

## Design of Phase-Shifting Transformer Based on Simulink Matlab Simulation

<sup>a</sup>I Made Wiwit Kastawan\*, <sup>a</sup>Erwin Yusuf, <sup>a</sup>Affif Fadhilah

<sup>a</sup>Department of Energy Conversion Engineering, Politeknik Negeri Bandung, Bandung 40559, Indonesia

Received 2 July 2019; accepted 25 September 2020

### ABSTRACT

Using variable speed drive for controlling speed of three-phase induction motor in industrial sector gives an advantage of reducing consumption of electrical energy; on the other hand, it also causes a disadvantage of source current harmonic. To solve the problem of source current harmonic, a method of using phase-shifting transformer is applied. This method may be applied in a system with two VSDs or more connected to a three-phase power supply. The application of this phase-shifting transformer method could be as simple as using of two transformer with Y-y (wye-wye) and Y-d (wye-delta) three-phase winding connections to give a phase-shifting of 30° or more complex as it uses two transformer with Y-y and Y-z (wye-zigzag) three-phase winding connections to give a phase-shifting less than 30°. This paper proposes design of five different phase-shifting transformer configurations to produce 30°, 20°, 15°, 12° and 10° phase-shifting. Simulation on a computer-based software, Simulink Matlab, then confirmed that the proposed phase-shifting transformer design gives a very accurate result regarding to phase-shifting and magnitudes of input and output voltage of the phase-shifting transformers.

### KEYWORDS

Current harmonic  
Phase-shifting  
Simulation  
Three-phase  
Transformer

## INTRODUCTION

Harmonic in an electrical power system is mainly caused by the use of non-linear loads. Personal computer, LED lamp, LED tv, air conditioning and fridge with inverter technology and battery charger are several examples of non-linear load. When a non-linear load is connected to a power source, a non-sinusoidal source current waveform that contains harmonics will be drawn (Harrison, 2010). The more distorted the current waveform from sinusoidal, the higher the harmonics content is. Total Harmonic Distortion (THD), expressed in percent, is a parameter commonly used to indicate the harmonics content of a non-sinusoidal current waveform. THD is a measured of effective value of harmonics of a distorted current waveform (Rashid, 2011). The higher THD means the higher harmonics content will be. VSD is a kind of non-linear load massively used in industrial sector, and it is used to control speed of three-phase induction motor, an electrical motor widely used in industrial process. Using VSD gives a main advantage of reducing electrical energy consumption; therefore, it increases the efficiency of the industrial

\*Corresponding Author: [wiwit.kastawan@polban.ac.id](mailto:wiwit.kastawan@polban.ac.id)

process. Moreover, it has been well recognized that VSD has become the major source of harmonics in an industrial electrical power system (Bambiso and Kusakana, 2018), (Robak et al., 2016), (Saidur et al., 2012).

Harmonics due to the use of VSD may give negative effects to electrical power devices or installation of an industrial electrical power system. Those negative effects are: reduction in efficiency of electrical power devices and installation, unwanted circuit resonance, overheat on transformer and cable, motor and generator malfunction, neutral current flow in a three-phase four wire circuit, circuit breaker malfunction or fuse explosion (Pinyol, 2011). High frequency harmonics will significantly reduce reactance of a power capacitor, so it results in poor electrical system power factor. Furthermore, present of harmonics will increase copper and core losses of motor and transformer (Davudi et al., 2011). Considering all those negative effects, some efforts to reduce or eliminate harmonics are required. Various methods have been proposed to reduce or to eliminate harmonics among others are: the use of passive filter, active filter, reactor (ac line or dc link) and phase-shifting transformer. The passive filter method is based on resonance circuit principle. A passive filter basically consists of a connection of inductor and capacitor that have been adjusted to work on certain frequency to pass only harmonic at this working frequency (Pinyol, 2011). The advantages of using passive filter are less costly, relatively simple circuit and could also be used to improve power factor. Meanwhile, disadvantages of using passive filter are requiring computer-based software to analyze and to determine harmonics to be eliminated. Not complying with standard of IEEE 519-1992 guidelines, may cause leading power factor and it needs many passive filters for eliminating many harmonics (Abdelaziz, 2012). Solving harmonic problem by using active filter is based on principle of generating opposite waveform to eliminate harmonic waveform (Pinyol, 2011). Advantages of using active filter are: it is free from resonance problems, it complies with standard of IEEE 519-1992, and it has wide range of harmonic elimination and ability to provide reactive power compensation. Meanwhile disadvantages of using active filter are: they are expensive, in particular for serial type active filter, and demand hard maintenance (Abdelaziz, 2012). The phase-shifting transformer method is specially developed for solving harmonic problem due to the use of three-phase rectifier. Moreover, phase-shifting transformer may also serve as voltage changer and provide isolation between rectifier unit and power supply (Gamit and Chaudhari, 2016). The phase-shifting transformer method is used in a multi rectifier system where more than one three-phase rectifier units are installed. Method of preference to be used is based on considerations of harmonics to being reduced or eliminated, and the complexity of circuit and cost incurred.

In case of source current harmonics generated by using of VSD, the most appropriate method is using of phase-shifting transformer. As it has been explained, phase-shifting transformer method is originally developed for reducing source current harmonics generated by using of three-phase rectifier. Considering that a VSD basically consists of a three-phase rectifier at the ac input side, a dc regulator at the intermediate side and a three-phase inverter at the ac output side, then phase-shifting transformer method gets suitable to solve the source current harmonics problems due to the use of VSD (Rashid, 2011). There are two phase-shifting transformer groups that are commonly used in a multi rectifier system, namely; Y-z and D-z then, the Y-y, Y-d, D-y and D-d groups (Gamit and Chaudhari, 2016).

