Simulation of source current harmonic elimination technique using phase shifting transformer

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Abstract. This paper presents design of phase shifting transformer to reduce source current harmonic generated by using of variable speed drive (VSD) in textile industry. Nine VSDs are used in a stenter machine of a selected textile industry. Each of these VSD generates source current total harmonic distortion (THD) in range of 43.91% to 50.34%, which contains all odd order harmonics except the triplen ones. The first method to reduce this source current harmonic is by using arrangement of three phase shifting transformers, which requires one Yy three-phase winding connection to produce 0° phase shifting, one Yz three-phase winding connection to produce 20° phase shifting and one Yz three-phase winding connection to produce –20° phase shifting. The second method is by using arrangement of nine phase shifting transformers, which requires one Yy three-phase winding connection with 0° phase shifting, four Yz three-phase winding connections with 6.67°, 13.34°, 20° and 26.67° phase shifting respectively and four Yz three-phase winding connections with –6.67°, –13.34°, –20° and –26.67° phase shifting respectively. Simulation results using MATLAB SIMULINK show that source current THD successfully reduced to 1.99% and 1.74% respectively when arrangements of three phase shifting transformers and nine phase shifting transformers are used.

1. Introduction
Variable Speed Drive (VSD) has been widely used to control speed of three-phase ac industrial motors. By using VSD, electrical energy consumption of the motors can be significantly reduced [1-3]. A VSD basically consists of a three-phase diode rectifier unit at the input side to produce dc voltage that is further inverted into a variable three-phase ac output voltage. Conversion of three-phase ac input voltage into dc voltage by the three-phase diode rectifier unit results in a non-sinusoidal source current waveform that contains all odd harmonic orders except the triplen ones [4]. The harmonic content of source current is indicated by the Total Harmonic Distortion (THD) figure [5].

Current harmonic gives negative impacts to electrical power system such as reducing efficiency of electrical power equipment and system, failure of logic circuit operation, overload on transformer, abnormal operation of motor and generator, neutral current flows and maloperation of circuit breaker [6–8]. Obviously measures to overcome these current harmonic problems are needed. In general, these measures can be classified into principle of reduction (mitigation) or elimination (cancellation) of certain current harmonic orders. Numerous methods have been developed based on these principles, among them is the use of phase shifting transformer [6].
Handling current harmonic using phase shifting transformer is based on elimination (cancellation) of certain current harmonic orders principle. It is in particular very suitable for handling source current harmonic problem produced by three-phase diode rectifier. Initially phase shifting transformer is used to give multi-pulse rectification of dc output voltage. Then it is found that using phase shifting transformer gives other benefits as well including magnetic isolation and source current harmonic elimination. Although application of phase shifting transformer for supplying VSD unit may not give multi-pulse rectification of dc output voltage, it will fix the source current waveform to be closer to sinusoidal, thus reducing its harmonic content. The available arrangements or connections of three-phase transformer to achieve specific phase shifting are Yy, Yd, Dy, Dd, Yz, and Dz [9].

2. Method

2.1. Observation
Observation is made to gather source current harmonic data generated by using of VSD in industry. Textile industry is the kind of industry being selected to carry out this observation, since a lot of use of VSD in it. Textile industry is one of the main industries in Indonesia with approximately 16 – 17 MTOE (Million Ton Oil Equivalent) of annual energy-use in 2017 – 2019 [10]. The textile industry can be divided into several sectors, one of them is the wet-processing textile industry which has several processes to run including pre-treatment, dyeing and finishing [11]. One of the process with highest energy-use and a lot of VSD use is the finishing process (also known as heat setting) to heat the fabric after being dyed in an equipment called stenter [12]. Thus, stenter equipment becomes the particular object being observed in this paper.

2.2. Source current harmonic handling method
The source current harmonic handling performed in this paper is based on the multi-pulse rectification method arranged from multiple parallel six-pulse rectifiers. The six pulse rectifier itself generates source current, which contains harmonics of the order of 5th, 7th, 11th, 13th and so on as presented in the Fourier series in equation (1) below [13] and [14].

$$i_A = \frac{2\sqrt{3}}{\pi} I_d \left( \cos \omega t - \frac{1}{5} \cos 5\omega t + \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + \cdots \right)$$

(1)

