MODELING AND SIMULATION STUDY OF MULTI-OUTPUT PHASE SHIFTING TRANSFORMER APPLICATION IN HIGH POWER AC- DC CONVERTERS

A PROJECT REPORT

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CERTIFICATE

This is to certify that the project report entitled being **"MODELING AND SIMULATION STUDY OF MULTI OUTPUT PHASE SHIFTING TRANSFORMER APPLICATION IN HIGH POWER AC-DC CONVERTERS"** submitted by **HIMANSHU PATEL** to the Indian Institute of Technology Madras, for the award of degree of Bachelor of Technology in Electrical Engineering is a bona fide record of project work done by him under my supervision. The contents of this thesis, in full or in parts have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Diode bridge rectifiers fed from three phase AC supply have problems of power quality in terms of harmonics injected into the supply which results poor input power factor and AC voltage distortion. This issue can be addressed by multi-output phase shifting transformer with appropriate phase shift in secondary windings. It will help to connect more number of rectifiers from the secondary windings of multi-output phase shifting transformer.

Modular multilevel Cascaded converter (MMCC) based AC drives with input diode bridge rectifier faces a serious problem of poor power quality at input side. In this converter several isolated three-phase diode bridge rectifiers are required which pollutes AC mains. To improve the power quality, it is advisable to stagger these current with appropriate phase shift. A multi-output/multi terminal transformer is an automatic choice for this application. Now converter is having more steps in AC input current. The main focus of this project is to model and analyse different phase shifting transformer topologies. These topologies have been discussed and verified by the simulation done in MATLAB/SIMULINK environment. It is proved by mathematical analyse and simulation results that these topologies provide less input current harmonics and better input power factor.

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ABBREVIATIONS

PST	Phase Shifting Transformer
THD	Total Harmonic Distortion
AC	Alternating current
DC	Direct current
VSCF	Variable Speed Constant Frequency System
UPS	Interruptible Power Supplies
PQ	Power Quality
HVDC	High Voltage Direct Current
FACTS	Flexible Alternating Current Transmission System
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator

NOTATIONS

δ	Phase shifting angle between primary and secondary line to line current, degree
N_1	No. of turns in primary winding of phase shifting transformer
N_2	No. of turns in secondary winding of phase shifting transformer connected to Delta.
N_3	No. of turns in secondary winding of phase shifting transformer connected to Star.
R_m	Magnetization resistance
L_m	Magnetization inductance
Y	Star connected windings
Δ	delta connected windings
Z	Zig-Zag connected windings
V_{AB}	Primary line to line voltage, V
V_{ab}	Secondary line to line voltage, V
h	The order of harmonics in source current
k	Transformation ratio
I_{Ah}	A- phase line current with harmonics in primary side, A
I_{Bh}	B- phase line current with harmonics in primary side, A
I_{Ch}	C- phase line current with harmonics in primary side, A
I_{ah}	a- phase line current with harmonics in secondary side, A
I_{bh}	b- phase line current with harmonics in secondary side, A
I_{ch}	c- phase line current with harmonics in secondary side, A
I_1	fundamental component of current, A

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In the present scenario of power supply, distortion due to harmonics is major challenge in the field of power quality. The widespread application of semiconductor devices challenge increases manifold. Power electronics based equipment such as AC-DC converter or DC-AC converters find an indispensable place in all industrial utilities [1-5], [8]. These three phase AC-DC converters have wide range of applications, from small converter to large high voltage direct current transmission (HVDC) system and flexible alternating current transmission system (FACTS). They are used in electromechanical process, motor drives, traction equipment, controlled power supplies and many other applications.

In most power electronic applications, the power input is in the form of 50Hz sine wave AC voltage provided by electric utility that is first converted to DC voltage. Increasingly, the trend is to use the inexpensive rectifiers with diodes to convert the input ac to dc in an uncontrolled manner. The dc output voltage of a rectifier should have ripple as low as possible. Therefore a large capacitor is connected as a filter on the DC side. This capacitor gets charged to a value close to the peak of the ac input voltage. As a consequence the current through the rectifier is very large near the peak of the 50Hz ac input voltage and it does not flow continuously and it becomes zero for finite durations during each half-cycle of the line frequency. These rectifiers draw highly distorted current from the grid that causes huge harmonics in input source current and reduction in power factor. As IEEE Standard 519, THD of general system below 69kV should be less than 5%. Hence, simple diode rectifiers may not be suitable for these applications.

This work deals with the reduction of Total Harmonic Distortion (THD) and improving the input power factor using phase shifting transformer in AC to DC conversion scheme [2-4], [8]. Phase shifting transformers are also used in modelling of static synchronous series compensator (SSSC) and static synchronous compensator (STATCOM) for improving the power flow. Normal phase shifting transformer has three inputs and three outputs. Hence more number of phase shifting transformers are required in order to connect multiple converter cells (more numbers of six pulse rectifier). This can be modified by using single multi output phase shifting transformer [4]. It will help to connect more number of six pulse rectifier (multiple converter cells). This harmonic current injection is mainly due to the non-linear nature of the loads connected to electrical utility.

The multi pulse converter has different connections possible including series/parallel in which all rectifiers are fed by multi output phase shifting transformer to shape secondary windings voltages of a transformer by shaping the primary current close to sinusoidal. With increasing the number of output in phase shifting transformer in order to connect more number of rectifiers increase the number of steps in the primary current waveform which improves the shape of input current.

When passive filters are used with nonlinear loads, resonance conditions can occur that may result in even higher levels of harmonic voltage and current distortion, thereby causing equipment failure, disruption of power services and fire hazards in extreme conditions [1-3]. To obviate the above said drawbacks, this project incorporates designing a special type of phase shifting transformer which has more number of outputs with different phase shift. This multi output phase shifting ensures THD of input current within the permissible limit at different load conditions

1.2 Need of phase shifting transformer

The harmonics in the source current and reduction in power factor cause serious problem in power quality due to the wide application of power electronics converter. Some of the most common application for multi output phase shifting transformer/rectifier system includes motor drive, interruptible power supplies (UPS) system, aircraft variable speed constant frequency (VSCF) system and frequency changer system. For these application many multilevel converter are used. These converters are require DC supply, which generally fed from six pulse rectifiers. They will causes huge harmonics in input source current and reduction in power factor. Harmonic distortion in the source current and power factor can be improved by using different multi output phase shifting transformers with appropriate phase shift in secondary line to line voltage.

The PST is an indispensable device in multi pulse rectifier, and has three main functions:

1- It provides the phase displacement between the primary and secondary line-to-line voltages for harmonic cancellation and improves power factor for the multi pulse rectifiers.
2- A proper secondary voltage.
3- It provides an electric isolation between the rectifier and the utility supply.

When a multi output transformer is required to be built, the function of few smaller modules must be known a priori. Then there are mainly two basic building blocks are used for this purpose:-

● Y/Z

● Δ/Z

Where the primary winding can be connected in to Y or Δ where the secondary winding is normally connected in Zig-Zag (Z). Both configurations can be equally used in multi pulse rectifier.

1.3 Y/Z and Δ/Z Phase shifting transformers

Depending on phase displacement δ between primary side and secondary side voltages, the winding connection of the conventional Y/Z phase shifting transformer may be Y/Z-1 and Y/Z-2. Similarly the winding connection of the conventional Δ/Z phase shifting transformer may be Δ/Z-1 and Δ/Z-2.

1.4 Brief description of present work

The present work is an effort towards modelling and analysing the different multi-output phase shifting transformers in solving the harmonic problem in a three phase AC-DC converter system. The list of multi-output PST which is modelled in this project is given below.

● Three input-six output phase shifting transformer (for 2 six pulse rectifiers)

- Three input-nine output phase shifting transformer (for 3 six pulse rectifiers)
- Three input-twelve output phase shifting transformer (for 4 six pulse rectifiers)
- Three input-fifteen output phase shifting transformer (for 5 six pulse rectifiers)
- Three input-twenty seven output phase shifting transformer (for 9 six pulse rectifiers)
- Three input- twenty seven output model using three similar PSTs (for 9 six pulse rectifiers)
- Three input-twenty seven output model using three different PSTs (for 9 six pulse rectifiers)
- Three input- forty five output model using three similar PSTs (for 15 six pulse rectifiers)

The effect of increasing the number of outputs on the multi-output phase shifting transformer has been analysed. For performance comparison the total harmonic distortion of input current and source power factor are considered. In this thesis the three inputs-twenty seven outputs PST and three inputs-forty five outputs PST are basically designed for modular multilevel cascaded converters (MMCC). In this converter several isolated three-phase diode bridge rectifiers are connected. These diode bridge rectifiers are fed from multi output PSTs. One of the modular multilevel cascaded converter is shown in figure 1.1 and 1.2.

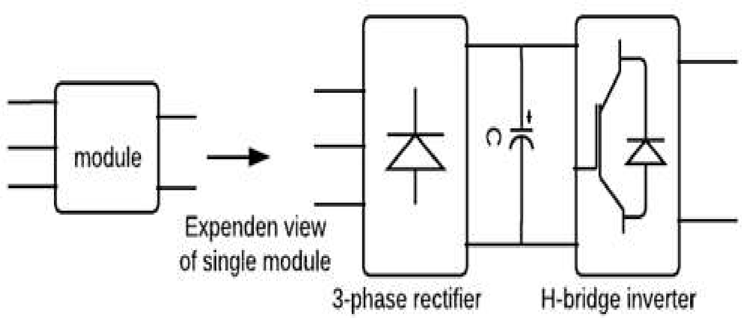

Figure 1.1: Expended view of single module

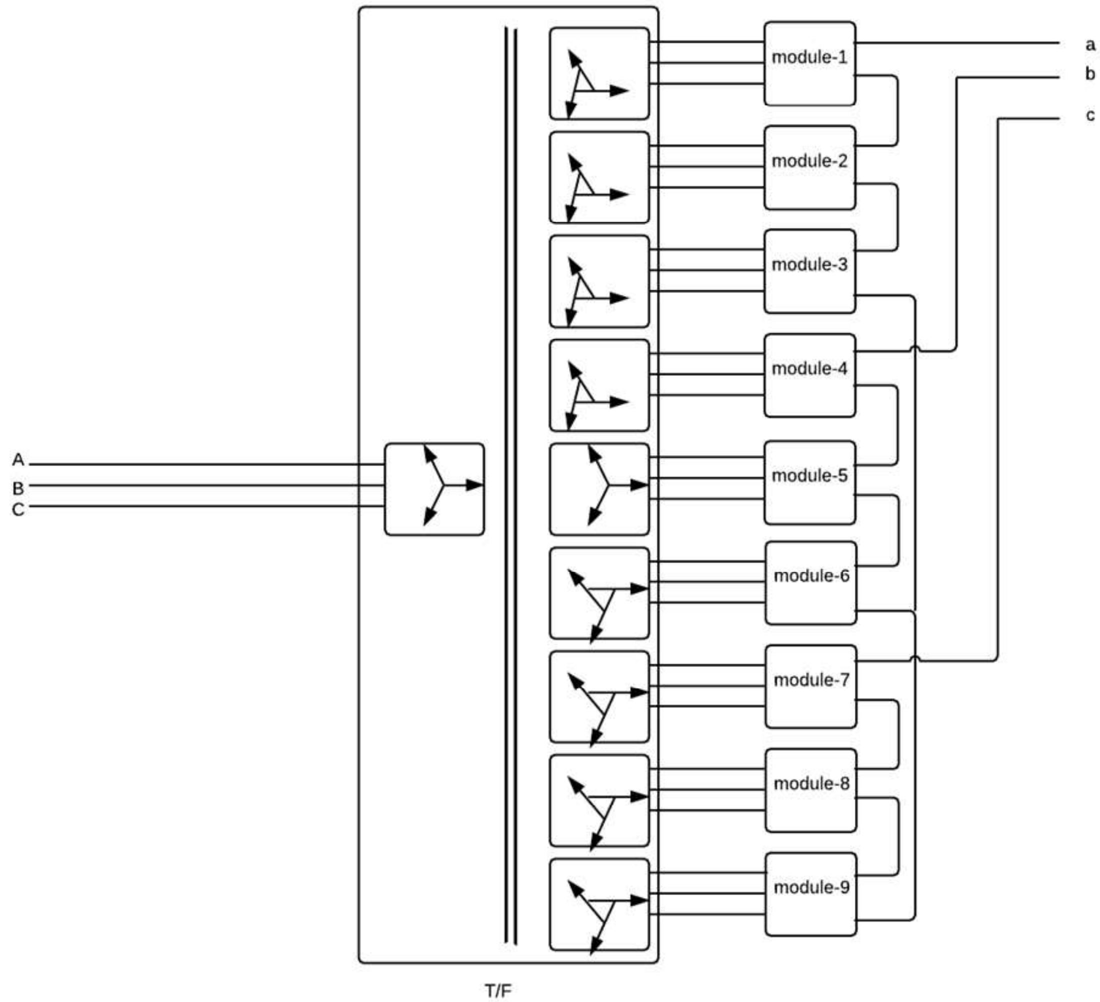

Figure 1.2: Example of modular multilevel cascaded converter.

1.5 Organization of the Thesis

The thesis is organized as follows.

Chapter 2: The basic principal of phase shifting transformer is explained in this chapter. By using basic principal of phase shifting transformer, the various types of multi-output phase shifting transformers are modeled. Mathematical modeling of each multi-output phase shifting transformer is explained with circuit diagram. The order of current harmonics for each multi-output phase shifting transformer is explained with mathematical equations.

Chapter 3: This chapter deals with simulation of different types of multi output phase shifting transformer in simulation software (MATLAB). Performance parameters (THD, source power factor, harmonics order, and ripple factor in load voltage) of each PST are analyzed with simulation results. These performance parameters of different PST are also compared to each other. These simulation results are also verified with mathematical results in this chapter.

Chapter 4: This chapter presents the summary of work done.

CHAPTER 2

MULTI OUTPUT PHASE SHIFTING TRANSFORMER (PST)

2.1 Introduction

Modular multilevel cascaded converters require isolated DC supply. This DC supply is generated by a diode bridge rectifier. The rectifier operation leads to reduction in source power factor, which is inconvenience for power quality. Even if additional LC filters are able to absorb the most important part of harmonics content, they may introduce resonance problems that may result in even higher levels of harmonic voltage and current distortion thereby causing equipment failure. The harmonic distortion and source power factor can be improved by using phase shifting transformers. But normal phase shifting transformer has three inputs and three outputs. So more number of phase shifting transformer are required in order to connect more no of six pulse rectifiers. So this will become more uneconomical and size of converters will also increase. So this can be replace by using multi output phase shifting transformer which has three inputs and multi output in order to connect more number of six pulse rectifiers.

2.2 Configurations and turns ratio calculation of normal phase shifting Transformer (PST)

According to winding arrangements, phase shifting transformer can be classified as given in Figure 2.1.

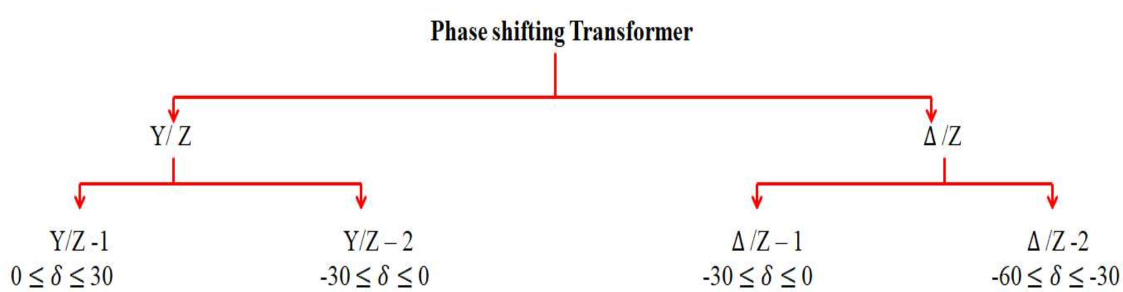

Figure 2.1: Phase shifting transformer configurations.

2.2.1 Y/Z Phase shifting transformers

Depending on phase displacement δ between primary side and secondary side voltages, the winding connection of the conventional phase shifting transformer may be Y/Z-1 with $\delta>0$ and Y/Z-2 with $\delta<0$.

2.2.1(a) Y/Z-1 Phase shifting transformers

Fig 2.2 shows, primary winding is connected in star with N1 turn per phase. The secondary is composed of two sets of coil having N1 and N3 turn per phase. The N2 coil is connected in delta and then in series with the N3 coils. Such an arrangement is known as **Zig–Zag** or **extended-delta** connection.

The transformer can produce phase shifting angle, $\delta = \angle V_{ab} - V_{AB}$

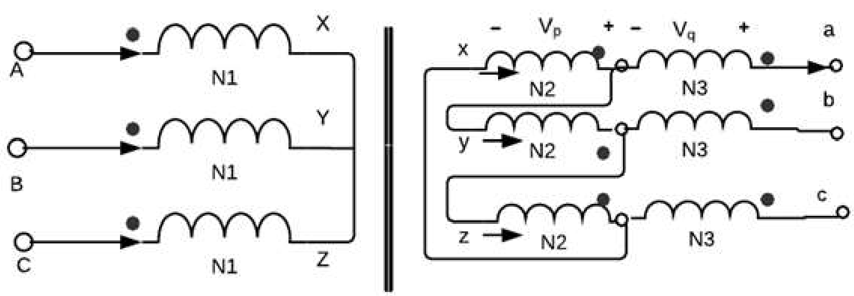

Figure 2.2: Connection diagram for Y/Z-1 phase shifting transformer [1].

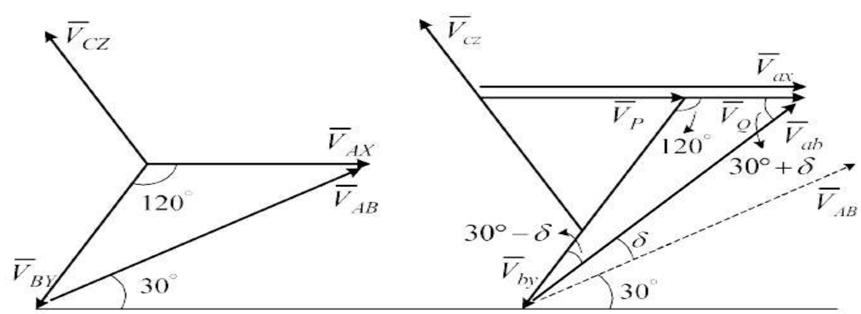

Figure 2.3: Phasor diagram for Y/Z-1 phase shifting transformer [1].

Where $\overline{V}_{AB}$ and $\overline{V}_{ab}$ are the primary and secondary line to line voltages. To determine the turns ratio for the transformer, let's a take triangle composed by $\overline{V}_{Q}$, $\overline{V}_{by}$ and $\overline{V}_{ab}$ as shown in Figure 2.3.

$$\frac{V_{ab}}{\sin(120^\circ)} = \frac{V_Q}{\sin(30^\circ - \delta)} = \frac{V_{by}}{\sin(30^\circ + \delta)} \quad , \qquad 0^\circ \leq \delta \leq 30^\circ \tag{2.1}$$

Where V_Q is the rms voltage across the N_3 coil and V_{by} is the rms voltage between b and y.

Since $V_{by} = V_{ax}$ for the balanced three phase system, the equation (2.1) can be written as

$$\frac{V_Q}{V_{ax}} = \frac{\sin(30^\circ - \delta)}{\sin(30^\circ + \delta)} \tag{2.2}$$

The turns ratio of secondary coil is given as

$$\frac{N_3}{N_2 + N_3} = \frac{V_Q}{V_{ax}} = \frac{\sin(30^\circ - \delta)}{\sin(30^\circ + \delta)} \tag{2.3}$$

From equation (2.1)

$$V_{ax} = V_{by} = \frac{2}{\sqrt{3}} \sin(30^\circ + \delta) V_{ab} \tag{2.4}$$

The turns ratio of transformer is defined by

$$\frac{N_1}{N_2 + N_3} = \frac{V_{AX}}{V_{ax}} \tag{2.5}$$

From equation (2.4) and (2.5)

$$\frac{N_1}{N_2 + N_3} = \frac{1}{2\sin(30^\circ + \delta)} \frac{V_{AB}}{V_{ab}} \tag{2.6}$$

Now examine two extreme cases:

Case(1)-If N2 is reduce to zero, then secondary winding becomes star connected. Thus δ=0°

Case(2)-If N3 is reduce to zero, then secondary winding becomes delta connected. Thus δ=30°

Therefore phase shifting angle δ for Y/Z-1 transformer is in range of 0° to 30 °.

2.2.1b Y/Z-2 Phase shifting transformers

The configuration Y/Z-2 phase shifting transformer is shown in Figure 2.4, where primary winding remains the same as that the Y/Z-1 while the secondary delta connected coils are connected in a reverse order.

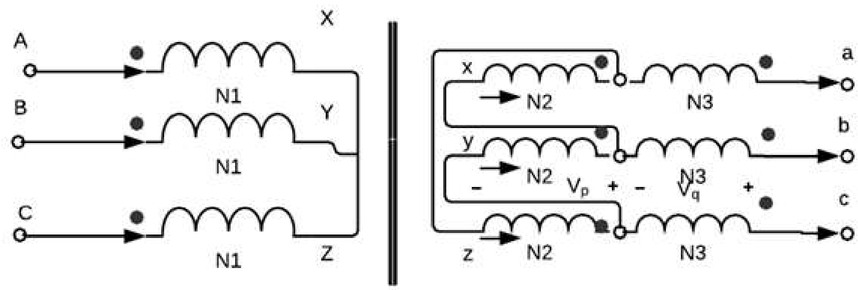

Figure 2.4: Connection diagram for Y/Z-2 phase shifting transformer.

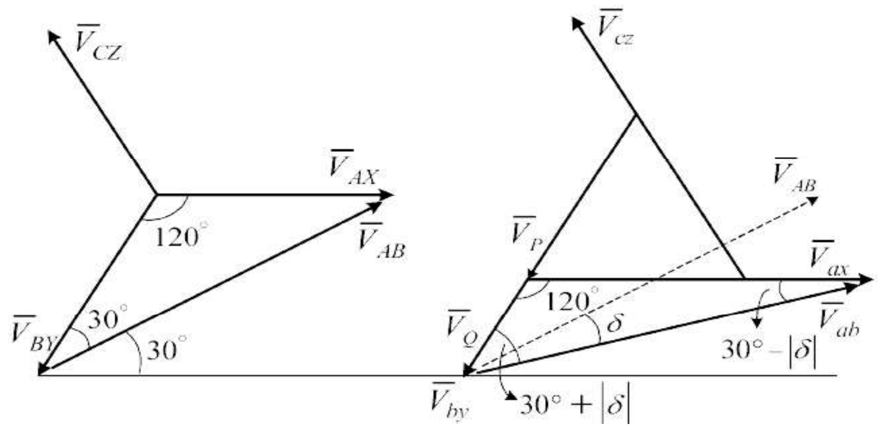

Figure 2.5: Phasor diagram for Y/Z-1 phase shifting transformer [1].

Following the same procedure presented earlier, the transformer turns ratio can be found from

$$\frac{N_3}{N_2+N_3}=\frac{\sin(30^\circ-|\delta|)}{\sin(30^\circ+|\delta|)} \qquad -30° \le \delta \le 0° \tag{1.7}$$

$$\frac{N_1}{N_2+N_3}=\frac{1}{2\sin(30^\circ+|\delta|)}\frac{V_{AB}}{V_{ab}} \tag{1.8}$$

The phase angle δ has negative value for the Y/Z-2, it indicate that V_{ab} lags V_{AB} by $|\delta|$ as shown in Figure 2.5

2.2.2 Δ/Z Phase shifting transformers

Depending on phase displacement δ between primary side and valve side voltages, the winding connection of the conventional phase shifting transformer may be **Δ**/Z-1 with $-30° \le \delta \le 0°$ and **Δ**/Z -2 with $-60° \le \delta \le -30°$.

2.2.2(a) Δ /Z-1 Phase shifting transformers

Figure 2.6 shows, primary winding is connected in delta with N1 turn per phase. The secondary is composed of two sets of coil having N1 and N3 turns per phase. The N2 coil is connected in delta and then in series with the N3 coils. Such an arrangement is known as Zig–Zag or extended-delta connection.

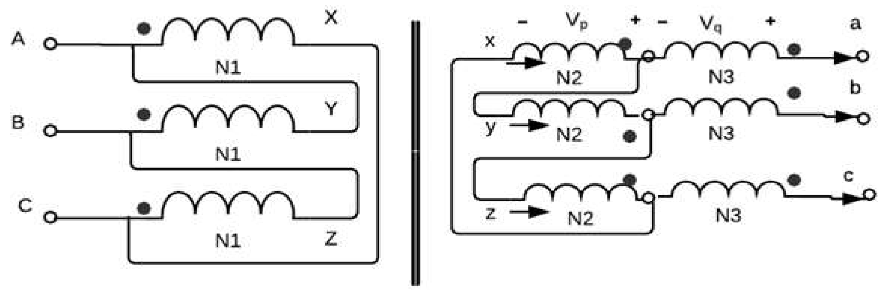

Figure 2.6: Connection diagram for Δ/Z-1 phase shifting transformer [1].

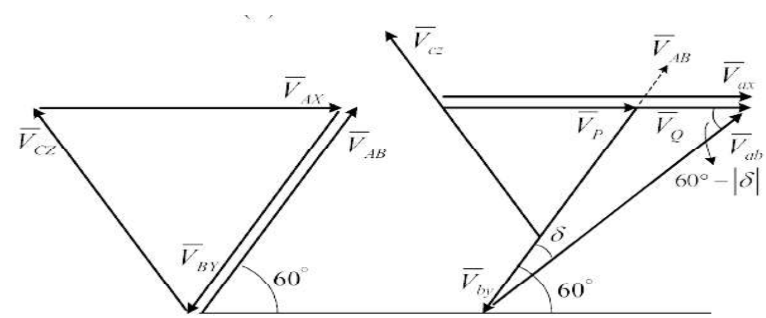

Figure 2.7: Phasor diagram for Δ/Z-1 phase shifting transformer [1].

Following the same procedure presented earlier, the transformer turns ratio can be derived:

$$\frac{N_3}{N_2+N_3}=\frac{V_Q}{V_{ax}}=\frac{\sin(|\delta|)}{\sin(60^\circ-|\delta|)} \qquad -30^\circ \le \delta \le 0^\circ \tag{2.9}$$

$$\frac{N_1}{N_2+N_3}=\frac{V_{AX}}{V_{ax}}=\frac{\sqrt{3}}{2\sin(60^\circ-|\delta|)}\frac{V_{AB}}{V_{ab}} \tag{2.10}$$

2.2.2(b) Δ /Z-1 Phase shifting transformers

configuration **Δ**/Z-2 phase shifting transformer is shown in Figure 2.8, where primary winding remains the same as that the **Δ**/Z-1 while the secondary delta connected coils are connected in a reverse order.