This paper explains the design of two groups of phase-shifting transformer that are: Y-d and Y-z. It is clear that both phase-shifting transformers have the same three-phase primary winding connection i.e. wye while its three-phase secondary winding is connected to either in delta or zigzag. The design consists of two major steps, the first step is, calculating the voltage ratio between primary and secondary windings of the transformer to give the expected phase-shifting and the second step is, verifying it on Simulink Matlab, computer-based simulation software.

## SOURCE CURRENT HARMONIC DUE TO THE USE OF VSD

As it has been explained previously, VSD basically is a device that consists of three types of power converter, namely: three-phase rectifier, dc regulator and three-phase inverter at its input, intermediate and output sides respectively. Another kind of VSD may use single-phase rectifier instead of three-phase. However, in most industrial applications VSD with three-phase rectifier is commonly used (Toshiba, 2012). Having three-phase rectifier at the input side then source or input side current of VSD will be the same as source current of a three-phase rectifier. Figure 1 shows the topology of a three-phase rectifier, also known as a six-pulse rectifier, while Figure 2 shows a typical source current waveform for phase R ( $i_R$ ) (Kastawan, 2017). The same source current waveforms but with phase shifted by  $120^\circ$  and  $240^\circ$  flow in the remaining phases S and T respectively. The result of a simulation running on Simulink Matlab shows that the distorted source current waveform in Figure 2 has a harmonics spectrum shown in Figure 3 (Mahar, 2011). This harmonics spectrum is similar to normalized current harmonic magnitudes given in Table 1 (Nsir, 1985). Referring to Figure 3 and Table 1, it can be seen that the magnitudes of the 5<sup>th</sup> and 7<sup>th</sup> current harmonics are significantly higher than other harmonic orders. The 5<sup>th</sup> and 7<sup>th</sup> current harmonics show to be the dominant harmonic orders. Also, the higher the current harmonic order, the lower the magnitudes.

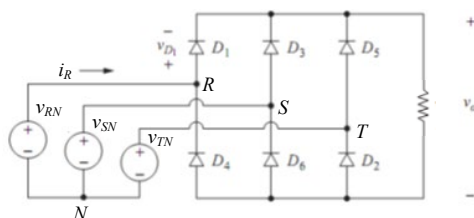
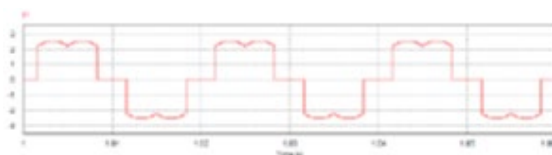


Figure 1. Topology of three-phase rectifier



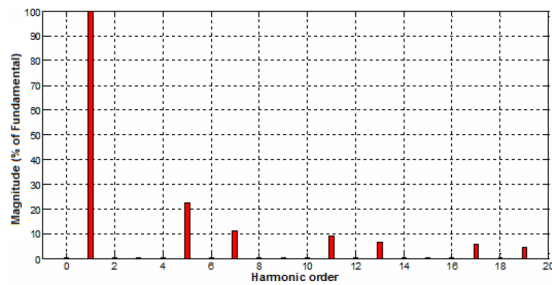


Table 1. Source current harmonics normalized to its fundamental of a three-phase rectifier

Harmonic order	Normalized value
5 <sup>th</sup>	0.200
7 <sup>th</sup>	0.143
11 <sup>th</sup>	0.091
13 <sup>th</sup>	0.077
17 <sup>th</sup>	0.059
19 <sup>th</sup>	0.053
23 <sup>rd</sup>	0.043
25 <sup>th</sup>	0.040

Figure 4 shows two three-phase rectifiers connected in parallel by a transformer that has two different secondary winding connections i.e. y (wye) and d (delta). This structure is commonly known as twelve-pulse rectifier. Using of two different secondary winding connections (y and d) instead of using two same ones (y and y) is aimed to give a phase-shifting of  $30^\circ$ . Therefore, source current waveform for phase R ( $i_R$ ) now becomes resultant of current waveforms for phase R of y secondary winding connection ( $i_{Ry}$ ) and d secondary winding connection ( $i_{Rd}$ ). The source current waveform for phase R of this twelve-pulse rectifier is shown in Figure 5 (Kastawan, 2017). This relatively lighter distorted source current waveform contains harmonics represented by equation (1) below (Rashid, 2011), (Pyakuryal and Matin, 2013).

$$i_R = 2 \left( \frac{2\sqrt{3}}{\pi} \right) I_D (\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \dots) \quad (1)$$

Series in equation (1) shows that current harmonics with orders of  $12k \pm 1$ , where  $k$  is integer 1,2,3, ..., are emerged. The 5<sup>th</sup>, 7<sup>th</sup>, 17<sup>th</sup> and 19<sup>th</sup> current harmonic orders in source current waveform of a six-pulse rectifier are now eliminated. Furthermore, higher multi-pulse rectifier, for example eighteen-pulse rectifier, twenty four-pulse rectifier, thirty-pulse rectifier and others contain much lower harmonics. In general,  $n$ -pulse rectifier, with  $n$  is multiple of six i.e. 6, 12, 18, 24, ..., generate harmonic orders of  $nk \pm 1$  (Rashid, 2011). To develop multi-pulse rectifier using of phase-shifting transformer is inevitable. Meanwhile for twelve-pulse rectifier, as explained above, two transformers with phase-shifting of  $30^\circ$  are necessary. For eighteen-pulse rectifier, twenty-four-pulse rectifier, thirty-pulse rectifier and others, three, four, five, and other transformers with phase-shifting of  $20^\circ$ ,  $15^\circ$ ,  $12^\circ$ , and others are necessary. The design of transformer to give these various phase-shifting is described in the next section.

