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 T_1 and T_2 should *turn* on and create a current flow in phase A. In the case that the current is much bigger than reference

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Received ; Accepted

value, a control command is applied to T_1 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 (D_1, D2) are biased in forward directions and subsequently the DC supply will be charged.

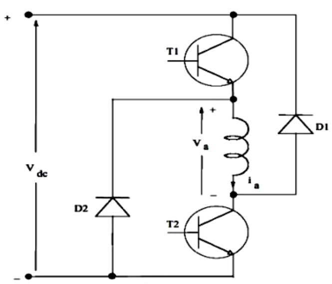

Fig. 1 . Phase A conventional asymmetric converter

2.2 four-level converter

The structure of a four-level converter is shown in figure 2. This converter has the advantage of voltage demagnetization increment up to two times DC-Link voltage by using minimum number of electronic component. Also it has the control capability over related capacitance voltage due to including variable voltage demagnetization. Furthermore, in this scheme, previous converter defects have been eliminated so that the negative voltage demagnetization magnitude constraint in interference angles is removed and also due to reduction in using electrical components and applying a smaller DC-Link capacitance, the size of electrical drive is considerably decreased.

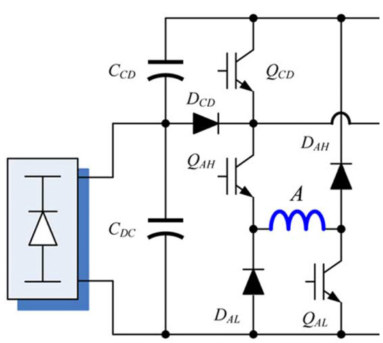

Fig. 1. four-level converter

3. RCD Snubber circuit Design and its optimization

The current value IL 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]:

$$i_{switch}(\mathrm{t}) = \begin{cases} I_L(1-\dfrac{t}{t_f}) & 0 \le t < t_f \\ 0 & t \ge t_f \end{cases} \quad (1)$$

$$i_C(\mathrm{t}) = \begin{cases} I_L - i_{switch}(\mathrm{t}) & 0 \le \mathrm{t} < \mathrm{t}_f \\ I_L & t_f \le t < t_x \\ 0 & t \ge t_x \end{cases} \quad (2)$$

where tx is the time when the capacitor voltage reaches its final value and tf 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:

$$V_C(\mathrm{t}) = \begin{cases} \dfrac{I_L\, t^2}{2\, C\, t_f} & 0 \le t < t_f \\ \dfrac{I_L}{C}(t-t_f) + \dfrac{I_L\, t_f}{2\, C} & t_f \le t < t_x \\ V_S & t \ge t_x \end{cases} \quad (3)$$

The Snubber capacitor value can be obtained as:

$$V_f = \frac{I_L\ t_f}{2\,C} \Rightarrow C = \frac{I_L\, t_f}{2\, V_f} \quad (4)$$

This method assumes that the value of V_f is equal to V_s and thus the capacitor value is obtained as:

$$C = \frac{I_L \, t_f}{2V_S} \qquad (5)$$

The design schemes for snubber circuits are taken from [3]. In the case that the switch is off, snubber capacitor voltage will reaches to Link Voltage (V_s). 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).

$$\begin{aligned} &C_n \rangle C_s \rightarrow W_{Qoff} = 2 * V_S^{\,2} * C_n(.25\beta^2 - .667\beta + .5) \\ &C_n \langle C_s \rightarrow W_{Qoff} = \frac{V_S^{\,2} * C_n}{6\beta^2} \qquad (6) \\ &\beta = \sqrt{\frac{C_s}{C_n}} \end{aligned}$$

As a result, the energy loss over switch outage condition is independent of the Snubber resistance. In fact, an outage snubber circuit which is designed for switched reluctance machines to operate in nominal torque and speed must satisfy the following conditions:

1) Snubber resistance should be selected such that during switching condition, the switch peak current must be less than the diode reverse recovery peak current value.

2) The amount of time that switch must be turned on is so that the capacitor voltage reduced to a minimum 0.1E and then its associate snubber to provide itself for the next switching process.

