Analysis and Design of a Turn-off Snubber Circuit for Four Level SRM Converter

Abstract – This paper presents an optimal RCD snubber design for switched reluctance machines (SRM) drives based on conventional asymmetric and bidirectional converters. The main objective is to improve the performance of drive in wide speed range of operations by reducing the switching power loss using well designed RCD snubber. In order to evaluate the performance of the designed snubber circuit, the effectiveness of the proposed design is validated by both the simulation and experimental results for different operating speeds.

Keywords: Switched Reluctance Drives, Four Level converter, Snubber

1. Introduction

Switched reluctance machine applications in variable speed drives applications is growing in recent years due to its high reliability, low manufacturing and maintenance cost because of its simple and robust structure since they are magnet-free and winding-free in the rotor and also high efficiency in a wide range of speed and torque even at low speeds. By rapidly advent of high efficiency, high-power and low-cost semiconductor switches, as well as advances in integrated circuit technology, this machine is pretty much considered in a wide range of domestic and industrial applications. The snubber circuits have crucial role in power loss optimization of switching components in a switching power supply circuit. Power losses reduction yield to choose appropriate switches more economically. Moreover, snubber circuits have positive impact on the operation of switches such as its turn on and turn off, as well as current and voltage spikes and also its lifetime. Discharged energy of snubber when stored in the load prevents switch damage. In the type of connected inductive load to the switch, a large transient voltage can be located on switch terminals which can create an electrical arc and eventually destroying the switch. This condition can be occurred when the induced currents generated in the switch. Fortunately, by using snubber circuit not only this negatively affect can be minimized, but also it can mitigate the other negative effects. In this paper, the performance of RCD snubber circuit which is one of the most popular snubber circuits in high power applications applied for two type of switched reluctance machines converters.

2. Switched reluctance machines converter

2.1 asymmetric converter

A single phase SRM using conventional asymmetric converter is illustrated in Figure 1. It should be noticed that other phase is connected similarly. This configuration shows that when power is applied, both transistor T1 and T2 should turn on and create a current flow in phase A. In the case that the current is much bigger than reference
value, a control command is applied to T1 and T2 which yield transistors to be turned off. The current is kept in the winding of phase A, until the current is discharged. Due to this reason both diodes (D1, D2) are biased in forward directions and subsequently the DC supply will be charged.

\[ i_{\text{switch}}(t) = \begin{cases} I_L(1 - \frac{t}{t_f}) & 0 \leq t < t_f \\ 0 & t \geq t_f \end{cases} \]  

where \( t_x \) is the time when the capacitor voltage reaches its final value and \( t_f \) is the time that Transistor current reaches zero.

By following the capacitor current value that is obtained in (1), it is possible to calculate the capacitor voltage value as follows:

\[ V_c(t) = \begin{cases} \frac{I_L t^2}{2 C t_f} & 0 \leq t < t_f \\ \frac{I_L}{C} (t - t_f) + \frac{I_L t_f}{2 C} & t_f \leq t < t_x \\ V_f & t \geq t_x \end{cases} \]

The Snubber capacitor value can be obtained as:

\[ V_f = \frac{I_L t_f}{2 C} \Rightarrow C = \frac{I_L t_f}{2 V_f} \]

This method assumes that the value of \( V_f \) is equal to \( V_c \) and thus the capacitor value is obtained as:

3. RCD Snubber circuit Design and its optimization

The current value \( I_L \) is passed through the transistor before it becomes turn off which at this moment its current will drop linearly to converge to zero. While reducing the current through the transistor, Snubber capacitor will pass the current and in this interval the transistor and capacitor current during turning off is shown as [1]:
The design schemes for snubber circuits are taken from [3]. In the case that the switch is off, snubber capacitor voltage will reach to Link Voltage ($V_L$). Here, it is assumed that switch current is changed and decreased linearly with time and the calculation is carried out based on this assumption. The amount of switch energy losses in this situation is related to the size of the snubber capacitor (i.e. $C_s$).

$$C_s = \frac{I_s t_f}{2V_s} \quad (5)$$

Assuming that the current operational region is varied over $(0, I_{\text{max}})$ and the value of the current is defined, the optimization problem can be formulated in these terms as follows:

$$I_s = \frac{2E}{C_s} \quad (9)$$

$$f_{(a)} = \alpha^3 - 18\alpha^2 + 81\alpha - 16 = 0, 0 < \alpha = \frac{I_s}{I_{\text{max}}} < 1 \quad (11)$$