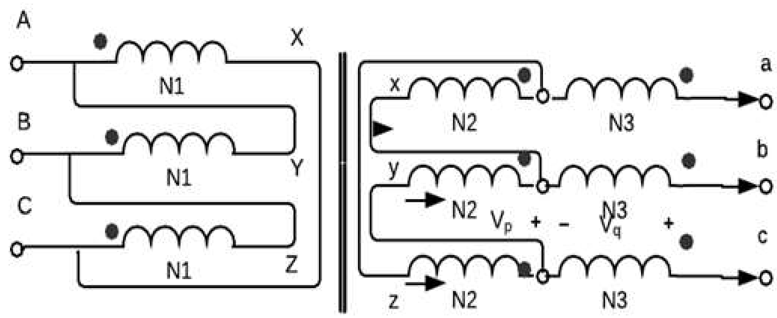

Figure 2.8: Connection diagram for Δ/Z-2 phase shifting transformer [1].

Following the same procedure presented earlier, the transformer turns ratio can be written as

$$\frac{N_3}{N_2+N_3}=\frac{V_Q}{V_{ax}}=\frac{\sin(|\delta|)}{\sin(60^\circ-|\delta|)} \qquad -60^\circ \le \delta \le -30^\circ \tag{2.10}$$

$$\frac{N_1}{N_2+N_3}=\frac{V_{AX}}{V_{ax}}=\frac{\sqrt{3}}{2\sin(60^\circ-|\delta|)}\frac{V_{AB}}{V_{ab}} \tag{2.12}$$

2.3 Classification of multi output phase shifting transformer based on number of outputs

Types of multi output phase shifting transformer are not fixed. It can be modelled using different topologies of three phase star-delta, delta-star, star-star, delta-delta, and ziz-zag connection of transformer for different phase shifts according to requirement of number of outputs. Some of these are listed below

- Three input-six output phase shifting transformer
- Three input-nine output phase shifting transformer
- Three inputs-twelve output phase shifting transformer
- Three input-fifteen output phase shifting transformer
- Three input-eighteen output phase shifting transformer
- Three input-twenty one output phase shifting transformer
- Three input-twenty fore output phase shifting transformer
- Three input-twenty seven output phase shifting transformer

2.3.1(a) Three input-six output phase shifting transformer (PST)

In this configuration either star or delta may be used for the primary winding. The phase shifting angle δ of the star- and delta-connected secondary windings is 0° and -30° in order to connect 2 six pulse rectifiers. The main purpose of this section is to investigate the phase displacement of harmonic current when it is referred from the secondary to primary side of phase shifting transformers. This phase displacement makes it possible to cancel the certain harmonic currents generated by a three –phase nonlinear load. The symbol and connection diagram of three inputs-six outputs phase shifting transformer are shown in Figure 2.9 and Figure 2.10 respectively.

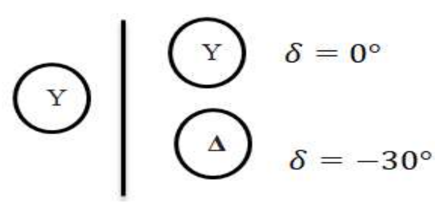

Figure 2.9: Symbol of Three inputs-six outputs phase shifting transformer.

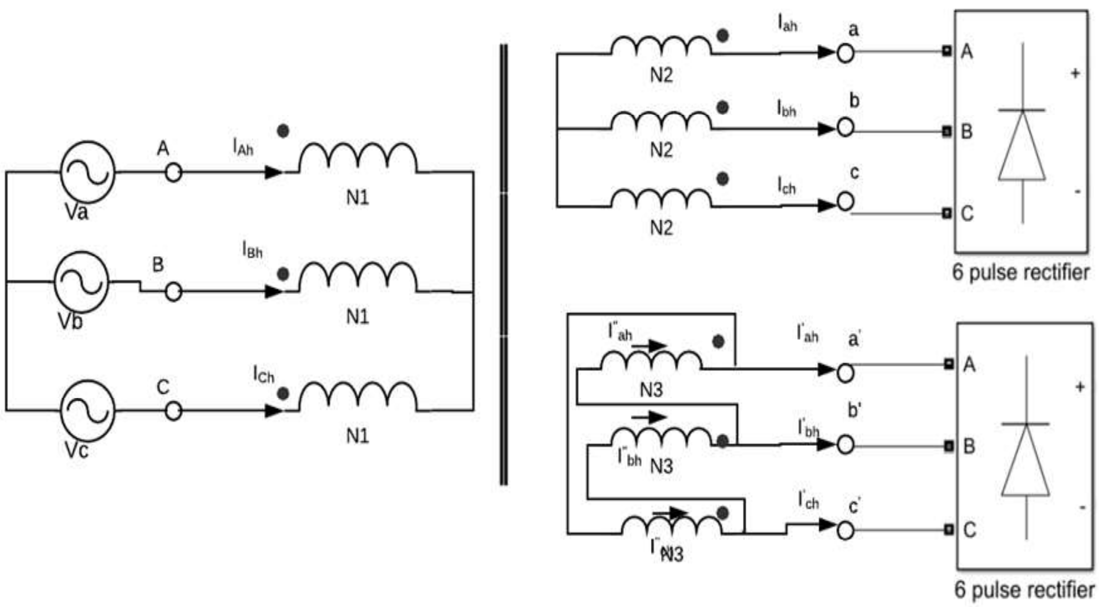

Figure 2.10: Connection diagram of three inputs-six outputs phase shifting transformer.

2.3.1(b) Harmonics analysis of three inputs six outputs phase shifting transformer

From the figure 2.10, fundamental and harmonic currents of all phases in primary and secondary side of phase shifting transformer are written as:

$$\overrightarrow{I_{a1}} = I_1\angle 0\ ,\quad \overrightarrow{I_{b1}} = I_1\angle -120\ ,\quad \overrightarrow{I_{c1}} = I_1\angle 120$$

$$\overrightarrow{I'_{a1}} = I_1\angle -30\ ,\quad \overrightarrow{I'_{b1}} = I_1\angle -150\ ,\quad \overrightarrow{I'_{c1}} = I_1\angle 90$$

$$\overrightarrow{I_{a5}} = I_5\angle 0\ ,\quad \overrightarrow{I_{b5}} = I_5\angle -120*5\ ,\quad \overrightarrow{I_{c5}} = I_5\angle 120*5$$

$$\overrightarrow{I'_{a5}} = I_5\angle(-30*5)\ ,\quad \overrightarrow{I'_{b5}} = I_5\angle(-150*5)\ ,\quad \overrightarrow{I'_{c5}} = I_5\angle(90*5)$$

Third harmonic components of line current are not present. Now general current equations can be written as follow:

$$\overrightarrow{I_{ah}} = I_h\angle 0\ ,\quad \overrightarrow{I_{bh}} = I_h\angle -120h\ ,\quad \overrightarrow{I_{ch}} = I_h\angle 120h$$

$$\overrightarrow{I'_{ah}} = I_h\angle -30h\ ,\quad \overrightarrow{I'_{bh}} = I_h\angle -150h\ ,\quad \overrightarrow{I'_{ch}} = I_h\angle 90h$$

Where h=1, for fundamental

$h = 6k \pm 1$, for harmonic order

For an ideal transformer, permeability of the core (μ) is infinite, magnetizing resistance (R_m) and inductances (Lm) are infinite. From figure 2.16, mmf equation of transformer can be written as:

$$\overrightarrow{I_{Ah}} = \frac{N_2}{N_1}\overrightarrow{I_{ah}} + \frac{\sqrt{3}N_2}{N_1}\overrightarrow{I_{ah}''} \tag{2.13}$$

$$\overrightarrow{I_{Bh}} = \frac{N_2}{N_1}\overrightarrow{I_{bh}} + \frac{\sqrt{3}N_2}{N_1}\overline{I_{bh}''} \tag{2.14}$$

$$\overrightarrow{I_{Ch}} = \frac{N_2}{N_1}\overrightarrow{I_{ch}} + \frac{\sqrt{3}N_2}{N_1}\overrightarrow{I_{ch}''} \tag{2.15}$$

From the figure 2.10 it can also be written

$$\overrightarrow{I_{Ah}} + \overrightarrow{I_{Bh}} + \overrightarrow{I_{Ch}} = 0 \tag{2.16}$$

$$\overrightarrow{I_{ah}} + \overrightarrow{I_{bh}} + \overrightarrow{I_{ch}} = 0 \tag{2.17}$$

From the addition of equations (2.13-2.15),

$$\overrightarrow{I_{ah}''} + \overrightarrow{I_{bh}''} + \overrightarrow{I_{ch}''} = 0 \tag{2.18}$$

From figure 2.10 we can write

$$\left.\begin{aligned} \overline{I_{ah}'} &= \overline{I_{ah}''} - \overline{I_{ah}''} \\ \overline{I_{bh}'} &= \overline{I_{bh}''} - \overline{I_{ah}''} \\ \overline{I_{ch}'} &= \overline{I_{ch}''} - \overline{I_{bh}''} \end{aligned}\right\} \tag{2.19}$$

Now from equation (2.18) and set of equations (2.19) ,

$$\left.\begin{aligned}\overline{I_{ah}''} &= \frac{1}{3}(\overline{I_{ah}'} - \overline{I_{bh}'})\\ \overline{I_{bh}''} &= \frac{1}{3}(\overline{I_{bh}'} - \overline{I_{ch}'})\\ \overline{I_{ch}''} &= \frac{1}{3}(\overline{I_{ch}'} - \overline{I_{ah}'})\end{aligned}\right\} \quad (2.20)$$

From equation 2.13 and equations 2.20,

$$\overline{\vec{I_{Ah}}} = \frac{N_2}{N_1}\overline{\vec{I_{ah}}} + \frac{\sqrt{3}N_2}{N_1}\frac{1}{3}(\overline{I_{ah}'} - \overline{I_{bh}'}) \quad (2.21)$$

$$\overline{I_{Ah}} = \frac{N_2}{N_1} I_h\angle 0 + \frac{N_2}{\sqrt{3}N_1}(I_h\angle -30h - I_h\angle -150h) \quad (2.22)$$

$$\overline{I_{Ah}} = \frac{N_2}{N_1} I_h\angle 0 + \frac{N_2}{\sqrt{3}N_1}(I_h\angle -30(6k \pm 1) - I_h\angle -150(6k \pm 1))$$

(2.23)

$$\overline{I_{A1}} = \frac{N_2}{N_1} I_1\angle 0 + \frac{N_2}{\sqrt{3}N_1}(I_1\angle -30 - I_1\angle -150), \text{ if h=1 for fundamental} \quad (2.24)$$

$$\overline{I_{A1}} = \frac{2N_2}{N_1} I_1\angle 0$$

$$\overline{I_{Ah}} = \frac{N_2}{N_1} I_h\angle 0 + \frac{N_2}{\sqrt{3}N_1}(I_h\angle \mp 30 - I_h\angle \mp 150) \text{ if } h = 6k \pm 1, \text{ k=even= 2,4,6,.....} \quad (2.25)$$

$$\overline{I_{Ah}} = \frac{N_2}{N_1} I_h\angle 0 + \frac{N_2}{\sqrt{3}N_1}(I_h\angle \pm 150 - I_h\angle \pm 30) \text{ if } h = 6k \pm 1, \text{ k=odd= 1,3,5,.....} \quad (2.26)$$

From equation 2.26,

$$\overline{I_{A1}} = \frac{2N_2}{N_1} I_1\angle 0, \qquad \text{if h=1 for fundamental}$$

$$\overline{I_{Ah}} = \frac{N_2}{N_1} I_h\angle 0 \qquad \text{if } h = 6k \pm 1, \text{ k=even= 2,4,6,.....} \quad (2.27)$$

$$\overline{I_{Ah}} = 0 \qquad \text{if } h = 6k \pm 1, \text{ k=odd= 1,3,5,....} \quad (2.28)$$

Similarly for B and C phase input current

$$\overline{I_{B1}} = \frac{2N_2}{N_1} I_1 \angle -120, \quad \text{if h=1 for fundamental}$$

$$\overline{I_{Bh}} = \frac{N_2}{N_1} I_h \angle \mp 120 \qquad \text{if } h = 6k \pm 1, \text{ k=even= 2,4,6,…..} \tag{2.29}$$

$$\overline{I_{Bh}} = 0 \qquad \text{if } h = 6k \pm 1, \text{ k=odd= 1,3,5,….} \tag{2.30}$$

$$\overline{I_{C1}} = \frac{2N_2}{N_1} I_1 \angle 120, \qquad \text{if h=1 for fundamental}$$

$$\overline{I_{Ch}} = \frac{N_2}{N_1} I_h \angle \pm 120 \qquad \text{if } h = 6k \pm 1, \text{ k=even= 2,4,6,…..} \tag{2.31}$$

$$\overline{I_{Ch}} = 0 \qquad \text{if } h = 6k \pm 1, \text{ k=odd= 1,3,5,….} \tag{2.32}$$

2.3.1c Discussion for harmonics analysis of three inputs six outputs PST

From equation 2.27, 2.28 and 2.29, 2.30 and 2.31, 2.32, it is observed that the lower order harmonic components which are present in source current are 11^{th} and 13^{th} while 5^{th} and 7^{th} harmonic components get eliminated. Hence order of harmonics that are present in line current is $h = 12m \pm 1$ where m=1,2,3,4…

2.3.2(a) Three inputs-nine outputs phase shifting transformer (PST)

In this configuration primary can be use either star or delta. The phase shifting angle δ of the zigzag-2, star and zigzag-1-connected secondary windings is -20°, 0° and 20° in order to connect 3 six pulse rectifier. The main purpose of this section is to investigate the phase displacement of harmonic current when it referred from the secondary to primary side of phase shifting transformers. This phase displacement makes it possible to cancel the more harmonic current generated by a three –phase nonlinear load. The symbol and Connection diagram of three inputs-nine outputs phase shifting transformer are shown in Figure 2.11 and 2.12 respectively.

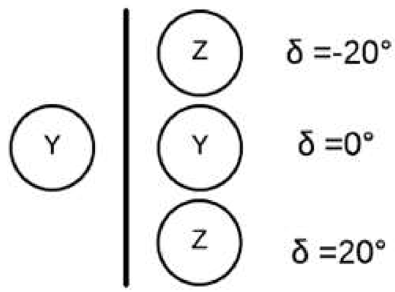

Figure 2.11: Symbol of Three inputs-nine outputs phase shifting transformer.

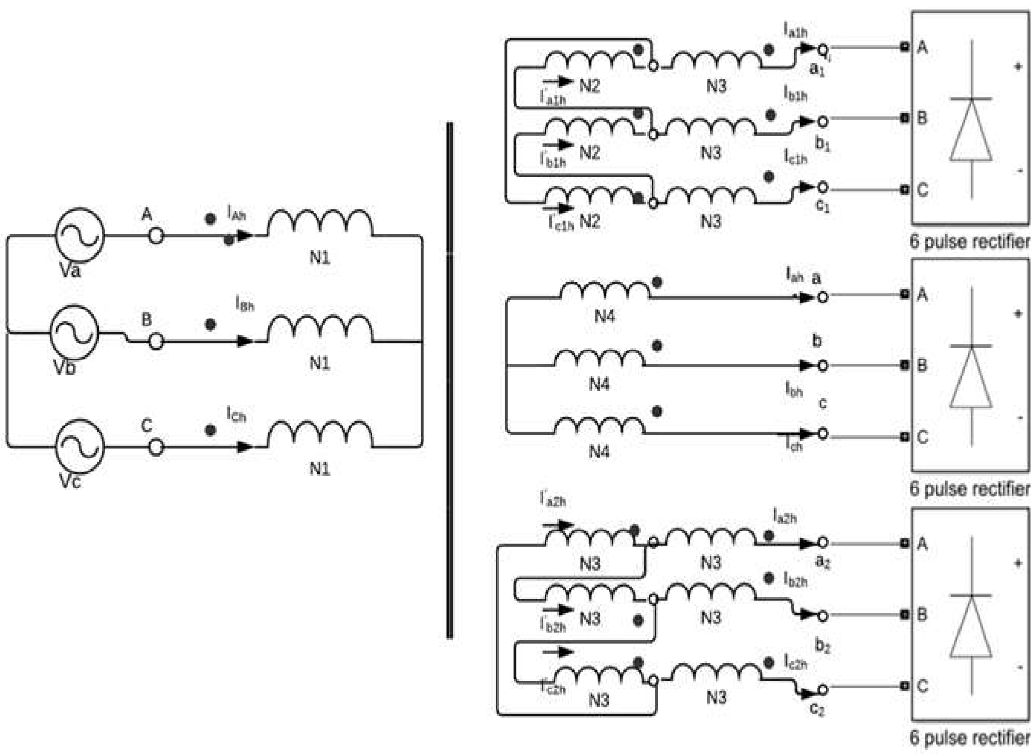

Figure 2.12: Connection diagram for three inputs-nine outputs phase shifting transformer.

2.3.2(b) Harmonics analysis of three inputs six outputs phase shifting transformer

From the Figure 2.12, fundamental and harmonic currents component of line current in secondary side of phase shifting transformer can be written as:

$\overrightarrow{I_{a1}} = I_1 \angle 0$, $\overrightarrow{I_{b1}} = I_1 \angle -120$, $\overrightarrow{I_{c1}} = I_1 \angle 120$

$\overrightarrow{I_{a11}} = I_1 \angle -20$, $\overrightarrow{I_{b11}} = I_1 \angle -140$, $\overrightarrow{I_{c11}} = I_1 \angle 100$

$\overrightarrow{I_{a21}} = I_1 \angle 20$, $\overrightarrow{I_{b21}} = I_1 \angle -100$, $\overrightarrow{I_{c21}} = I_1 \angle 100$

Third harmonic components of line current are not present. Now general line current in secondary side can be written as follow:

$\overrightarrow{I_{ah}} = I_h \angle 0$, $\overrightarrow{I_{bh}} = I_h \angle -120 * h$, $\overrightarrow{I_{ch}} = I_h \angle 120 * h$

$\overrightarrow{I_{a1h}} = I_h \angle -20h$, $\overrightarrow{I_{b1h}} = I_h \angle -140 * h$, $\overrightarrow{I_{c1h}} = I_h \angle 100 * h$

$\overrightarrow{I_{a2h}} = I_h \angle 20h$, $\overrightarrow{I_{b2h}} = I_h \angle -100 * h$, $\overrightarrow{I_{c2h}} = I_h \angle 140 * h$

Where h=1, for fundamental

$h = 6k \pm 1$, for harmonic order

From the figure 2.12 we can write

$$\left.\begin{aligned} \overline{I_{a1h}} &= \overline{I_{a1h}}' - \overline{I_{c1h}}' \\ \overline{I_{b1h}} &= \overline{I_{b1h}}' - \overline{I_{a1h}}' \\ \overline{I_{c1h}} &= \overline{I_{c1h}}' - \overline{I_{b1h}}' \end{aligned}\right\} \tag{2.33}$$

$$\left.\begin{aligned} \overline{I_{a2h}} &= \overline{I_{a2h}}' - \overline{I_{b2h}}' \\ \overline{I_{b2h}} &= \overline{I_{b2h}}' - \overline{I_{c2h}}' \\ \overline{I_{c2h}} &= \overline{I_{c2h}}' - \overline{I_{a2h}}' \end{aligned}\right\} \tag{2.34}$$

From the addition of set of equations in (2.33),

$$\overrightarrow{I_{a1h}} + \overrightarrow{I_{b1h}} + \overrightarrow{I_{c1h}} = 0 \tag{2.35}$$

From the addition of set of equations in (2.34),

$$\overrightarrow{I_{a2h}} + \overrightarrow{I_{b2h}} + \overrightarrow{I_{c2h}} = 0 \quad (2.36)$$

For an ideal transformer, permeability of the core (μ) is infinite, magnetizing resistance (R_m) and inductances (Lm) are infinite. From figure 2.16, mmf equation of transformer can be written as:

$$\overline{I_{Ah}} = \frac{N_4}{N_1}\overline{I_{ah}} + \frac{N_2}{N_1}\overline{I_{a1h}'} + \frac{N_3}{N_1}\overline{I_{a1h}} + \frac{N_2}{N_1}\overline{I_{a2h}'} + \frac{N_3}{N_1}\overline{I_{a2h}} \quad (2.37)$$

$$\overline{I_{Bh}} = \frac{N_4}{N_1}\overline{I_{bh}} + \frac{N_2}{N_1}\overline{I_{b1h}'} + \frac{N_3}{N_1}\overline{I_{b1h}} + \frac{N_2}{N_1}\overline{I_{b2h}'} + \frac{N_3}{N_1}\overline{I_{b2h}} \quad (2.38)$$

$$\overline{I_{Ch}} = \frac{N_4}{N_1}\overline{I_{ch}} + \frac{N_2}{N_1}\overline{I_{c1h}'} + \frac{N_3}{N_1}\overline{I_{c1h}} + \frac{N_2}{N_1}\overline{I_{c2h}'} + \frac{N_3}{N_1}\overline{I_{c2h}} \quad (2.39)$$

From the figure 2.12 it can be written

$$\overrightarrow{I_{Ah}} + \overrightarrow{I_{Bh}} + \overrightarrow{I_{Ch}} = 0 \quad (2.40)$$

$$\overrightarrow{I_{ah}} + \overrightarrow{I_{bh}} + \overrightarrow{I_{ch}} = 0 \quad (2.41)$$

On simplifying equations (2.35- 2.41),

$$\overrightarrow{I_{a1h}'} + \overrightarrow{I_{b1h}'} + \overrightarrow{I_{c1h}'} = 0 \quad (2.42)$$

$$\overrightarrow{I_{a2h}'} + \overrightarrow{I_{b2h}'} + \overrightarrow{I_{c2h}'} = 0 \quad (2.43)$$

Now from equations (2.33) and equations (2.42) it can be calculated:

$$\left.\begin{aligned} \overline{I_{a1h}'} &= \frac{1}{3}(\overline{I_{a1h}} - \overline{I_{b1h}}) \\ \overline{I_{b1h}'} &= \frac{1}{3}(\overline{I_{b1h}} - \overline{I_{c1h}}) \\ \overline{I_{c1h}'} &= \frac{1}{3}(\overline{I_{c1h}} - \overline{I_{a1h}}) \end{aligned}\right\} \quad (2.44)$$

Now from equations (2.34) and equations (2.43) it can be calculated:

$$\left.\begin{aligned}\overline{I_{a2h}'} &= \frac{1}{3}(\overline{I_{a2h}} - \overline{I_{c2h}}) \\ \overline{I_{b2h}'} &= \frac{1}{3}(\overline{I_{b2h}} - \overline{I_{a2h}}) \\ \overline{I_{c2h}'} &= \frac{1}{3}(\overline{I_{c2h}} - \overline{I_{b2h}})\end{aligned}\right\} \qquad (2.45)$$

Now from equation 2.37 and equations 2.44 and 2.45,

$$\overline{I_{Ah}} = \frac{N_4}{N_1}\overline{I_{ah}} + \frac{N_2}{N_1}\frac{1}{3}\left(\overline{I_{a1h}} - \overline{I_{b1h}}\right) + \frac{N_3}{N_1}\overline{I_{a1h}} + \frac{N_2}{N_1}\frac{1}{3}\left(\overline{I_{a2h}} - \overline{I_{c2h}}\right) + \frac{N_3}{N_1}\overline{I_{a2h}} \qquad (2.46)$$

$$\overline{I_{Ah}} = \frac{N_4}{N_1}I_h\angle 0 + \frac{N_2}{N_1}\frac{1}{3}[(I_h\angle -20h - I_h\angle -140h) + (I_h\angle 20h - I_h\angle 140h)] + \frac{N_3}{N_1}(I_h\angle -20h + I_h\angle 20h)$$

(2.47)

As secondary line-line voltage are balanced,

$$\frac{V_{ab}}{V_{AB}} = \frac{V_{a1b1}}{V_{AB}} = \frac{V_{a2b2}}{V_{AB}} = k \qquad (2.48)$$

Where k is transformation ratio of three input nine output phase shifting transformer

From equations 2.48, 2.3, 2.6 and from Figure 2.11, turns ratio can be computed as:

$$\frac{N_4}{N_1} = k \text{, and} \qquad \frac{N_3}{N_1} = 0.347296k, \qquad \frac{N_2}{N_1} = 1.18472k \qquad (2.49)$$

Where δ =20°

Substituting equation 2.49 in equation 2.47,

$$\overline{I_{Ah}} = kI_h\angle 0 + .3949\,k[(I_h\angle -20h - I_h\angle -140h) + (I_h\angle 20h - I_h\angle 140h)] + .34729\,k(I_h\angle -20h + I_h\angle 20h)$$

(2.50)

$$\overline{I_{Ah}} = kI_h\{1\angle 0 + .3949[(1\angle -20h - 1\angle -140h) + (1\angle 20h - 1\angle 140h)] + .34729(1\angle -20h + 1\angle 20h)\}$$

(2.51)

If h=1, for fundamental

$$\overline{I_{A1}} = kI_1\{1\angle 0 + .3949[(1\angle -20 - 1\angle -140) + (1\angle 20 - 1\angle 140)] + .34729\,(1\angle -20 + 1\angle 20)\}$$

$$\overline{I_{Ah}} = 3kI_1\angle 0 \qquad (2.52)$$

If $h = 6k \pm 1$ then from equation 2.51,

$$\overline{I_{Ah}} = kI_h\{1\angle 0 + .3949[(1\angle -20(6k\pm 1) - 1\angle -140(6k\pm 1)) + (1\angle 20(6k\pm 1) - 1\angle 140(6k\pm 1))] + 0.34729(1\angle -20(6k\pm 1) + 1\angle 20(6k\pm 1))\}$$

(2.53)

$\overline{I_{A1}} = 3kI_1\angle 0$ if h=1, for fundamental

$\overline{I_{Ah}} = 3kI_h\angle 0$ if $h = 6k \pm 1$ where k=3,6,9,12…. (2.54)

or $h = 18m \pm 1$ where m=1,2,3,4

$\overline{I_{Ah}} = 0$ if $h = 6k \pm 1$ for all value of k except k=3,6,9,12… (2.55)

Similarly for B and C phase input current

$\overline{I_{B1}} = 3kI_1\angle -120$ if h=1, for fundamental

$\overline{I_{Bh}} = 3kI_h\angle \mp 120$ if $h = 6k \pm 1$ where k=3,6,9,12…. (2.56)

or $h = 18m \pm 1$ where m=1,2,3,4

$\overline{I_{Bh}} = 0$ if $h = 6k \pm 1$ for all value of k except k=3,6,9,12… (2.57)

$\overline{I_{C1}} = 3k * I_1\angle 120$ if h=1, for fundamental

$\overline{I_{Ch}} = 3k * I_h\angle \pm 120$ if $h = 6k \pm 1$ where k=3,6,9,12…. (2.58)

or $h = 18m \pm 1$ where m=1,2,3,4

$\overline{I_{Ch}} = 0$ if $h = 6k \pm 1$ for all value of k except k=3,6,9,12… (2.59)

2.3.2c Discussion for harmonics analysis of three inputs six outputs PST

From equation 2.54, 2.55 and 2.56, 2.57 and 2.58, 2.59, it is observed that the lower order harmonic components which are present in source current are 17th and 19th while 5th, 7th and 11th, 13th harmonic components get eliminated. Hance order of harmonics that are present in line current is $h = 18m \pm 1$ where m=1, 2, 3, 4…

2.3.3(a) Three inputs-twelve outputs phase shifting transformer (PST)

In this configuration primary can be use either star or delta. The phase shifting angle δ of the zigzag-2, star, zigzag-1 and delta-connected secondary windings is -15°, 0°, 15° and 30° in order to connect 4 six pulse rectifier. The main purpose of this section is to investigate the phase displacement of harmonic current when it referred from the secondary to primary side of phase shifting transformers. This phase displacement makes it possible to cancel the more harmonic current compare to previous model which are generated by a three-phase nonlinear load. The symbol and Connection diagram of three inputs-nine outputs phase shifting transformer are shown in Figure 2.13 and 2.14 respectively.

