	53.50	53.70	37.20
110	58.00	59.50	40.40
120	62.50	65.20	43.50
130	66.50	71.30	46.30
140	71.40	77.90	49.70
150	77.30	84.80	53.80

From Table 4.5, the experimental results showed the output voltage of step down transformer. For this transformer system has a 1:0.7, input: output ratio, hence, the output voltage was lower than the input voltage. From the Table 4.5, it showed that this transformer had successfully to step-down the input voltage and produce lower output voltage.

- **COMPARISON BETWEEN CALCULATED RESULTS AND EXPERIMENTAL RESULTS FOR STEP-DOWN TRANSFORMER**

Table 4.6 shows the comparison between the calculated and experimental results for voltage per phase at primary and the percentages of error.

$$\text{Percentage of error is, } \left|\frac{V_{\emptyset P(calc)} - V_{\emptyset P(exp)}}{V_{\emptyset P(exp)}}\right| \times 100\% \quad (4.5)$$

Table 4.6: Comparison between calculated and experimental results for primary voltage per phase (step-down transformer)

Input voltage, V_{LP} (V)	**Calculated secondary voltage per phase, $V_{\emptyset S}$ (V)**	**Experimental secondary voltage per phase, $V_{\emptyset S}$ (V)**	**Percentage error, %**
10	5.8	5.5	5.45
20	11.5	11.5	0.00
30	17.3	17.2	0.58
40	23.1	22.9	0.87
50	28.9	28.3	2.12
60	34.6	33.8	2.37
70	40.4	38.7	4.39
80	46.2	43.8	5.48
90	52.0	48.8	6.56
100	57.7	53.5	7.85
110	63.5	58.0	9.48
120	69.3	62.5	10.88
130	75.1	66.5	12.93
140	80.8	71.4	13.17
150	86.6	77.3	12.03

Table 4.7 shows the comparison between the calculated and experimental results for line-to-line secondary voltages and the percentages of error.

$$\text{Percentage of error is, } \left|\frac{V_{LS(calc)} - V_{LS(exp)}}{V_{LS(exp)}}\right| \times 100\% \qquad (4.6)$$

Table 4.7: Comparison between calculated and experimental results for line-to-line secondary voltages (step-down transformer)

Input voltage, V_{LP} (V)	**Calculated secondary voltage line-to-line, $V_{LS\ (CALC)}$ (V)**	**Experimental secondary voltage line-to-line, $V_{LS\ (EXP)}$ (V)**	**Percentage error, %**
10	5.2	4.8	8.33
20	10.4	10.0	4.00
30	15.7	15.1	3.97
40	20.9	20.4	2.45
50	26.1	25.9	0.77
60	31.3	31.2	0.32
70	36.5	36.8	0.82
80	41.7	42.4	1.65
90	46.9	48.0	2.29
100	52.2	53.7	2.79
110	57.4	59.5	3.53
120	62.6	65.2	3.99
130	67.8	71.3	4.91
140	73.0	77.9	6.29
150	78.3	84.8	7.67

Table 4.8 shows the comparison between the calculated and experimental results for line-to-line secondary voltages and the percentages of error.

$$\text{Percentage of error is, } \left|\frac{V_{\phi S(calc)} - V_{\phi S(exp)}}{V_{\phi S(exp)}}\right| \times 100\% \qquad (4.7)$$

Table 4.8: Comparison between calculated and experimental results for secondary voltage per phase (step-down transformer)

Input voltage, V_{LP} (V)	**Calculated secondary voltage per phase, $V_{\phi S(CALC)}$ (V)**	**Experimental secondary voltage per phase, $V_{\phi S(EXP)}$ (V)**	**Percentage error, %**
10	4.04	3.80	6.32
20	8.08	7.90	2.28
30	12.10	11.90	1.68
40	16.20	15.90	1.89
50	20.20	19.70	2.54
60	24.30	23.50	3.40
70	28.30	26.90	5.20
80	32.30	30.50	5.90
90	36.40	34.00	7.06
100	40.40	37.20	8.60
110	44.50	40.40	10.15
120	48.50	43.50	11.49
130	52.50	46.30	13.39
140	56.60	49.70	13.88
150	60.60	53.80	12.64

For step-down transformer, it had the same case as 1-to-1 ratio transformer. Although the step-down transformer had successfully developed, but, from the Table 4.6 until Table 4.8, it was also shown that there was still had some percentage error between the calculation and the experimental results.

4.2.2 WAVEFORM FOR FIVE PHASE TRANSFORMER

4.2.2.1 1-TO-1 TRANSFORMER

Figure 4.1 below shows the waveform between V_a and V_b.

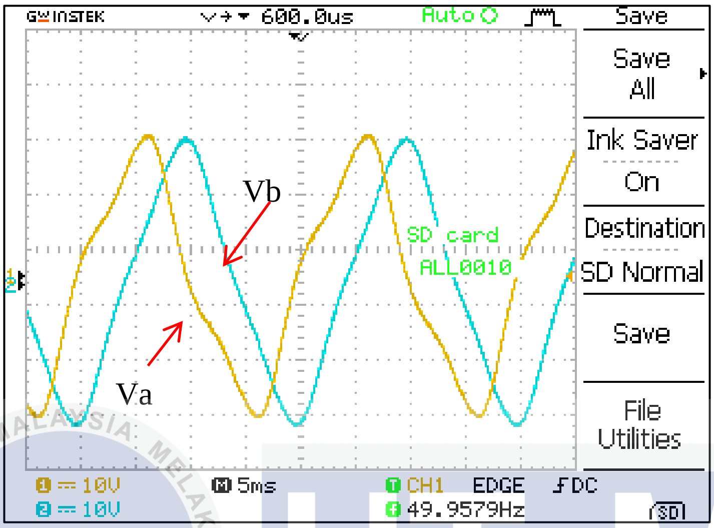

Figure 4.1: Waveform between V_a and V_b

From Figure 4.1, 4 boxes represented a sinusoidal wave which is 360°. Each box has 5 dots inside.

Total dots are, $4\ boxes \times 5 dots = 20$.

Each dots represented, $\frac{360°}{20} = 18°$.

The distance between V_a and V_b is 4 dots, therefore, the phase shift between V_a and V_b is $4 \times 18° = 72°$.

Figure 4.2 shows the waveform between V_a and V_c.

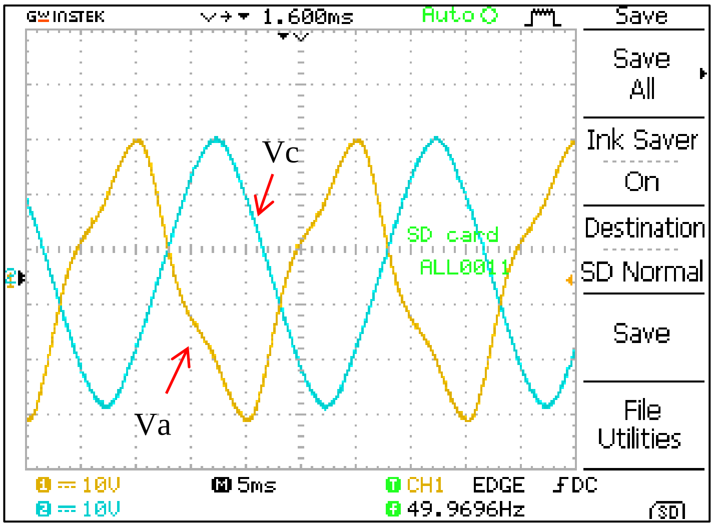

Figure 4.2: Waveform between V_a and V_c

From Figure 4.2, the distance between V_a and V_c is 8 dots, therefore, the phase shift between V_a and V_c is $8 \times 18° = 144°$.

Figure 4.3 shows the waveform between V_a and V_d.

