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Improvement of Power Quality in VSI Drives

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ABSTRACT
The popular VSI (Voltage source inverters) drives in use today are mostly PWM (pulse width modulated) drives. Harmonics produced by these drives cause heat losses, reduce the efficiency of the machine and also cause vibrations in the rotor. Active and passive filters are some of the methods to reduce the harmonics generated by these drives. A novel method is discussed which not only eliminates the 5th harmonic but also any other negative sequence harmonics. This method, based on a reactor circuit, shows a reduction in harmonics and an improvement in the efficiency of the machine. The method can also reduce negative sequence harmonics produced by other non-linear devices.

The VSI drive with and without the reactor circuit is modeled in ACSL (Advanced Continuous Simulation Language). Simulation results are provided.

Keywords: Adjustable speed drives, harmonic distortion, pulse-width modulation, reactor circuit, simulation and modeling, voltage source inverter.

I. INTRODUCTION
Harmonics cause distortion of voltage and current waveforms and they cause considerable concern to the power system as well as to the customers. The increasing use of adjustable-speed drives (ASD’s) in the industry is prompting a closer look at harmonic distortion.

Harmonic voltage and current distortion in three-phase induction machine drives are discussed. Comparisons are made with and without a reactor circuit meant to reduce or eliminate the fifth harmonic. The behavior of the reactor circuit in the presence of positive sequence, negative sequence and the zero sequence harmonics are also discussed. The reactor circuit is also used with a Brushless DC (BDC) machine and an analysis is made with regard to its losses and efficiency.

II. THE REACTOR CIRCUIT
The concept of a reactor circuit was first introduced in [1]. Fig. 1 shows a basic reactor circuit for a three-phase system. In the figure $E_a$, $E_b$, and $E_c$ represent the three-phase voltage source which is later substituted by the voltage output from a three-phase PWM drive.

Fig. 1 Basic reactor circuit

$E_a$, $E_b$, and $E_c$ represent the line-line voltage. The primary and secondary turns in the transformer shown are “N” and “n” respectively. A series reactance $L$ is used as shown. The output voltage $E_0$ is used to feed the load connected after this circuit. The equation governing the reactor circuit is [1]:

$$K^2 \tau (dE_0/dt) + E_0 = E_{ab} - K \tau (dE_0/dt) \quad (1)$$

Where $K = n/N$ and $\tau = L/R$

The phase sequences of the harmonics are shown in Table 1. The influence of these harmonics on the reactor circuit can be studied using phasor diagrams.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>+ 1,4,7,10,13,16…</td>
</tr>
<tr>
<td>Negative</td>
<td>- 2,5,8,11,14,17…</td>
</tr>
<tr>
<td>Zero</td>
<td>0 3,6,9,12,15,18…</td>
</tr>
</tbody>
</table>

A. CASE I:
Let us suppose that the voltage source consists of a fundamental frequency and a negative sequence harmonic. The phasor diagram of the fundamental (positive sequence) rotates with a speed of $\omega$ rad/sec in the direction of the arrow as shown in Fig. 2a and the nth negative sequence harmonic rotates with a speed of $n\omega$ rad/sec in the direction of the arrow as shown in Fig. 2b. Let the voltage magnitude of $E_{ab}$ be $E_i$ and the voltage magnitude of $E_{nbn}$ be $E_n$. 

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\[ E_{ab} = E_1e^{j\omega t} + E_ne^{jn\omega t} \quad (2) \]
\[ E_c = j(E_1/\sqrt{3})e^{j\omega t} - j(E_n/\sqrt{3})e^{jn\omega t} \quad (3) \]
\[ E_0 = \left[ \frac{1 + (K\tau_0/\sqrt{3})}{1 + jK^2\tau_0 n} \right] E_1e^{j\omega t} + \left[ \frac{1 - (nK\tau_0/\sqrt{3})}{1 + jK^2\tau_0 n} \right] E_ne^{jn\omega t} \quad (4) \]

Eq. (4) is obtained by solving Eq. (1).

This circuit does not reduce the negative sequence harmonics. Moreover they will increase due to the term \( nK\tau_0 \) which is present in the coefficient of \( E_n \). So in order to eliminate the positive sequence harmonics we use other techniques such as passive filters.

C. CASE III

Let us suppose that the voltage consists of fundamental frequency component and an nth order zero sequence harmonic. The phasor diagram of the fundamental voltage and the nth harmonic voltage is shown in Fig. 4. Let the voltage magnitude of \( E_b \) be \( E_1 \) and the voltage magnitude of \( E_{bn} \) be \( E_n \). The equations governing the circuit are shown below.

\[ E_{ab} = \sqrt{3}E_1e^{j\omega t} \quad (8) \]
\[ E_c = j(E_1/\sqrt{3})e^{j\omega t} - j(E_n/\sqrt{3})e^{jn\omega t} - (E_n/\sqrt{3})e^{jn\omega t} \quad (9) \]
\[ E_0 = \left[ \frac{\sqrt{3} + K\tau_0}{(1 + jK^2\tau_0)} \right] E_1e^{j\omega t} - \left[ \frac{nK\tau_0}{(1 + jK^2\tau_0)} \right] E_ne^{jn\omega t} \quad (10) \]

This circuit does not reduce the zero sequence harmonics. The zero sequence harmonic component present in the output voltage cannot be reduced to any great extent. Though small amounts of zero sequence harmonics can be eliminated using this circuit if we connect the output windings of the transformer in a delta connection, this technique is not used to eliminate zero sequence harmonics.