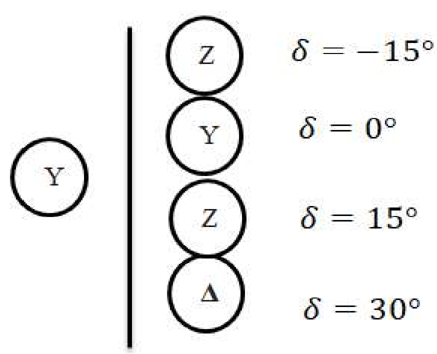

Figure 2.13: Symbol of Three inputs-twelve outputs phase shifting transformer.

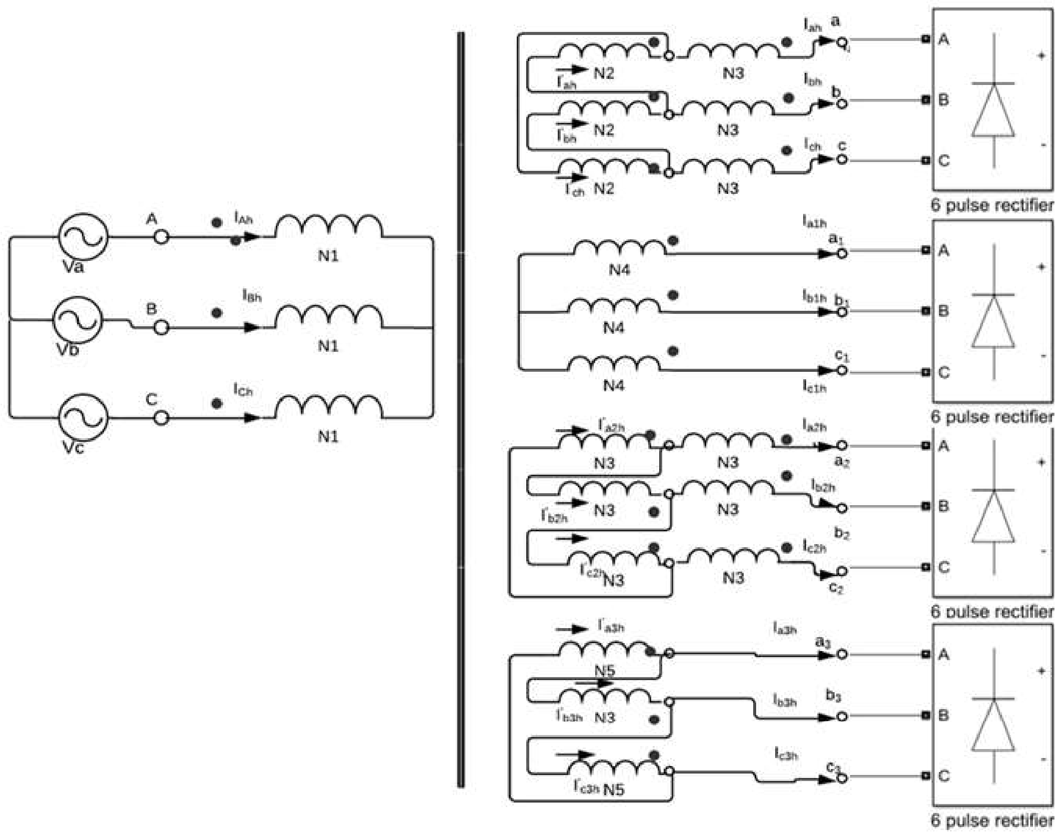

Figure 2.14: Connection diagram for three inputs-twelve outputs phase shifting transformer.

2.3.3(b) Harmonics analysis of three inputs twelve outputs phase shifting transformer.

From the figure 2.14, fundamental and harmonic currents component of line current in secondary side of phase shifting transformer can be written as:

$\overline{I_{a1}} = I_1\angle -15$, $\overrightarrow{I_{b1}} = I_1\angle -135$, $\overrightarrow{I_{c1}} = I_1\angle 105$

$\overrightarrow{I_{a11}} = I_1\angle 0$, $\overrightarrow{I_{b11}} = I_1\angle -120$, $\overrightarrow{I_{c11}} = I_1\angle 120$

$\overrightarrow{I_{a21}} = I_1\angle 15$, $\overrightarrow{I_{b21}} = I_1\angle -105$, $\overrightarrow{I_{c21}} = I_1\angle 135$

$\overrightarrow{I_{a31}} = I_1\angle 30$, $\overrightarrow{I_{b31}} = I_1\angle -90$, $\overrightarrow{I_{c31}} = I_1\angle 150$

Now general line current equations in secondary side can be written as follow:

$\overrightarrow{I_{ah}} = I_h\angle -15h$, $\overline{I_{bh}} = I_h\angle -135h$, $\overline{I_{ch}} = I_h\angle 105h$

$\overline{I_{a1h}} = I_h\angle 0$, $\overline{I_{b1h}} = I_h\angle -120h$, $\overline{I_{c1h}} = I_h\angle 120h$

$\overrightarrow{I_{a2h}} = I_h\angle 15h$, $\overline{I_{b2h}} = I_h\angle -105h$, $\overline{I_{c2h}} = I_h\angle 135h$

$\overrightarrow{I_{a3h}} = I_h\angle 30h$, $\overrightarrow{I_{b3h}} = I_h\angle -90h$, $\overrightarrow{I_{c3h}} = I_h\angle 150h$

From the Figure 2.14 we can write

$$\left.\begin{aligned} \overline{I_{ah}} &= \overline{I_{ah}'} - \overline{I_{ch}'} \\ \overline{I_{bh}} &= \overline{I_{bh}'} - \overline{I_{ah}'} \\ \overline{I_{ch}} &= \overline{I_{ch}'} - \overline{I_{bh}'} \end{aligned}\right\} \qquad (2.60)$$

$$\left.\begin{aligned} \overline{I_{a2h}} &= \overline{I_{a2h}'} - \overline{I_{b2h}'} \\ \overline{I_{b2h}} &= \overline{I_{b2h}'} - \overline{I_{c2h}'} \\ \overline{I_{c2h}} &= \overline{I_{c2h}'} - \overline{I_{a2h}'} \end{aligned}\right\} \qquad (2.61)$$

$$\left.\begin{aligned} \overline{I_{a3h}} &= \overline{I_{a3h}'} - \overline{I_{b3h}'} \\ \overline{I_{b3h}} &= \overline{I_{b3h}'} - \overline{I_{c3h}'} \\ \overline{I_{c3h}} &= \overline{I_{c3h}'} - \overline{I_{a3h}'} \end{aligned}\right\} \qquad (2.62)$$

From the addition of set of equations in (2.60),

$$\overrightarrow{I_{ah}} + \overrightarrow{I_{bh}} + \overrightarrow{I_{ch}} = 0 \qquad (2.63)$$

From the addition of set of equations in (2.61),

$$\overline{I_{a2h}} + \overline{I_{b2h}} + \overline{I_{c2h}} = 0 \qquad (2.64)$$

From the addition of set of equations in (2.61),

$$\overrightarrow{I_{a3h}} + \overrightarrow{I_{b3h}} + \overrightarrow{I_{c3h}} = 0 \tag{2.65}$$

From the Figure 2.14, it can be written

$$\overrightarrow{I_{Ah}} + \overrightarrow{I_{Bh}} + \overrightarrow{I_{Ch}} = 0 \tag{2.66}$$

$$\overrightarrow{I_{a1h}} + \overrightarrow{I_{b1h}} + \overrightarrow{I_{c1h}} = 0 \tag{2.67}$$

For an ideal transformer, permeability of the core (μ) is infinite, magnetizing resistance (R_m) and inductances (Lm) are infinite. From Figure 2.16, mmf equation of transformer can be written as:

$$\overline{I_{Ah}} = \frac{N_2}{N_1}\overline{I_{ah}'} + \frac{N_3}{N_1}\overline{I_{ah}} + \frac{N_4}{N_1}\overline{I_{a1h}} + \frac{N_2}{N_1}\overline{I_{a2h}'} + \frac{N_3}{N_1}\overline{I_{a2h}} + \frac{N_5}{N_1}\overline{I_{a3h}'} \tag{2.68}$$

$$\overline{I_{Bh}} = \frac{N_2}{N_1}\overline{I_{bh}'} + \frac{N_3}{N_1}\overline{I_{bh}} + \frac{N_4}{N_1}\overline{I_{b1h}} + \frac{N_2}{N_1}\overline{I_{b2h}'} + \frac{N_3}{N_1}\overline{I_{b2h}} + \frac{N_5}{N_1}\overline{I_{b3h}'} \tag{2.69}$$

$$\overline{I_{Ch}} = \frac{N_2}{N_1}\overline{I_{ch}'} + \frac{N_3}{N_1}\overline{I_{ch}} + \frac{N_4}{N_1}\overline{I_{c1h}} + \frac{N_2}{N_1}\overline{I_{c2h}'} + \frac{N_3}{N_1}\overline{I_{c2h}} + \frac{N_5}{N_1}\overline{I_{c3h}'} \tag{2.70}$$

On simplifying equations (2.63, - 2.70),

$$\overline{I_{ah}'} + \overline{I_{bh}'} + \overline{I_{ch}'} = 0 \tag{2.71}$$

$$\overline{I_{a2h}'} + \overline{I_{b2h}'} + \overline{I_{c2h}'} = 0 \tag{2.72}$$

$$\overline{I_{a3h}'} + \overline{I_{b3h}'} + \overline{I_{c3h}'} = 0 \tag{2.73}$$

Now from equations (2.60) and equation (2.71),

$$\left.\begin{aligned} \overline{I_{ah}'} &= \frac{1}{3}(\overline{I_{ah}} - \overline{I_{bh}}) \\ \overline{I_{bh}'} &= \frac{1}{3}(\overline{I_{bh}} - \overline{I_{ch}}) \\ \overline{I_{ch}'} &= \frac{1}{3}(\overline{I_{ch}} - \overline{I_{ah}}) \end{aligned}\right\} \tag{2.74}$$

Now from equations (2.61) and equation (2.72),

$$\left.\begin{aligned} \overline{I_{a2h}}' &= \frac{1}{3}(\overline{I_{a2h}} - \overline{I_{c2h}}) \\ \overline{I_{b2h}}' &= \frac{1}{3}(\overline{I_{b2h}} - \overline{I_{a2h}}) \\ \overline{I_{c2h}}' &= \frac{1}{3}(\overline{I_{c2h}} - \overline{I_{b2h}}) \end{aligned}\right\} \tag{2.75}$$

Now from equations (2.62) and equation (2.73),

$$\left.\begin{aligned} \overline{I_{a3h}}' &= \frac{1}{3}(\overline{I_{a3h}} - \overline{I_{c3h}}) \\ \overline{I_{b3h}}' &= \frac{1}{3}(\overline{I_{b3h}} - \overline{I_{a3h}}) \\ \overline{I_{c3h}}' &= \frac{1}{3}(\overline{I_{c3h}} - \overline{I_{b3h}}) \end{aligned}\right\} \tag{2.76}$$

Substituting equations (2.74, - 2.76) in equation 2.68,

$$\overline{I_{Ah}} = \frac{N_2}{N_1}\frac{1}{3}\left(\overline{I_{ah}} - \overline{I_{bh}}\right) + \frac{N_3}{N_1}\overline{I_{ah}} + \frac{N_4}{N_1}\overline{I_{a1h}} + \frac{N_2}{N_1}\frac{1}{3}\left(\overline{I_{a2h}} - \overline{I_{c2h}}\right) + \frac{N_3}{N_1}\overline{I_{a2h}} + \frac{N_5}{N_1}\frac{1}{3}\left(\overline{I_{a3h}} - \overline{I_{c3h}}\right) \tag{2.77}$$

$$\overline{I_{Ah}} = \frac{N_2}{N_1}\frac{1}{3}[(I_h\angle -15h - I_h\angle -135h) + (I_h\angle 15h - I_h\angle 135h)] + \frac{N_3}{N_1}(I_h\angle -15h + I_h\angle 15h) + \frac{N_4}{N_1}I_h\angle 0 + \frac{N_5}{N_1}\frac{1}{3}(I_h\angle 30h - I_h\angle 150h) \tag{2.78}$$

As secondary line-line voltage are balanced,

$$\frac{V_{ab}}{V_{AB}} = \frac{V_{a1b1}}{V_{AB}} = \frac{V_{a2b2}}{V_{AB}} = \frac{V_{a3b3}}{V_{AB}} = k \tag{2.79}$$

Where k is transformation ratio of three input twelve output phase shifting transformer:

From equations 2.79, 2.3, 2.6 and from Figure 2.13, turns ratio can be computed as:

$$\frac{N_4}{N_1} = k \text{, and } \frac{N_5}{N_1} = \sqrt{3}k \quad \frac{N_3}{N_1} = 0.517638k \text{ ,} \quad \frac{N_2}{N_1} = 0.896575k \tag{2.80}$$

Where δ =15°,

Substituting equation 2.80 in equation 2.78,

$$\overline{I_{Ah}} = .298858k[(I_h\angle -15h - I_h\angle -135h) + (I_h\angle 15h - I_h\angle 135h)] + .517638k(I_h\angle -15h + I_h\angle 15h)$$
$$+ kI_h\angle 0 + \frac{k}{\sqrt{3}}(I_h\angle 30h - I_h\angle 150h)$$

(2.81)

$$\overline{I_{Ah}} = kI_h\{.298858[(1\angle -15h - 1\angle -135h) + (1\angle 15h - 1\angle 135h)] + .517638(1\angle -15h + 1\angle 15h)$$
$$+ 1\angle 0 + \frac{1}{\sqrt{3}}(1\angle 30h - 1\angle 150h)\}$$

. (2.82)

If h=1, for fundamental

$$\overline{I_{A1}} = kI_1\{.298858[(1\angle -15 - 1\angle -135) + (1\angle 15 - 1\angle 135)] + .517638(1\angle -15 + 1\angle 15)$$
$$+ 1\angle 0 + \frac{1}{\sqrt{3}}(1\angle 30 - 1\angle 150)\}$$

$$\overline{I_{A1}} = 4kI_1\angle 0 \quad (2.83)$$

If $h = 6k \pm 1$ then from equation 2.82,

$$\overline{I_{Ah}} = kI_h\{.298858[(1\angle -15(6k \pm 1) - 1\angle -135(6k \pm 1)) + (1\angle 15(6k \pm 1) - 1\angle 135(6k \pm 1))]$$
$$+ 0.517638(1\angle -15(6k \pm 1) + 1\angle 15(6k \pm 1)) + 1\angle 0 + \frac{1}{\sqrt{3}}(1\angle 30(6k \pm 1) - 1\angle 150(6k \pm 1))\}$$

(2.84)

$\overline{I_{A1}} = 4kI_1\angle 0$ if h=1, for fundamental

$\overline{I_{Ah}} = 4kI_h\angle 0$ if $h = 6k \pm 1$ where k=4,8,12,16…. (2.85)

or $h = 24m \pm 1$ where m=1,2,3,4

$\overline{I_{Ah}} = 0$ if $h = 6k \pm 1$ for all value of k except k=4,8,12,16…. (2.86)

Similarly for B and C phase input current

$\overline{I_{B1}} = 4kI_1\angle -120$ if h=1, for fundamental

$\overline{I_{Bh}} = 4kI_h\angle\mp 120$ if $h = 6k \pm 1$ where k=4,8,12,16…. (2.87)

or $h = 24m \pm 1$ where m=1,2,3,4

$\overline{I_{Bh}} = 0$ if $h = 6k \pm 1$ for all value of k except k=4,8,12,16…. (2.88)

$\overline{I_{C1}} = 4kI_1\angle 120$ if h=1, for fundamental

$\overline{I_{Ch}} = 4kI_h\angle\pm 120$ if $h = 6k \pm 1$ where k=4,8,12,16…. (2.89)

or $h = 24m \pm 1$ where m=1,2,3,4

$\overline{I_{Ch}} = 0$ if $h = 6k \pm 1$ for all value of k except k=4,8,12,16…. (2.90)

2.2.3c Discussion for harmonics analysis of three inputs twelve output PST

From equation (2.86, - 2.90), it is observed that the lower order harmonic components which are present in source current are 23th and 25th while other lower order harmonic components 5th, 7th and 11th, 13th and 17th, 19th get eliminated. Hence order of harmonics that are present in line current is $h = 24m \pm 1$ where m=1,2,3,4…

2.3.4a Three input-fifteen output phase shifting transformer (PST)

In this configuration primary can be use either star or delta. The phase shifting angle δ of the zigzag-2, zigzag-2,star, zigzag-1 and zigzag-1-connected secondary windings is -24°, -12°, 0°, 12° and 24° in order to connect 5 six pulse rectifier. The main purpose of this section is to investigate the phase displacement of harmonic current when it referred from the secondary to primary side of phase shifting transformers. This phase displacement makes it possible to cancel the more harmonic current compare to all previous models which are generated by a three-phase nonlinear load. The symbol and Connection diagram of three inputs-nine outputs phase shifting transformer are shown in Figure 2.15 and 2.16 respectively.

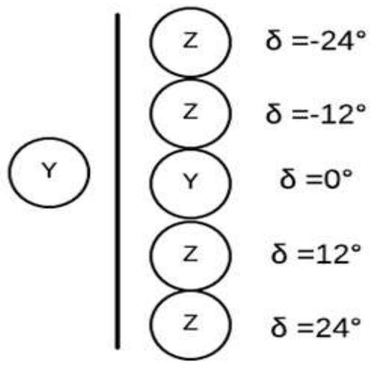

Figure 2.15: Symbol of three input-twelve output phase shifting transformer.

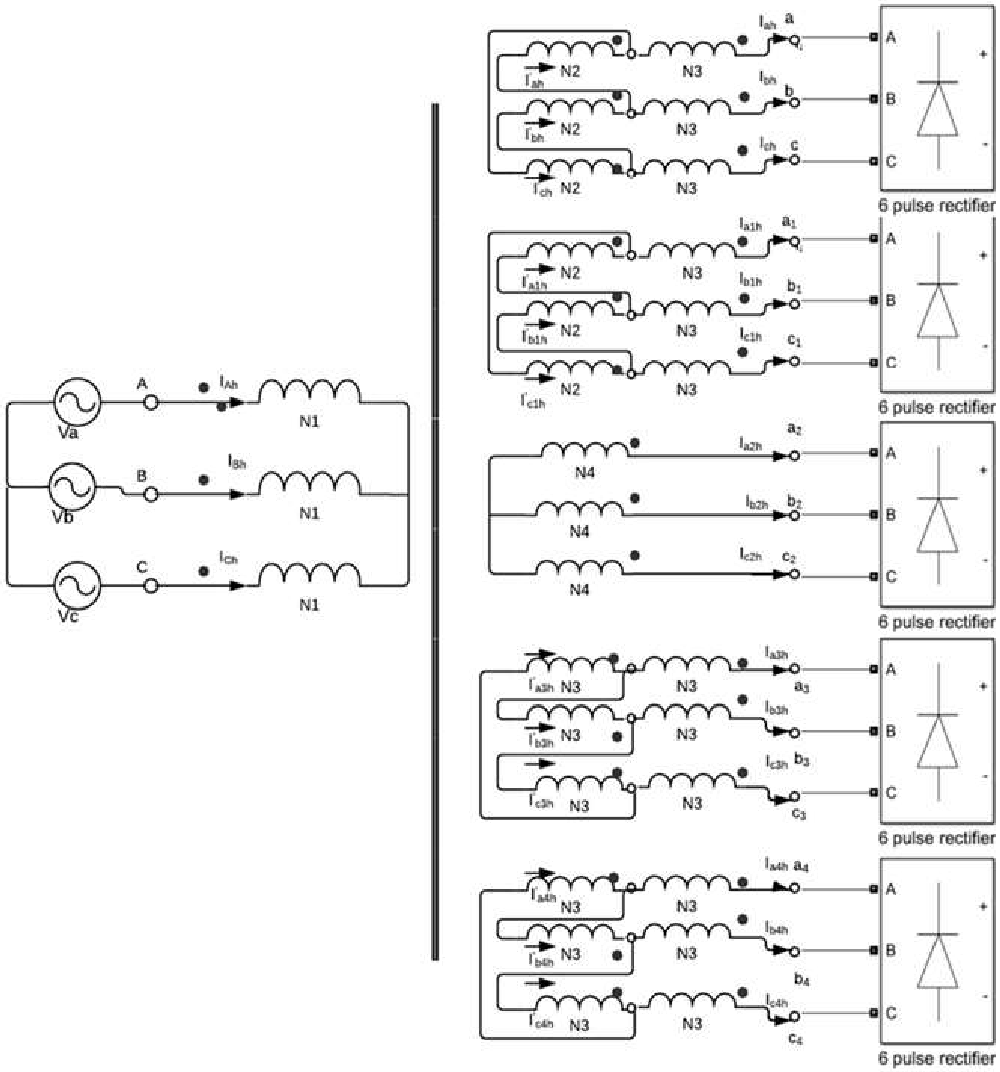

Figure 2.16: Connection diagram for three input-fifteen output phase shifting transformer.

2.3.4b Harmonics analysis of three input six output phase shifting transformer

From the figure 2.16, fundamental and harmonic currents component of line current in secondary side of phase shifting transformer can be written as:

$$\overline{I_{a1}} = I_1\angle -24 \;,\quad \overrightarrow{I_{b1}} = I_1\angle -144 \;,\quad \overrightarrow{I_{c1}} = I_1\angle 96$$

$$\overrightarrow{I_{a11}} = I_1\angle -12 \;,\quad \overrightarrow{I_{b11}} = I_1\angle -132 \;,\quad \overrightarrow{I_{c11}} = I_1\angle 108$$

$$\overrightarrow{I_{a21}} = I_1\angle 0 \;,\quad \overrightarrow{I_{b21}} = I_1\angle -120 \;,\quad \overrightarrow{I_{c21}} = I_1\angle 120$$

$$\overrightarrow{I_{a31}} = I_1\angle 12 \;,\quad \overrightarrow{I_{b31}} = I_1\angle -108 \;,\quad \overrightarrow{I_{c31}} = I_1\angle 132$$

$$\overline{I_{a41}} = I_1\angle 24 \;,\quad \overrightarrow{I_{b41}} = I_1\angle -96 \;,\quad \overrightarrow{I_{c41}} = I_1\angle 144$$

Now general line current equations in secondary side can be written as follow:

$$\overline{I_{ah}} = I_h\angle -24h \;,\quad \overline{I_{bh}} = I_h\angle -144h \;,\quad \overline{I_{ch}} = I_h\angle 96h$$

$$\overline{I_{a1h}} = I_h\angle -12 \;,\quad \overline{I_{b1h}} = I_h\angle -132h \;,\quad \overline{I_{c1h}} = I_h\angle 108h$$

$$\overline{I_{a2h}} = I_h\angle 0 \;,\quad \overline{I_{b2h}} = I_h\angle -120h \;,\quad \overline{I_{c2h}} = I_h\angle 120h$$

$$\overline{I_{a3h}} = I_h\angle 12h \;,\quad \overline{I_{b3h}} = I_h\angle -108h \;,\quad \overline{I_{c3h}} = I_h\angle 132h$$

$$\overline{I_{a4h}} = I_h\angle 24h \;,\quad \overline{I_{b4h}} = I_h\angle -96h \;,\quad \overline{I_{c4h}} = I_h\angle 144h$$

From the figure 2.16,

$$\left.\begin{aligned} \overline{I_{ah}} &= \overline{I_{ah}'} - \overline{I_{ch}'} \\ \overline{I_{bh}} &= \overline{I_{bh}'} - \overline{I_{ah}'} \\ \overline{I_{ch}} &= \overline{I_{ch}'} - \overline{I_{bh}'} \end{aligned}\right\} \qquad (2.91)$$

$$\left.\begin{aligned} \overline{I_{a1h}} &= \overline{I_{a1h}^{'}} - \overline{I_{c1h}^{'}} \\ \overline{I_{b1h}} &= \overline{I_{b1h}^{'}} - \overline{I_{a1h}^{'}} \\ \overline{I_{c1h}} &= \overline{I_{c1h}^{'}} - \overline{I_{b1h}^{'}} \end{aligned}\right\} \quad (2.92)$$

$$\left.\begin{aligned} \overline{I_{a3h}} &= \overline{I_{a3h}^{'}} - \overline{I_{b3h}^{'}} \\ \overline{I_{b3h}} &= \overline{I_{b3h}^{'}} - \overline{I_{c3h}^{'}} \\ \overline{I_{c3h}} &= \overline{I_{c3h}^{'}} - \overline{I_{a3h}^{'}} \end{aligned}\right\} \quad (2.93)$$

$$\left.\begin{aligned} \overline{I_{a4h}} &= \overline{I_{a4h}^{'}} - \overline{I_{b4h}^{'}} \\ \overline{I_{b4h}} &= \overline{I_{b4h}^{'}} - \overline{I_{c4h}^{'}} \\ \overline{I_{c4h}} &= \overline{I_{c4h}^{'}} - \overline{I_{a4h}^{'}} \end{aligned}\right\} \quad (2.94)$$

From the addition of set of equations in (2.91),

$$\overrightarrow{I_{ah}} + \overrightarrow{I_{bh}} + \overrightarrow{I_{ch}} = 0 \quad (2.95)$$

From the addition of set of equations in (2.92),

$$\overline{I_{a1h}} + \overline{I_{b1h}} + \overline{I_{c1h}} = 0 \quad (2.96)$$

From the addition of set of equations in (2.93),

$$\overrightarrow{I_{a3h}} + \overrightarrow{I_{b3h}} + \overrightarrow{I_{c3h}} = 0 \quad (2.97)$$

From the addition of set of equations in (2.94),

$$\overline{I_{a4h}} + \overline{I_{b4h}} + \overline{I_{c4h}} = 0 \quad (2.98)$$