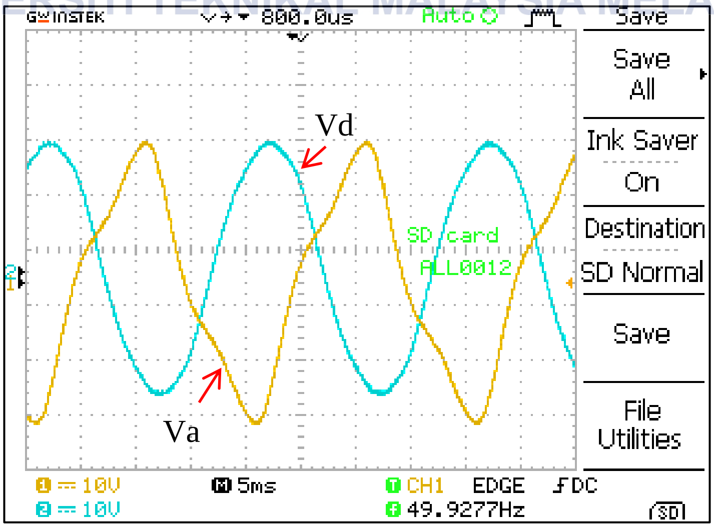

Figure 4.3: Waveform between V_a and V_d

From Figure 4.3, the distance between V_a and V_d is 12 dots, therefore, the phase shift between V_a and V_d is $12 \times 18° = 216°$.

Figure 4.4 shows the waveform between V_a and V_e.

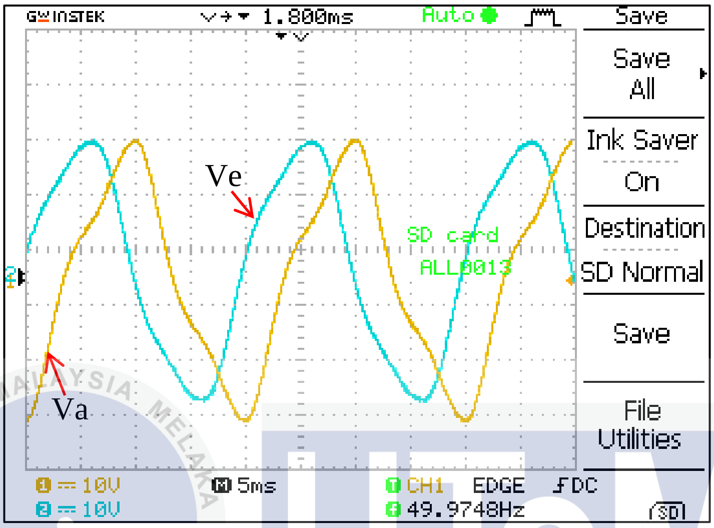

Figure 4.4: Waveform between V_a and V_e

From Figure 4.4, the distance between V_a and V_e is 16 dots, therefore, the phase shift between V_a and V_e is $16 \times 18° = 288°$.

- **COMPARISON BETWEEN EXPECTED RESULTS AND EXPERIMENTAL RESULTS**

Table 4.9 showed the phase shift between V_a and V_b, V_a and V_c, V_a and V_d, V_a and V_e for 1-to-1 ratio transformer.

Table 4.9: Comparison the expected and experimental results for 1-to-1 transformer

Reference voltage	Phase voltage	Expected phase shift (°)	Experimental phase shift (°)
V_a	V_b	72	72
	V_c	144	144
	V_d	216	216
	V_e	288	288

From Table 4.9, the phase shifts between theoretical and experimental were same as shown in Table 3.7. This result verified the functionality of the developed transformer.

4.2.2.2 STEP-DOWN TRANSFORMER

Figure 4.5 below shows the waveform between V_a and V_b.

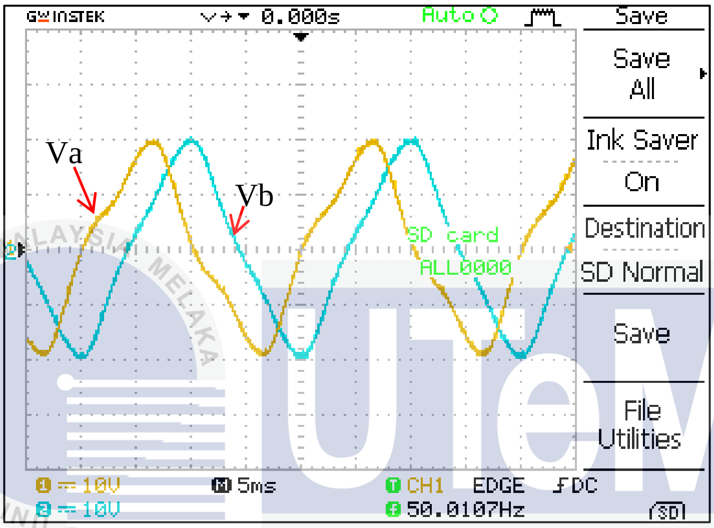

Figure 4.5: Waveform between V_a and V_b

From Figure 4.5, 4 boxes represented a sinusoidal wave which is 360°. Each box has 5 dots inside.

Total dots are, $4\ boxes \times 5 dots = 20$.

Each dots represented, $\frac{360°}{20} = 18°$.

The distance between V_a and V_b is 4 dots, therefore, the phase shift between V_a and V_b is $4 \times 18° = 72°$.

Figure 4.6 shows the waveform between V_a and V_c.

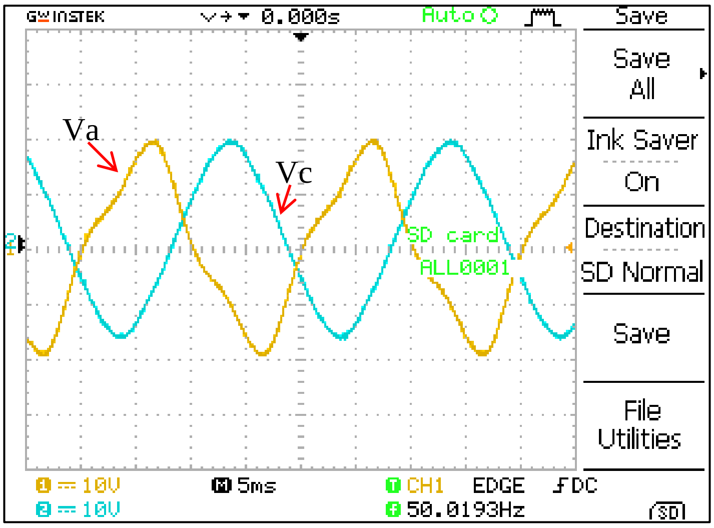

Figure 4.6: Waveform between V_a and V_c

From Figure 4.6, the distance between V_a and V_c is 8 dots, therefore, the phase shift between V_a and V_c is $8 \times 18° = 144°$.

Figure 4.7 shows the waveform between V_a and V_d.

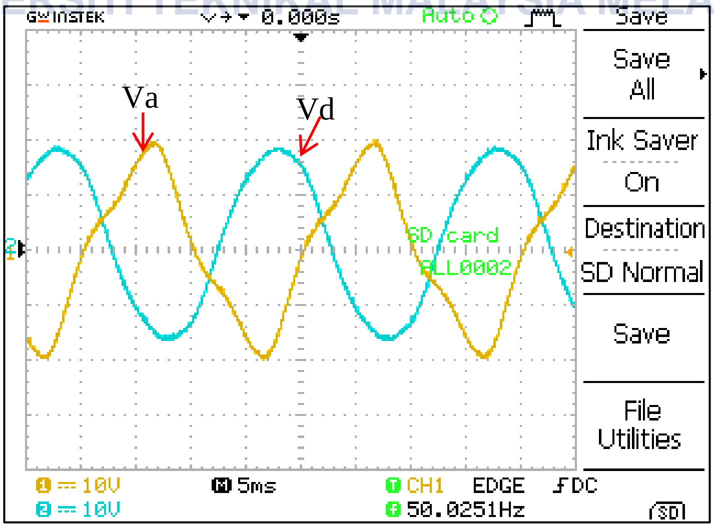

Figure 4.7: Waveform between V_a and V_d

From Figure 4.7, the distance between V_a and V_d is 12 dots, therefore, the phase shift between V_a and V_d is $12 \times 18° = 216°$.