3) The total energy dissipated in switch and energy stored in the Snubber capacitor must be kept minimum. This criteria and principals are the main issues in designing snubber circuits. Finally, optimization problem can be stated as follows:

$$\begin{cases} \min_{Cs} \quad W_{Qoff} + W_R \\ S.t \quad C_s \langle \dfrac{t_{on,state} I_r}{2.3V_S} \end{cases} \qquad (7)$$

$$W_R = .5 C_s * V_S^{\,2}$$

WR is amount of energy stored in the capacitor that is dissipated in the snubber resistance. The amount of Cs will be obtained by substituting the W_{Qoff} obtained from (7) to (6) as:

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

Assuming that the current operational region is varied over (0, Imax) and the value of the current is defined, the optimization problem can be formulated in these terms as follows:

$$I_s = \frac{2\,E\,C_s}{t_f} \qquad (9)$$

Assuming that the switch outage time is being fi xed, then the mentioned problem can be reduced as:

$$\begin{cases} \min \; W_R I_{\max} + \int_0^{I_x} W_{Qoff\,(C_n<C_s)} dI + \int_{I_s}^{I_{\max}} W_{Qoff\,(C_n>C_s)} dI \\ S.t \quad I_s < \dfrac{t_{on,state}\, I_r}{1.15\, t_f} \end{cases} \qquad (10)$$

The solution of the problem by using the equations techniques is given by:

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

It is noticeable that this value is equal to the value which is obtained from (7).

$$I_s^* = .20694\, I_{\max} \qquad (12)$$

For Switched reluctance machine the operational region of drive is included in the interval of (Imin,Imax). In this case the snubber optimization problem can be expressed as follows:

$$\begin{cases} \min W_R(I_{\max} - I_{\min}) + \int_{I_{\min}}^{I_x} W_{Qoff\,(C_n<C_s)} dI + \int_{I_x}^{I_{\max}} W_{Qoff\,(C_n>C_s)} dI \\ S.t \quad I_s < \dfrac{t_{on,state} I_r}{1.15\, t_f} \end{cases} \qquad (13)$$

After solving the optimization problem, one can obtain:

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

$$\left(A < \alpha = \frac{I_s}{I_{\max}} < 1 \right) \qquad (14)$$

If we consider the value of A as:

$$A = \frac{I_{\min}}{I_{\max}} \tag{15}$$

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 stablished (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.

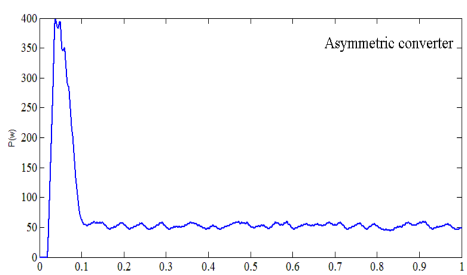

Fig.2. Switch power without snubber

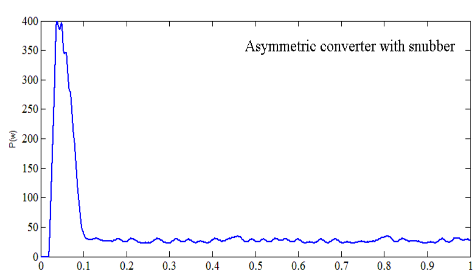

Fig. 4. Switch power with snubber

The simulation results for the voltage across the switch with presence of snubber and without Snubber for conventional asymmetric converter is shown in Fig 5 and 6.

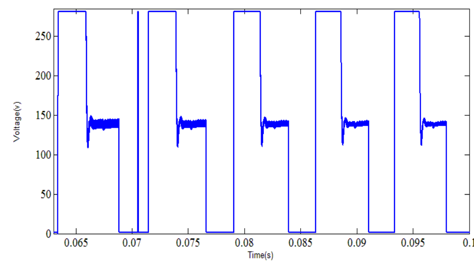

Fig. 5. Switch voltage without snubber

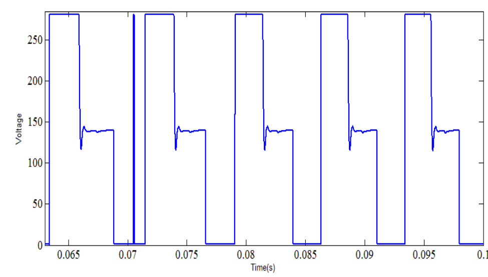

Fig. 6. Switch voltage with snubber

Switch power losses and switch terminal voltage by performing four-level converter is shown in Figs. 7 to10 with the snubber parameters as C=1100 PF , R= 1000Ω.

