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A Novel Converter for Switched Reluctance Motor Drive with Minimum Number of Switching Components

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Abstract: This paper presents a novel converter for switched reluctance motor with reduced number of switches when compared to conventional asymmetrical converter for switched reluctance motor. As the number of switches are reduced, number of gate driver circuits are reduced and as a result switching losses also gets reduced. Comparative analysis of conventional asymmetrical converter with proposed novel converter were discussed in terms of number of switches, number of gate driver circuits, switching losses and volume of heat sink required. Complete operation of proposed novel converter was illustrated with different modes of operation. Simulation model of proposed novel converter for switched reluctance motor was built using MATLAB/SIMULINK software and the results were obtained showing torque, speed, three phase stator currents.

Keywords: Switched reluctance motor (SRM), converter, switching components, asymmetrical.

1. INTRODUCTION

The simplest construction of all the available electrical motors are switched reluctance motor (SRM). SRM consists of windings on its stator part and only salient type metal in its rotor part. No windings are present in rotor. This makes the construction of SRM easy, simple with less cost. High reliability and low cost makes SRM very much applicable to many of the applications [1-3]. SRM, these days is a predominant option as a motor in adjustable speed drive system with minimum cost and high reliability. Due to non-existence of windings on rotor, weight of the rotor part reduces and as a result rotor can rotate at high speeds. SRM finds the applications in high speed drives [4].

SRM is a double salient type machine where both stator and rotor are constructed with salient type steel material. Salient type stator is excited with concentrated coils wounded on it. Core of SRM is laminated in order to reduce eddy current losses. Rotor is a salient type structure but does not consist of any windings on it. When the phase of the stator is excited, the rotor tends to align in low reluctance path. SRM operates on reluctance torque. By switching of phases of SRM, reluctance torque is produced which rotates rotor. The sequence of switching of stator poles decide the direction of rotation in SRM [5-8]. Sequential switching of stator phases rotates the SRM. For reluctance torque to produce for the operation of SRM, the number of stator poles should not be equal to number of rotor poles. Depending on the operation, a designer can design 4/2, 6/4, 8/6 SRM. Numerator denotes the number of stator poles and denominator indicates the number of rotor poles. High torque ripples is the main disadvantage in SRM.

As discussed earlier, the sequential excitation of stator poles makes the rotor rotates as rotor always tries to align in low reluctance path thus producing reluctance torque. For sequential switching of stator poles, SRM needs a front-end converter for its operation. Converter is very crucial in operation of SRM

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drive system. Many converter topologies are available for SRM [9-12]. Converter for SRM consists of power electronic switches to excite the phases of stator in SRM. Information regarding rotor position is very important for the operation of SRM. Rotor position is sensed and fed to controller of converter to produce gate pulses to the static switches in converter for SRM. If stator phases are excited in clockwise direction, the rotation of rotor of SRM will also be in clockwise and if excited in anti-clockwise, rotor rotates in anti-clockwise direction. Sequence of phase excitation decides the direction of rotation of SRM.

This paper illustrates a novel converter topology for SRM drive with minimum number of switches. The new proposed converter is compared with conventional asymmetrical type of converter for SRM. Comparative analysis is tabulated in respect with number of switches used, number of gate drivers needed, and switching losses between conventional asymmetrical converter and proposed novel converter. Results were illustrated for novel converter for SRM describing speed, torque characteristics. Model was developed and results were obtained using MATLAB/SIMULINK software.