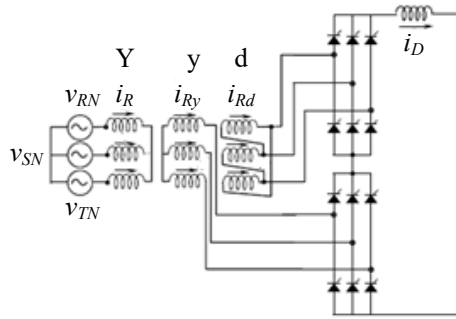


Figure 4. Two three-phase rectifiers connected through y and d transformers

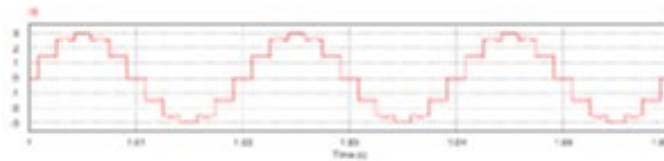


Figure 4. Source current waveform for phase R of a twelve-pulse rectifier

**PHASE-SHIFTING TRANSFORMER DESIGN**

All phase-shifting transformers described in this paper have primary three-phase windings connected in Y while the secondary three-phase windings may be connected either in d (delta) or in z (zigzag).

**The Y-d connection**

As they have been shown in Figure 6 (a) and (b), two kinds of d connection of secondary three-phase windings of transformer are possible. These two d connections give different phase-shifting as shown by phasor diagram in Figure 7. The Y-d<sub>1</sub> connection gives a positive 30° phase-shifting which means that secondary V<sub>ab</sub> voltage leads primary V<sub>AB</sub> voltage by 30°. Whereas, the Y-d<sub>2</sub> connection gives a negative 30° phase-shifting which means that secondary V<sub>ab</sub> voltage lags primary V<sub>AB</sub> voltage by 30°. Another way to express transformer phase-shifting is by clock notation, in which twelve o'clock represents 0° or 360°. Therefore, the Y-d<sub>1</sub> and Y-d<sub>2</sub> connections are expressed as Y-d<sub>1</sub> and Y-d<sub>11</sub> respectively (Ikheola and Aibangbee, 2019).

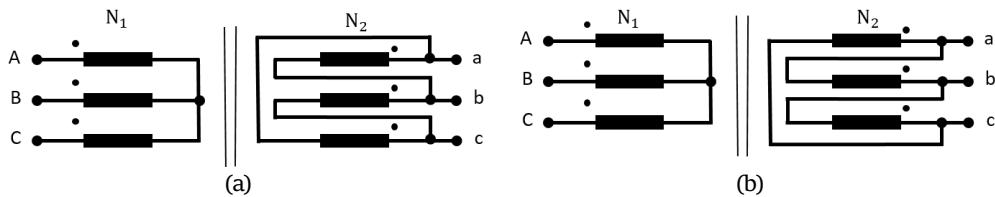


Figure 6. Two d connections of transformer secondary windings (a) Y-d<sub>1</sub> and (b) Y-d<sub>2</sub>

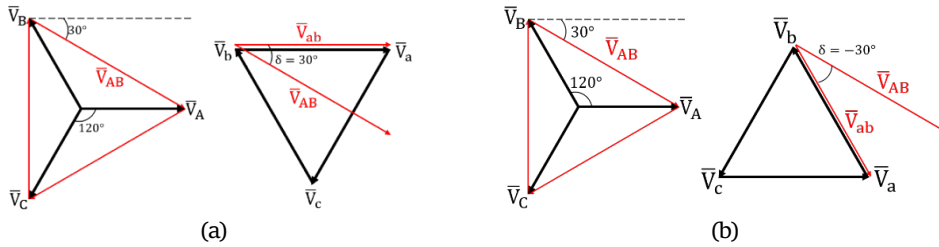


Figure 7. Phasor diagram for (a) Y-d<sub>1</sub> and (b) Y-d<sub>2</sub>

**The Y-z connection**

Being similar to d connection, two kinds of z connection of secondary three-phase windings of transformer are also possible. Figure 8 shows both of these z connections. It has been shown previously that the Y-d connection gives constant phase-shifting of  $\pm 30^\circ$ . It will be shown shortly that variable phase-shifting could be obtained for Y-z connection by adjusting voltages ratio  $V_P$  and  $V_Q$  of secondary windings  $N_2$  and  $N_3$ . Figure 9 illustrates how this voltages ratio results in variable phase-shifting of the transformer. Figure 9 (a) shows phasor diagram of secondary windings of Y-z<sub>1</sub> transformer and illustration of its phase-shifting angle,  $\delta$ , to primary voltage  $V_{AB}$ . In Figure 9 (a), voltages ratio  $V_P/V_Q$  of phasor diagram on the right side is bigger than phasor diagram on the left side. However, the phase-shifting angle  $\delta$  of phasor diagram on the right side is smaller than phasor diagram on the left side. Therefore, the voltages ratio  $V_P/V_Q$  of secondary windings of Y-z<sub>1</sub> transformer is inversely proportional to the phase-shifting angle,  $\delta$ . The same condition and rule are applied for Y-z<sub>2</sub> transformer as shown by Figure 9 (b).

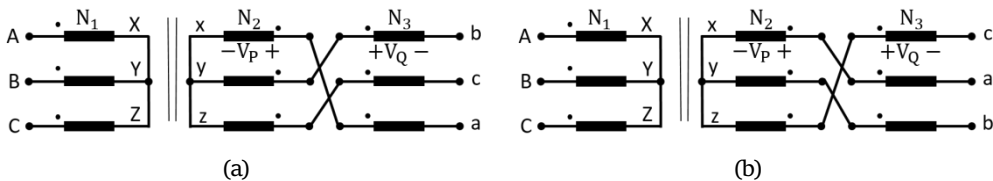


Figure 8. Two z connections of transformer secondary windings (a) Y-z<sub>1</sub> and (b) Y-z<sub>2</sub>