III. PWM-VSI

This drive is used extensively in the industrial drives with different kinds of loads. There is reduction in the amount of distortion on current due to introduction of a series choke into
the circuit [2,3]. The drive used in this case is a three-phase rectifier-inverter bridge based on PWM with 180° operating mode. The 5th harmonic is the major harmonic present in the voltage and current waveforms. A diagram representing the voltage source, converter, inverter and the induction motor is shown in Fig. 5. Dynamic simulations were carried out for the above drive using ACSL [4]. The voltage plot and its harmonic spectrum are shown in Figs. 6a and 6b. The current plot and the corresponding harmonic spectrum is shown in Figs 7a and 7b. Table 2 shows the percentage of harmonic distortion of the significant harmonic present in voltage waveform as introduced by the drive. Table 3 shows the percentage of harmonic distortion of the significant harmonic in the current waveform.

We observe that the 5th harmonic is the most significant harmonic present in the harmonic spectrum and the next significant harmonic present is the 7th harmonic. The same is true with the current harmonic spectrum.

<table>
<thead>
<tr>
<th>Harmonic present</th>
<th>% distortion with respect to fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th Harmonic</td>
<td>19.81%</td>
</tr>
<tr>
<td>7th Harmonic</td>
<td>14.4%</td>
</tr>
<tr>
<td>11th Harmonic</td>
<td>8.9%</td>
</tr>
<tr>
<td>13th Harmonic</td>
<td>7.8%</td>
</tr>
</tbody>
</table>

The THD is 28.8%. The above results were obtained from ACSL simulations [4].
Table 3. Individual harmonic distortion of voltage waveform

<table>
<thead>
<tr>
<th>Harmonic present</th>
<th>% distortion with respect to fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th Harmonic</td>
<td>20.19%</td>
</tr>
<tr>
<td>7th Harmonic</td>
<td>10.33%</td>
</tr>
<tr>
<td>11th Harmonic</td>
<td>4.16%</td>
</tr>
<tr>
<td>13th Harmonic</td>
<td>2.99%</td>
</tr>
</tbody>
</table>

The THD is 23.4%. Above results were also obtained from ACSL simulations.

IV. PWM-VSI WITH THE REACTOR CIRCUIT

The reactor circuit is introduced along with the PWM-VSI as shown in Fig. 8. This circuit eliminates all the negative sequence harmonics. The voltage plot and the harmonic spectrum of the voltage plot after the circuit is introduced is shown in Figs. 9a and 9b. If we look at the voltage waveform in figure 9a it almost looks sinusoidal. The current plot and its harmonic spectrum of the current plot is shown in Figs 10a and 10b. The current plot almost looks sinusoidal except for a harmonic present in it.

Table 4 and 5 show the harmonic distortion of voltage and current waveforms respectively of each significant harmonic as percentages of the fundamental.

Table 4. Voltage harmonic distortion after the introduction of the reactor circuit with R=100 Ohms.

<table>
<thead>
<tr>
<th>Harmonic present</th>
<th>% distortion with respect to fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th Harmonic</td>
<td>2.49%</td>
</tr>
<tr>
<td>7th Harmonic</td>
<td>13.2%</td>
</tr>
<tr>
<td>11th Harmonic</td>
<td>1.54%</td>
</tr>
<tr>
<td>13th Harmonic</td>
<td>2.49%</td>
</tr>
</tbody>
</table>

The THD is 13.9% at R=100 Ohms.

Table 5. Current harmonic distortion after the introduction of the reactor circuit with R=100 Ohms.

<table>
<thead>
<tr>
<th>Harmonic present</th>
<th>% distortion with respect to fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th Harmonic</td>
<td>2.04%</td>
</tr>
<tr>
<td>7th Harmonic</td>
<td>12.72%</td>
</tr>
<tr>
<td>11th Harmonic</td>
<td>0.143%</td>
</tr>
<tr>
<td>13th Harmonic</td>
<td>0.235%</td>
</tr>
</tbody>
</table>

THD after the introduction of reactor circuit is 13.1%.

Fig. 8. PWM-VSI with the reactor circuit.

Fig. 9a. The output voltage waveform from the reactor circuit

Fig. 9a. The harmonic spectrum of output voltage waveform from the reactor circuit
VI. CONCLUSION

The reactor circuit can reduce negative sequence harmonics, reduce copper losses and improve efficiency of the operating load. Though this circuit cannot reduce the positive sequence harmonics, other methods such as passive or active filters can be used to eliminate or reduce these harmonics. For example, a tuned filter can be used along with the reactor circuit to reduce the 7th harmonic - the second most predominant harmonic present in a PWM-VSI drive. To eliminate more than one harmonic, one has to use multiple passive filters.

VII. REFERENCES


Ravi Bantu obtained his B.S degree in Electrical Engineering from Nagarjuna University, AP, INDIA in 1999. He is currently seeking his M.S. degree in Electrical Engineering at the University of Missouri-Rolla. During the summer of 2000, he was a summer intern at Kansas City Power & Light's power generation department. His interests are power system analysis, power electronics and drives.

Badrul H. Chowdhury (SM’91) obtained his M.S. and Ph.D. degrees also in Electrical Engineering from Virginia Tech, Blacksburg, VA in 1983 and 1987 respectively. He is currently a Professor in the Electrical & Computer Engineering department of the University of Missouri-Rolla. From 1987 to 1998 he was with the University of Wyoming’s Electrical Engineering department where he reached the rank of Professor. His industrial experience includes work at the Bonneville Power Administration’s Transmission Planning office where he spent a year on sabbatical leave. Dr. Chowdhury’s research interests are in power system modeling, analysis and control; power electronics and drives. He is a member of Tau Beta Pi and Sigma Xi.