2. CONVENTIONAL ASYMMETRICAL CONVERTER FOR THREE-PHASE 6/4 POLE SRM

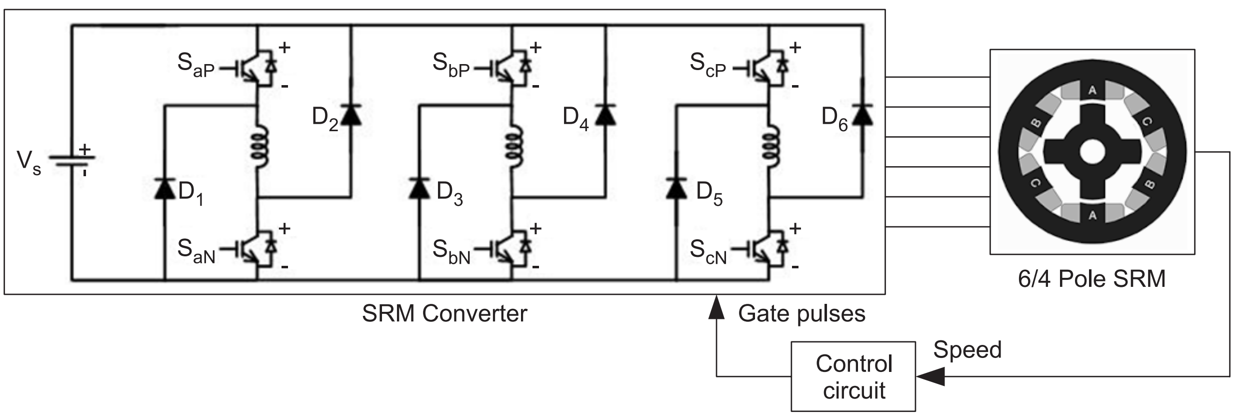


Figure 1: Asymmetrical converter driving SRM

Figure 1 shows the conventional asymmetrical converter for three phase 6/4 SRM. Typical asymmetrical converter consists of six switches operating two at a time to energize a phase of SRM. Asymmetrical converter comprises of two diodes per phase of operation for free-wheeling operation and for discharge. When pair of poles is turned ON, the phase is excited producing flux. Rotor searches for low reluctance path and gets aligned in stator flux axis. The rotor position is fed back to the controller and then the controller produces gate pulses to the power switches in converter. Asymmetrical converter for SRM operates in three modes of operation excitation, freewheeling and de-energizing modes.

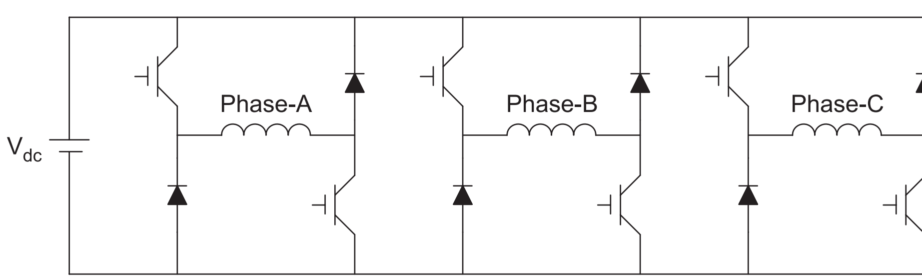


Figure 2: Asymmetrical converter circuit

Mode 1: Phase Excitation

Figure 2 shows the asymmetrical converter circuit. Asymmetrical converter operates in three different modes of operation namely excitation, free-wheeling and de-energizing modes of operation. All the three modes will be same in all three phases of SRM. Only the three modes of operation of asymmetrical converter are illustrated for phase-A and the same operation carries-out for phase-B and phase-C too.