From the Figure 2.16 it can be written

$$\overrightarrow{I_{Ah}} + \overrightarrow{I_{Bh}} + \overrightarrow{I_{Ch}} = 0 \quad (2.99)$$

$$\overrightarrow{I_{a2h}} + \overrightarrow{I_{b2h}} + \overrightarrow{I_{c2h}} = 0 \quad (2.100)$$

For an ideal transformer, permeability of the core (μ) is infinite, magnetizing resistance (R_m) and inductances (Lm) are infinite. From figure 2.16, mmf equation of transformer can be written as:

$$\overline{I_{Ah}} = \frac{N_2}{N_1}\overline{I_{ah}^{'}} + \frac{N_3}{N_1}\overline{I_{ah}} + \frac{N_2}{N_1}\overline{I_{a1h}^{'}} + \frac{N_3}{N_1}\overline{I_{a1h}} + \frac{N_4}{N_1}\overline{I_{a2h}} + \frac{N_2}{N_1}\overline{I_{a3h}^{'}} + \frac{N_3}{N_1}\overline{I_{a3h}} + \frac{N_2}{N_1}\overline{I_{a4h}^{'}} + \frac{N_3}{N_1}\overline{I_{a4h}} \tag{2.101}$$

$$\overline{I_{Bh}} = \frac{N_2}{N_1}\overline{I_{bh}^{'}} + \frac{N_3}{N_1}\overline{I_{bh}} + \frac{N_2}{N_1}\overline{I_{b1h}^{'}} + \frac{N_3}{N_1}\overline{I_{b1h}} + \frac{N_4}{N_1}\overline{I_{b2h}} + \frac{N_2}{N_1}\overline{I_{b3h}^{'}} + \frac{N_3}{N_1}\overline{I_{b3h}} + \frac{N_2}{N_1}\overline{I_{b4h}^{'}} + \frac{N_3}{N_1}\overline{I_{b4h}} \tag{2.102}$$

$$\overline{I_{Ch}} = \frac{N_2}{N_1}\overline{I_{ch}^{'}} + \frac{N_3}{N_1}\overline{I_{ch}} + \frac{N_2}{N_1}\overline{I_{c1h}^{'}} + \frac{N_3}{N_1}\overline{I_{c1h}} + \frac{N_4}{N_1}\overline{I_{c2h}} + \frac{N_2}{N_1}\overline{I_{c3h}^{'}} + \frac{N_3}{N_1}\overline{I_{c3h}} + \frac{N_2}{N_1}\overline{I_{c4h}^{'}} + \frac{N_3}{N_1}\overline{I_{c4h}} \tag{2.103}$$

On simplifying equations (2.95 - 2.103),

$$\overline{I_{ah}^{'}} + \overline{I_{bh}^{'}} + \overline{I_{ch}^{'}} = 0 \tag{2.104}$$

$$\overline{I_{a1h}^{'}} + \overline{I_{b1h}^{'}} + \overline{I_{c1h}^{'}} = 0 \tag{2.105}$$

$$\overline{I_{a3h}^{'}} + \overline{I_{b3h}^{'}} + \overline{I_{c3h}^{'}} = 0 \tag{2.106}$$

$$\overline{I_{a4h}^{'}} + \overline{I_{b4h}^{'}} + \overline{I_{c4h}^{'}} = 0 \tag{2.107}$$

Now from equations (2.91) and equation (2.104) ,

$$\left.\begin{aligned} \overline{I_{ah}^{'}} &= \frac{1}{3}(\overline{I_{ah}} - \overline{I_{bh}}) \\ \overline{I_{bh}^{'}} &= \frac{1}{3}(\overline{I_{bh}} - \overline{I_{ch}}) \\ \overline{I_{ch}^{'}} &= \frac{1}{3}(\overline{I_{ch}} - \overline{I_{ah}}) \end{aligned}\right\} \tag{2.108}$$

Now from equations (2.92) and equation (2.105),

$$\left.\begin{aligned}\overline{I_{a1h}'} &= \frac{1}{3}(\overline{I_{a1h}} - \overline{I_{c1h}}) \\ \overline{I_{b1h}'} &= \frac{1}{3}(\overline{I_{b1h}} - \overline{I_{a1h}}) \\ \overline{I_{c1h}'} &= \frac{1}{3}(\overline{I_{c1h}} - \overline{I_{b1h}})\end{aligned}\right\} \qquad (2.109)$$

Now from equations (2.93) and equation (2.106),

$$\left.\begin{aligned}\overline{I_{a3h}'} &= \frac{1}{3}(\overline{I_{a3h}} - \overline{I_{c3h}}) \\ \overline{I_{b3h}'} &= \frac{1}{3}(\overline{I_{b3h}} - \overline{I_{a3h}}) \\ \overline{I_{c3h}'} &= \frac{1}{3}(\overline{I_{c3h}} - \overline{I_{b3h}})\end{aligned}\right\} \qquad (2.110)$$

Now from equations (2.94) and equation (2.107),

$$\left.\begin{aligned}\overline{I_{a4h}'} &= \frac{1}{3}(\overline{I_{a4h}} - \overline{I_{c4h}}) \\ \overline{I_{b4h}'} &= \frac{1}{3}(\overline{I_{b4h}} - \overline{I_{a4h}}) \\ \overline{I_{c4h}'} &= \frac{1}{3}(\overline{I_{c4h}} - \overline{I_{b4h}})\end{aligned}\right\} \qquad (2.111)$$

Substituting equations (2.95 - 2.98) in equation 2.88,

$$\overline{I_{Ah}} = \frac{N_2}{N_1}\frac{1}{3}(\overline{I_{ah}} - \overline{I_{bh}}) + \frac{N_3}{N_1}\overline{I_{ah}} + \frac{N_2}{N_1}\frac{1}{3}(\overline{I_{a1h}} - \overline{I_{b1h}}) + \frac{N_3}{N_1}\overline{I_{a1h}} + \frac{N_4}{N_1}\overline{I_{a2h}} + \frac{N_2}{N_1}\frac{1}{3}(\overline{I_{a3h}} - \overline{I_{c3h}})$$
$$+ \frac{N_3}{N_1}\overline{I_{a3h}} + \frac{N_2}{N_1}\frac{1}{3}(\overline{I_{a4h}} - \overline{I_{c4h}}) + \frac{N_3}{N_1}\overline{I_{a4h}}$$

(2.112)

$$\overline{I_{Ah}} = \frac{N_2}{N_1}\frac{1}{3}[I_h\angle -24h - I_h\angle -144h + (I_h\angle -12h - I_h\angle -132h + I_h\angle 12h - I_h\angle 132h$$

$$+ I_h\angle 24h - I_h\angle 144h] + \frac{N_3}{N_1}[I_h\angle -24h + I_h\angle -12h + I_h\angle 12h + I_h\angle 24h] + \frac{N_4}{N_1} I_h\angle 0$$

(2.113)

As secondary line-line voltage are balanced,

$$\frac{V_{ab}}{V_{AB}} = \frac{V_{a1b1}}{V_{AB}} = \frac{V_{a2b2}}{V_{AB}} = \frac{V_{a3b3}}{V_{AB}} = \frac{V_{a4b4}}{V_{AB}} = k \tag{2.114}$$

Where k is transformation ratio of the phase shifting transformer:

From equations 2.114, 2.3, 2.6 and from Figure 2.16, turns ratio is computed computed as:

$\frac{N_4}{N_1} = k$, and $\frac{N_3}{N_1} = 0.618k$, $\frac{N_2}{N_1} = 0.72022k$ (2.115)

Where δ =12°

Substituting equation 2.115 in equation 2.113,

$$\overline{I_{Ah}} = kI_h\{0.24[1\angle -24h - 1\angle -144h + 1\angle -12h - 1\angle -132h + 1\angle 12h - 1\angle 132h + 1\angle 24h - 1\angle 144h]$$

$$+ 0.618[1\angle -24h + 1\angle -12h + 1\angle 12h + 1\angle 24h] + 1\angle 0\}$$

(2.116)

If h=1, for fundamental

$$\overline{I_{A1}} = kI_1\{0.24[1\angle -24 - 1\angle -144 + 1\angle -12 - 1\angle -132 + 1\angle 12 - 1\angle 132 + 1\angle 24 - 1\angle 144]$$

$$+ 0.618[1\angle -24 + 1\angle -12 + 1\angle 12 + 1\angle 24] + 1\angle 0\}$$

$$\overline{I_{A1}} = 5kI_1\angle 0 \tag{2.117}$$

If $h = 6k \pm 1$ then from equation 2.116,

$$\overline{I_{Ah}} = kI_h\{0.24[1\angle-24(6k\pm1)-1\angle-144(6k\pm1)+1\angle-12(6k\pm1)-1\angle-132(6k\pm1)$$
$$+1\angle12(6k\pm1)-1\angle132(6k\pm1)+1\angle24(6k\pm1)-1\angle144(6k\pm1)]+0.618[1\angle-24(6k\pm1)$$
$$+1\angle-12(6k\pm1)+1\angle12(6k\pm1)+1\angle24(6k\pm1)]+1\angle0\}$$

(2.118)

$\overline{I_{A1}} = 5kI_1\angle 0$ if h=1, for fundamental

$\overline{I_{Ah}} = 5kI_h\angle 0$ if $h = 6k \pm 1$ where k=5,10,15,20…. (2.119)

or $h = 30m \pm 1$ where m=1,2,3,4

$\overline{I_{Ah}} = 0$ if $h = 6k \pm 1$ for all value of k except k=5,10,15,20…. (2.120)

Similarly for B and C phase input current

$\overline{I_{B1}} = 5kI_1\angle -120$ if h=1, for fundamental

$\overline{I_{Bh}} = 5kI_h\angle \mp 120$ if $h = 6k \pm 1$ where k=5,10,15,20…. (2.121)

or $h = 30m \pm 1$ where m=1,2,3,4

$\overline{I_{Bh}} = 0$ if $h = 6k \pm 1$ for all value of k except k=5,10,15,20 (2.122)

$\overline{I_{C1}} = 5kI_1\angle 120$ if h=1, for fundamental

$\overline{I_{Ch}} = 5kI_h\angle \pm 120$ if $h = 6k \pm 1$ where k=5,10,15,20…. (2.123)

or $h = 30m \pm 1$ where m=1,2,3,4

$\overline{I_{Ch}} = 0$ if $h = 6k \pm 1$ for all value of k except k=5,10,15,20… (2.124)

2.3.4(c) Discussion for Harmonics analysis of three inputs fifteen output PST

From equation (2.119 - 2.124), it is observed that the lower order harmonic components which are present in source current are 29th and 31th while other lower order harmonic components 5th, 7th and 11th, 13th and 17th, 19th and 23th, 25th are eliminated. Hence order of harmonics that are present in line current is $h = 30m \pm 1$ where m=1, 2, 3, 4…

Hence it is proved that by increasing the number of windings in secondary side of phase shifting transformer, harmonic content in the current can be reduced. But the design complexity increases with the increase in the number of windings of secondary in PST.

CHAPTER 3

MODELLING AND SIMULATION OF MULTI DIFFERENT OUTPUT PHASE SHIFTING TRANSFORMER

3.1 Introduction

The modelling of multi output phase shifting transformer uses three single phase multi winding transformers. The primary winding can be connected either star or delta and secondary can be connected in star, delta, and zig-zag (extended delta). The selection of number of secondary windings is based on requirements. In this part the output of each star, delta and extended delta winding are supplying power to each rectifier block separately. The expanded view of rectifier block is shown in figure 3.1.

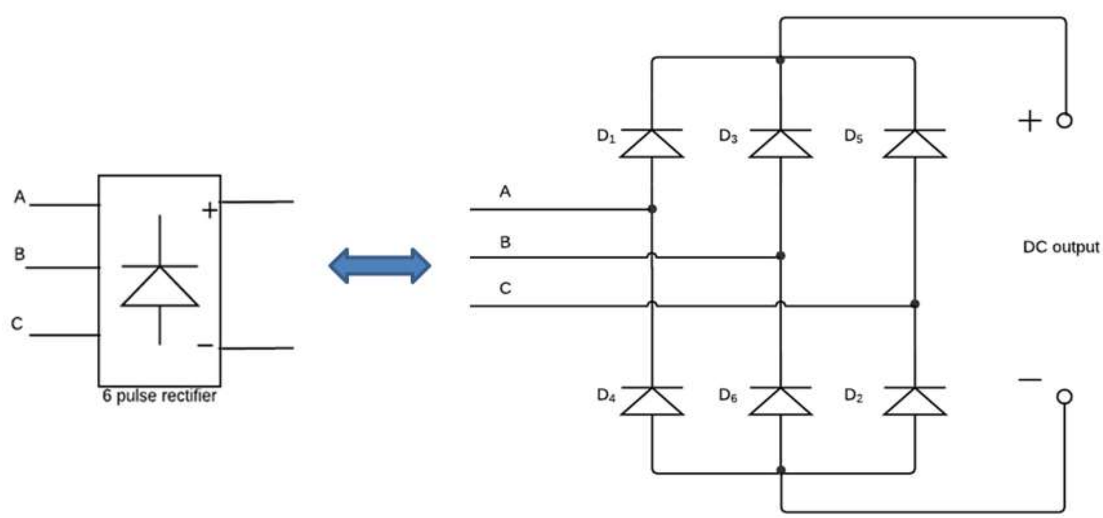

Figure 3.1 Expanded view of single module in six pulse rectifier.

3.2 Turns ratio calculations for different phase shifting transformer

Turns ratio of the phase shifting transformer is calculated based on the flow chart in Figure 3.2. If turns ratio is fractional value, then it is approximated to nearest integer. This approximation leads to small change in effective phase shifting angle. This change is minimized by increasing the turns ratio.

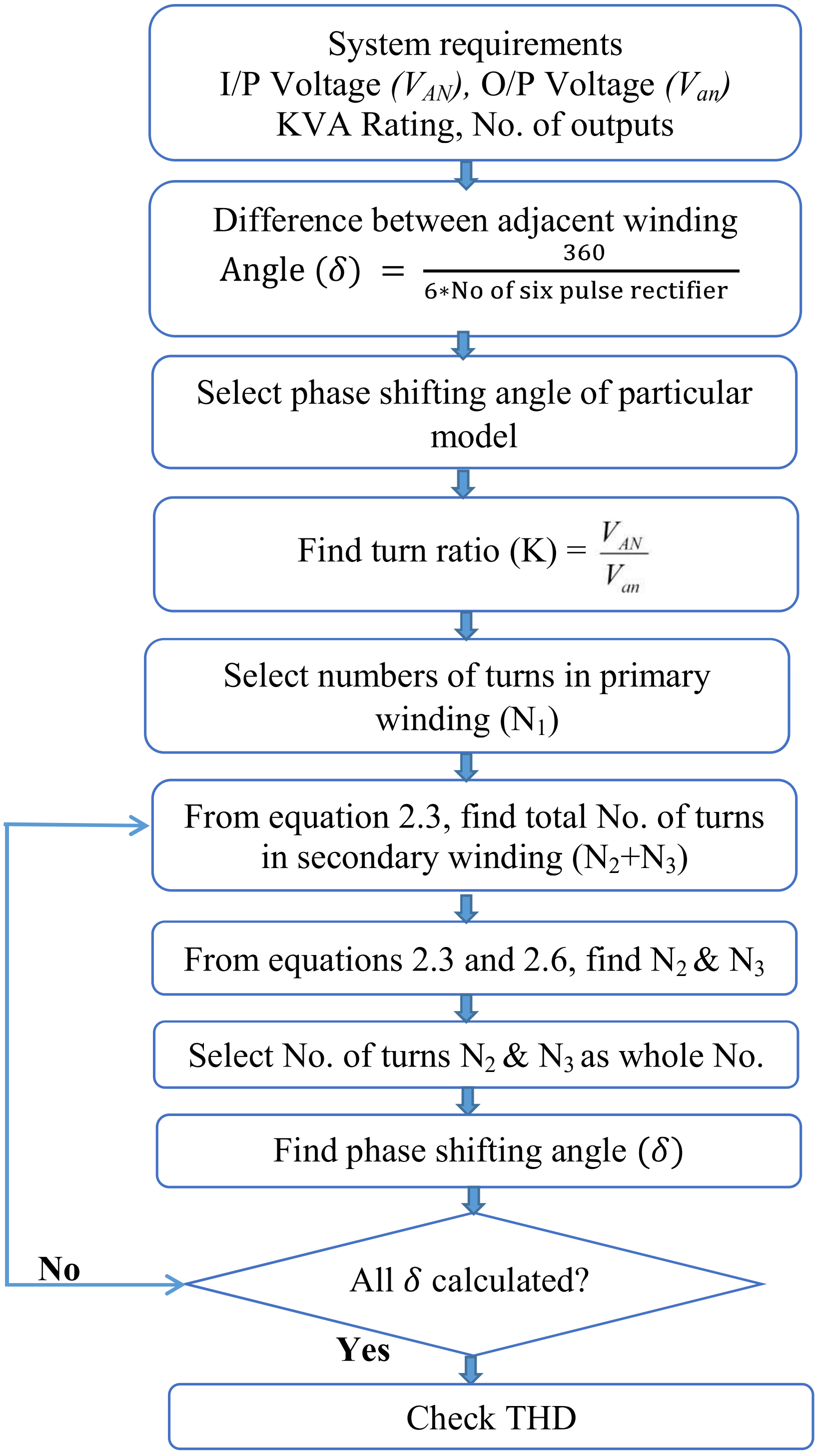

Figure 3.2: Flowchart for winding turns ratio calculation.

3.3 Modelling and simulation of three input-six output phase shifting transformer (PST)

For this design, transformer is modelled using three primary windings and six secondary windings. This transformer has the connection **Yy0d11** with phase shift 0° and -30°. Two six pulse rectifiers are connected to the star and delta connected secondary windings with a phase shift of 0° and -30° with respect to primary respectively. The corresponding circuit diagram is represented in Figure 3.2.

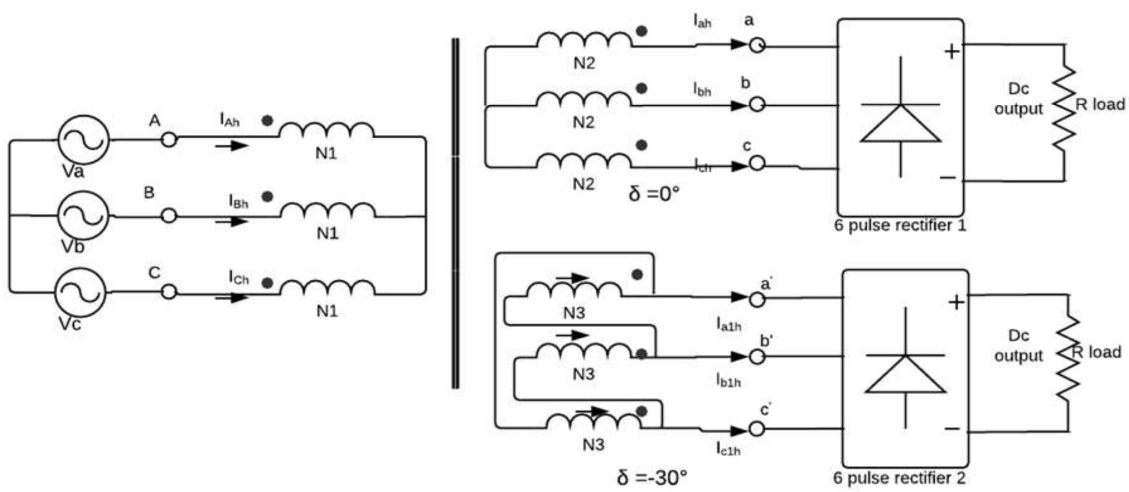

Figure 3.3: Circuit diagram of three inputs-six outputs phase shifting transformer.

3.3.1 Simulation results of three inputs-six outputs PST

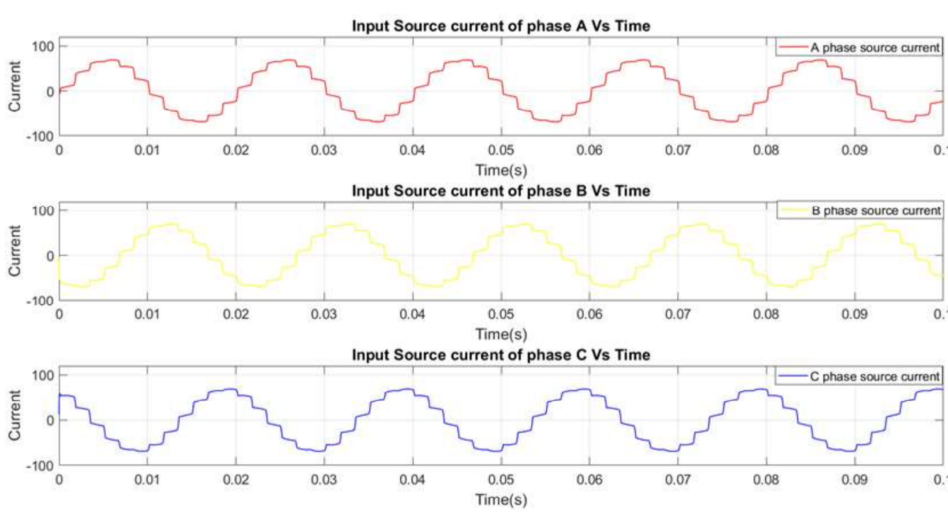

Figure 3.4: Input current waveforms of three input-six output PST.

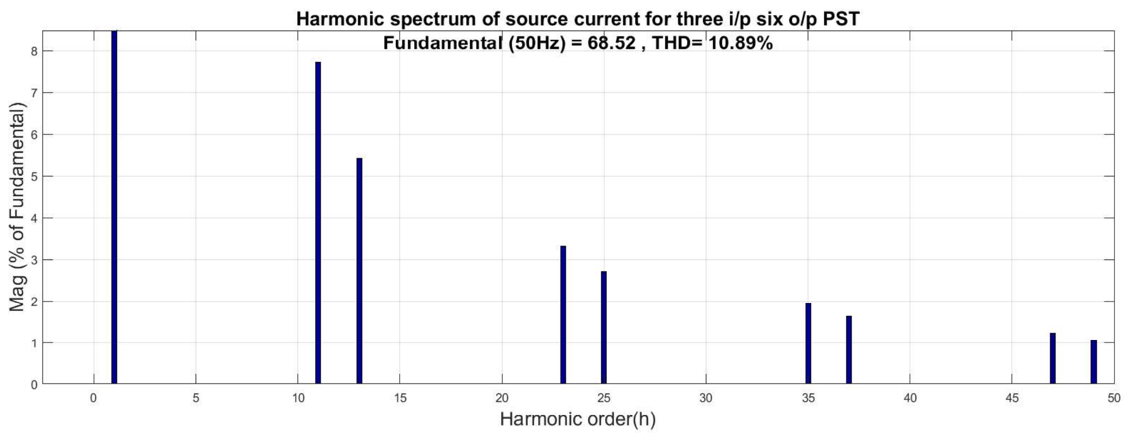

Figure 3.5: Harmonic spectrum of input current for three input-six output PST.

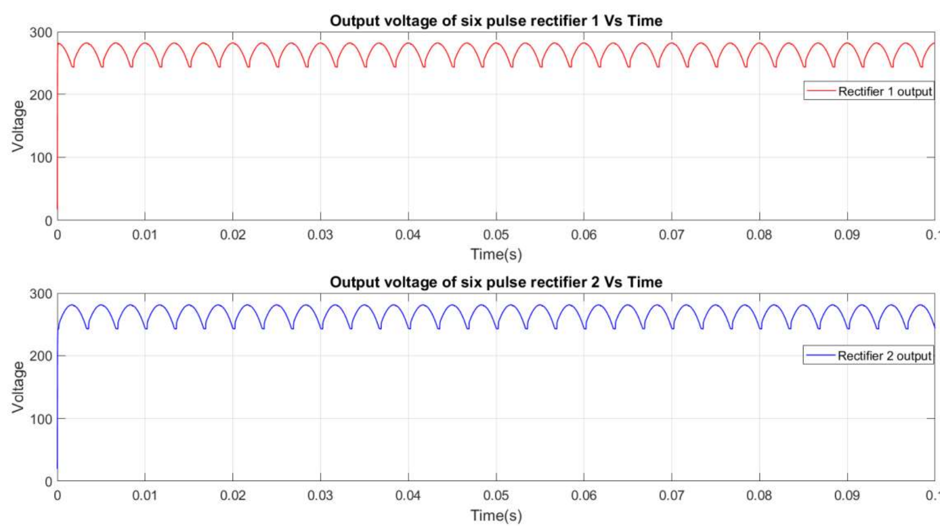

Figure 3.6: Rectifier output voltage waveforms for three input-six output PST.

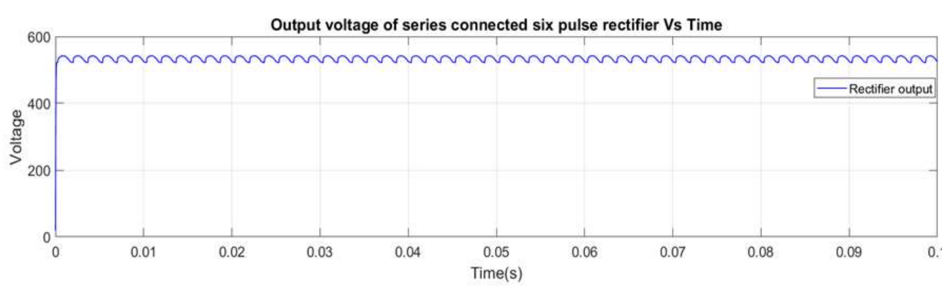

Figure 3.7: Output voltage of series connected rectifiers for three input-six output PST.

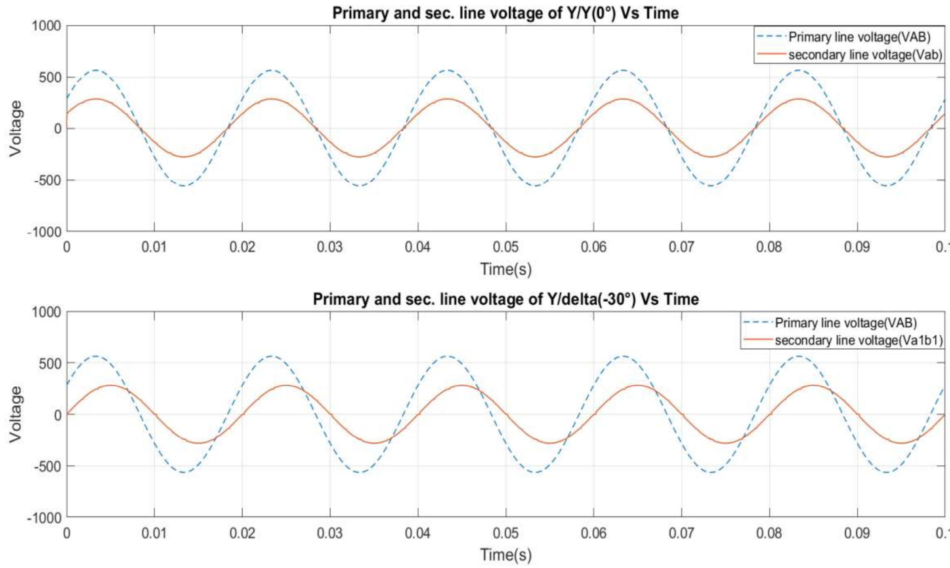

Figure 3.8: Primary and secondary voltages of three input-six output PST at k (transformation ratio) = 0.5.