For Switched reluctance machine the operational region of drive is included in the interval of $(I_{\text{min}}, I_{\text{max}})$. In this case the snubber optimization problem can be expressed as follows:

$$\begin{align*}
\min_{W_R} & W_{Q_{\text{off}}} + W_R \\
\text{s.t.} & C_s \left( \frac{I_{\text{on,min}} t_f}{2.3V_s} \right) \\
& W_g = 0.5C_s \cdot V_s^2 \\
& W_R = \text{amount of energy stored in the capacitor that is dissipated in the snubber resistance. The amount of } C_s \text{ will be obtained by substituting the } W_{Q_{\text{off}}} \text{ obtained from (7) to (6) as:}
\end{align*}$$

$$C_s = \frac{4C_n}{9} \quad (8)$$

$$f_{(a)} = 2\alpha^3 - 9(2 - A)\alpha^2 + 8\alpha\sqrt{A} - A^3 = 0 \quad (14)$$

$$A < \alpha = \frac{I_s}{I_{\text{max}}} < 1$$

$$W_R$$ is amount of energy stored in the capacitor that is dissipated in the snubber resistance. The amount of $C_s$ will be obtained by substituting the $W_{Q_{\text{off}}}$ obtained from (7) to (6) as:
If we consider the value of $A$ as:

$$A = \frac{I_{\text{min}}}{I_{\text{max}}}$$  \hspace{1cm} (15)

The value obtained for snubber capacitance is equal to the value obtained from (8), which indicate that the value is obtained accurately. Subsequently, in order to associate snubber capacitor to discharge sufficiently and provide for advance switching, snubber resistance value should be such that the RC circuit well established (by switch turn on), and during the time switch is on, the value of the capacitor voltage entirely reach 0.1 $E$.

### 4. Simulation Results

The simulation is carried out based on the parameter values which are obtained from RCD Snubber design of previous section. Moreover, the switch effective power dissipated curve with presence of snubber and without snubber for conventional asymmetric converter is shown in Fig. 3 and 4 without and with snubber with parameters of $C=2200$ PF, $R=500$.

Snubber for conventional asymmetric converter is shown in Fig 5 and 6.

Switch power losses and switch terminal voltage by performing four-level converter is shown in Figs. 7 to 10 with the snubber parameters as $C=1100$ PF, $R=1000\Omega$.

The simulation results for the voltage across the switch with presence of snubber and without
4. Experimental Results

The proposed snubber circuit used in four-level converter is tested experimentally on the implemented 4 Kw, 280v switched reluctance motor drive. The obtained results are shown in Table 1.

The voltage and current waveforms for two phase of switched reluctance converter is shown in Figs. 11 to 13.

### Table 1

<table>
<thead>
<tr>
<th>A (ampere)</th>
<th>B (voltage)</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>0.65 A</td>
</tr>
<tr>
<td>b</td>
<td>1.32 A</td>
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</table>

### Table 2

<table>
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<tr>
<th>speed (rpm)</th>
<th>Power (w)</th>
<th>Torque (N.m)</th>
<th>Output Power (w)</th>
<th>Without snubber (w)</th>
<th>with snubber (w)</th>
<th>Improve (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>250</td>
<td>2.9</td>
<td>204</td>
<td>11</td>
<td>6.38</td>
<td>42</td>
</tr>
<tr>
<td>1000</td>
<td>255.6</td>
<td>2.1</td>
<td>219</td>
<td>10.23</td>
<td>6.1</td>
<td>41</td>
</tr>
<tr>
<td>1500</td>
<td>350</td>
<td>2</td>
<td>314.3</td>
<td>15</td>
<td>8.85</td>
<td>41</td>
</tr>
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</table>
5. Conclusion

As it is observed in both simulation and experimental result with presence of snubber circuit, the voltage and current spikes can be reduced. Full comparison between two converters is done and is illustrated in Table 2.

1) 42% reduction in the switch power losses (delivered power losses to Snubber circuit)
2) Reduction in outage (turn off) time
3) Reduction or elimination of voltage and current Transient (spike)
4) Speed switching increment capability.

In the operation of new bidirectional converter doubling voltage values must be involved in determination of snubber values in the case of outage time because in this new converter scheme, voltage values are reversed twice. In the case of bidirectional converter, doubling the amount of snubber capacitance and resistance should be considered. It is evident that the switch losses is twice so that this issue restrict the increment on switching speed in comparison with asymmetric converter and also higher switch power loss will cause to reduce the switch lifetime. Consequently, in comparison with conventional asymmetric converter, sufficient and more robust switches in new converter than mode should be selected.

References