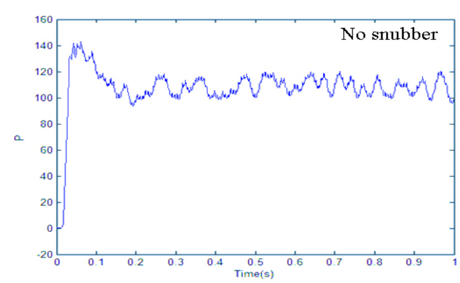

Fig. 3. Switch power without snubber in four-level converter

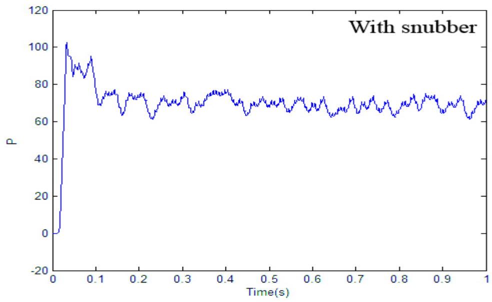

Fig. 4. Switch power with snubber in Bidirectional converter

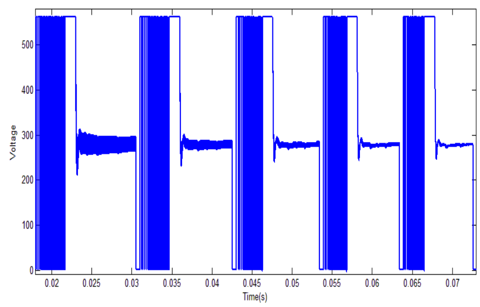

Fig. 5. Switch voltage without snubber in Bidirectional converter

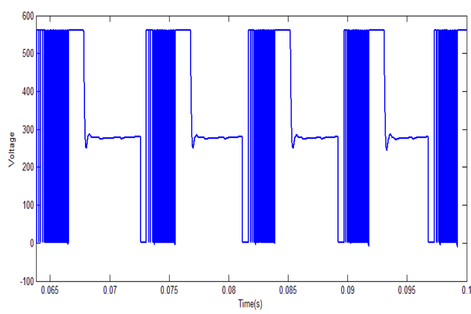

Fig. 6. Switch voltage with snubber in Bi directional converter

Table 1. The caption must be followed by the table

	A (ampere)	B (voltage)
a	0.65 A	0.83 V
b	1.32 A	1.09 V

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.

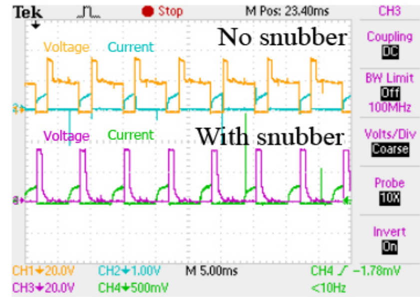

Fig. 7. Switch voltage and current phase a ,b (speed=500 Rpm)

Fig. 8. Switch voltage and current phase a, b (speed=1000 Rpm)

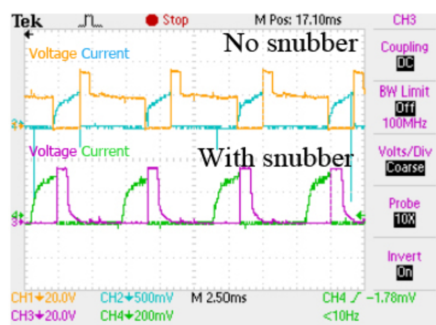

Fig. 9. Switch voltage and current phase a, b (speed=1500 Rpm)

Table 2

speed (rpm)	Power (w)	Torque (N.m)	Output Power (w)	Without snubber (w)	with snubber (w)	Improve (%)
500	250	2.9	204	11	6.38	42
1000	255.6	2.1	219	10.23	6.1	41
1500	350	2	314.3	15	8.85	41

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 (turnoff) 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.

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