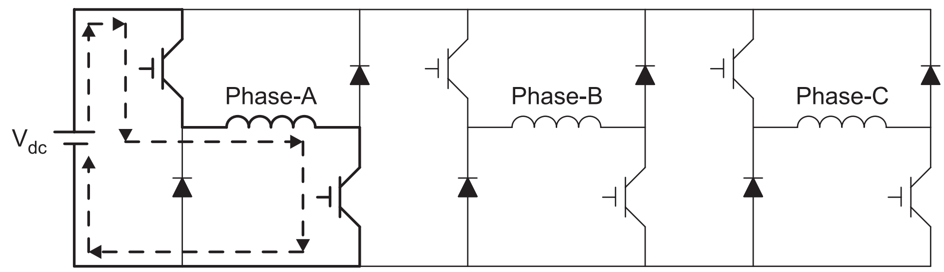


Figure 3: Phase-A excitation of asymmetrical converter

Figure 3 shows phase excitation mode of asymmetrical converter in phase-A. When two power switches corresponding to phase-A, Sap and San are turned ON, the current takes path from source V_{dc} to switch Sap through phase-A and San and circuit closes at negative terminal of V_{dc}. In this mode of operation only switches Sap and San are turned ON and all other power switches are turned OFF. This mode of operation excites phase-A and flux is produced due to excitation of phase-A.

Mode 2: Free-wheeling operation of phase-A

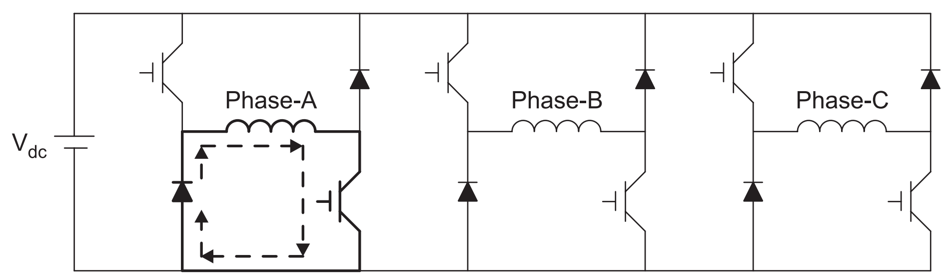


Figure 4: Freewheeling operation of phase-A in asymmetrical converter

In free-wheeling mode of operation, power switch Sap is turned OFF while power switch San is still ON. The stored energy in phase-A due to excitation mode now starts free-wheel through windings of phase-A, San and diode D_1. Figure 4 shows the freewheeling operation of phase-A in asymmetrical converter for SRM.

Mode 3: De-energizing mode of phase-A

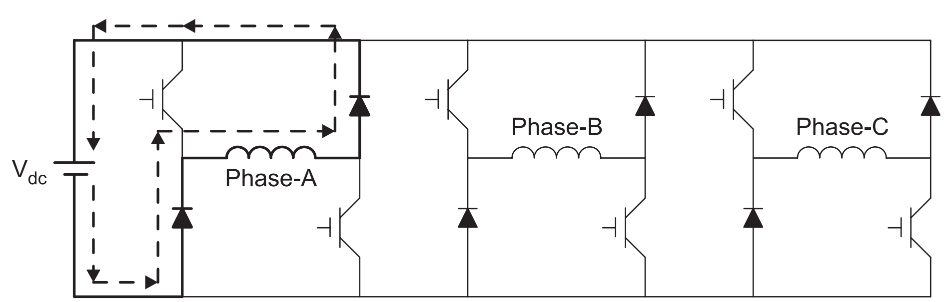


Figure 5: De-energizing operation of phase-A in asymmetrical converter

In this mode of operation both power switches corresponding to phase-A, Sap and San are turned OFF and the stored energy in phase-A winding due to excitation and free-wheeling modes of operation, is now fed back to the source via phase winding to diode D_2 to source V_{dc} positive to V_{dc} negative through diode D_1. De-energizing mode of phase winding in phase-A is shown in Figure 5.