Figure 4.8 shows the waveform between V_a and V_e.

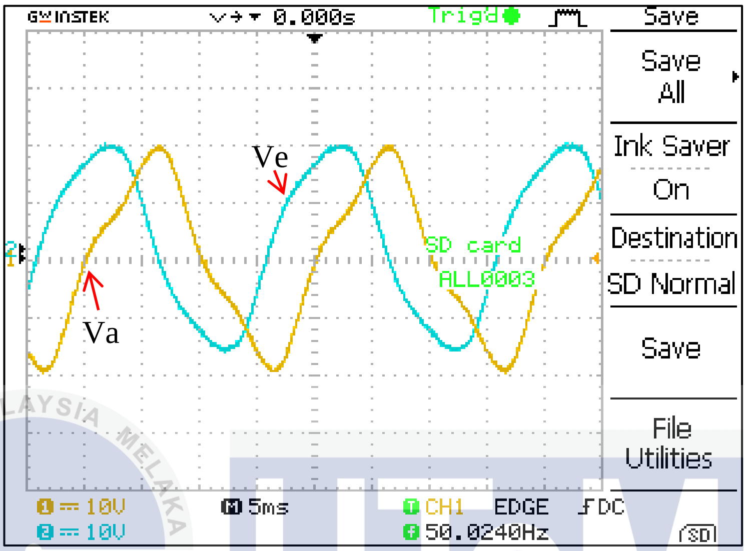

Figure 4.8: Waveform between V_a and V_e

From Figure 4.8, the distance between V_a and V_e is 16 dots, therefore, the phase shift between V_a and V_e is $16 \times 18° = 288°$.

- **Comparison between expected results and experimental results**

Table 4.10 showed the phase shift between V_a and V_b, V_a and V_c, V_a and V_d, V_a and V_e for 1-to-1 ratio transformer.

Table 4.10: Comparison the expected and experimental results for 1-to-1 transformer

Reference voltage	**Phase voltage**	**Expected phase shift (°)**	**Experimental phase shift (°)**
V_a	V_b	72	72
	V_c	144	144
	V_d	216	216
	V_e	288	288

From Table 4.10, the phase shifts between theoretical and experimental were also same as shown in Table 3.7.

4.2.3 OVERALL FOR NO LOAD TEST

The purpose of develop two different ratio transformers were to test the consistency. From Table 4.1 and Table 4.5, it was obviously shown that the method to develop these transformers was successfully. It was able to convert the 3 phase input into 5 phase output. For the 1-to-1 ratio, the input voltage and output voltage per phase are closely matches. Besides, the step-down transformer was able to step-down the voltage which was the output voltage smaller than the input voltage following the given ratio. Although both of the transformers had successfully developed, however, there was still having percentage error between the calculated results and the experimental results.

Besides, the phase shift for both 1-to-1 ratio transformer and step-down transformer which showed in Table 4.9 and Table 4.10, the phase shift between V_a and V_b, V_a and V_c, V_a and V_c, V_a and V_d, V_a and V_e were same as the theoretical (see Table 3.7). Therefore, it can say that the alternative way (Table 3.2) used to design the transformer was correct instead of using Table 3.1 (see Appendix C). However, the waveforms for some phases did not achieve a pure sinusoidal waveform. In addition, the waveform between phases was not identical too (see Figure 4.1 to Figure 4.8) .

The performance of the transformer was not good due to the improper of develop the hardware. It was because the copper wires were not arranged in neatly and fitted to each other as shown in Figure 4.9 and Figure 4.10. This was called as copper (I^2R) losses. Copper losses were the resistive heating losses in the primary and secondary windings of the transformer. Besides, it was also due to the hardware had air gap between the core plates as shown in Figure 4.11. Therefore, leakage flux is take place. This is because the fluxes $\emptyset_{LP}$ and $\emptyset_{LS}$ which escape the core and pass through only one of the transformer windings. These escape flux produce a leakage inductance in the primary and secondary coils.

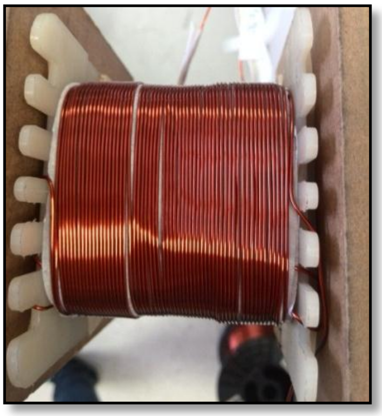

Figure 4.9: Copper wires was not arrange neatly

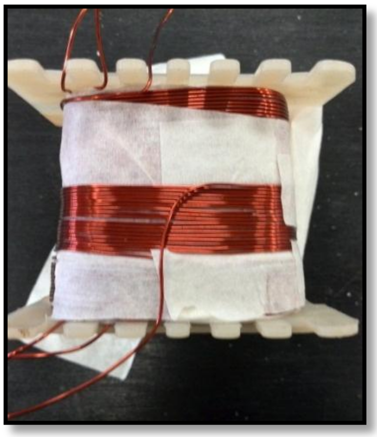

Figure 4.10: Copper wires was not arrange fitted

Figure 4.11: Air gap between core plates

Furthermore, the waveform between phases was not identical mainly cause by the hardware development since theory and simulation had proven it is balance (see Appendix A). In addition, the number of secondary turn was not integer because the ratio number had round off to integer. This might affect the values of resistance and inductance of each phase. Besides, the outer winding was having larger turning for the same number of turns compared to inner winding. Due to this large turning required longer wire and thus also affect resistance and inductance of each phase. It also may cause by the hysteresis of the core that cause the distortion in the waveform.

A proper way to develop the transformer should be press, glue and bake for at least 8 hours. Therefore, in order to improve the performance of the transformer, the way to develop the transformer must be in a proper way so that it can achieve the industrial or commercial standard.

4.3 RESISTIVE LOAD TEST

4.3.1 RESISTIVE LOAD REMAINED CONSTANT

The resistive load, R_L was fixed.

$R_L = 268\Omega$

In this part, the efficiency and voltage regulation of the transformer bank through resistive load test is explained.

Equation for

$$Efficiency, \eta = \frac{total\ five\ phase\ power\ at\ secondary}{total\ three\ phase\ power\ at\ primary} \times 100\% \quad (4.8)$$

Assumption made: power factor at both primary and secondary is 1, thus

$$Efficiency, \eta = \frac{5V_{\emptyset S}I_{\emptyset S}}{3V_{\emptyset P}I_{\emptyset P}} \times 100\% \quad (4.9)$$

Equation for

$$\text{Regulation percentage} = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100\% = \frac{V_{\emptyset P} - V_{\emptyset S}}{V_{\emptyset P}} \times 100\% \quad (4.10)$$

The efficiency and voltage regulation of the transformer is shown in Table 4.11.

