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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.

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From (4) when $nK\tau\omega$ approximately equals $\sqrt{3}$, then the nth harmonic can be eliminated.

### B. CASE II

Let us suppose that the voltage consists of fundamental frequency component and an nth order positive sequence harmonic. The phasor diagram of the fundamental voltage and the nth harmonic voltage is shown in Fig. 3. Let the voltage magnitude of $E_a$ be $E_1$ and the voltage magnitude of $E_{an}$ be $E_n$. The equations governing the circuit are shown below.

\begin{equation}
E_{ab} = E_1 e^{j\omega t} + E_n e^{jn\omega t} \tag{5}
\end{equation}

\begin{equation}
E_c = j(E_1/\sqrt{3}) e^{j\omega t} + j(E_n/\sqrt{3}) e^{jn\omega t} \tag{6}
\end{equation}

\begin{equation}
E_0 = \left[1 + (K\tau\omega/\sqrt{3}) \right]/\left[1 + jK^2\tau\omega n \right] E_1 e^{j\omega t} + \left[1 + (nK\tau\omega/\sqrt{3}) \right]/\left[1 + jK^2\tau\omega n \right] E_n e^{jn\omega t} \tag{7}
\end{equation}

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.

### 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 $E_a$ be $E_1$ and the voltage magnitude of $E_{an}$ be $E_n$. The equations governing the circuit are shown below.

\begin{equation}
E_{ab} = \sqrt{3} E_1 e^{j\omega t} \tag{8}
\end{equation}

\begin{equation}
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} \tag{9}
\end{equation}

\begin{equation}
E_0 = \left[\sqrt{3} + (nK\tau\omega) \right]/\left[1 + jK^2\tau\omega \right] E_1 e^{j\omega t} - \left[\sqrt{3} + (nK\tau\omega) \right]/\left[1 + jK^2\tau\omega \right] E_n e^{j(n\omega t + \pi/3)} \tag{10}
\end{equation}

Due to the above reasons the reactor circuit can be used with circuits, which generate negative sequence harmonics. The other harmonics generated by the non-linear devices can be eliminated using other methods. A study of PWM-VSI and the effects of using this reactor circuit is studied next.

### 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 5\textsuperscript{th} 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 5\textsuperscript{th} harmonic is the most significant harmonic present in the harmonic spectrum and the next significant harmonic present is the 7\textsuperscript{th} harmonic. The same is true with the current harmonic spectrum.

Table 2. 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>5\textsuperscript{th} Harmonic</td>
<td>19.81%</td>
</tr>
<tr>
<td>7\textsuperscript{th} Harmonic</td>
<td>14.4%</td>
</tr>
<tr>
<td>11\textsuperscript{th} Harmonic</td>
<td>8.9%</td>
</tr>
<tr>
<td>13\textsuperscript{th} 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 shows the harmonic distortion of voltage and current waveforms respectively of each significant harmonic as percentages of the fundamental.

Table 5. 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 harmonic spectrum of output voltage waveform from the reactor circuit
RESULTS AND DISCUSSION

The reactor circuit could successfully reduce the negative sequence harmonics (5th and 11th). Comparing Tables 2 and 4, we notice that there is a reduction of 87% in magnitude of 5th harmonic voltage and a reduction of 84% in magnitude of the 11th harmonic voltage. We also notice that there is not much change in the positive sequence harmonics – the 7th and the 13th harmonics. The THD of the voltage reduced from 28.8% to 13.9%. Comparing Tables 3 and 5 we observe that there is a reduction of 90% in the 5th harmonic and 97% in the 11th harmonic. Again, there is not much change in the positive sequence harmonics. The THD of the current has reduced from 23.4% to 13.1%. There is, however, a reduction of fundamental current due to the voltage drop in the reactor circuit.

The ratio of copper losses without the reactor circuit to the case with the reactor circuit is given by the formula $(1+\text{THD}_\text{final})^2/\text{fund} : (1+\text{THD}_\text{final})^2/\text{fund}$. The ratio can be evaluated to 0.40571. Copper loss reduction of 60% was possible with the use of the reactor circuit. Due to the reduction in the copper losses the efficiency of the machine is increased.

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.