3. PROPOSED NOVEL CONVERTER FOR SRM WITH MINIMUM NUMBER OF SWITCHES

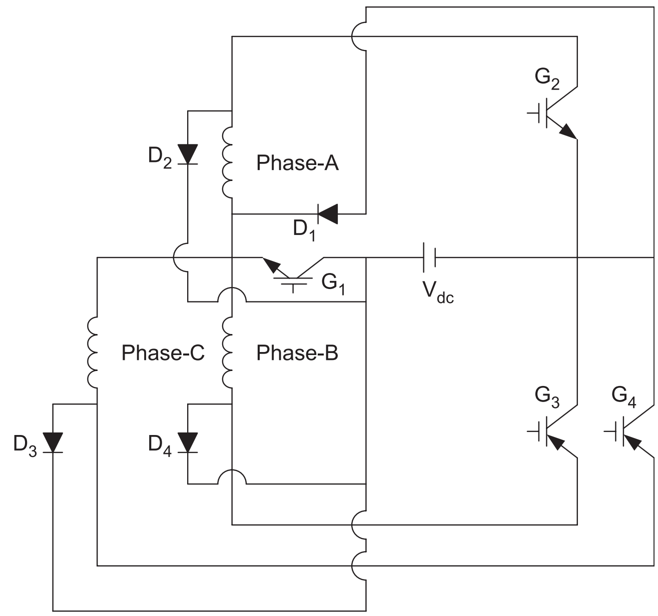


Figure 6: A novel converter for SRM

A novel converter for SRM is illustrated in Figure 6. The converter uses only four switches G_1 to G_4 and four diodes D_1 to D_4 along with a DC source. The four switches along with the operation of diodes excite three phases of SRM and thus creates low reluctance path in SRM. Phase-A, phase-B and phase-C are shown in circuit configuration. This converter utilizes less number of power switches for its operation and thus gives less switching losses as compared to conventional asymmetrical converter. Also number of gate driver circuits required to trigger the power switches is less in this novel converter compared to number of gate driver circuits in conventional symmetrical converter for SRM. As less number of switches are used, number of heat sinks also get reduced for the proposed novel converter. The proposed novel converter operates in three modes of operation as same as the asymmetrical converter namely excitation mode, free-wheeling mode and de-energizing mode.

Mode 1: Excitation of phase-A

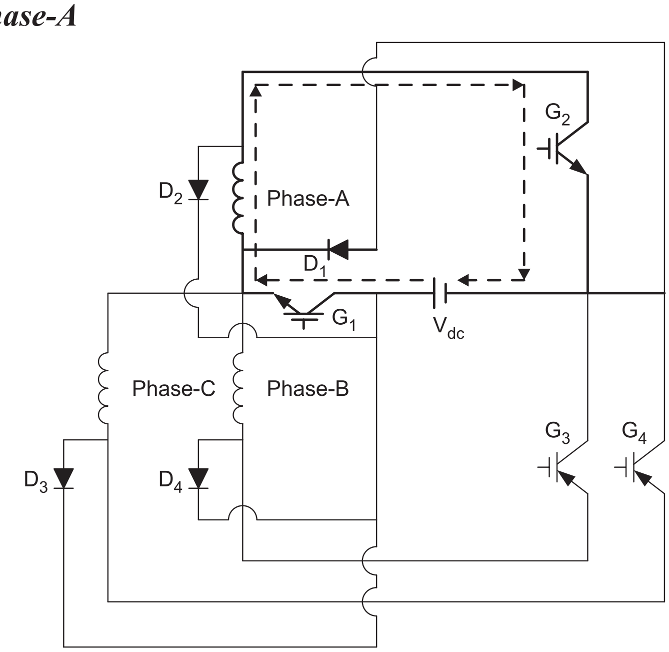


Figure 7: Excitation mode of operating phase-A

During excitation mode of phase-A operation, power switches G_1 and G_2 are turned ON. The current takes the path from source positive, power switch G_1, phase winding of phase-A, switch G_2 and closes at source negative terminal. During this mode of operation, phase winding gets excited and produces flux or low reluctance path for the rotor to be aligned. During this mode of operation other power switches are turned OFF.