Table 4.11: Secondary output current vs primary output current when R_L constant

$V_{\phi P}$, (V)	$I_{\phi P}$, (A)	$V_{\phi S}$, (V)	$I_{\phi S}$, (A)	Voltage regulation, %	Efficiency, %
5	0.02	3.5	0.01	42.9	58.3
10	0.05	6.9	0.02	44.9	46.0
15	0.07	10.4	0.03	44.2	49.5
20	0.09	13.9	0.04	43.9	51.5
25	0.11	17.5	0.05	42.9	53.0
30	0.13	20.9	0.06	43.5	53.6
35	0.15	24.4	0.08	43.4	62.0
40	0.17	28	0.09	42.9	61.8
45	0.19	31.5	0.1	42.9	61.4
50	0.22	35	0.11	42.9	58.3
55	0.24	38.4	0.13	43.2	63.0
60	0.26	42	0.14	42.9	62.8
65	0.29	45.6	0.15	42.5	60.5
70	0.31	49.1	0.17	42.6	64.1
75	0.34	52.7	0.19	42.3	65.4
80	0.38	56.5	0.2	41.6	62.0
86	0.44	60.6	0.22	41.9	58.7

Since the transformer was having 1-to-1 ratio, the secondary output voltage with no load was same as the primary input voltage as shown in Table 4.1. The average efficiency of the transformer was about 60%. The voltage regulation for this transformer was in between 29.38% to 43.07%. It shows that the voltage regulation was high and the efficiency was not very good due to the transformer was developing in a manual way. Therefore, the arrangement of the transformer which was not neatly and fitted indirectly also affected the voltage regulation and efficiency.

4.3.2 INPUT VOLTAGE REMAINED CONSTANT

Table 4.12 shows the experimental results for resistive load test while the input voltage was remained constant.

The input voltage, $V_{øP}$ was constant.

$$V_{\emptyset P} = 80.0V$$

Table 4.12: Secondary output current vs primary output current when $V_{øP}$ constant

R_L, (Ω)	$I_{øP}$, (A)	$V_{øS}$, (V)	$I_{øS}$, (A)
30	2.21	49.90	1.61
50	1.40	52.20	1.00
70	1.04	53.30	0.72
90	0.84	54.00	0.57
110	0.71	54.20	0.46
130	0.64	54.70	0.40
150	0.57	55.60	0.35
170	0.52	55.70	0.31
190	0.48	55.80	0.27
210	0.45	55.90	0.25
230	0.42	56.10	0.23
250	0.40	56.30	0.21
268	0.38	56.50	0.20

From Table 4.12, it showed that the resistive load inversely proportional to the current per phase. When the resistive load, R_L was increased, the current per phase decreased.

Calculation for the output current per phase when $I_{\emptyset P} = 2.21A$,

$$I_{\emptyset S} = \frac{2.21\sqrt{3}}{\sqrt{5}} = 1.71A$$

When $I_{\emptyset P} = 0.64A$,

$$I_{\emptyset S} = \frac{0.64\sqrt{3}}{\sqrt{5}} = 0.5A$$

When $I_{\emptyset P} = 0.38A$,

$$I_{\emptyset S} = \frac{0.38\sqrt{3}}{\sqrt{5}} = 0.29A$$

Therefore, from the calculation, there was only a small differences between the calculation value and the experimental value for output current per phase, $I_{\emptyset S}$. Besides, the calculation was also used to prove that the configuration of this five-phase transformer is correct. From Table 4.12, it was also shown that the input current, $I_{\emptyset P}$ was higher than the output current per phase, $I_{\emptyset S}$. Thus, it was one of the advantages of 5 phase transformer which that the current per phase applied to load was must smaller compared to 3 phase.

4.3.3 TOTAL HARMONIC DISTORTION

This part was to test the total harmonic distortion (THD) of the transformer when tested with resistive load. Figure 4.12 and Figure 4.13 showed the THD of phase voltage and THD of phase current when $V_{\emptyset P} = 80V$, $R_L = 150\Omega$.

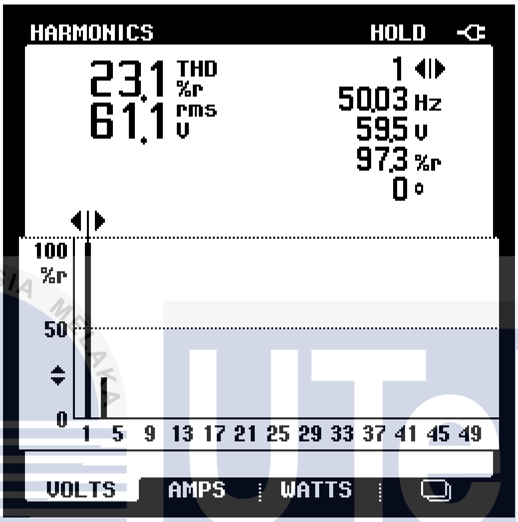

Figure 4.12: THD for phase voltage

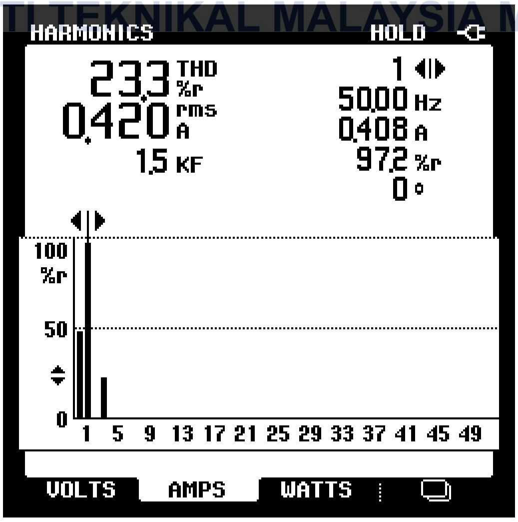

Figure 4.13: THD for phase current

From Figure 4.12, the THD for phase voltage was 23.1% and from Figure 4.13, the THD for phase current was 23.3%.

Therefore, for this part, there was a comparison of THD between transformer and unfiltered unipolar three-phase inverter. Figure 4.14 and Figure 4.15 were the result of THD for unipolar inverter.

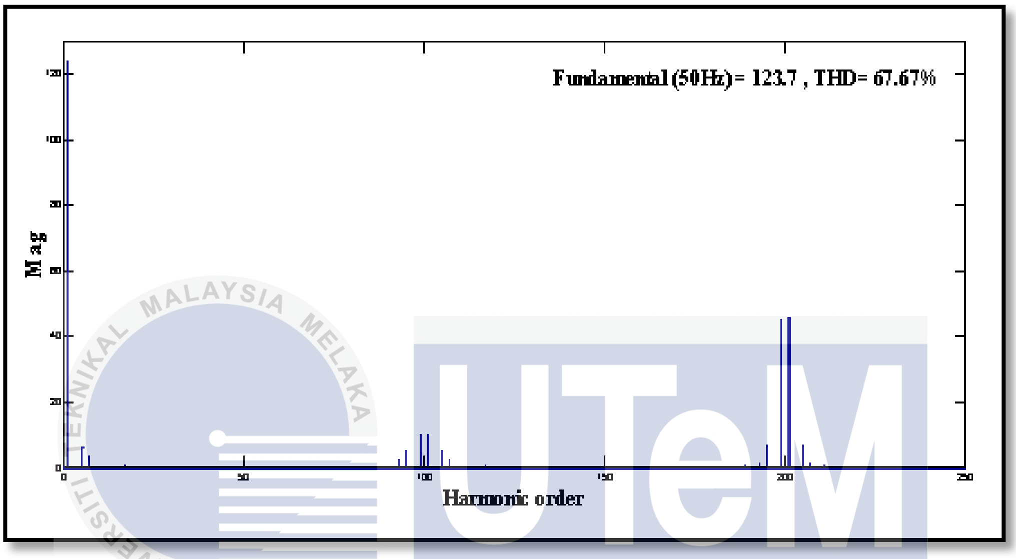

Figure 4.14: THD for phase voltage (inverter) [23]