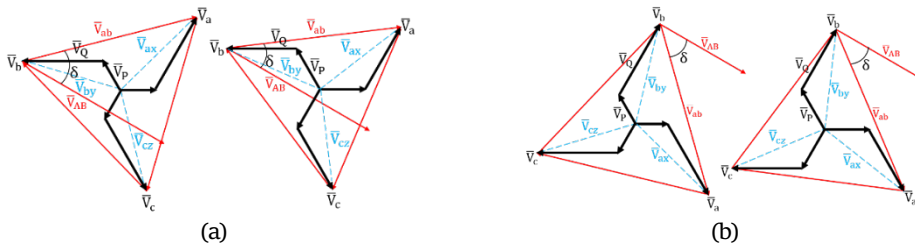


Figure 9. The effect of secondary voltages  $V_P$  and  $V_Q$  ratio to phase-shifting,  $\delta$ , for (a) Y-z<sub>1</sub> and (b) Y-z<sub>2</sub> connections

To determine range of phase-shifting for Y-z<sub>1</sub> and Y-z<sub>2</sub> transformers, the voltages ratio  $V_P/V_Q$  has to be set in minimum and maximum. For Y-z<sub>1</sub> transformers, when  $V_P/V_Q$  is minimum ( $V_P = 0$ ) then  $\delta = 60^\circ$  and when  $V_P/V_Q$  is maximum ( $V_P = 0$ ) then  $\delta = 0^\circ$ . Meanwhile for Y-z<sub>2</sub> transformers, when  $V_P/V_Q$  is minimum ( $V_P = 0$ ) then  $\delta = -60^\circ$  and when  $V_P/V_Q$  is maximum ( $V_P$

= 0) then  $\delta = 0^\circ$ . Therefore, phase-shifting range for Y-z<sub>1</sub> transformer is  $0^\circ - 60^\circ$  meanwhile, phase-shifting range for Y-z<sub>2</sub> transformer is  $-60^\circ - 0^\circ$ . After determining range of phase-shifting angle for Y-z transformer, equation for phase-shifting angle can be derived. Using the phasor diagram shown in Figure 10 (a),  $\alpha$  is angle between  $V_{AB}$  and  $V_{by}$  while  $\beta$  is angle between  $V_{by}$  and  $V_Q$ . Since angle between  $V_{ab}$  and  $V_{by}$  is equal to  $30^\circ$  then relation among all these angles are as follows:

$$\begin{aligned}\delta &= 30^\circ + \alpha \\ \alpha + \beta &= 30^\circ \\ \alpha &= 30^\circ - \beta \\ \delta &= 60^\circ - \beta\end{aligned}\quad (2)$$

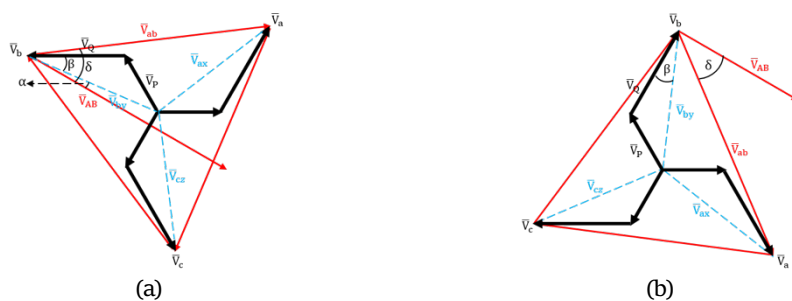


Figure 10. Phasor diagram for (a) Y-z<sub>1</sub> and (b) Y-z<sub>2</sub> connections

Next, the angle  $\beta$  could be determined through triangle relation of  $V_P$ ,  $V_Q$  and  $V_{by}$  as shown in Figure 11 below. Referring to Figure 11 the following equation is obtained:

$$\begin{aligned}\frac{V_P}{\sin \beta} &= \frac{V_{by}}{\sin 120^\circ} \\ V_P &= \frac{V_{by}}{\sqrt{3}/2} \sin \beta\end{aligned}\quad (3)$$

As  $V_{by} = V_{ab}/\sqrt{3}$  (the line to neutral voltage of zigzag transformer) then equation (3) becomes:

$$\begin{aligned}V_P &= \frac{V_{ab}/\sqrt{3}}{\sqrt{3}/2} \sin \beta \\ V_P &= \frac{2}{3} V_{ab} \sin \beta\end{aligned}\quad (4)$$

By substituting  $\beta$  in equation (2) into equation (4) then the following equation is obtained:

$$V_P = \frac{2}{3} V_{ab} \sin(60^\circ - \delta) \quad (5)$$

The next equation can be obtained by making the use of voltage phasors  $V_{X1}$  and  $V_{X2}$  as follow:

$$\begin{aligned}
 V_{X1} &= V_P \sin 60^\circ = V_{by} \sin \beta \\
 V_{X2} &= V_Q \sin 60^\circ = V_{by} \sin(60^\circ - \beta) \\
 \frac{V_{X1}}{V_{X2}} &= \frac{V_P \sin 60^\circ}{V_Q \sin 60^\circ} = \frac{V_{by} \sin \beta}{V_{by} \sin(60^\circ - \beta)} \\
 \frac{V_P}{V_Q} &= \frac{\sin \beta}{\sin(60^\circ - \beta)} \\
 \frac{V_P}{V_Q} &= \frac{\sin(60^\circ - \delta)}{\sin \delta} \\
 V_Q &= V_P \frac{\sin \delta}{\sin(60^\circ - \delta)}
 \end{aligned} \tag{6}$$

By substituting  $V_P$  in equation (5) into equation (6) the following equation is obtained:

$$\begin{aligned}
 V_Q &= \frac{2}{3} V_{ab} \sin(60^\circ - \delta) \frac{\sin \delta}{\sin(60^\circ - \delta)} \\
 V_Q &= \frac{2}{3} V_{ab} \sin \delta
 \end{aligned} \tag{7}$$

Equation (5) and (7) tell that  $V_P$  and  $V_Q$  are both functions of transformer output voltage,  $V_{ab}$ , and phase-shifting angle,  $\delta$ . Thus, by setting the values of  $V_{ab}$  and  $\delta$  the required values of  $V_P$  and  $V_Q$  can be determined.