Mode 2: Free-wheeling mode of phase-A Mode 3: De-energizing mode of phase-A

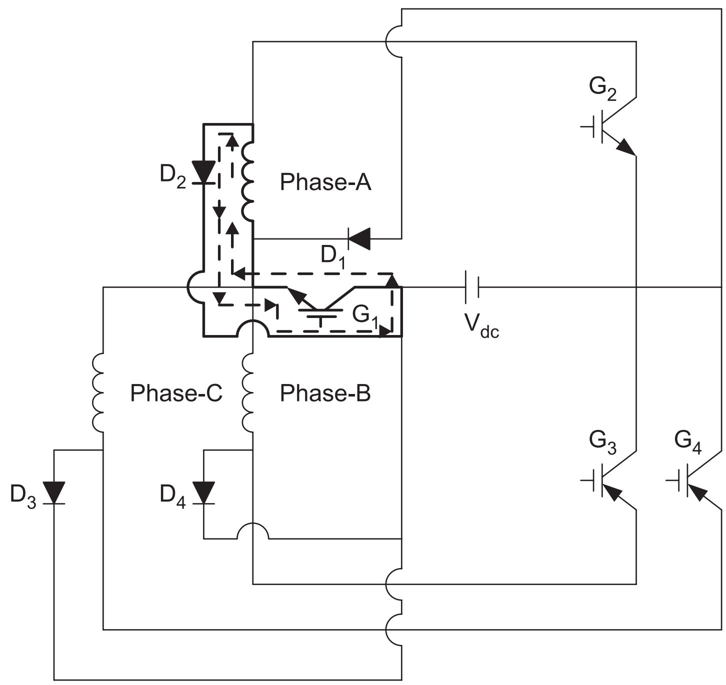


Figure 8 Freewheeling mode of phase-A

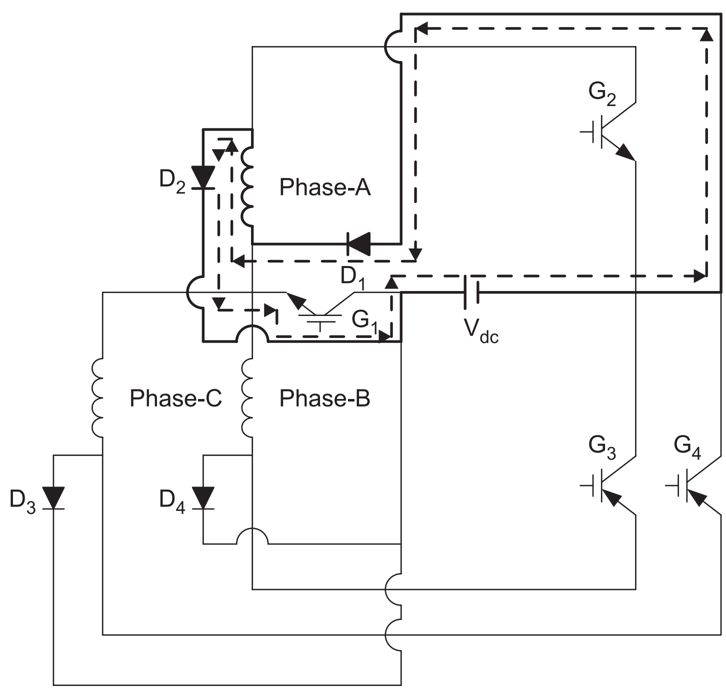


Figure 9: De-excitation of phase-A

Free-wheeling mode of operation and de-energizing mode of operating phase-A is shown in Figure 8 and Figure 9 respectively. During free-wheeling operation power switch G_2 is turned OFF while power switch G_1 is still ON. The stored energy in phase winding during excitation mode in phase-A, now free-wheels through diode D_2 being forward bias. In de-energizing of operation in phase-A, power switch G_1 is also now turned OFF. No power switch will be in ON state during this mode of operation. But the stored energy in phase winding of phase-A de-energizes through diode D_2, source positive, source negative, diode D_1 as shown in figure.