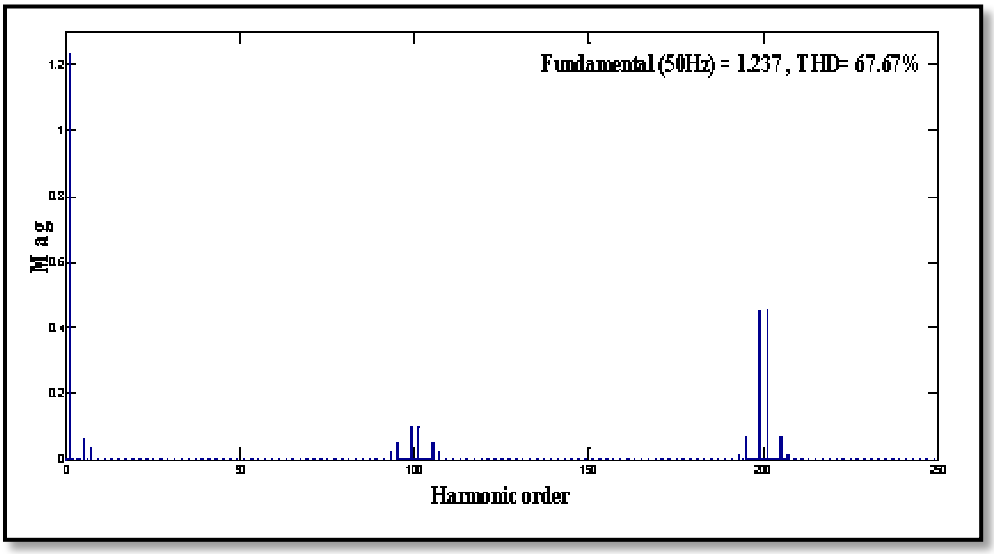

Figure 4.15: THD for phase current (inverter) [23]

Thus, from Figure 4.14 and Figure 4.15, the THD for phase voltage and phase current were 67.67%. Table 4.13 showed the comparison of THD between transformer and inverter.

Table 4.13: Comparison between transformer and inverter

THD	Transformer	Inverter
Phase Voltage	23.10%	67.67%
Phase Current	23.30%	67.67%

From Table 4.13, it showed that the THD for transformer was better than inverter because the percentage of THD for converter was lower than the inverter. Besides, lesser THD allowed the components in an amplifier or other equipment to produce a more accurate reproduction by reducing harmonics.

4.3.4 OVERALL FOR RESISTIVE LOAD TEST

While doing the resistive load test, there was a noise from transformer. Suppose the maximum voltage per phase for this transformer was 86.6V. However, there was noise occurred when the voltage adjusted up to a certain values. Transformer noise was caused by a phenomenon called magnetostriction. It meant that core (laminations) of the alternating current flowing through the coil of the transformer magnetic effect due to the expansion and contraction. Therefore, it produced an audible hum. The transformers besides having noise but also having vibration while doing load and no load test. This is because when voltage is applied to a transformer, which generates a magnetic flux in the core. The degree of the flux determined the amount of magnetostriction and also the noise level [26]. However, this transformer noise cannot be eliminated. It can be only reduced the noise by design and develop the transformer properly.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The transformers that had been developed were five-phase transformers, converts the three-phase grid supply to a five-phase fixed voltage by maintaining a constant frequency supply. The design of these transformers was able to step-down the input voltage and gets a lower output voltage as well as the 1-to-1 ratio transformer able to get the output voltage per phase same as the input voltage per phase. Therefore, it had proved the consistency of the five phase transformer. However, it had the percentage of error between calculated results and experimental results. Besides, there were still need to have some improvement in the output waveform in order to achieve the pure sinusoidal. Furthermore, the voltage regulation was high and the efficiency was not very good due to the construction of the transformer was in a manual way. Therefore, it affected the performance of the transformer. In addition, the harmonic distortion for five-phase transformer was better than the inverter.

5.2 RECOMMENDATION

After completing this final year project, there were some issues and problems had been identified. Therefore, below are the recommendations for solving those problems;

1. The transformer needs to be constructed in a proper way in order to avoid the poor performance of the transformer.
2. Need to do more research on multiphase transformer in order to implement it to the industry.

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APPENDICES

Appendix A – Paper Publication

Abstract has been submitted to International Integrated Engineering Summit 2014

Design and Development of Five Phase Transformer

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***Abstract* - The interests of multiphase (more than three) system are increasing recently especially in motor drive application. Thus, this paper introduces the graphical phasor diagram method in designing the multiphase transformer connection. The proposed method eases the design process of the static multiphase transformer that produce multiphase output from the standard three phase input. The transformer connection has been simulated in ANSYS Maxwell and the multiphase waveform with appropriate phase angle is obtained. The design of five phase transformer is presented in this paper.**

***Index Term* - Multiphase, Five phase, Transformer, Winding, Phasor diagram.**

I. INTRODUCTION

Transformers have been an essential component in both electrical and electronic circuits. Although there are new technologies in digital and power electronic circuits have reduced the need for transformer, but they are still important in many applications.

A transformer is a static electric device that uses electromagnetic principle to change AC voltage from one level to another or to isolate one side of voltage from another through the process of mutual induction. The turn's ratio represents the ratio of the voltage in the primary winding to the voltage in the secondary winding. Nowadays, almost all electrical power in used is generated by three-phase generators. Transformers are primarily used to change the voltage level for transmission and distribution purposes [2].

Transformer for three-phase circuits can be constructed in one of two ways. It is simply to take an identical three single-phase transformers and connect them in such way to work as a three-phase transformer bank. An alternating way is to build a three-phase transformer consisting of three sets of winding wrapped on a common core [3]. The three-phase transformer can be connected in several configurations. The most common configurations are to connect both transformer and load in either delta or wye connections. For delta connection, the end terminal of each phase winding are connected end-to-end to form a closed loop, and while a wye connection is a three-phase connection that has one end of each coil connected together and the other end of each coil left open for external connections [2]. The common three-phase transformer connection which listing primary winding first are:

- wye-wye is commonly used for interior wiring systems
- wye-delta is used to step-down utilities high line voltages
- delta-wye is often used for industrial applications
- delta-delta is often used for industrial applications

In addition, three-phase supplies have many electrical advantages over single-phase power and when considering three-phase transformers need to deal with three alternating voltages and currents differing in phase-time by 120 degrees [4].

Multiphase system is the system that has more than three-phase system. The application of multiphase system is discovered in electric power generation, transmission and utilization. Multiphase system such as six-phase transmission lines can deliver the same power capacity with a lower phase-to-phase voltage and smaller. Besides, it is more compact towers when compared to a standard double-circuit three-phase line. With this six-phase compact towers may also help in the reduction of magnetic field [5].

The advantage of multiphase transformer is it can reduce the total harmonic distortion and improve the phasor diagram. There are many electrical system require direct current power. Those direct current (DC) is typically produced by rectifying three-phase alternating current (AC) voltage. The rectifiers, yet, induce harmonic distortion in the input line [6].

Multiphase such as 6- and 12-phase transformers are designed to feed a multipulse rectifier system and the technology has matured. With 6- and 12-phase system, there is found to produce less ripple with high frequency of ripple in an AC-DC rectifier system. The reason of choosing 6-, 12- or 24-phase system is that these numbers are multiple of 3. Besides, designing this type of system is simple and straightforward. However, none of these designs are available for an odd number of phases such as 5, 7 and 11. Therefore, there is a special transformer connection scheme to obtain a balanced five-phase supply with the input as balanced three-phase was introduced in [1].

In addition to that, this paper will introduced the simple and flexible method in designing any multiphase transformer system from three phase supply. This method utilized the knowledge of graphical phasor diagram. The remainder of this paper is start with the explanation of designing multiphase transformer; follow by the simulation resulted from ANSYS

Maxwell finite elements software, and the experimental result of three to five phase transformer for no load and loading condition. The last section concludes the paper and suggests future works for improvement.

II. DESIGN OF MULTIPHASE TRANSFORMER

Transformer core

The transformer core provides the path for the flux to link the primary and secondary winding. Thus the selection of the core in term of size and material will surely limit the power rating of the designed transformer. The transformer core used in this paper is based on the available core in laboratory's shelf. The dimension of the transformer is shown in Figure 2.