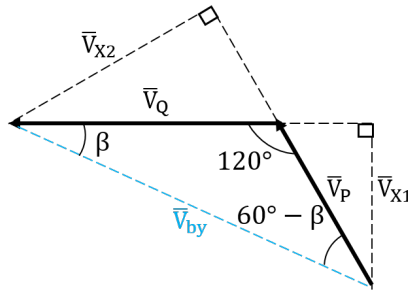


Figure 11. Phasor triangle of  $V_P$ ,  $V_Q$  and  $V_Q$  for Y-z1 transformer

Meanwhile for Y-z<sub>2</sub> transformer shown in Figure 10 (b),  $\beta$  is angle between  $V_{by}$  and  $V_Q$ . The angle between  $V_{AB}$  and  $V_Q$  is equal to  $90^\circ$  ( $V_{AB} = -30^\circ$  and  $V_Q = -120^\circ$ ) and angle between  $V_{ab}$  and  $V_{by}$  is equal to  $30^\circ$ . Relation among all these angles is derived as follows:

$$\begin{aligned}
 \delta + \beta + 30^\circ &= 90^\circ \\
 \delta &= 60^\circ - \beta
 \end{aligned} \tag{8}$$

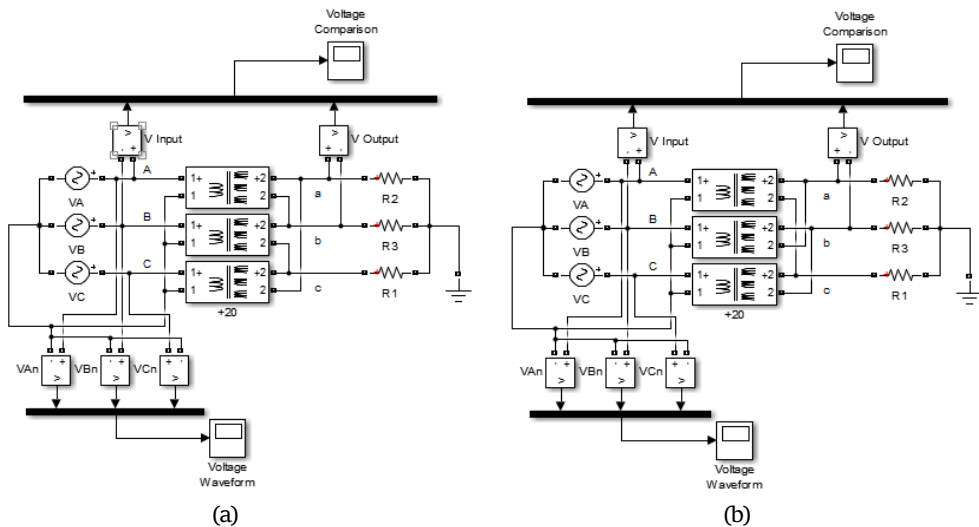
Since the relation between phase-shifting angle,  $\delta$ , and  $\beta$  in equation (8) is identic to equation (2) and relation of triangle phasor  $V_P$ ,  $V_Q$  and  $V_{by}$  of Y-z<sub>1</sub> transformer is also identic to that of Y-z<sub>2</sub> transformer then equation (4) and (6) apply for both Y-z<sub>1</sub> and Y-z<sub>2</sub> transformers.

## SIMULATION RESULTS AND ANALYSIS

The simulation runs on computer-based simulation software, Simulink Matlab 2015a. The phase-shifting is simulated for four different transformer configurations, those are: Y-d<sub>1</sub>, Y-d<sub>11</sub>, Y-z<sub>1</sub> and Y-z<sub>2</sub>. The simulation circuits are shown in Figure 12. Specifications of three-phase primary source voltage for the transformer are:

$$\begin{aligned} V_A &= 220\sqrt{2} \sin 100\pi t \\ V_B &= 220\sqrt{2} \sin(100\pi t + 2\pi/3) \\ V_C &= 220\sqrt{2} \sin(100\pi t - 2\pi/3) \end{aligned} \quad (9)$$

After running the simulation, three main parameters are observed i.e. phase-shifting magnitude, direction of phase-shifting and difference between the rms values of input and output voltages. The phase-shifting simulated are those that give twelve, eighteen, twenty four, thirty and thirty six pulses rectification in which two, three, four, five and six transformers respectively are required.



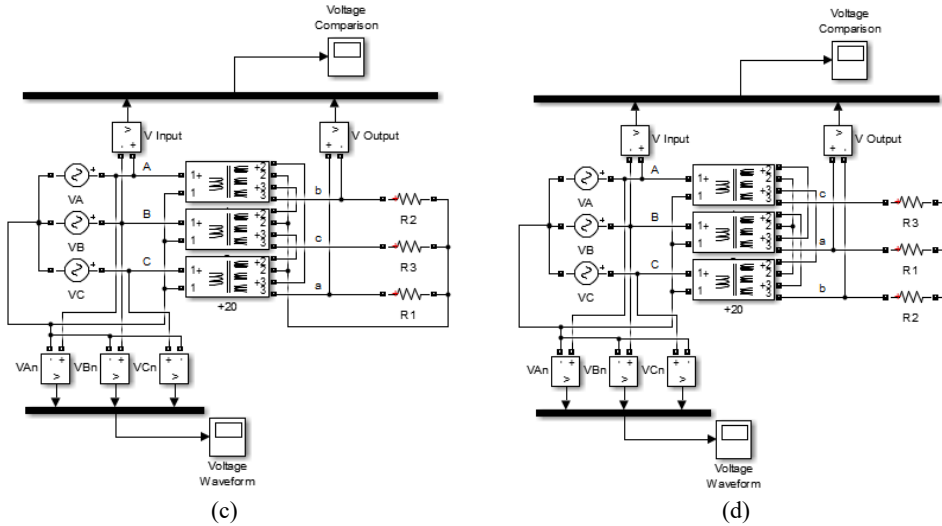


Figure 12. Circuit for simulating phase-shifting of transformer with secondary windings connected in (a)  $d_1$ , (b)  $d_{11}$ , (c)  $z_1$  and (d)  $z_2$