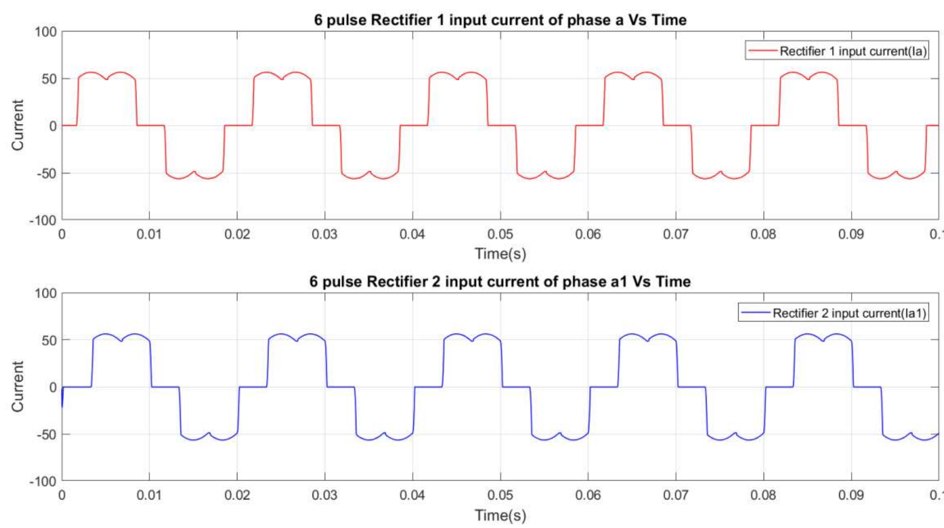

Figure 3.9: Rectifier input current waveforms for three input-six output PST.

3.3.2 Discussion for simulation results of three input six output PST

Figure 3.4 shows the input current waveforms of three inputs-six outputs PST. From these waveforms it is observed that the input current is improved compared to input current waveforms in the conventional rectifier. Figure 3.5 shows the harmonics spectrum of input current/source current. From this harmonic spectrum, it is observed that lower order harmonic components which are present in source current are 11th and 13th while 5th and 7th harmonic components are eliminated. The THD of source currents is 10.89 %, which is less compared to THD in Input current of the conventional rectifier. But this THD value is not within IEEE Standard 519 limit. As IEEE Standard 519, THD of general system below 69kv should be less than 5%. These results indicate the need to improve PQ in ADCs, which can replace the existing three input six output model. From Figure 3.5, it is observed that the harmonic order for this model is $12k \pm 1$ which is verified with mathematical result of this model. Form this model it is observed that input power factor is improved and power factor for purely resistive load is 0.9809.

Figure 3.6 shows the rectifier output voltage waveforms. In this waveform it is observed that output waveforms have six pulses in each cycle because both rectifiers are not connected in series. Figure 3.7 shows the output voltage of series connected rectifiers. In this figure it is observed that rectifier output voltage/load voltage waveform consist 12 pulses per cycle of supply voltage. Ripple in output voltage is reduced. Ripple content in output DC voltage is 1.349%.

Figure 3.8 shows the primary and secondary voltage waveforms of three inputs-six outputs PST. In this figure it is observed that secondary voltages have same magnitude with 30° phase shift. Figure 3.9 shows the rectifier input current waveforms.

3.4 Modelling and simulation of three input-nine output phase shifting transformer (PST)

For this design, transformer is modelled using three primary windings and fifteen secondary windings. This transformer has the connection **Yz-2y0z-1** with phase shift -20°, 0°and 20°. Three six pulse rectifiers are connected to the star and zig-zag connected secondary windings with a phase shift of -20°, 0°and 20° with respect to primary respectively. The corresponding circuit diagram is represented in figure 3.10.

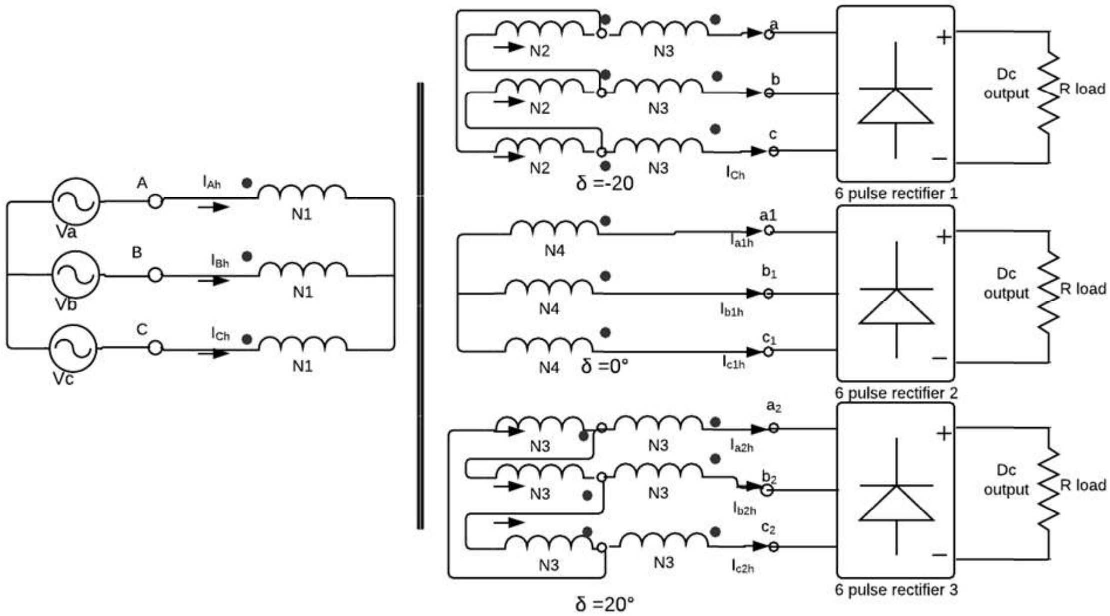

Figure 3.10: Circuit diagram of three input-nine output phase shifting transformer.

3.4.1 Simulation results of three input-nine output PST

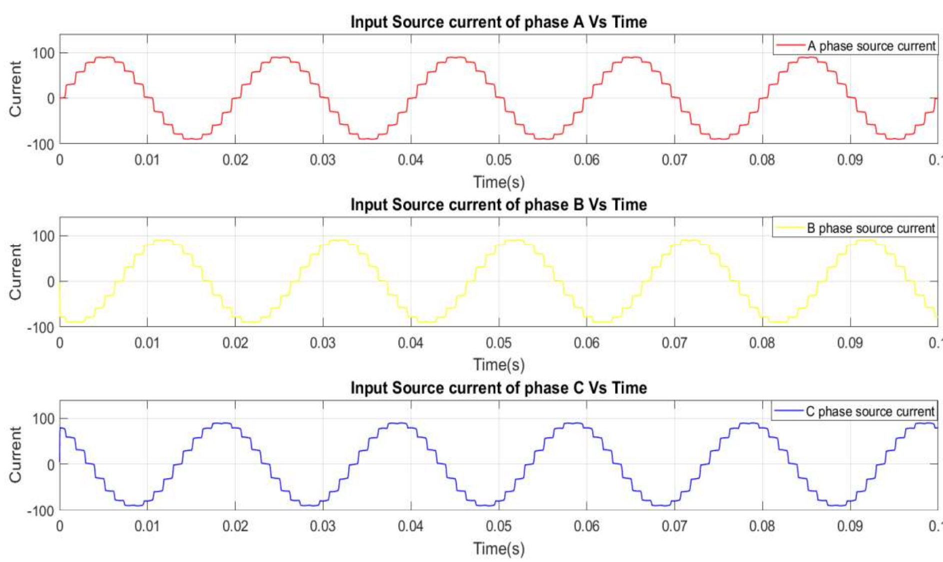

Figure 3.11: Source current waveforms for three input-nine output PST.

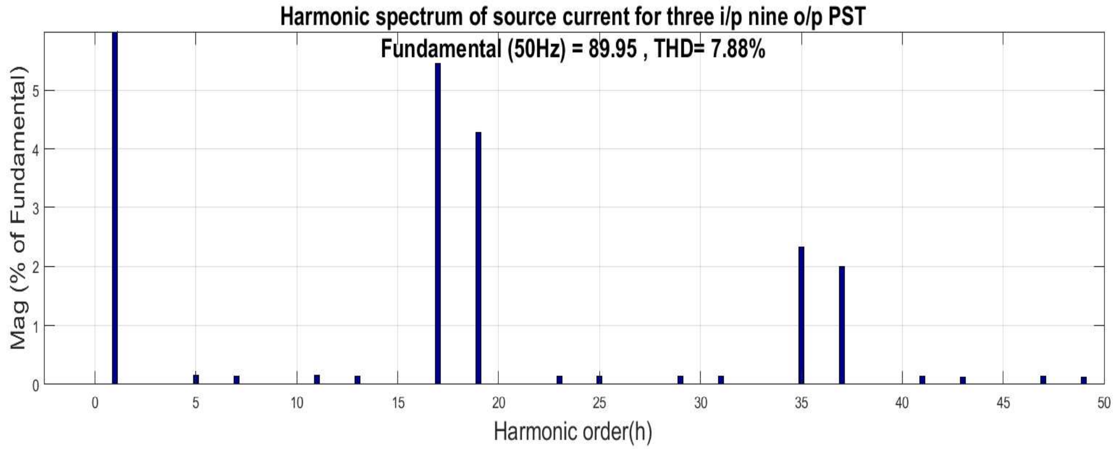

Figure 3.12: Harmonic spectrum of Source current for three input-nine output PST.

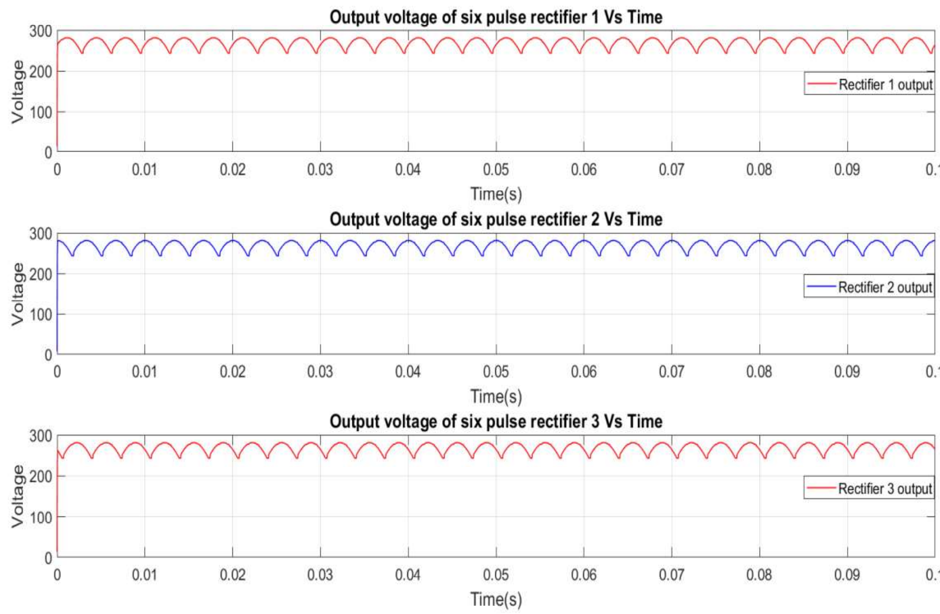

Figure 3.13: Rectifier output voltage waveforms for three input-nine output PST.

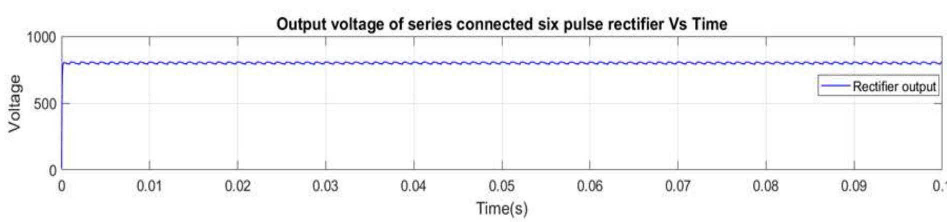

Figure 3.14: Output voltage of series connected rectifiers for three input-nine output PST.

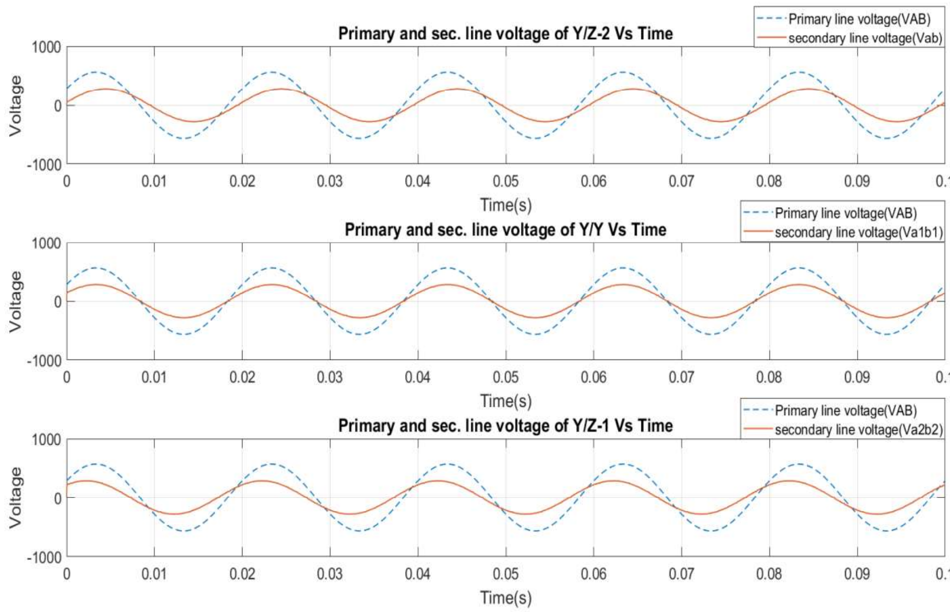

Figure 3.15: Primary and secondary voltages of three input-nine output PST at k (transformation ratio) = 0.5.

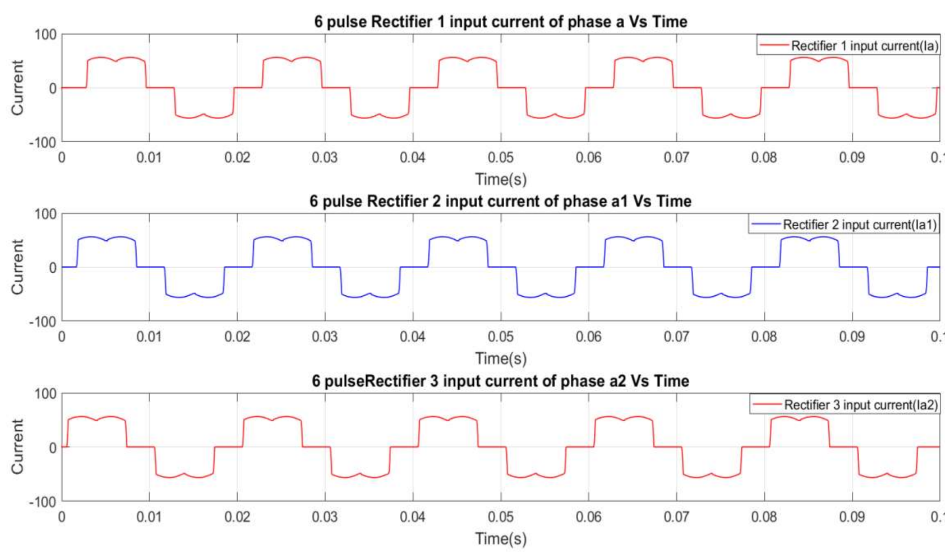

Figure 3.16: Rectifier input current waveforms for three input-nine output PST.

3.4.2 Discussion for simulation results of three input nine output PST

Figure 3.11 shows the input current waveforms of three inputs-nine outputs PST. In these waveforms it is observed that the input current is improved compared to input current waveforms in three input-six output PST. Figure 3.12 shows the harmonics spectrum of input current/source current. From this harmonic spectrum it is observed that the lower order harmonic components which are present in source current are 17^{th} and 18^{th} and 5^{th} and 7^{th}, 11^{th} and 13^{th} harmonic components are eliminated. THD in source current is 7.88 % which is less compared to THD in source current of three inputs-six outputs PST. But this THD value is also not within IEEE Standard 519 limit. These results indicate the need to improve PQ in AC-DC converters, which can replace the existing three inputs nine output model. From Figure 3.12, it is observed that the harmonic order for this model is $18k \pm 1$ which is verified with mathematical result of this model. Form this model it is observed that source power factor is improved and power factor for purely resistive load is 0.9809.

Figure 3.13 shows the rectifier output voltage waveforms. In this waveform it can be observed that output waveforms have six pulses per cycle of supply voltage because all three rectifiers are not connected in series. Figure 3.14 shows the output of series connected rectifiers. In this figure it is observed that rectifier output voltage/load voltage waveform consist 18 pulses per cycle of supply voltage. Ripple in load voltage is reduced which is less compare to ripple in load voltage for three input-six output PST. And ripple content in output DC voltage is 0.66%.

Figure 3.15 shows the primary and secondary voltage waveforms of three inputs-nine outputs PST. In this figure it is observed that secondary voltages have same magnitude with 20° phase shift. Figure 3.16 shows the rectifier input current waveforms.

3.5 Modelling and simulation of three input-twelve output phase shifting transformer (PST)

For this design, transformer is modelled using three primary windings and twenty one secondary windings. This transformer has the connection **Yz-2y0z-1d1** with phase shift -15°, 0°, 15° and 30°. Three six pulse rectifiers are connected to the star, delta and zig-zag connected secondary windings with a phase shift of -15°, 0°, 15° and 30° with respect to primary respectively. The corresponding circuit diagram is represented in Figure 3.17.

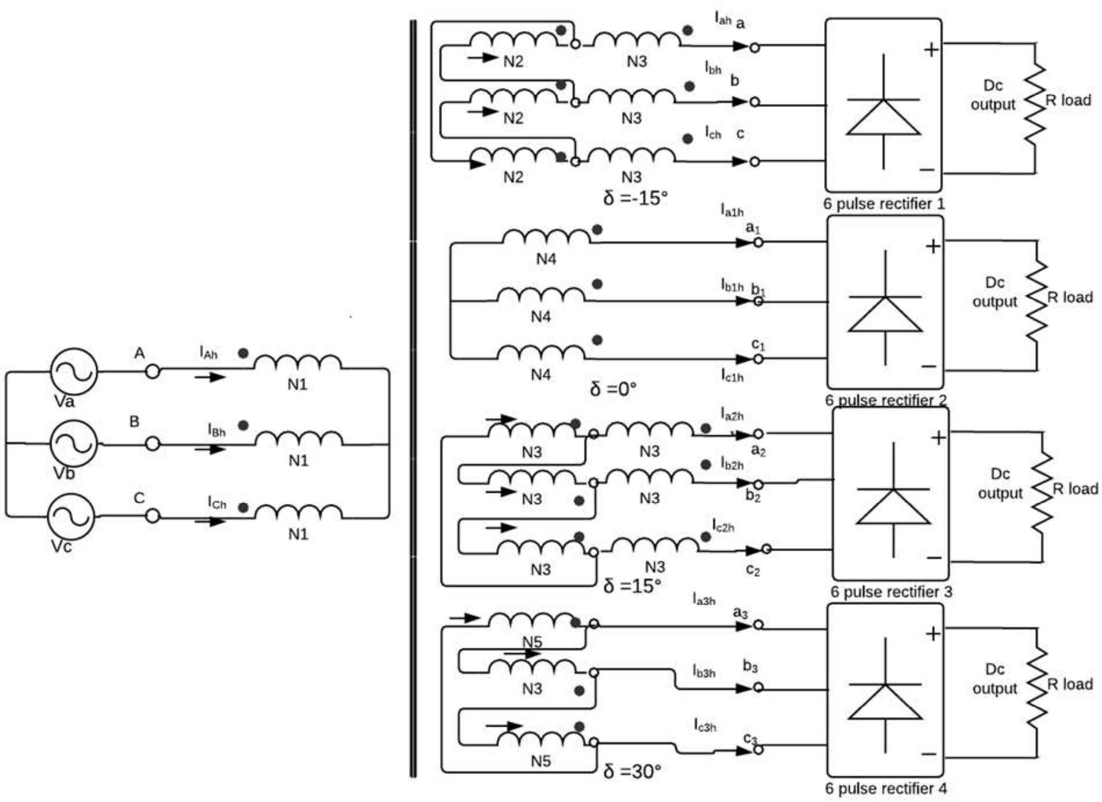

Figure 3.17: Circuit diagram of three inputs-twelve outputs PST.

3.5.1 Simulation results of three input- twelve output PST

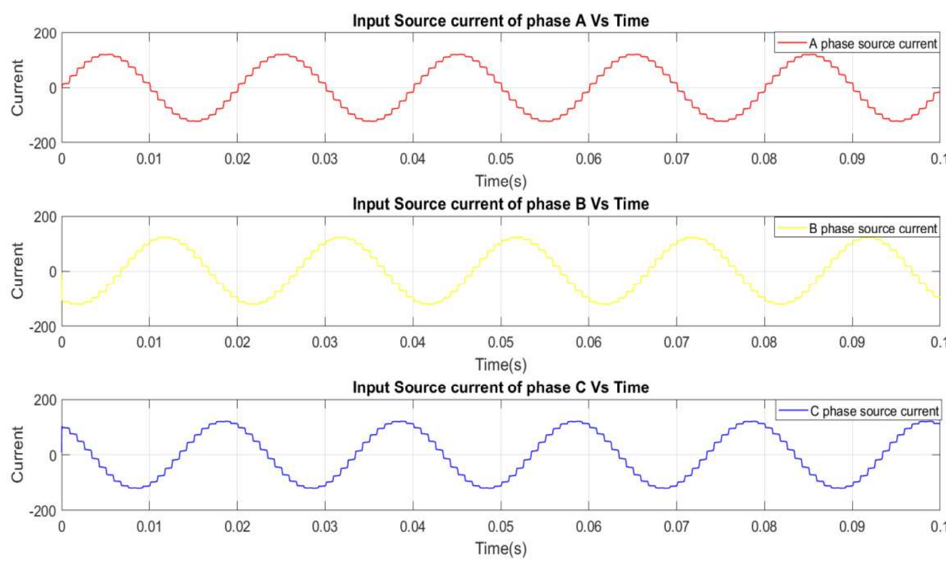

Figure 3.18: Source current waveforms of three input-twelve output PST.

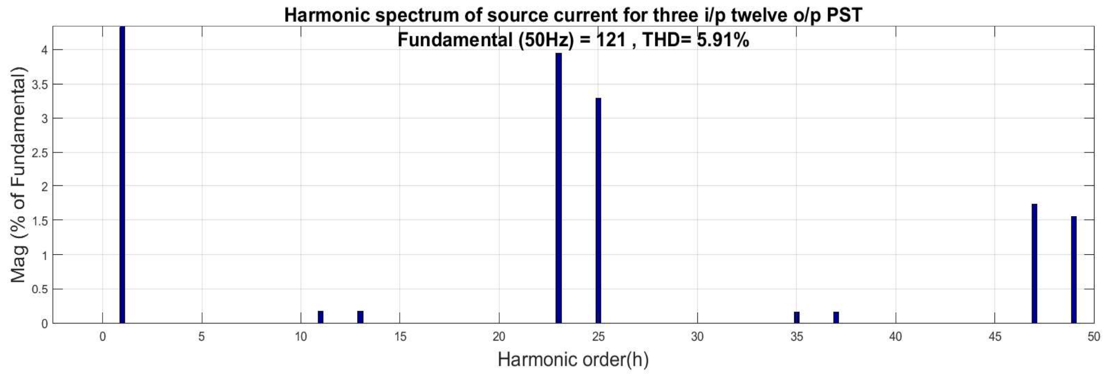

Figure 3.19: Harmonic spectrum of Source current for three input-twelve output PST.

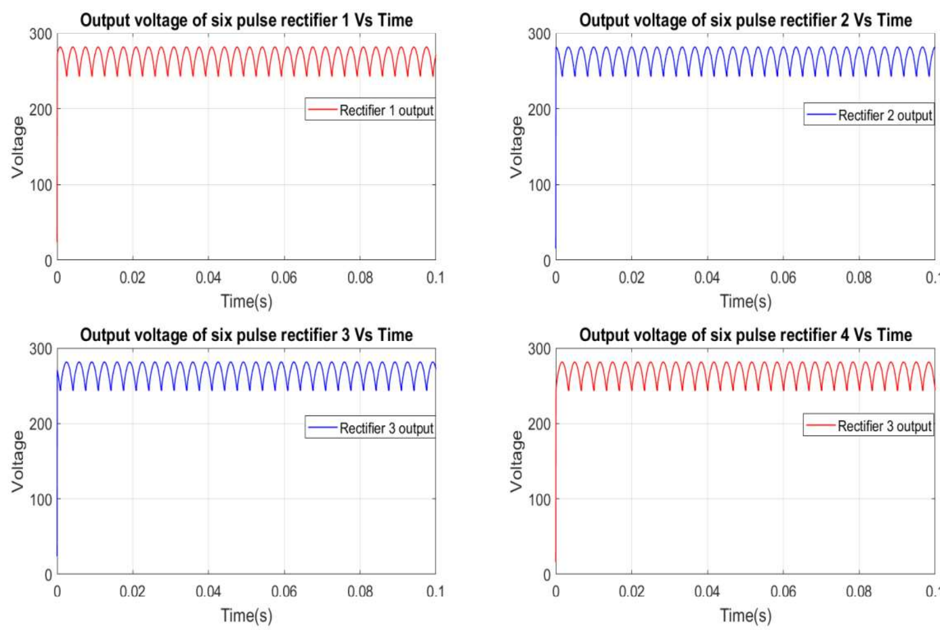

Figure 3.20: Rectifier output voltage waveforms for three input-twelve output PST.