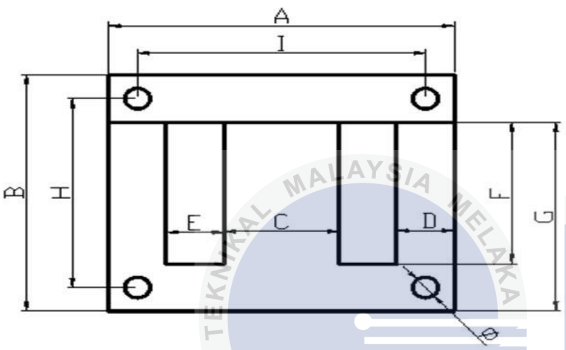


Figure 1: Dimension of the core

The E and I core of the transformer is stacked and secured using nuts and bolts. The stack length of this transformer is 57mm.

Primary winding turns

At the initial of design stage, the transformer desired specification are presented:

1. Peak primary voltage is 240V
2. Power rating for each transformer is 700VA
3. Maximum voltage regulation is 20%
4. Minimum efficiency is 80%
5. Primary phase to secondary phase ratio is 1

According to faraday law, the induced voltage, e_{ind}, in a coil with N number of turns is proportional to the changed of magnetic flux, Ø over rate of times, t can be written as:

$$e_{ind} = N\frac{d\emptyset}{dt} \quad (1)$$

For the transformer that designed to operate with sinusoidal excitation signal, the peak value of the induced voltage of the primary winding with core area of A and a core flux density of B can be calculated using this equation:

$$e_{ind} = 2\pi BAN \quad (2)$$

Equation (2) is rearranged into (3) in order to calculate the minimum number of primary turns and later used to determine a suitable number of turns for secondary windings based on turns ratio.

$$N = \frac{e_{ind}}{2\pi BA} \quad (3)$$

In contrary to regular transformer, a turn ratio for three to five phase transformers has to be determined by the proposed graphical phasor diagram.

Graphical phasor diagram

The proposed graphical phasor diagram provides an easy and flexible ways to design any multiphase output from three phase supply. The graphical phasor diagram can be easily implemented in 2D CAD platforms such as Autocad and Draftsight. Figure 2 show the graphical phasor diagram of five phase transformer

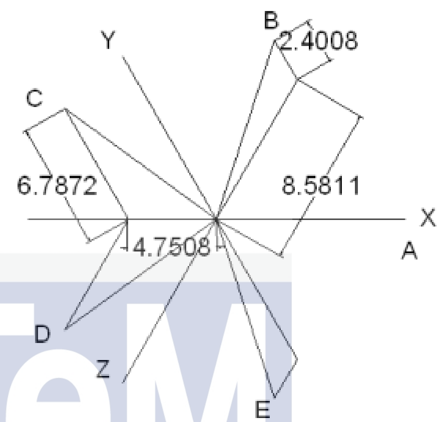


Figure 2: Three to five phase graphical phasor diagram

Graphical phasor not only allow us to determine a turn ratio but also a possible winding arrangement. Three spokes namely X, Y and Z represent 3 phase supply. The length for each spoke is 10 units. The offset between each phase is 120 degree. The spokes of A, B, C, D and E represent the five phase output. In this case, on the output side, the spoke A is aligned with spoke X and other spokes are 72 degree offset is respective order.

As can be seen from Figure 2, phase B can be produce from phase Y and phase Z, and the winding arrangement for all output phases can be expressed as:

$$A = X \quad (4)$$

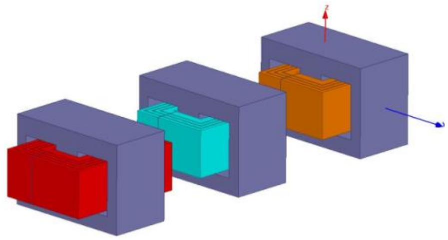
$$B = \frac{2.4008}{10}Y + \frac{8.5811}{10}Z' \quad (5)$$

$$C = \frac{6.7872}{10}Y + \frac{4.7508}{10}X' \quad (6)$$

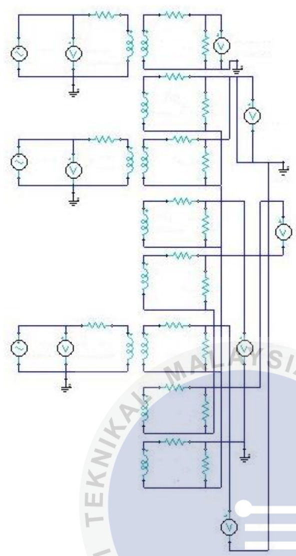
$$D = \frac{6.7872}{10}Z + \frac{4.7508}{10}X' \quad (7)$$

$$E = \frac{2.4008}{10}Z + \frac{8.5811}{10}Y' \quad (8)$$

According to winding arrangement and turns ratio from equation (4) until (8), the transformer is modelled in ANSYS Maxwell as in Figure 3.



(a)



(b)

Figure 3: (a) Transformer in ANSYS Maxwell, (b) Winding configuration circuit

The five phase output can also be generated by an alternative winding arrangement as in Figure 4. This arrangement is accomplish by shifting the five phase spokes by six degree anti-clockwise direction. This shown the flexibility of graphical phasor diagram proposed in the paper.

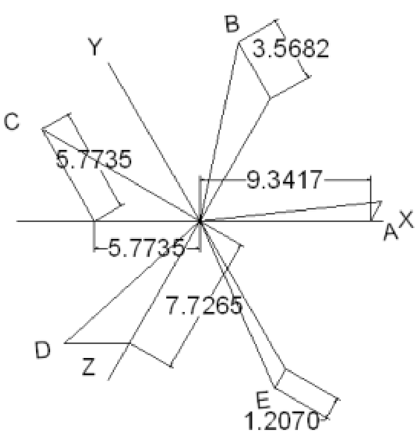


Figure 4: Alternative three to five phase graphical phasor diagram

From Figure 4, the winding arrangement for all output phases can be expressed as:

$$A = \frac{9.3417}{10}X + \frac{1.2070}{10}Z' \quad (9)$$

$$B = \frac{7.7265}{10}Z' + \frac{3.5682}{10}Y \quad (10)$$

$$C = \frac{5.7735}{10}Y + \frac{5.7732}{10}X' \quad (11)$$

$$D = \frac{7.7265}{10}Z + \frac{3.5682}{10}X' \quad (12)$$

$$E = \frac{1.2070}{10}Z + \frac{9.3417}{10}Y' \quad (13)$$

Wire size and current carrying capacity

Wire size for winding on primary and secondary based on number of turns and the slot area. Referring to (3), the required number of turns for 240V is 480 turns. If the fill factor for the slot is 100%, the maximum enamelled wire cross section can be calculated by:

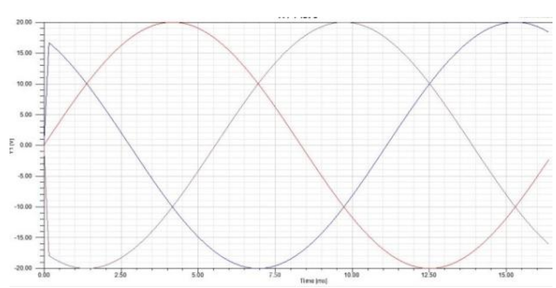
$$wire\ cross\ section\ area = \frac{phase\ slot\ area}{number\ of\ turn} \quad (14)$$

Appropriate enamelled wire can be determined from standard wire gauge table according to calculated wire cross section area. The apparent power, VA for each of single transformer can be estimated by multiplying the input voltage with the maximum allowable current for enamelled wire.

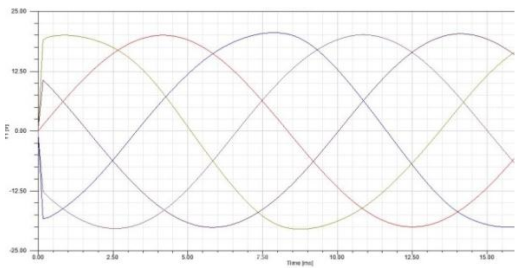
I. SIMULATION RESULTS

Simulation for both winding arrangement as in Figure 2 and Figure 4 has been carried out to verify the calculation of the proposed graphical phasor diagram. The transformer connection has been simulated in ANSYS Maxwell due to its capabilities to predict the performance with details and thus saves both time and cost in making an expensive prototype.