### Phase-shifting of twelve-pulse rectifier

Twelve-pulse rectifier required two transformers to give  $30^\circ$  phase-shifting. A Y-y transformer and a Y-d transformer, either Y- $d_1$  or Y- $d_{11}$ , could be used for this purpose. In order to have line to line output voltage ( $V_{oLL}$ ) that is equal to line to line input voltage ( $V_{iLL}$ ), the ratio of primary and secondary winding voltages is calculated as follows:

$$\begin{aligned}
 V_{iLL} &= 220\sqrt{3} \\
 V_{Primary} &= V_{iLN} = 220 \\
 V_{Secondary} &= V_{oLL} = 220\sqrt{3} \\
 \text{Therefore, } \frac{V_P}{V_S} &= \frac{220}{220\sqrt{3}}
 \end{aligned}
 \tag{10}$$

in which  $V_{Primary}$  and  $V_{Secondary}$  are the primary and secondary winding voltages of transformer while  $V_{iLN}$  is the line to neutral input voltage. The ratio of primary and secondary winding voltages in equation (10) is used as an input parameter of the simulation. The simulation then generates voltage waveforms shown in Figure 13 below.

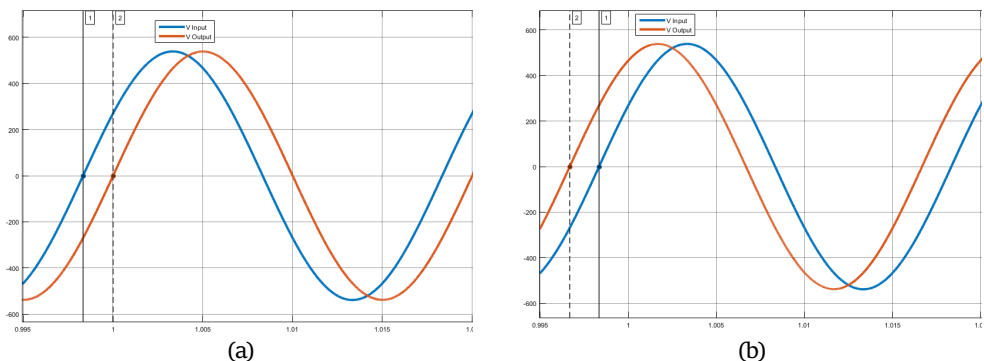


Figure 13. Simulation result shows the phase-shifting of transformer with secondary windings connected in (a)  $d_1$ , (b)  $d_{11}$

Observing voltage waveforms in Figure 13 shows that for  $d_1$  connection the output voltage waveform, represented by sinusoidal waveform colored in red, lags behind the input voltage waveform, represented by sinusoidal waveform colored in blue. On the other hand, for  $d_{11}$  connection the output voltage waveform leads the input voltage waveform. Time difference between input and output voltages is displayed as  $\Delta T$  in the cursor measurements column. Figure 14 shows the values of  $\Delta T$  of voltage waveforms in Figure 13.

Time (seconds)		Value
1	0.998	957.491 p
2	1.000	-1.178 n
$\Delta T$	1.671 ms	$\Delta V$ 2.136 n
1 / $\Delta T$		598.265 Hz
$\Delta V / \Delta T$		1.278 V/MS

(a)

Time (seconds)		Value
1	0.998	995.083 p
2	0.997	-1.598 $\mu$
$\Delta T$	1.665 ms	$\Delta V$ 1.599 $\mu$
1 / $\Delta T$		600.733 Hz
$\Delta V / \Delta T$		960.375 V/MS

(b)

Figure 14. Time difference between input and output voltages of transformer with secondary windings connected in (a)  $d_1$ , (b)  $d_{11}$

The time difference,  $\Delta T$ , is then converted into phase-shifting angle,  $\delta$ , by the following formulation:

$$\delta = \frac{\Delta T}{T} \times 360^\circ \tag{11}$$

For  $T = 20$  ms, the phase-shifting of  $d_1$  will be equal to  $30.08^\circ$  while the phase-shifting of  $d_{11}$  will be equal to  $-29.97^\circ$ . Next, from the signal statistics column, the difference between magnitudes of input voltage and output voltage can be calculated. Referring to Figure 15 below, the difference between magnitudes of input voltage and output voltage for both  $d_1$  and  $d_{11}$  connections is about 0.314 V.

V Input		V Output		V Input		V Output	
Signal Statistics		Signal Statistics		Signal Statistics		Signal Statistics	
	Value		Value		Value		Value
Max	538.888	Max	538.521	Max	538.888	Max	539.007
Min	-538.888	Min	-538.441	Min	-538.888	Min	-538.376
Peak to Peak	1.078 k	Peak to Peak	1.077 k	Peak to Peak	1.078 k	Peak to Peak	1.077 k
Mean	431.527 $\mu$	Mean	21.320 m	Mean	431.527 $\mu$	Mean	233.944 m
Median	-1.111 m	Median	14.052 m	Median	-1.111 m	Median	239.971 m
RMS	381.051	RMS	380.737	RMS	381.051	RMS	380.737

Figure 15. The input and output voltage values of transformer with secondary windings connected in (a)  $d_1$ , (b)  $d_{11}$

All simulation results above are then summarized in Table 2 below.