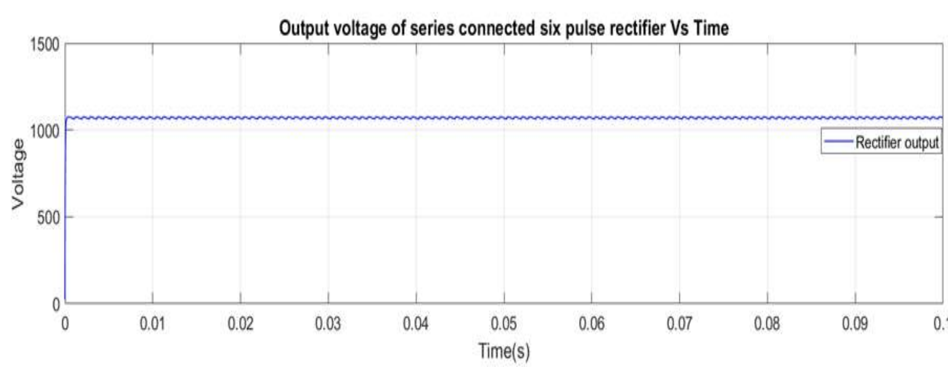

Figure 3.21: Output voltage of series connected rectifier for three input-twelve output PST.

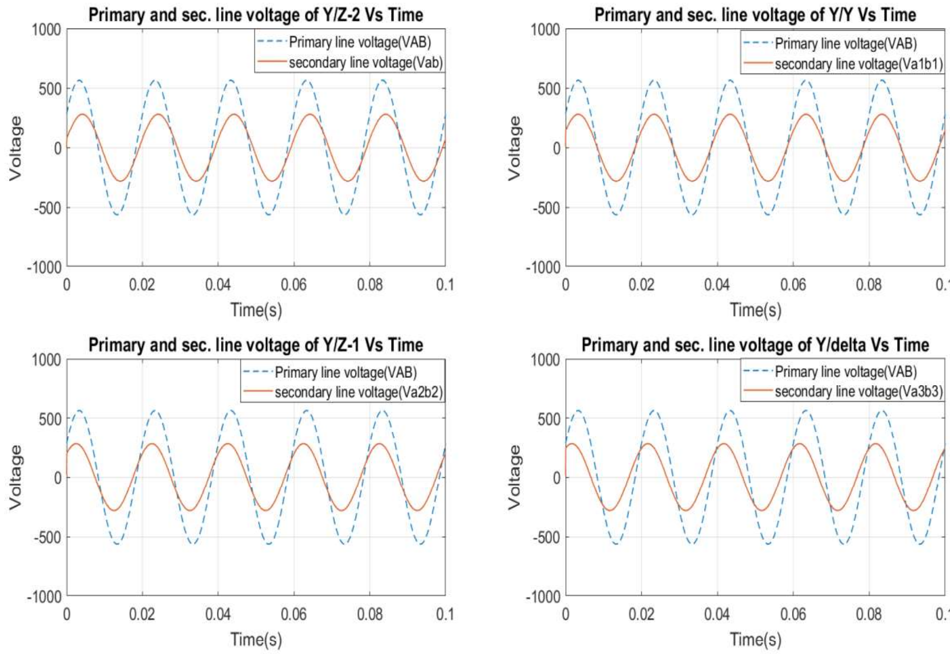

Figure 3.22: Primary and secondary voltages of three input-twelve output PST at k (transformation ratio) = 0.5.

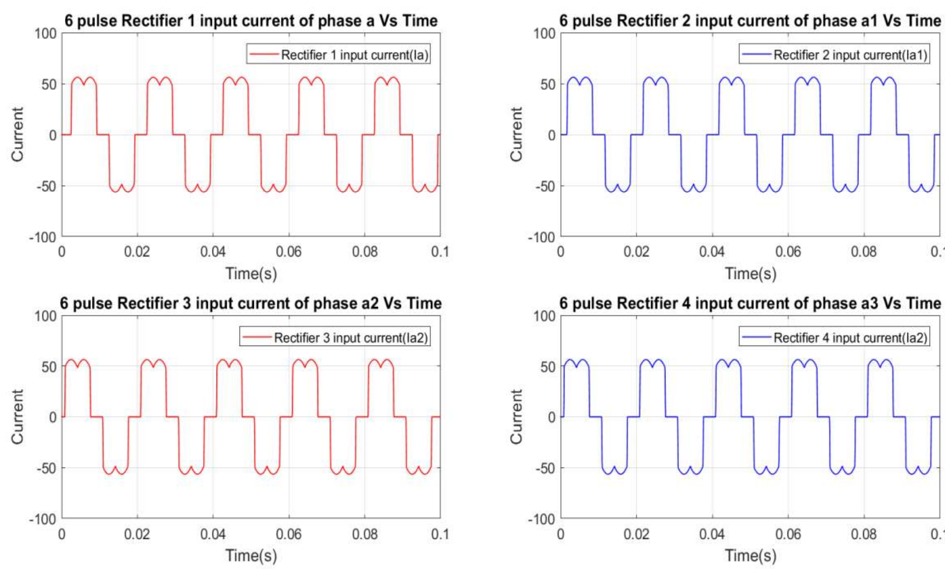

Figure 3.23: Rectifier input current waveforms for three input-twelve output PST.

3.5.2 Discussion for simulation results of three input-twelve output PST

Figure 3.18 shows the input current waveforms of three inputs-twelve outputs PST. In these waveforms it is observed that the input current is improved compare to input current waveforms in three input-nine output PST. Figure 3.19 shows the harmonics spectrum of input current/source current. From this harmonic spectrum it is observed that the lower order harmonic components which are present in source current are 23^{th} and 25^{th} and 5^{th} and 7^{th}, 11^{th} and 13^{th}, 17^{th} and 19^{th} harmonic components get eliminated. THD in source current is 5.91 % which is less compared to THD in source current of three inputs-nine outputs PST. But this THD value is also not within IEEE Standard 519 limit. These results indicate the need to improve PQ in AC-DC converters, which can replace the existing three inputs twelve output model. From Figure 3.19 it is observed that the harmonic order for this model is $24k \pm 1$ which is verified with mathematical result of this model. Form this model it is observed that source power factor is improved and power factor for purely resistive load is 0.9969.

Figure 3.20 shows the rectifier output voltage waveforms. In this waveform it is observed that output waveforms have six pulses per cycle of supply voltage because all four rectifiers are not connected in series. Figure 3.21 shows the output voltage of series connected rectifiers. In this figure is observed that rectifier output voltage/load voltage waveform consist 24 pulses per cycle of supply voltage. Ripple in output is reduced which is less compared to ripple in load voltage for three input-nine output PST. Ripple content in output DC voltage is 0.379%.

Figure 3.22 shows the primary and secondary voltage waveforms of three input-twelve output PST. In this figure it is observed that secondary voltages have same magnitude with 15° phase shift. Figure 3.23 shows the rectifier input current waveforms.

3.6 Modelling and simulation of three input-fifteen output phase shifting transformer (PST)

For this design, transformer is modelled using three primary windings and twenty seven secondary windings. This transformer has the connection **Yz-2z-2y0z-1z-1** with phase shift -24°, -12°, 0°, 12° and 24°. Three six pulse rectifiers are connected to the star, and zig-zag connected secondary windings with a phase shift of -24°, -12°, 0°, 12° and 24° with respect to primary respectively. The corresponding circuit diagram is represented in figure 3.24.

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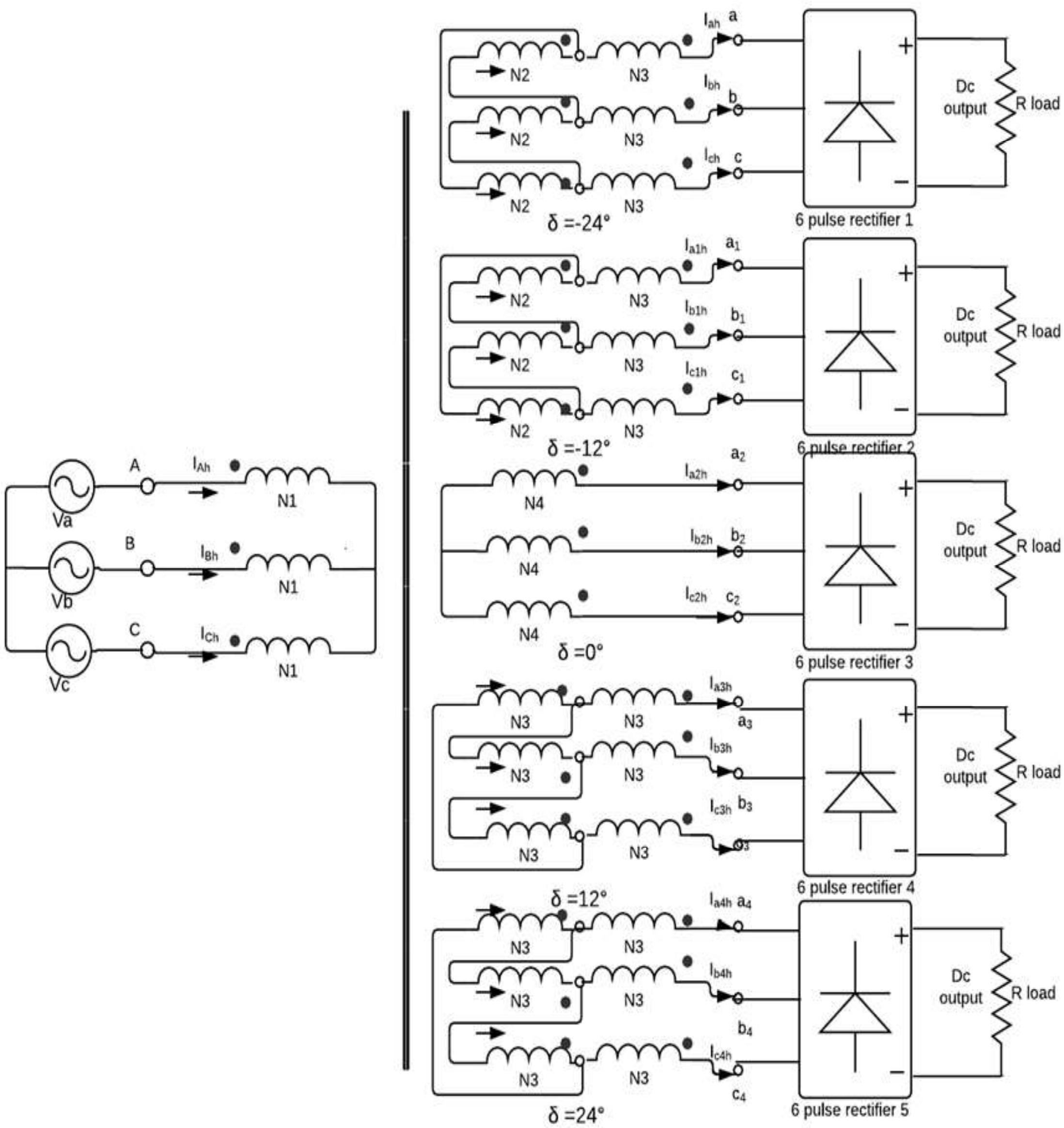

Figure 3.24: Circuit diagram of three input-fifteen output PST.

3.6.1 Simulation results of three input- fifteen output PST

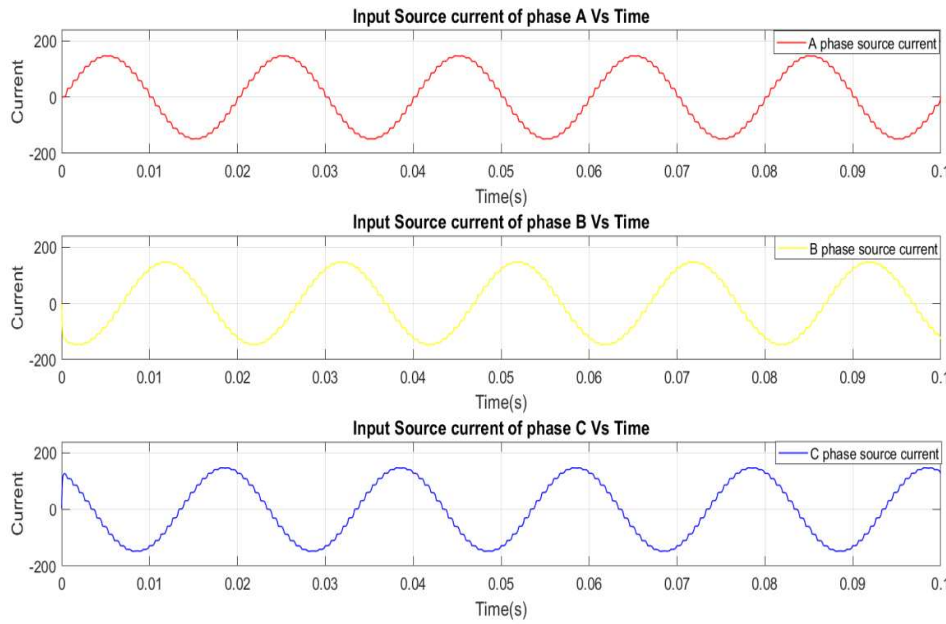

Figure 3.25: Source current waveforms of three inputs-fifteen outputs PST.

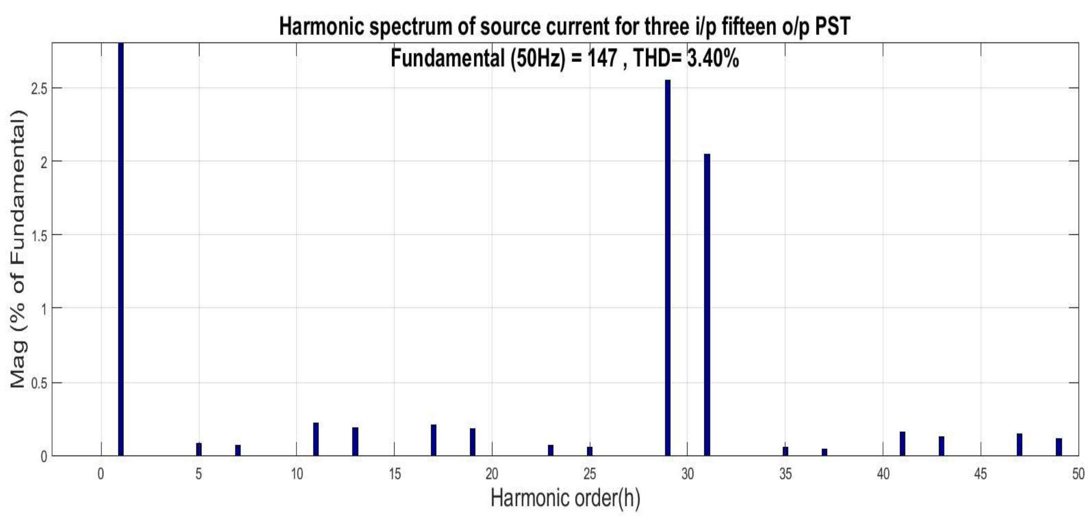

Figure 3.26: Harmonic spectrum of Source current for three input-fifteen output PST.

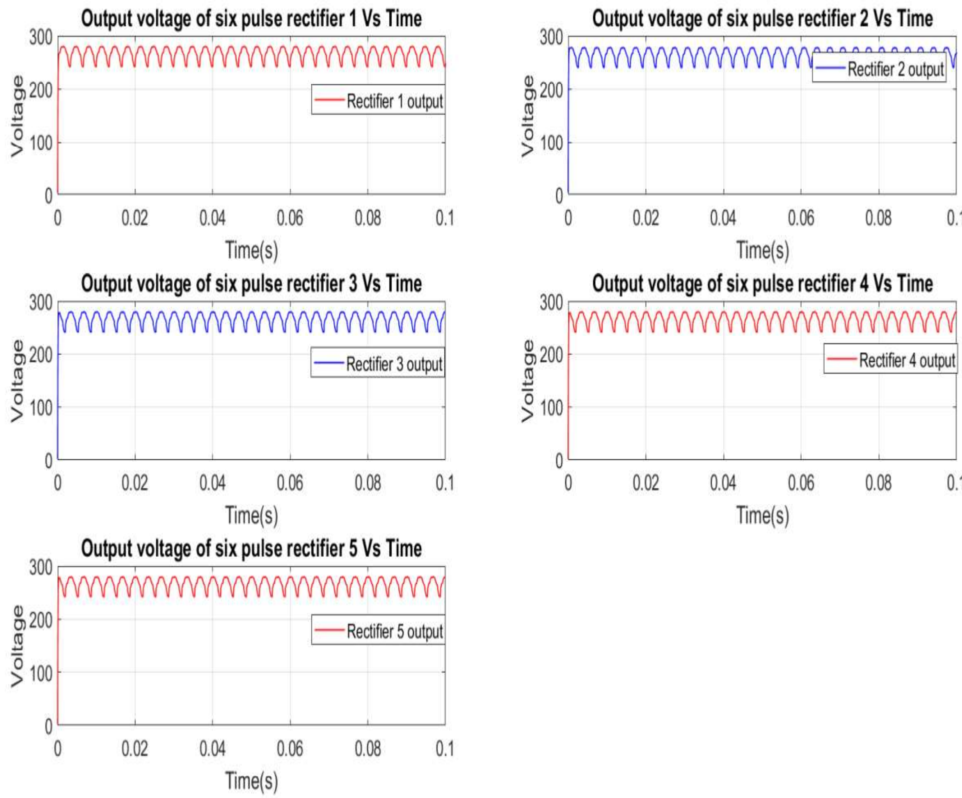

Figure 3.27: Rectifier output voltage waveforms for three input-fifteen output PST.

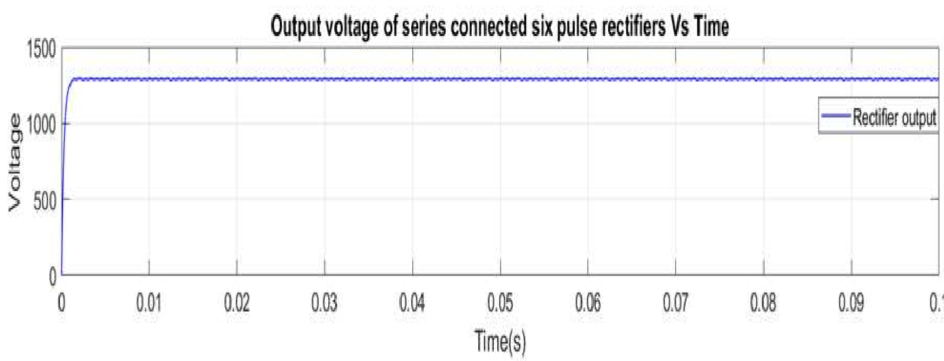

Figure 3.28: Output voltage of series connected rectifiers for three input-fifteen output PST.

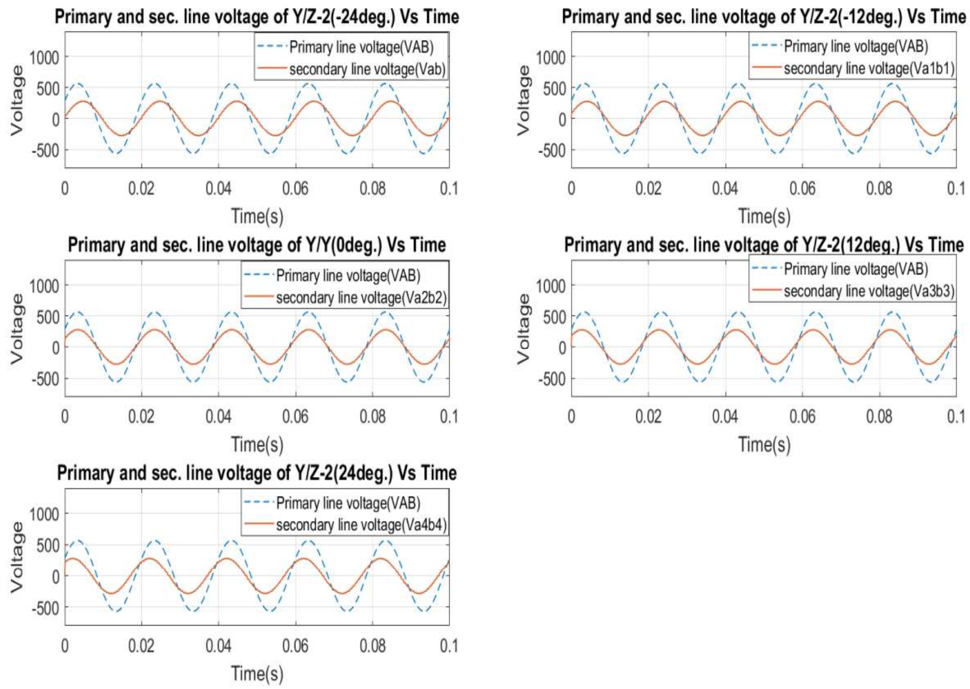

Figure 3.29: Primary and secondary voltages of three input-fifteen output PST at k (transformation ratio) = 0.5.

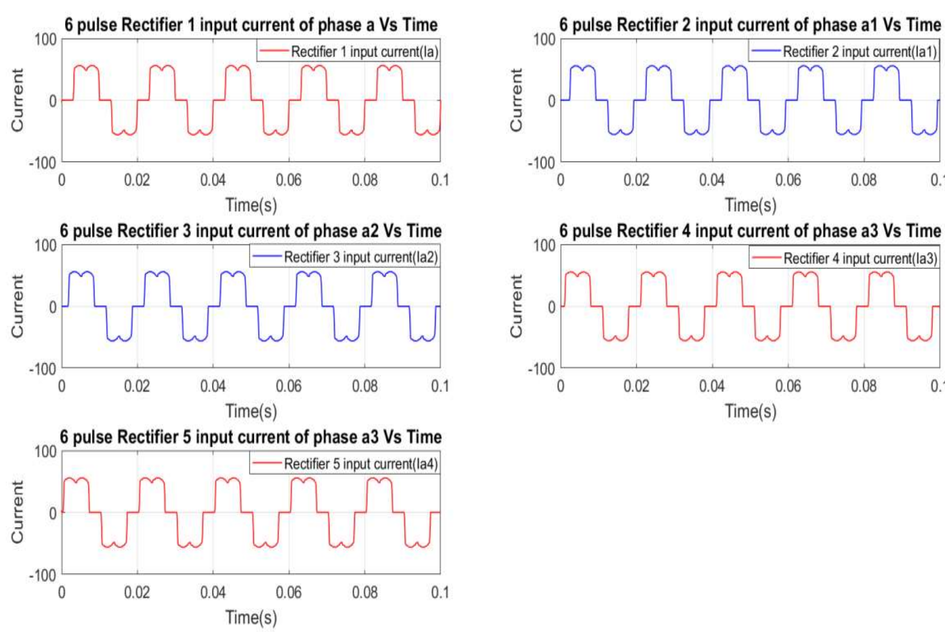

Figure 3.30: Rectifier input current waveforms for three input-twelve output PST.

3.6.2 Discussion for simulation results of three input fifteen output PST

Figure 3.25 shows the input current waveforms of three input-fifteen output PST. In these waveforms it is observed that the input current is improved compared to input current waveforms in three input-twelve output PST. Figure 3.26 shows the harmonics spectrum of input current/source current. From this harmonic spectrum it is observed that the lower order harmonic components which are present in source current are 29^{th} and 31^{th} and 5^{th} and 7^{th}, 11^{th} and 13^{th}, 17^{th} and 19^{th}, 17^{th} and 19^{th} harmonic components are eliminated. THD in source current is 3.4 % which is less compared to THD in source current of three input-twelve output PST. This THD value is within IEEE Standard 519 limit. From Figure 3.26 it is observed that the harmonic order for this model is $30k \pm 1$ which is verified with mathematical result of this model. Form this model it is observed that source power factor is improved and power factor for purely resistive load is 0.9973.

The DC voltages produced by each six pulse/bridge rectifier, add together, like five batteries connected in series to achieve full DC bus voltage for high power application. Figure 3.27 shows the rectifier output voltage waveforms. In this waveform it is observed that output waveforms have six pulses per cycle of supply voltage because all five rectifiers are not connected in series. Figure 3.28 shows the output voltage of series connected rectifiers. In this figure it can be observed that rectifier output voltage/load voltage waveform consist 30 pulses per cycle of supply voltage. Ripple in output is reduced which is less compared to ripple in load voltage for three input-twelve output PST. Ripple content in output DC voltage is 0.257%.

Figure 3.29 shows the primary and secondary voltage waveforms of three input-fifteen output PST. In this figure it is observed that secondary voltages have same magnitude with 12° phase shift. Figure 3.30 shows the rectifier input current waveforms.

3.7 Modelling and simulation of three input-twenty seven output phase shifting transformer (PST)

For this design, transformer is modelled using three primary windings and fifty one secondary windings. This transformer has the connection **Yz-2z-2z-2z-2y0z-1z- z-1z-1** with phase shift -26.66°, -20°, -13.33°, -6.66°, 0°, 6.66°, 13.33°, 20°, and 26.66°. Nine six pulse rectifiers are connected to the star, and zig-zag connected secondary windings with a phase shift of -26.66°, -20°, -13.33°, -6.66°, 0°, 6.66°, 13.33°, 20°, and 26.66° with respect to primary respectively. The corresponding circuit block diagram is represented in figure 3.31.