Figure 5 shows the no load performance of the designed transformer.



a) Three phase input for five phase transformer



b)

Figure 5: (a) Three phase input, (b) Five phase output

Figure 6 shows the no load performance of the designed transformer with alternative arrangement.

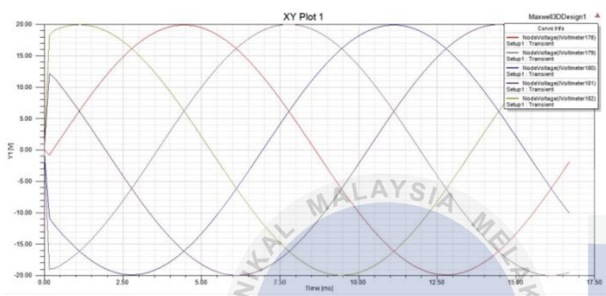


Figure 6: Five phase output for alternative winding

II. EXPERIMENTAL RESULTS

In order to verify the simulation result, the five phase transformer as in Figure 2 has been constructed in the laboratory. The no load experimental result is shown in Figure 7 and follow the load test result in Figure 8.

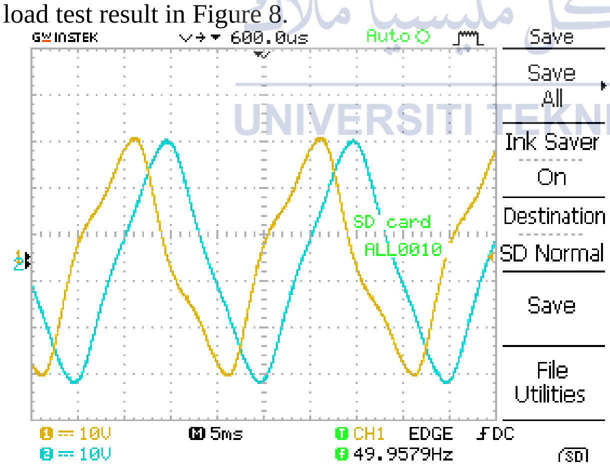


Figure 7: No load waveform for two phases of five phase transformer

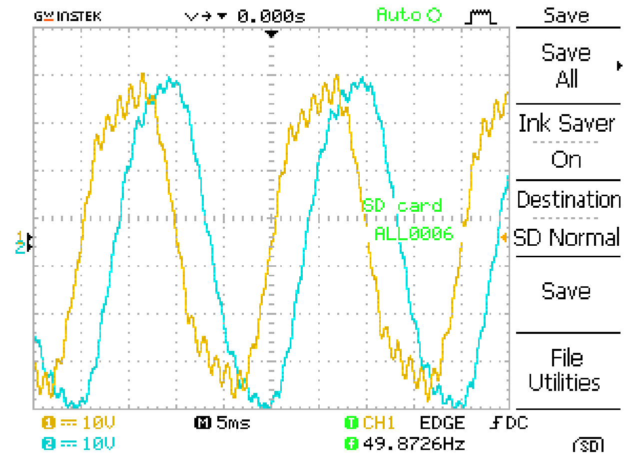


Figure 8: Output waveform for two phases of five phase transformer connected to four unfilled slots five phase induction motor

III. CONCLUSION

From both simulation and experimental result, the five phase transformer has been successfully designed and developed based on the proposed graphical phasor diagram. This static three to five phase transformer is suitable for power transmission and direct motor drive application

Acknowledgment

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM), Kemeterian Pendidikan Malaysia (KPM) and all Power Electronics and Drives (PED) group members for their full support to make this project successful.

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Appendix B – Project Planning (Gantt Chart)

Project Planning											
Project activities		FYP 1 (2013)				FYP 2 (2014)					
		Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Research and study on topic	Plan	■	■								
	Actual	■	■								
Literature review and gather information	Plan	■	■								
	Actual	■	■								
Draft out design, component listing	Plan	■	■								
	Actual	■	■								
Hardware building	Plan	■	■	■	■	■	■	■	■		
	Actual	■	■	■	■	■	■	■	■		
Test on hardware and troubleshootin	Plan			■	■	■	■	■	■		
	Actual			■	■	■	■	■	■		
Experiment and collect data	Plan			■	■	■	■	■	■		
	Actual			■	■	■	■	■	■		
Report preparation and presentation	Plan			■							
	Actual			■							
Analysis to hardware performance	Plan								■	■	■
	Actual								■	■	■
Write final report	Plan									■	■
	Actual									■	■
Final presentation	Plan										■
	Actual										■

(green)	Plan
(blue)	Actual on time
(red)	Plan delay

Appendix C - Waveform for Five-Phase Transformer

Figure I shows the waveform between V_a and V_b.

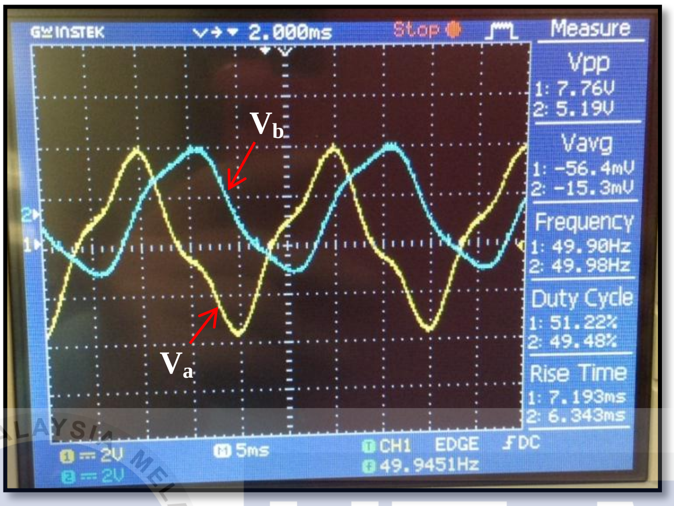

Figure I: Waveform between V_a and V_b

From Figure I, 4 boxes represented a sinusoidal wave which is 360°. Each box has 5 dots inside.

Total dots are, $4\ boxes \times 5 dots = 20$.

Each dots represented, $\frac{360°}{20} = 18°$.

The distance between V_a and V_b is 6 dots, therefore, the phase shift between V_a and V_b is $6 \times 18° = 108°$.

Figure II shows the waveform between V_a and V_c.

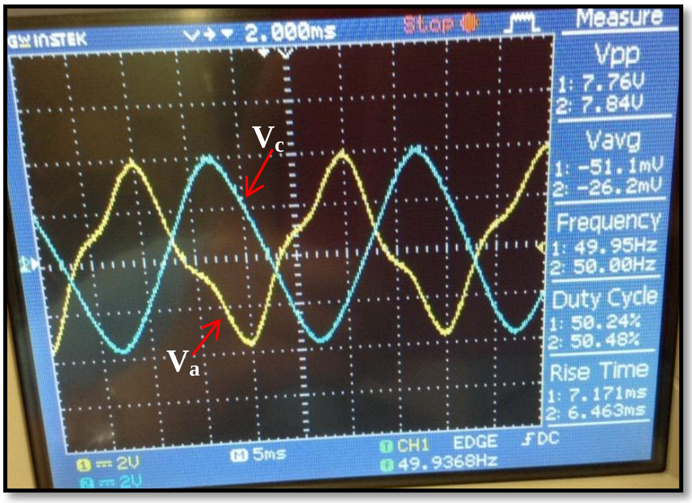

Figure II: Waveform between V_a and V_c

From Figure II, the distance between V_a and V_c is 8 dots, therefore, the phase shift between V_a and V_c is $8 \times 18° = 144°$.