Table 2. Simulation results of phase-shifting of two transformers configuration

$\delta_{set}$	Secondary windings connection	$\Delta T$ (ms)	$\delta_{simulation}$	$V_{ab(rms)}$ (V)	% difference	
					$\delta_{difference}$	$V_{difference}$
$30^\circ$	$d_1$	1.67	$30.08^\circ$	380.74	0.27	0.08
$-30^\circ$	$d_{11}$	1.66	$-29.97^\circ$	380.74	0.10	0.08

### Phase-shifting of eighteen-pulse rectifier

Eighteen-pulse rectifier requires three transformers that give  $20^\circ$  phase-shifting. A Y-y transformer, a Y- $z_1$  transformer and a Y- $z_2$  transformer may be used for this purpose. Parameters of the Y- $z_1$  and Y- $z_2$  phase-shifting transformers are calculated by equations (5) and (7) and summarized in Table 3 below.

Table 3. Parameters of three phase-shifting transformers configuration

$\delta_{set}$	Transformer windings connection	$V_{Primary(rms)}$ (V)	$V_{Secondary(rms)}$ (V)	
			$V_P$	$V_Q$
$0^\circ$	Y-y	220	220	
$20^\circ$	Y- $z_1$	220	163.29	86.88
$-20^\circ$	Y- $z_2$	220	163.29	86.88

All parameters in Table 3 are used for simulation following the same steps for two phase-shifting transformers described earlier in sub-section 4.1. The results of the simulation are summarized in Table 4 below.

Table 4. Simulation results of phase-shifting of three transformers configuration

$\delta_{set}$	Secondary windings connection	$\Delta T$ (ms)	$\delta_{simulation}$	$V_{ab(rms)}$ (V)	% difference	
					$\delta_{difference}$	$V_{difference}$
$20^\circ$	$z_1$	1.12	$20.07^\circ$	380.76	0.35	0.08
$-20^\circ$	$z_2$	1.11	$-19.93^\circ$	380.76	0.35	0.08

### Phase-shifting of twenty four-pulse rectifier

Scheme of twenty four-pulse rectifier requires phase-shifting of  $15^\circ$ . Therefore, four transformers are needed. For this purposes, a Y-y transformer, a Y-d transformer, a Y- $z_1$  transformer and a Y- $z_2$  transformer should be used. Parameters of the Y- $z_1$  and Y- $z_2$  phase-shifting transformers for this twenty four-pulse rectifier scheme are calculated by equations (5) and (7) and summarized in Table 5 below.

Table 5. Parameters of four phase-shifting transformers configuration

$\delta_{set}$	Transformer windings connection	$V_{Primary(rms)}$ (V)	$V_{Secondary(rms)}$ (V)	
			$V_P$	$V_Q$
$0^\circ$	Y-y	220	220	
$15^\circ$	Y- $z_1$	220	179.629	65.749
$-15^\circ$	Y- $z_2$	220	179.629	65.749
$30^\circ$	Y- $d_1$	220	$220\sqrt{3}$	

Again, all parameters in Table 5 are used for simulation following all general steps described earlier in sub-section 4.1 and the results are summarized in Table 6 below.

Table 6. Simulation results of phase-shifting of four transformers configuration

$\delta_{set}$	Secondary windings connection	$\Delta T$ (ms)	$\delta_{simulation}$	$V_{ab(rms)}$ (V)	% difference	
					$\delta_{difference}$	$V_{difference}$
$15^\circ$	$z_1$	0.84	$15.07^\circ$	380.75	0.47	0.08
$-15^\circ$	$z_2$	0.83	$-14.96^\circ$	380.75	0.27	0.08
$30^\circ$	$d_1$	1.67	$30.08^\circ$	380.74	0.27	0.08

### Phase-shifting of thirty-pulse rectifier

Thirty-pulse rectifier requires five transformers to produce phase-shifting of  $12^\circ$ . To fulfill this need, a Y-y transformer and two Y- $z_1$  transformers as well as two Y- $z_2$  transformers may be used. Parameters of all Y-z phase-shifting transformers are calculated by equations (5) and (7) and summarized in Table 7 below.

Table 7. Parameters of five phase-shifting transformers configuration

$\delta_{set}$	Transformer windings connection	$V_{Primary(rms)}$ (V)	$V_{Secondary(rms)}$ (V)	
			$V_P$	$V_Q$
$0^\circ$	Y-y	220	220	
$12^\circ$	Y- $z_1$	220	188.78	52.82
$-12^\circ$	Y- $z_2$	220	188.78	52.82
$24^\circ$	Y- $z_1$	220	149.32	103.33
$-24^\circ$	Y- $z_2$	220	149.32	103.33

Parameters in Table 7 above are used for simulation. The simulation results are shown in Table 8 below.

Table 8. Simulation results of phase-shifting of five transformers configuration

$\delta_{set}$	Secondary windings connection	$\Delta T$ (ms)	$\delta_{simulation}$	$V_{ab(rms)}$ (V)	% difference	
					$\delta_{difference}$	$V_{difference}$
$12^\circ$	$Z_1$	0.67	$12.08^\circ$	380.75	0.67	0.08
$-12^\circ$	$Z_2$	0.66	$-11.96^\circ$	380.75	0.33	0.08
$24^\circ$	$Z_1$	1.34	$24.07^\circ$	380.76	0.29	0.08
$-24^\circ$	$Z_2$	1.33	$-23.94^\circ$	380.76	0.25	0.08

### Phase-shifting of thirty six-pulse rectifier

Thirty six-pulse rectifier required six transformers to give  $10^\circ$  phase-shifting. Thus, a Y-y transformer, two Y- $Z_1$  transformers, two Y- $Z_2$  transformers and a Y-d transformer are needed. Parameters of all Y-z phase-shifting transformers are calculated by equations (5) and (7) and summarized in Table 9 below.

Table 9. Parameters of six phase-shifting transformers configuration

$\delta_{set}$	Transformer windings connection	$V_{Primary(rms)}$ (V)	$\frac{V_{Secondary(rms)} (V)}{V_P \quad V_Q}$	
			$V_P$	$V_Q$
$0^\circ$	Y-y	220	220	
$10^\circ$	Y- $Z_1$	220	194.60	44.11
$-10^\circ$	Y- $Z_2$	220	194.60	44.11
$20^\circ$	Y- $Z_1$	220	163.29	86.89
$-20^\circ$	Y- $Z_2$	220	163.29	86.89
$30^\circ$	Y- $d_1$	220	$220\sqrt{3}$	

Parameters in Table 9 are then used for simulation and the results are shown in Table 10 below.