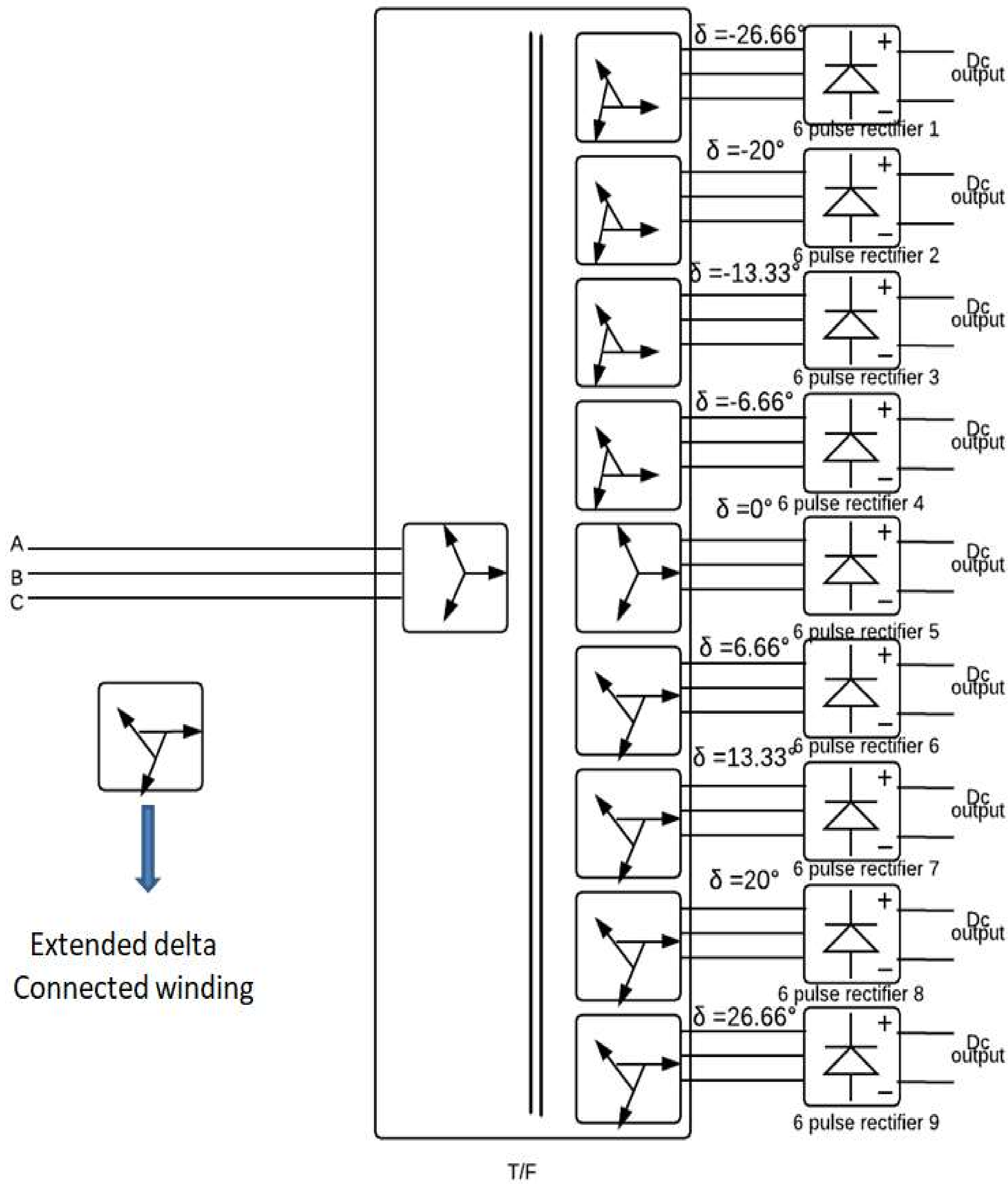

Figure 3.31: Block diagram of three input-twenty seven output PST.

3.7.1 Simulation results of three input- twenty seven output PST

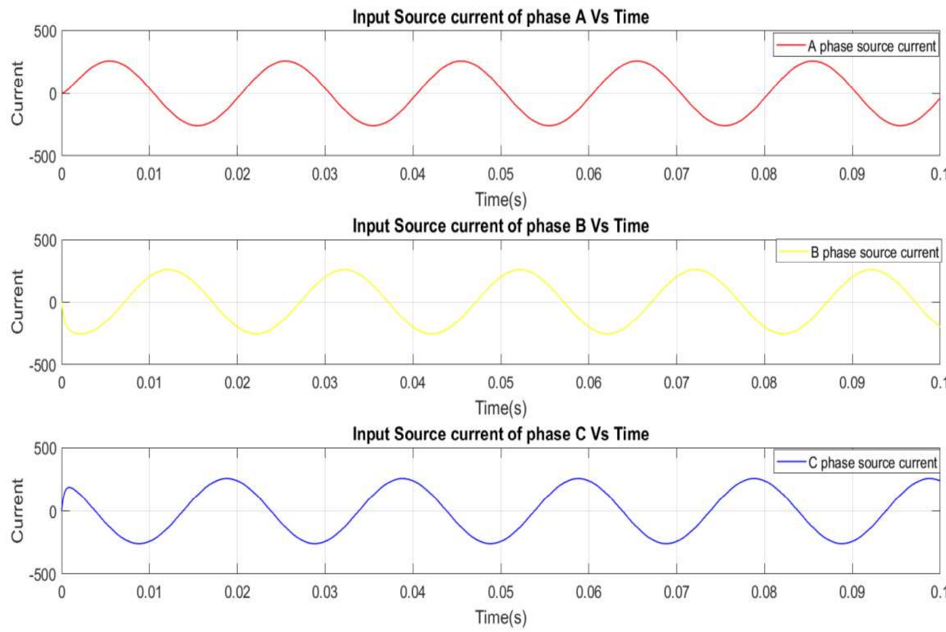

Figure 3.32: Source current waveforms of three input- twenty seven output PST.

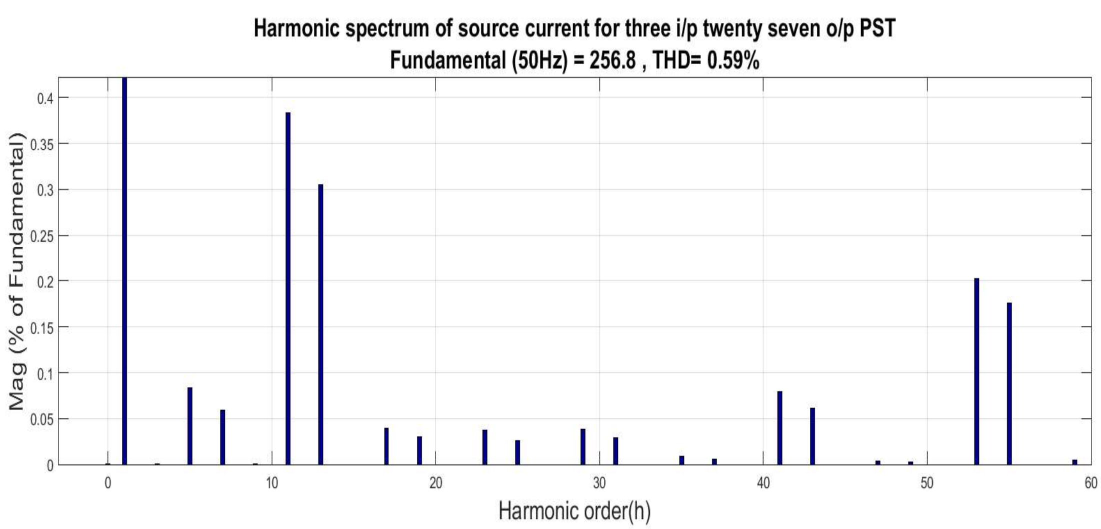

Figure 3.33: Harmonic spectrum of Source current for three input- twenty seven output PST.

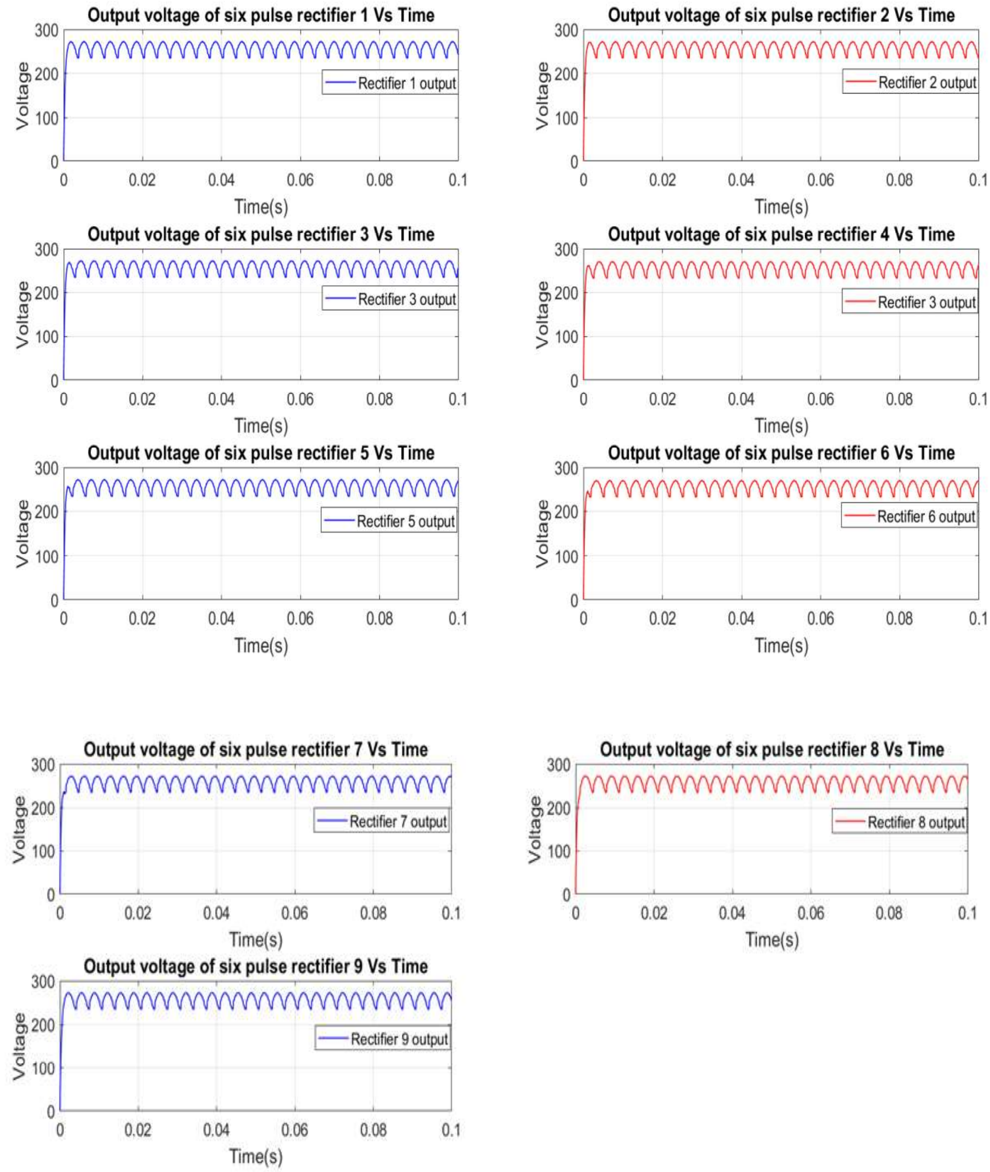

Figure 3.34: Rectifier output voltage waveforms for three input-twenty seven output PST.

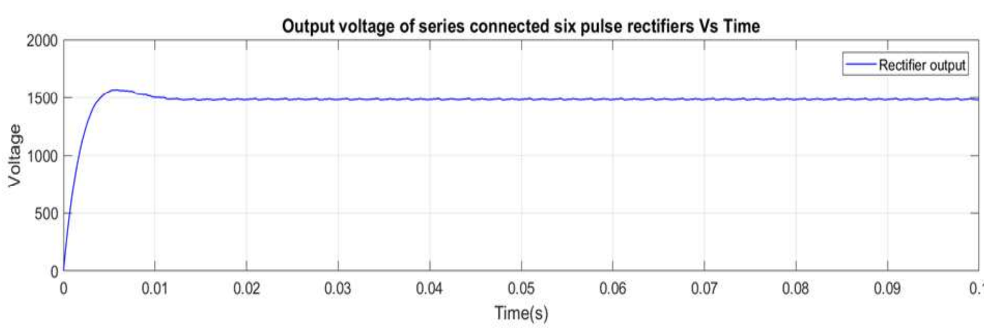

Figure 3.35: Output voltage of series connected rectifiers for three input-fifteen output PST.

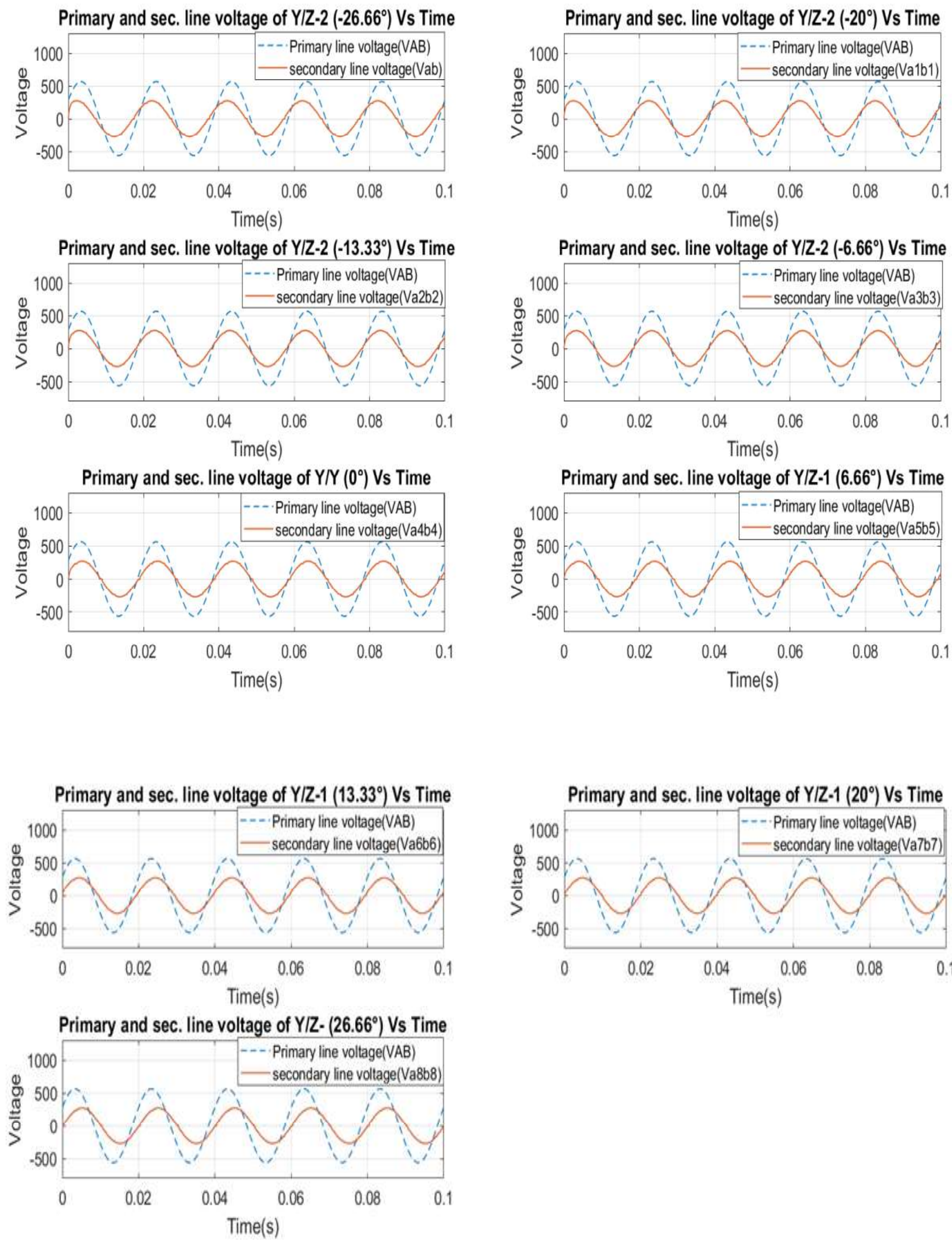

Figure 3.36: Primary and secondary voltages of three input- twenty seven output PST at k (transformation ratio) = 0.5.

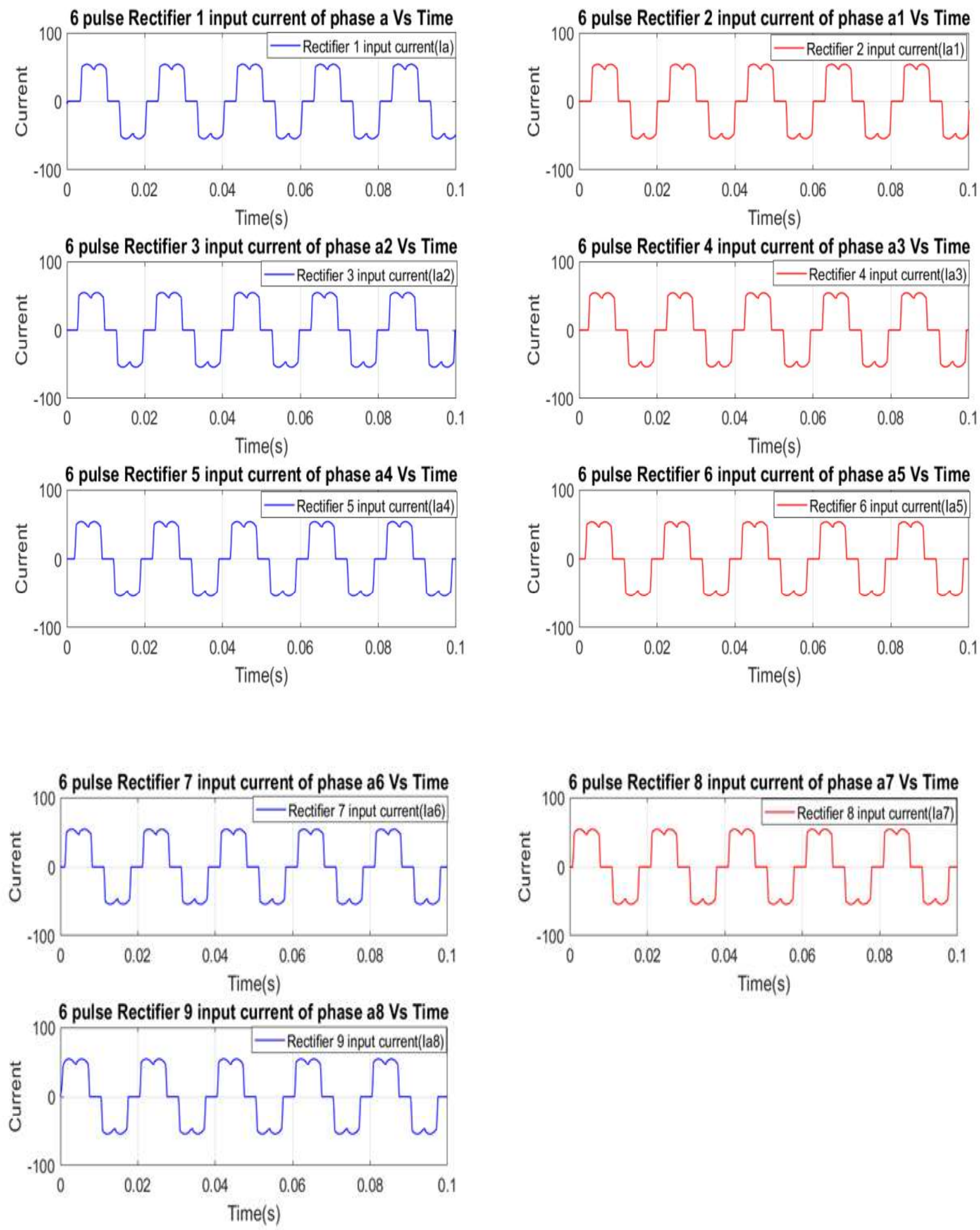

Figure 3.37: Rectifier input current waveforms for three input- twenty seven output PST.

3.7.2 Discussion for simulation result of three-input twenty seven Output PST

Figure 3.32 shows the input current waveforms of three input-fifteen output PST. From these waveforms it is observed that the input current is more improved and closed to sinusoidal compared to input current waveforms of all previous models. Figure 3.33 shows the harmonics spectrum of input current/source current. From this harmonic spectrum it is observed that the lower order harmonic components which are present in source current are 53^{th} and 55^{th}. And other lower order harmonic components are also present with very less magnitude, which can be neglected. THD in source current is 0.59 % which is very less compared to THD in source current of all previous model. Form this model it is observed that source power factor is improved.

Figure 3.34 shows the rectifier output voltage waveforms. In this waveform it is observed that output waveforms have six pulses per cycle of supply voltage because all five rectifiers are not connected in series. The DC voltages produced by each six pulse/bridge rectifier, add together, like nine batteries connected in series to achieve full DC bus voltage for high power application. Figure 3.35 shows the output voltage of series connected rectifiers. In this figure it can be observe that rectifier output voltage/load voltage waveform consist 54 pulses per cycle of supply voltage. Ripple in output is reduced which is less compared to ripple in load voltage of all previous model. And ripple content in output DC voltage is 0.19%.

Figure 3.36 shows the primary and secondary voltage waveforms of three inputs-twenty seven outputs PST. In this figure it is observed that secondary voltages have same magnitude with 6.66° phase shift. Figure 3.37 shows the rectifier input current waveforms.

3.8 Modelling and simulation for three input-twenty seven output model by using three similar phase shifting transformers

Dc supply for 9 cells MMCC is made by three input twenty seven output PST but due to more windings in secondary practical modelling of this PST is complicated. So this can be modified using three similar PSTs having three inputs and nine outputs. Each PST has the connection Yz-2y0z-1 with phase shift -20°, 0° and 20° respectively. This model allows supplying 9 six pulse rectifiers with shifted angles -20°, 0° and 20° respectively. The THD and source power factor of this arrangement are same as the THD and source power factor of three input- nine output phase shifting transformer. The corresponding circuit block diagram of this model is represented in Figure 3.38.

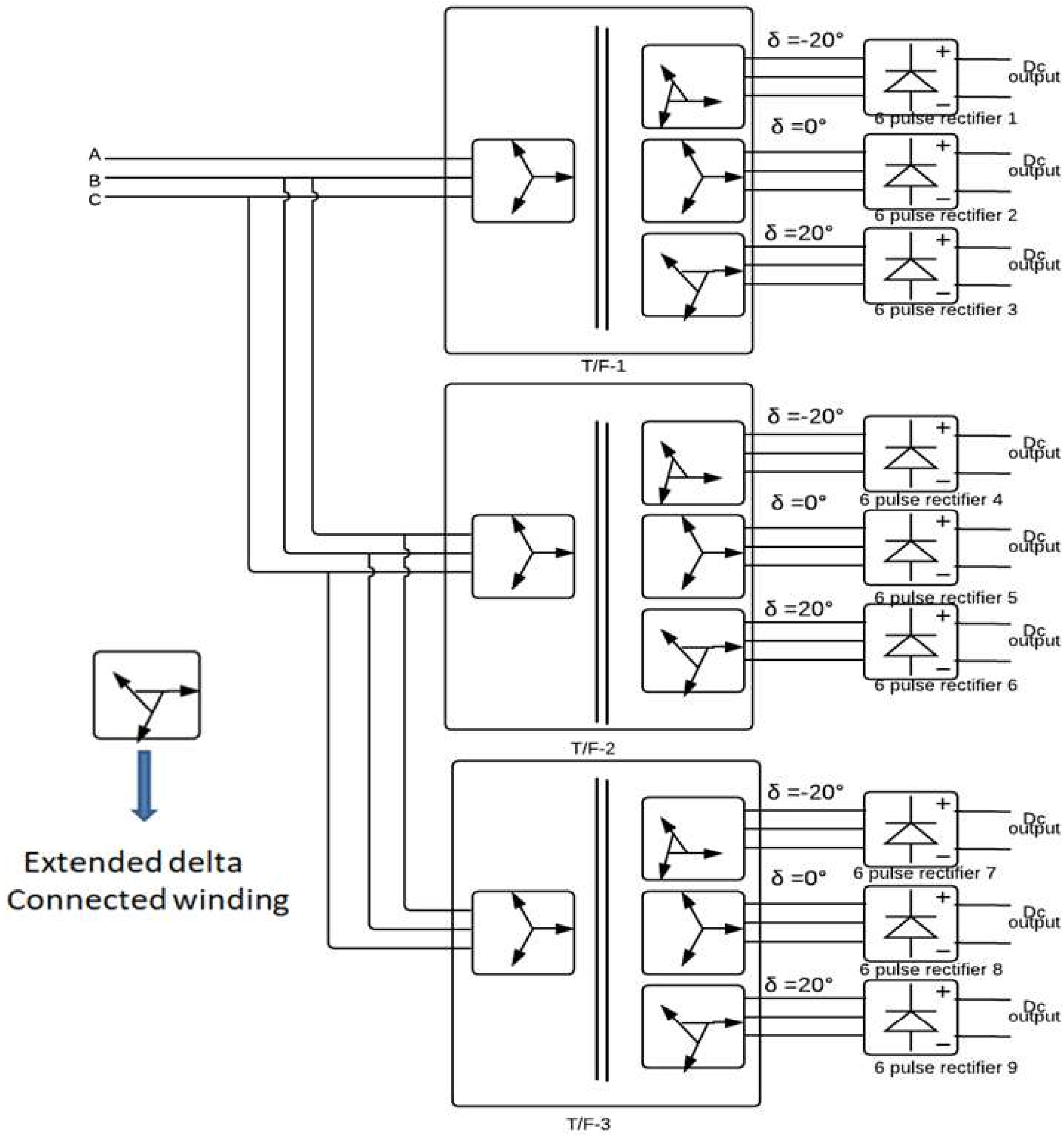

Figure 3.38: Block diagram of three input-twenty seven output model using three similar PSTs.

3.8.1 Simulation results for three input- twenty seven output model using three similar PSTs

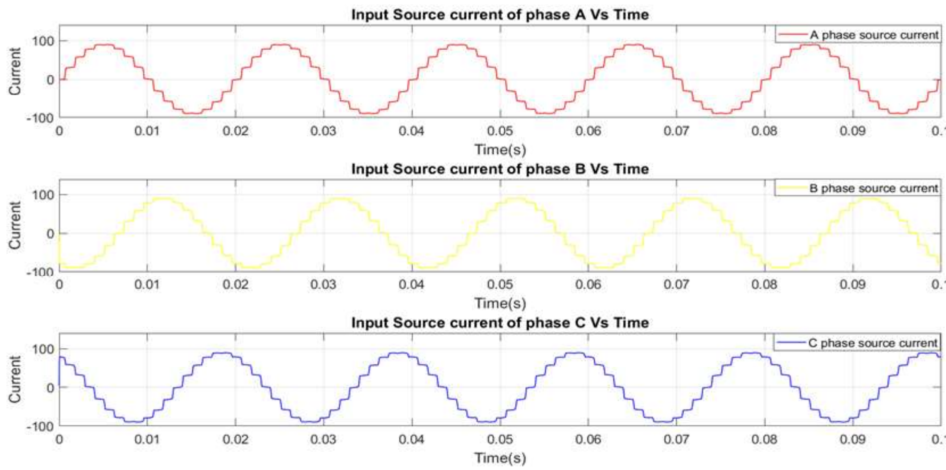

Figure 3.39: Source current waveforms for three input-twenty seven output model using three similar PSTs.

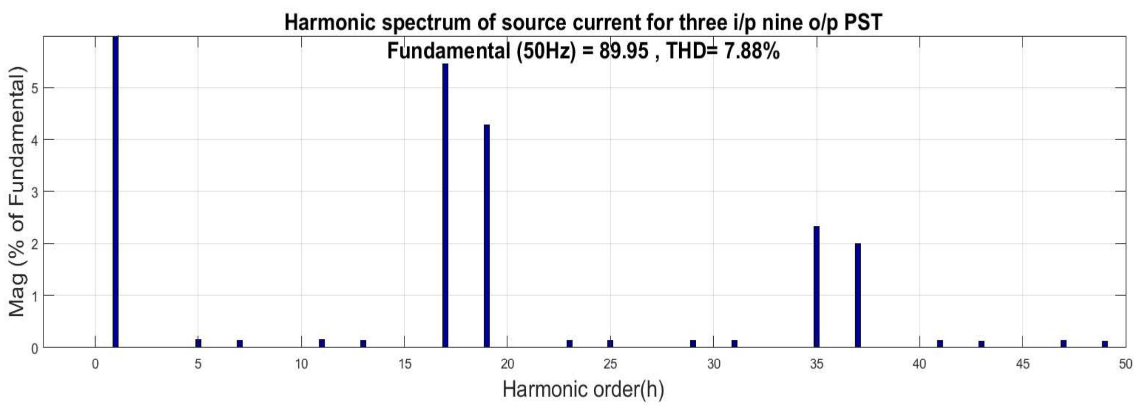

Figure 3.40: Harmonic spectrum of Source current for three input-twenty seven output model using three similar PSTs.