Meanwhile, the arrangement of multi-pulse rectifier, with n pulse dc output voltage, will only generate source current harmonics in order that meet the general equation of $nk \pm 1$, with k as an integer. For example, the arrangement of 12 pulse rectifier with Yy and Yd transformers to have 30° phase shifting, will generate source current harmonics in order of 11th, 13th, 23rd and so on that meet the Fourier series equation below.

$$i_A = 2 \left( \frac{2\sqrt{3}}{\pi} \right) I_d (\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \cdots )$$

(2)

Phase shifting transformers used for supplying VSDs work in a very similar principle, only the n-pulse rectification cannot be achieved. The source current harmonics generated remain in the same orders. By definition, current harmonic orders generated by the use of phase shifting transformers meet the general equation of 6mk ± 1, where m is the number of phase shifting transformers used.

3. Results and discussion

3.1. Observation result
A stenter in a selected wet-processing textile industry consists of nine drying chambers for the fabric to pass through and being contacted with hot air blown by blowers. There are two blowers in each chamber, and every two blowers are driven by a single VSD. So that the hot air flow system on the stenter is equipped with nine VSDs. All nine VSDs are in parallel and supplied by the same electrical power
source. The harmonics are measured for the source current of each VSD (see Figure 1). The result shows that the source current value for same harmonic order among all nine VSDs are close to each other (see Error! Reference source not found.). The current harmonics average magnitude shown in spectrum is given in Figure 2. Source current harmonic THD for each VSD varies from 43.91% − 50.34%, while the rms value varies from 12.11 − 12.77A.

![Figure 1. Stenter electrical system.](image1)

![Figure 2. Average of nine VSDs source current harmonic spectrum.](image2)

### Table 1. Source current harmonic orders.

| Order | Ch1   | Ch2   | Ch3   | Ch4   | Ch5   | Ch6   | Ch7   | Ch8   | Ch9   | % Fundamental Current |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----------------------|
| 1     | 11.69 | 10.78 | 10.32 | 10.65 | 10.76 | 10.72 | 10.69 | 10.84 | 9.78  | 100                   |
| 5     | 4.97  | 4.71  | 4.58  | 4.86  | 4.70  | 4.76  | 4.73  | 4.77  | 4.86  | 44.70                 |
| 7     | 1.95  | 1.96  | 1.94  | 2.08  | 1.92  | 1.94  | 1.93  | 1.98  | 2.23  | 18.68                 |
| 11    | 0.59  | 0.50  | 0.42  | 0.49  | 0.49  | 0.48  | 0.50  | 0.49  | 0.42  | 4.54                  |
| 13    | 0.32  | 0.31  | 0.29  | 0.34  | 0.31  | 0.30  | 0.32  | 0.32  | 0.34  | 2.97                  |
| 17    | 0.20  | 0.14  | 0.09  | 0.15  | 0.14  | 0.14  | 0.15  | 0.16  | 0.10  | 1.32                  |
| 19    | 0.18  | 0.19  | 0.18  | 0.18  | 0.19  | 0.20  | 0.16  | 0.18  | 0.13  | 1.65                  |

#### 3.2. Existing simulation
The operation of VSD was being simulated as existing condition using MATLAB SIMULINK. The simulation run with 400V 50Hz three-phase voltage source. VSD block is represented by a six-pulse rectifier and a parallel RC load with resistance and capacitance of 39 Ω and 100 μF respectively. The result shows that source current rms value of each VSD is 12.11A in a non-sinusoidal form shown in Figure 3. The harmonics consist of all odd order except the triplen one with THD equal to 48.29% (see...
Figure 4). The source current rms, harmonics and THD value from simulation meets the real condition. This existing simulation used as a reference to simulate the design of harmonics handling.

3.3. Design of phase shifting transformer for handling source current harmonic due to using of VSD in textile industry

The number of phase shifting transformers used and the phase shifts needed are based on the number of VSD. In order to achieve the optimum source current harmonics reduction, each transformer must be loaded equally. Considering that nine VSDs are used, two arrangement of phase shifting transformers are available namely three and nine transformers arrangements.