Table 10. Simulation results of phase-shifting of six transformers configuration

$\delta_{set}$	Secondary windings connection	$\Delta T$ (ms)	$\delta_{simulation}$	$V_{ab(rms)}$ (V)	% difference	
					$\delta_{difference}$	$V_{difference}$
$10^\circ$	$Z_1$	0.56	$10.08^\circ$	380.75	0.80	0.08
$-10^\circ$	$Z_2$	0.55	$-9.94^\circ$	380.75	0.60	0.08
$20^\circ$	$Z_1$	1.12	$20.07^\circ$	380.76	0.35	0.08
$-20^\circ$	$Z_2$	1.11	$-19.93^\circ$	380.76	0.35	0.08
$30^\circ$	$d_1$	1.67	$30.08^\circ$	380.74	0.27	0.08

Simulation results in Table 2, 4, 6, 8 and 10, show that in general design of the phase-shifting transformers proposed in this paper gives very accurate phase-shifting. The difference ( $\delta_{difference}$ ) between simulated phase-shifting ( $\delta_{simulation}$ ) and intended phase-shifting set ( $\delta_{set}$ ) is relatively small, not more than 1%, with an average of only 0.37%. Moreover, analysis shows that the smaller the  $\delta_{set}$ , the higher the  $\delta_{difference}$ . For  $\delta_{set}$  of  $30^\circ$ ,  $20^\circ$ ,  $15^\circ$ ,  $12^\circ$  and  $10^\circ$ , the average  $\delta_{difference}$  are about 0.23%, 0.35%, 0.37%, 0.5% and 0.7% respectively. In other words, for rectifier with higher number of rectification pulse that required many more of phase-shifting transformers, the difference between simulated phase-shifting and intended phase-shifting set is getting bigger. Simulation results also show that difference between magnitudes of input voltage and output voltage for all phase-shifting transformers configurations is very small and relatively constant at

0.08%, a value that is nearly 0%. Thus, design of the phase-shifting transformers proposed in this paper also gives very accurate result in magnitudes of input voltage and output voltage.

## CONCLUSION

Design of phase-shifting transformer based on simulation on computer-based software, Simulink Matlab, has been proposed. Formulas to determine voltage ratio of primary and secondary windings of the transformers which are to give intended phase-shifting set have been derived. The simulation results then confirmed that the proposed phase-shifting transformer design gives very accurate phase-shifting with only 0.37% in average difference between simulated phase-shifting and intended phase-shifting set. Also, the simulation results confirmed that the proposed design gives very accurate result in magnitudes of input voltage and output voltage of the phase-shifting transformers. The difference between magnitudes of input voltage and output voltage for all phase-shifting transformers configurations is nearly 0%.

## REFERENCES

- Abdelaziz, A. Y. 2012. Technical Comparison of Harmonic Mitigation Technique for Industrial Electrical Power System. Kairo: Ain Shams University.
- Bambiso, S. and Kusakana, K. 2018. Life Cycle Cost Comparison between Motor Equipped with Speed Drive and Dampers for Pumps and Fans. IEEE PES/IAS Power Africa, pp. 931-936.
- Davudi, M., Torabzad, S., and Ojaghi, B. 2011. Analysis of Harmonics and Harmonics Mitigation Methods in Distribution System. Australian Journal of Basic and Applied Science, Vol. 5, pp. 996-1005.
- Gamit, K. and Chaudhari, K. 2016. Multi-Phase Rectifier Using Difference Phase-Shifting Transformer and its THD Comparison for Power Quality Issues. CGPIT, Gujarat, India.
- Harrison, A. 2010. The Effect of Harmonics on Power Quality and Energy Efficiency. Dublin: Dublin Institute of Technology.
- Ikheloa, S. O., Aibangbee, J. O. 2019. Mathematical Modeling of Three-phase Power Transformer Phase-Shift Compensation Differential Protection Using Star/Star Connected Current Transformers. The International Journal of Engineering and Science (IJES), Vol.8, Issue 8, Series I, pp. 73-80.
- Kastawan, I M. W. 2017. Reduction of Three-Phase Source Current Harmonics By Using of Phase-Shifting Transformer (in Bahasa). Prosiding Seminar Nasional Teknoka 2, pp E-24 - E-30. UHAMKA, Jakarta, INDONESIA.
- Mahar, M. A. 2011. Harmonic Analysis of AC-DC Topologies and Their Impact on Power System. Jamshoro: Mehran University of Engineering and Technology.
- Nsir. M. S. 1985. A Study of Three-Phase Bridge Rectifier Line Current Harmonics. Stillwater, Oklahoma State University.
- Pinyol, R. 2011. Harmonics: Causes, Effects and Minimization. (Barcelona: SALICRU White Papers).
- Pyakuryal, S. and Matin, M. 2013 Harmonic Analysis for a 6-pulse Rectifier IOSR Journal of Engineering (IOSRJEN) 3 57-60 Rashid, M. H. 2011. Power electronics handbook : devices, circuits, and applications, Third Edition ed., Burlington: Elsevier Inc.

- Robak, S., Wasilewski, J., Dawidowski, P., and Szewczyk, M. 2016. Variable Speed Drive (VSD) - Toward Modern Industry and Electricity Power System, *Przeład Elektrotechniczny*, 92(6) 207-210.
- Saidur, R., Mekhilef, S., Ali, M. B., Safari, A., and Mohammed, H. A. 2012. Applications of Variable Speed Drive in Electrical Motor energy Savings. *Renewable and Sustainable Energy Reviews*, 16(1) 543-550.
- Toshiba. 2012. Industrial Inverter (For Three-Phase Induction Motor).