3.8.2 Discussion for simulation results of three input twenty seven Output model using three similar PSTs

This model is designed using three similar phase shifting transformers with phase shift -20°, 0° and 20°. So the results of this model are same as results of three input- nine output phase shifting transformer. Figure 3.39 and figure 3.40 show the input current/source current waveforms and harmonics spectrum of input current/source current for three inputs-twenty seven outputs model respectively. THD in source current is 7.88 %.

3.9 Modelling and simulation for three input-twenty seven output model using three different phase shifting transformers

Dc supply for 9 cells MMCC is made by three input twenty seven output PST but due to more windings in secondary practical modelling of this PST is complicated. So this can be modified using three different PSTs. Each PST has three input nine output. The first transformer has the connection Yz-2z-2z-2 with phase shift -26.66°, -20° and -13.33° respectively. The second transformer has the connection Yz-2y0z-1 with phase shift -6.66°, 0°, 6.66° respectively. Third one has the connection Yz-1z-1z-1 with phase shift 13.33°, 20° and 26.66° respectively. The corresponding circuit block diagram is represented in Figure 3.41.

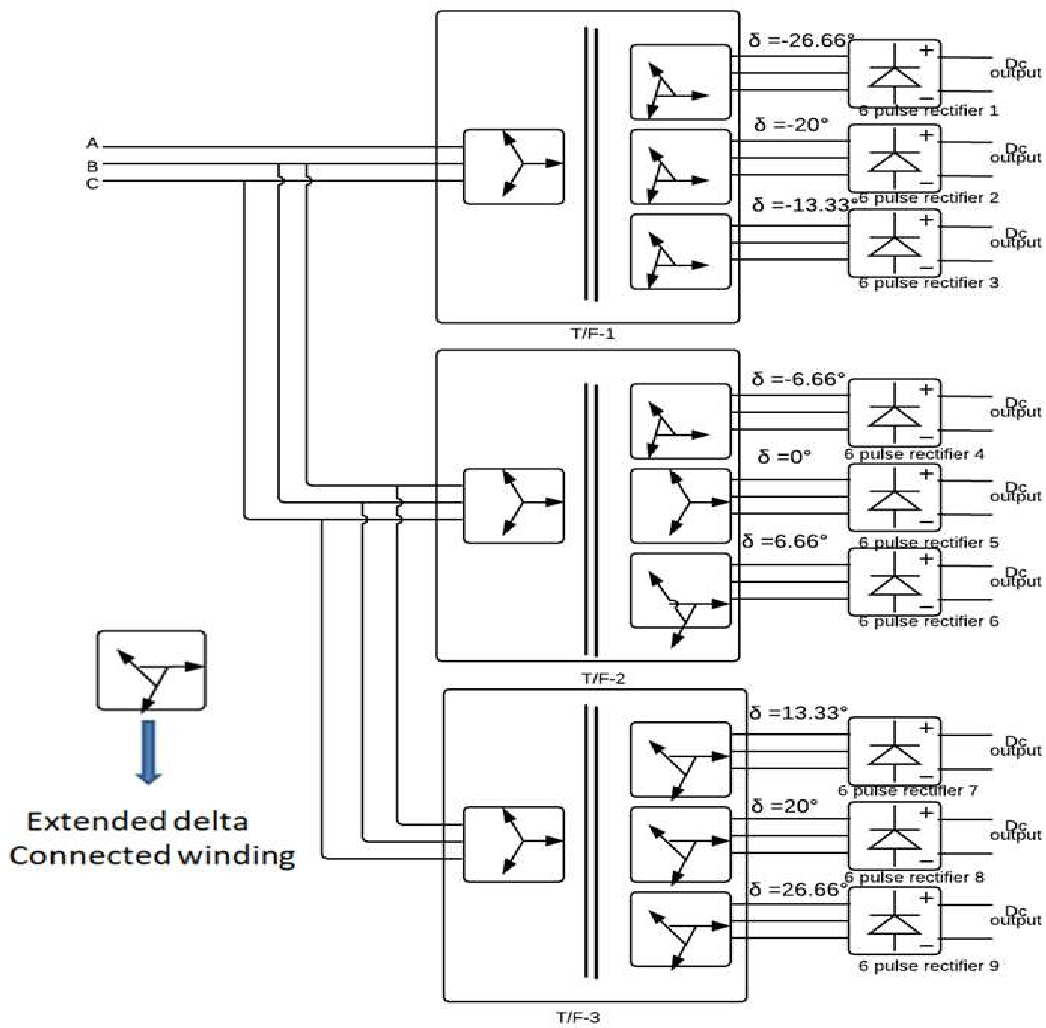

Figure 3.41: Block diagram of three input-twenty seven output model using three different PSTs.

3.9.1 Simulation results for three input- twenty seven output model using three different phase shifting transformers

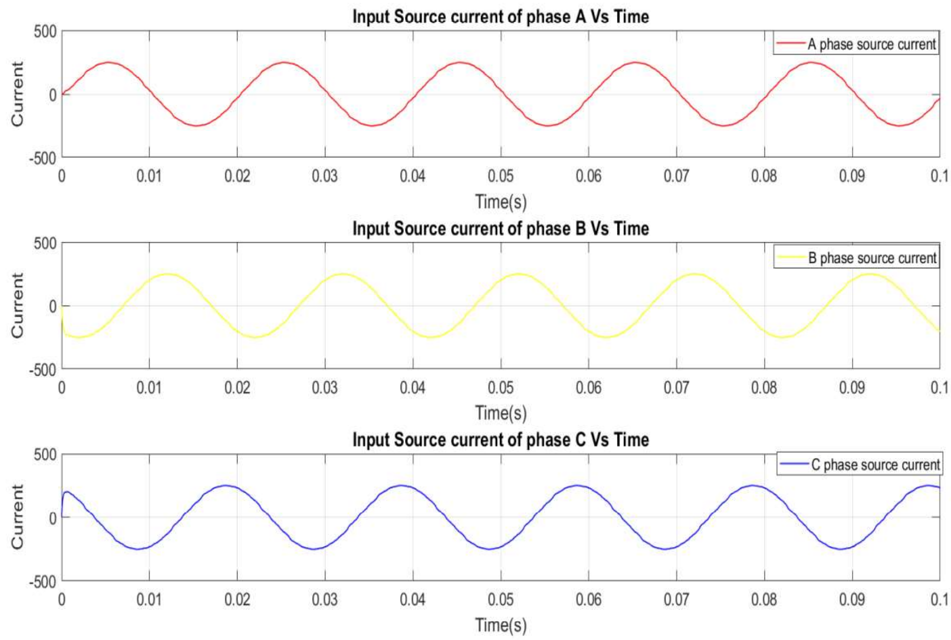

Figure 3.42: Source current waveforms for three inputs- twenty seven outputs PST.

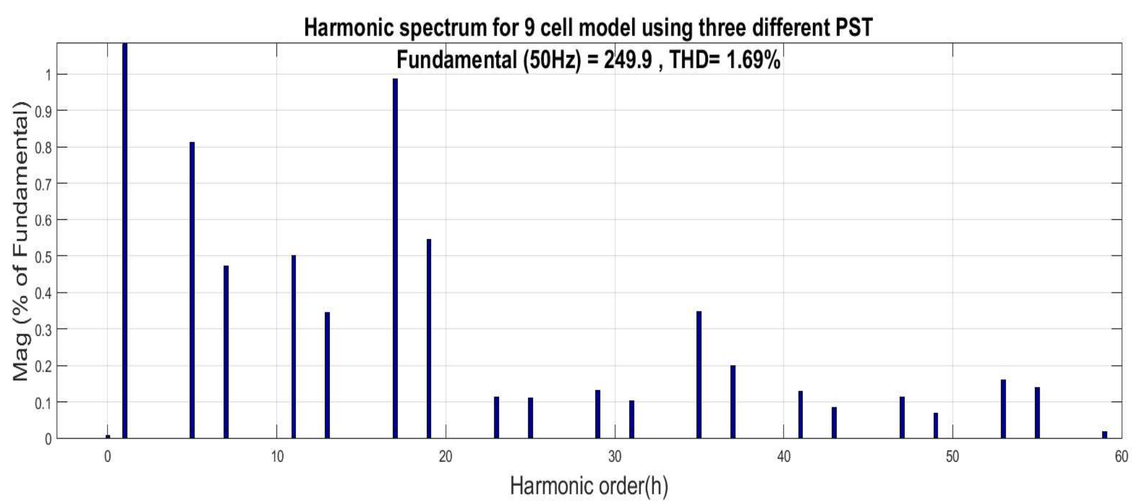

Figure 3.43: Harmonic spectrum of Source current for three input- twenty seven output model.

3.9.2 Discussion for simulation results of three inputs twenty seven Outputs model by using three different PSTs

This model is designed using three different phase shifting transformers with phase shift -26.66°, -20°, -13.33° and -6.66°, 0°, 6.66° and 13.33°, 20°, 26.66° respectively. So the simulation results of this model are approximately same as results of three input-twenty seven output phase shifting transformer. Figure 3.42 shows the input current waveforms for three inputs-twenty seven output model. From this waveform it is observed that the input current is more improved and closed to sinusoidal compared to input current waveforms of previous model. Figure 3.43 shows the harmonics spectrum of input current/source current. From this harmonic spectrum it is observed that the THD in source current is 1.69% which is very less compared to THD in source current of previous model. Form this model it is observed that source power factor is improved.

3.10 Modelling and simulation for three input- forty five output model using three similar phase shifting transformers

Dc supply for 15 cells MMCC is made by three inputs forty five outputs PST but due to more windings in secondary, practical modelling of this PST is complicated. So this can be modified using three similar PSTs having three inputs and fifteen outputs. Each PST has the connection Yz-2z-2y0z-1z-1 with phase shift -24°, -12°, 0°, 12° and 24° respectively. This model allows supplying 15 six pulse rectifiers with shifted angles -24°, -12°, 0°, 12° and 24° with respect to primary respectively. The THD and source power factor of this arrangement are same as the THD and source power factor of three input-fifteen output phase shifting transformer. The corresponding circuit block diagram is represented in Figure 3.44.

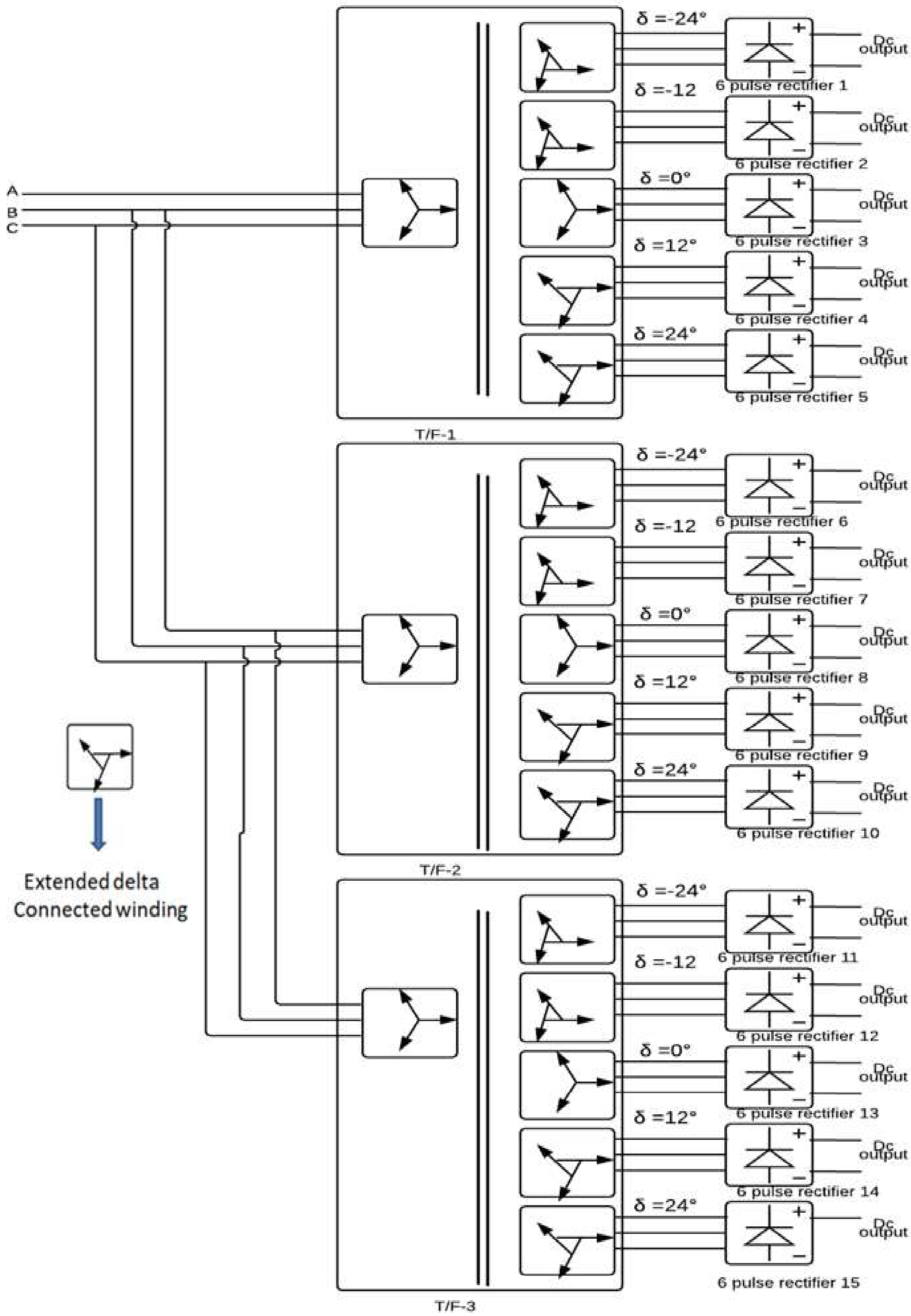

Figure 3.44: Block diagram of three input-forty five output model using three different PST.

3.10.1 Simulation results for three input- forty five output model using three similar PSTs

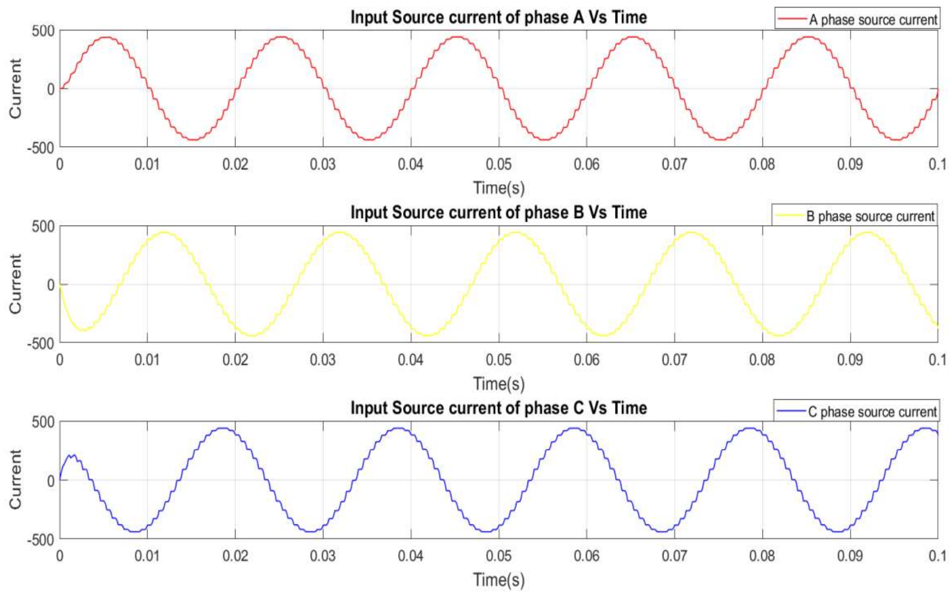

Figure 3.45: Source current waveforms for three input- forty five output using three similar PSTs.

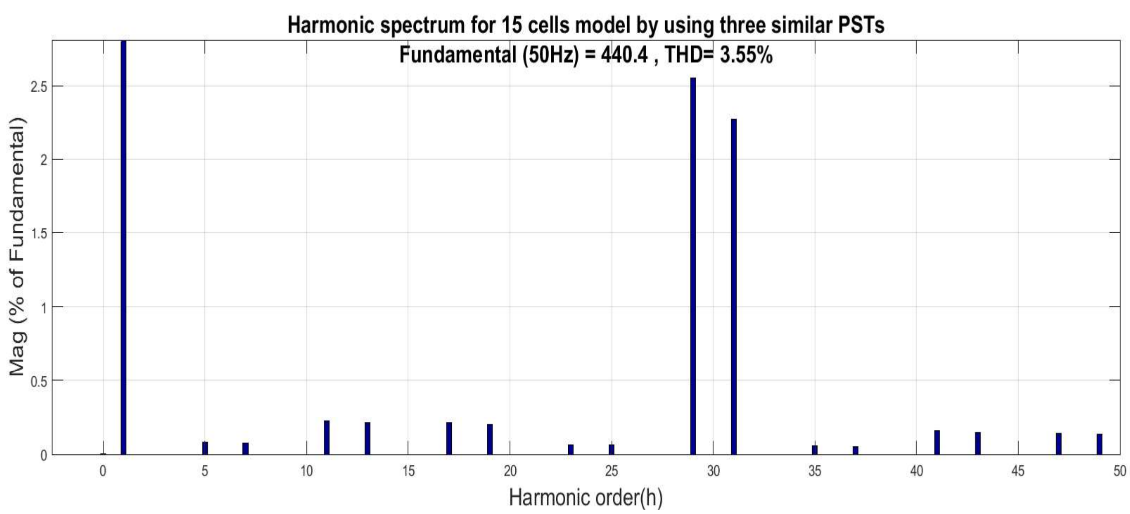

Figure 3.46: Harmonic spectrum of Source current for three input- forty five output model using three similar PSTs.

3.10.2 Discussion for simulation results of three input forty five output model using three similar PSTs

This model is designed using three similar phase shifting transformers with phase shift -24°, -12°, 0°, 12° and 24°. So the results of this model are same as results of three input- fifteen output phase shifting transformer. Figure 3.47 and figure 3.48 show the input current/source current waveforms and harmonics spectrum of input current/source current for three inputs-forty five outputs model respectively. THD in source current is 3.4 %.

3.11 Comparison tables of simulation results for different multi-output phase shifting transformers (PST)

Table 3.11.1 Analysis of total harmonic distortion (THD)

Sr.no.	Type of PST	%THD
1	**Three input-three output PST**	26.48
2	**Three input-six output PST**	10.89
3	**Three input-nine output PST**	7.88
4	**Three input-twelve output PST**	5.9
5	**Three input-fifteen output PST**	3.40
6	**Three input-twenty seven output PST**	.59

Table 3.11.2 Analysis of source power factor

Sr.no.	Type of PST	Power factor (R load)
1	**Three input-three output PST**	.9660
2	**Three input-six output PST**	.9809
3	**Three input-nine output PST**	.9957
4	**Three input-twelve output PST**	.9969
5	**Three input-fifteen output PST**	.9973
6	**Three input-twenty seven output PST**	.9989

Table 3.11.3 Analysis of ripple content in output DC voltage

Sr.no.	Type of PST	%Ripple content
1	Three input-three output PST	5.26
2	Three input-six output PST	1.349
3	Three input-nine output PST	0.66
4	Three input-twelve output PST	0.379
5	Three input-fifteen output PST	0.257
6	Three input-twenty seven output PST	0.19

Table 3.11.4 Analysis of harmonic order in source current

Sr.no.	Type of PST	Harmonic order
1	Three input-three output PST	$h = 6k \pm 1$, $k = 1,2,3,4\ldots\ldots$
2	Three input-six output PST	$h = 12k \pm 1$, $k = 1,2,3,4\ldots\ldots$
3	Three input-nine output PST	$h = 18k \pm 1$, $k = 1,2,3,4\ldots\ldots$
4	Three input-twelve output PST	$h = 24k \pm 1$, $k = 1,2,3,4\ldots\ldots$
5	Three input-fifteen output PST	$h = 30k \pm 1$, $k = 1,2,3,4\ldots\ldots$
6	Three input-twenty seven output PST	$h = 54k \pm 1$, $k = 1,2,3,4\ldots\ldots$

CHAPTER 4

CONCLUSION

4.1 Summary and Conclusions

The conventional rectifier has a few such as poor power quality in terms of input current harmonics, voltage distortion, and low efficiency that lead to design of proposed multi-output phase shifting transformer. Multi output phase shifting transformers are a suitable solution to address these issues. A modeling methodology has been developed. This method requires the main data of transformer, the phase shifting angles as well as the winding connections. Different multi-output phase shifting transformers like three input-six output PST, three input-nine output PST, three input-twelve output PST, three input-fifteen output PST and three input-twenty seven output PST have been modeled and simulated in MATLAB /Simulink environment.

The multi-output phase shifting transformers are analyzed considering harmonic spectrum of input source, THD, distortion factor, input power factor and ripple in output voltage as parameter. All mathematical calculations are verified by the simulation result. In three inputs-twenty seven outputs PST, it is observed that THD in source current is very less which implies that source current is almost purely sinusoidal. Hence three input-twenty seven output PST is better choice for nine cell MMCC. It is concluded that in general with increase in number of outputs in multi-output phase shifting transformer, the performance parameters (total harmonic distortion in source current, input power factor and ripple content in output voltage) of these multi output PSTs are remarkably improved.

The proposed multi output phase shifting transformer results in reduction in the rating of the magnetics, leading to savings in weight, size, volume, and finally the overall cost of converter system. The results obtained developed multi output PST configuration also validated the simulated models and the design procedure.

4.2 References

[1] Bin Wu "Phase-Shifting Transformers in High-Power Converters and ac Drives," *IEEE Press,* SN – 9780471731719 July 2005.

[2] Komal Gamit, Khushbu Chaudhari "Multi pulse rectifier using different phase shifting transformer and its THD comparison for power quality issues", *International Research Journal of Engineering and Technology (IRJET)* Volume: 03 Issue: 01 | Jan-2016.

[3] Anuj Patel, Henil Patel, Ruchi Joshi, Milap Patel , "Phase-Shifting Transformer" *International Journal of Advance Research in Engineering, Science &Technology(IJAREST)*, ISSN(O):2393-9877, ISSN(P): 2394-2444,Volume 2,Issue 5, May- 2015.

[4] A.D. Gaonkar, R.G. Rane, S.R. Wagh, N.M. Singh, "Multi-winding Phase-Shifting Transformer for 36-Pulse Rectifier: Winding Turns Design and Analysis" 978-1-5090-3270-9/16 ©2016 IEEE.

[5] A. Sapin, P. Allenbach, J.-J. Simond: Modeling of Multi-Winding Phase Shifting Transformers, Applications to DC Supplies. *ICEM* 2000, Helsinki.

[6] Paice D.: Power Electronic Converter Harmonics, Multipulse methods for clean power, *IEEE Press*, ISBN:978-0-780-35394-7, Sep. 1999.

[7] Hirofumi Akagi, "Classification, Terminology, and Application of the Modular Multilevel Cascade Converter (MMCC)" *IEEE Transactions on power electronic*, vol. 26, no. 11,november 2011.

[8] Nidhi Khurpia, R.S. Tare, Rahul Agrawal "Modeling, Design and Analysis of Multi Pulse Converter Using MATLAB Simulation" *International Journal of Software & Hardware Research in Engineering* ISSN-2347-4890 Volume 4 Issue 2 February, 2016.

[9] J. Venkat Nag Someswar Rao, Mahendra Ghat, S. Kumaravel " current harmonic analysis of multi pulse diode rectifiers with Phase shifting transformers" *International Conference on Emerging Trends in Engineering(ICETE)* 2011.

[10] Deependra Singh , Prof. Hemant Mahala , Prof. Paramjeet Kaur "Modeling & Simulation of Multi-Pulse Converters for Harmonic Reduction" *International Journal of Advanced Computer Research* (ISSN (print): 2249-7277 ISSN (online): 2277-7970) Volume-2 Number-3 Issue-5 September-2012.

[11] CHEN XIAO-QIANG, HAO CHUN-LING, QIU HAO, LI MIN "Thirty-six pulse rectifier scheme based on zigzag auto-connected transformer" *ARCHIVES OF ELECTRICAL ENGINEERING (AEE)* VOL. 65(1), pp. 117-132 (2016).

[12] Ms.Shruti Gour, Mr .Saurabh Gupta "Comparative Analysis of Multipulse AC-DC Converter Using Zig-Zag Transformer" *IOSR Journal of Engineering (IOSRJEN)* e-ISSN: 2250-3021, p-ISSN: 2278-8719 Vol. 3, Issue 7 (July. 2013), ||V5|| PP 38-42.

[13] Rohollah Abdollahi "Pulse doubling in ziz-zag connected auto transformer-based 12-pulse AC-DC converter for power quality improvement" *Journal of ELECTRICAL ENGINEERING*, VOL. 63, NO. 6, 2012, 357–364.

[14] Amarendra Pandey, Rakesh Narvey and Praveen Bansal "3-ϕ Multi-Pulse Ac To Dc Converter Through Zig Zag Transformer" *International Journal of Signal Processing, Image Processing and Pattern Recognition* Vol.8, No.7 (2015), pp.235-242.

[15] J. Wen, H. Qin, S. Wang, B. Zhou, "Basic connections and strategies of isolated phase-shifting transformers for multi pulse rectifiers: A review", in *Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC)*, pp.105-108, 21-24 May 2012.

[16] S. Iida, S. Masukawa, Y.Kubota, "Improved voltage source inverter with 18-step output waveforms," *Industry Applications Magazine, IEEE*, vol.4, no.1, pp.58-65, Jan/Feb 1998.

[17] Bhim Singh, Sanjay Gairola, Brij N. Singh, Ambrish Chandra, and Kamal Al-Haddad, Multi pulse AC–DC Converters for Improving Power Quality, *A Review IEEE Transaction on power electronics*, vol. 23, Issue 1, pp.206-275, 2008.

[18] Hussein A. Kazem "Harmonic Mitigation Techniques Applied to Power Distribution Networks" *Hindawi Publishing Corporation Advances in Power Electronics* Volume 2013, Article ID 591680.