3.3.1. Three phase shifting transformers arrangement. In three phase shifting transformers arrangement, a phase shift of 20° is required between each transformer. It is obtained by configuring each transformer with voltage ratio as shown in Table 1.

| Transformer Scheme | Phase Shifting | Primary Voltage | Secondary Voltage |
|--------------------|----------------|-----------------|-------------------|
| Yy                 | δ = 0°         | 230.94V         | 230.94V           |
| Yz(−)              | δ = −20°       | 230.94V         | 171.41V           |
| Yz(+)              | δ = +20°       | 230.94V         | 171.41V           |

Simulation of three phase shifting transformers arrangement results the improvement of source current waveform to be closer to sinusoidal and a significant reduction in its THD. Source current waveforms in this simulation are shown in Figure 5 with THD reduced from 48.29% to 1.99%. The currents value of each harmonic order as a percentage to its fundamental is given in Table 3. Based on these values it is known that the harmonics are significantly decreased from the existing condition, and the most
dominant harmonics order is in the 17th order. It meets the general equation of the harmonics order $6mk \pm 1$.

![Figure 3. Source current waveforms for three phase shifting transformers arrangement.](image)

### Table 2. Current harmonics as the percentage to its fundamental in three phase-shifting transformers arrangement.

| Order | % Fundamental Current |
|-------|-----------------------|
| 1     | 100                   |
| 5     | 1.02                  |
| 7     | 0.57                  |
| 11    | 0.40                  |
| 13    | 0.34                  |
| 17    | 1.15                  |
| 19    | 0.87                  |
| 23    | 0.18                  |
| 25    | 0.17                  |

3.3.2. *Nine phase shifting transformers arrangement.* In nine phase shifting transformers arrangement a phase shift of $6.67^\circ$ is required between each transformer. It can be obtained by configuring each transformer with voltage ratio as shown in Table 3.

### Table 3. Configuration and voltage of primary and secondary windings for each transformer.

| Transformer Scheme | Phase Shifting $\delta$ | Primary Voltage $V$ | Secondary Voltage $V$ |
|--------------------|-------------------------|---------------------|-----------------------|
| $Yy$               | $0^\circ$               | 230.94V             | 230.94V               |
| $Yz(-)$            | $+6.67^\circ$           | 230.94V             | 213.890V 30.973V      |
| $Yz(+)             | $-6.67^\circ$           | 230.94V             | 213.890V 30.973V      |
| $Yz(-)$            | $+13.34^\circ$          | 230.94V             | 193.964V 61.501V      |
| $Yz(+)             | $-13.34^\circ$          | 230.94V             | 193.964V 61.501V      |
| $Yz(-)$            | $+20^\circ$             | 230.94V             | 171.41V 91.20V        |
| $Yz(+)             | $-20^\circ$             | 230.94V             | 171.41V 91.20V        |
| $Yz(-)$            | $+26.67^\circ$          | 230.94 V            | 146.523 V 119.694 V   |
| $Yz(+)             | $-26.67^\circ$          | 230.94 V            | 146.523 V 119.694 V   |

Simulation of nine phase shifting transformers results the current waveforms improvement to be closer to sinusoidal as shown in Figure 6. The harmonics current value as percentage to its fundamental given in Table 4. The reduction of source current THD in nine phase shifting transformers arrangement is more significant than in the three phase shifting transformers arrangement, which drops to 1.74%. Meanwhile, based on Table 4 it is known that overall the current harmonics in this simulation is lower, except in the 5th and 7th orders which actually increased. After these two orders, the dominant current only reappeared in the 53rd and 55th orders.
Figure 4. Source current waveforms for nine phase shifting transformers arrangement.

Table 4. Current harmonics as the percentage to its fundamental in nine phase shifting transformers arrangement.

| Order | 1   | 5   | 7   | 11  | 13  | 17  | 19  | 23  | 25  | 53  | 55  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| % Fundamental Current | 100 | 1.26| 1.17| 0.08| 0.08| 0.03| 0.03| 0.02| 0.02| 0.14| 0.14|

4. Conclusion
Application of VSD as an ac three-phase motor driver in industry, sometimes does not consider yet the negative impacts of source current harmonics generation. It is illustrated in this paper the use of VSD for a stenter blower in a selected textile industry which generates source current harmonics with THD varies from 43.91% - 50.34%. An improvement can be designed to reduce source current harmonics with phase shifting transformers. There are two available arrangements namely the three phase shifting transformers and nine phase shifting transformers for a total number of nine VSDs used in a selected textile industry. Based on the simulation using MATLAB SIMULINK, it is known that the three phase shifting transformers arrangement is able to reduce the source current THD from 48.29% to 1.99%, while the nine phase shifting transformers arrangement is able to reduce the source current THD from 48.29% to 1.74%.

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