Figure III shows the waveform between V_a and V_d.

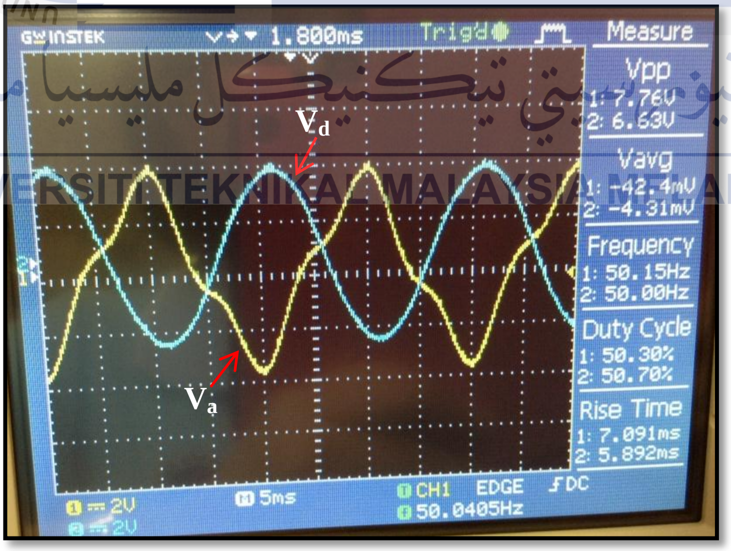

Figure III: Waveform between V_a and V_d

From Figure III, the distance between V_a and V_d is 12 dots, therefore, the phase shift between V_a and V_d is $12 \times 18° = 216°$.

Figure IV shows the waveform between V_a and V_e.

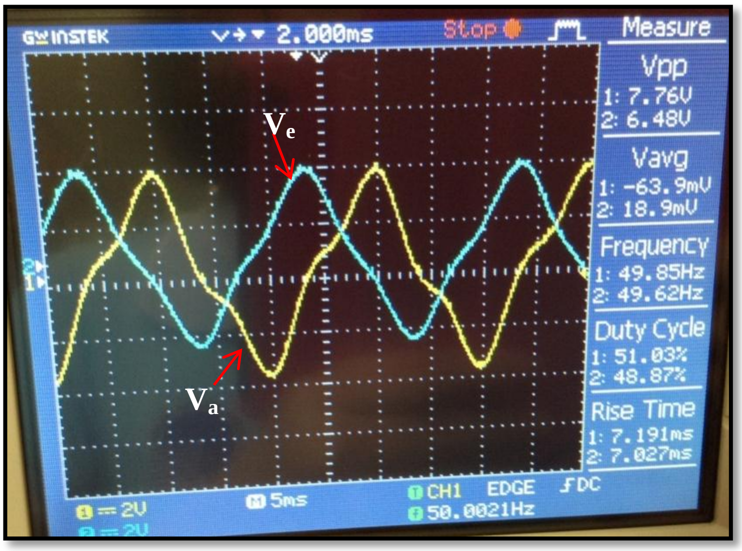

Figure IV: Waveform between V_a and V_e

From Figure IV, the distance between V_a and V_e is 8 dots, therefore, the phase shift between V_a and V_e is $15 \times 18° = 270°$.

- **Comparison between expected results and experimental results**

Table I: Comparison the expected and experimental results

Reference voltage	Phase voltage	Expected phase shift (°)	Experimental phase shift (°)
V_a	V_b	72	108
	V_c	144	144
	V_d	216	216
	V_e	288	270

Appendix D – Procedure to develop step down transformer

- **PHASE X HARDWARE BUILDED**

The steps to construct a step-down transformer for phase X were as below:

1. The first transformer bobbin for phase X was installed on the winding machine.
2. 0.70mm copper wire was used and inserted into the transformer bobbin and the winding machine was being rotated manually.
3. The copper wire was arranged neatly and fitted to each other; this step was repeated until 200 turns were made.
4. Separator was used on primary coil (phase X) after 200 turns were made.
5. For the phase X, it carried 2 secondary coils. Then for the secondary parts, the steps needed to repeat twice but with different number of turns.
6. The step was repeated but it was until 140 turns for the a_1a_2 of the secondary winding.
7. Separator was used on a_1a_2 after 140 turns were made.
8. The step was repeated but it was until 66 turns for the a_4a_3 of the secondary winding.
9. Separator was used on a_4a_3 after 66 turns were made.
10. E-I lamination plates were inserted on the coil case one by one.
11. The complete E-I lamination plates was screwed after the whole coil case was fully filled.

- **PHASE Y HARDWARE BUILDED**

The steps to construct a step-down transformer for phase Y were as below:

1. The second transformer bobbin for phase Y was installed on the winding machine.
2. 0.70mm copper wire was used and inserted into the transformer bobbin and the winding machine was being rotated manually.
3. The copper wire was arranged neatly and fitted to each other; this step was repeated until 200 turns were made.
4. Separator was used on primary coil (phase Y) after 200 turns were made.

5. For the phase Y, it carried 3 secondary coils. Then for the secondary parts, the steps needed to repeat three times but with different number of turns.
6. The step was repeated but it was until 34 turns for the b_1b_2 of the secondary winding.
7. Separator was used on b_1b_2 after 34 turns were made.
8. The step was repeated but it was until 95 turns for the b_4b_3 of the secondary winding.
9. Separator was used on b_4b_3 after 95 turns were made.
10. Then, the step was repeated again but it was until 120 turns for the b_5b_6 of the secondary winding.
11. Separator was used on b_5b_6 after 120 turns were made.
12. E-I lamination plates were inserted on the coil case one by one.
13. The complete E-I lamination plates was screwed after the whole coil case was fully filled.

- **PHASE Z HARDWARE BUILDED**

The steps to construct a step-down transformer for phase Z were as below:

1. The second transformer bobbin for phase Z was installed on the winding machine.
2. 0.70mm copper wire was used and inserted into the transformer bobbin and the winding machine was being rotated manually.
3. The copper wire was arranged neatly and fitted to each other; this step was repeated until 200 turns were made.
4. Separator was used on primary coil (phase Y) after 200 turns were made.
5. For the phase Z, it was also carried 3 secondary coils. Then for the secondary parts, the steps also needed to repeat three times but with different number of turns.
6. The step was repeated but it was until 95 turns for the c_1c_2 of the secondary winding.
7. Separator was used on c_1c_2 after 95 turns were made.
8. The step was repeated but it was until 34 turns for the c_4c_3 of the secondary winding.
9. Separator was used on c_4c_3 after 34 turns were made.
10. Then, the step was repeated again but it was until 120 turns for the c_5c_6 of the secondary winding.

11. Separator was used on c_5c_6 after 120 turns were made.
12. E-I lamination plates were inserted on the coil case one by one.
13. The complete E-I lamination plates was screwed after the whole coil case was fully filled.

Appendix E - Table of Enamelled Copper Wire Sizes

Metric	Decimal Equivalent	Standard Wire Gauge Guide
0.15mm	.0059"	39 swg
0.20mm	.0074"	36 swg
0.25mm	.0096"	33 swg
0.30mm	.0118"	32 swg
0.35mm	.0138"	29 swg
0.40mm	.0157"	27 swg
0.45mm	.0177"	26 swg
0.50mm	.0197"	25 swg
0.55mm	.0217"	24 swg
0.60mm	.0236"	23 swg
0.65mm	.0260"	22 swg
0.70mm	.0276"	22 swg
0.75mm	.0295"	22 swg
0.80mm	.0315"	21 swg
0.85mm	.0335"	20 swg
0.90mm	.0354"	20 swg
0.95mm	.0374"	20 swg
1.00mm	.0394"	19 swg

Appendix F – Turnitin Result

25/5/2014 Turnitin Originality Report

Turnitin Originality Report

5 phase transformer by Geok Yin Lim

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