Energizing and de-energizing in phase-B

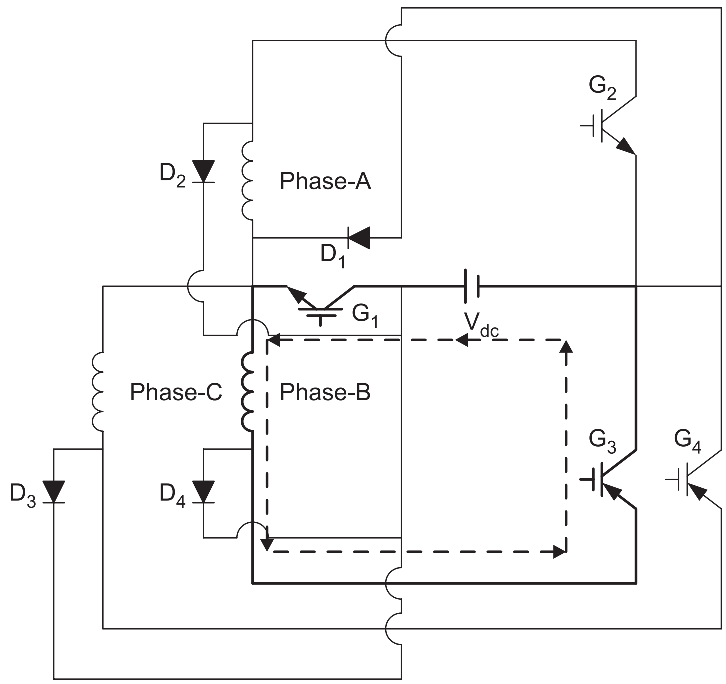


Figure 10: Phase-B excitation mode

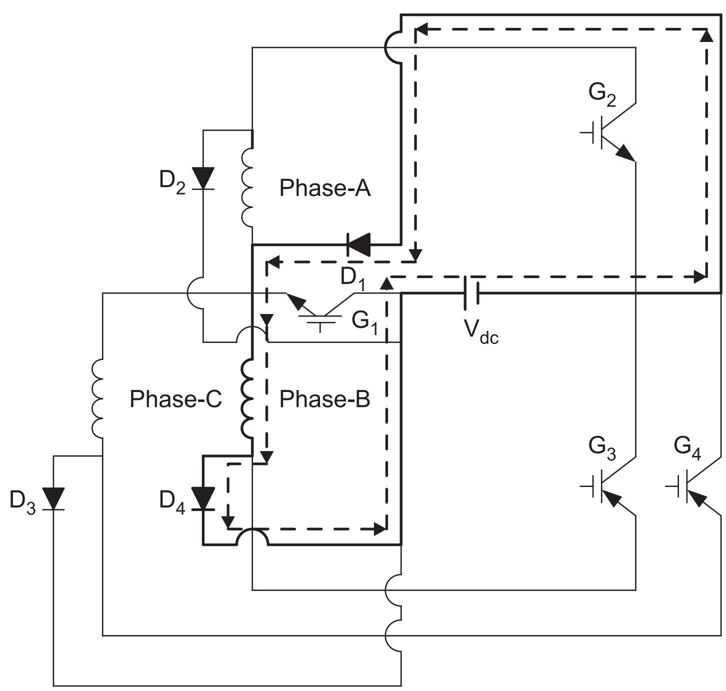


Figure 11: Phase-B de-excitation mode

Excitation mode of phase-B and de-energizing mode of phase-B is shown in Figure 10 and Figure 11 respectively. The mode of operations in phase-B is similar to that of phase-A but with different power switches and diodes for its operation in phase-B. For energizing mode of phase-B, power switches G_1 and G_3 are ON. Phase-B excites through source, G_1 and G_3 storing some energy in phase winding while producing low reluctance path. The stored energy in phase winding of phase-B is de-energized through diode D_1 and diode D_4 through source and the current path is shown.

Energizing and de-energizing in phase-C

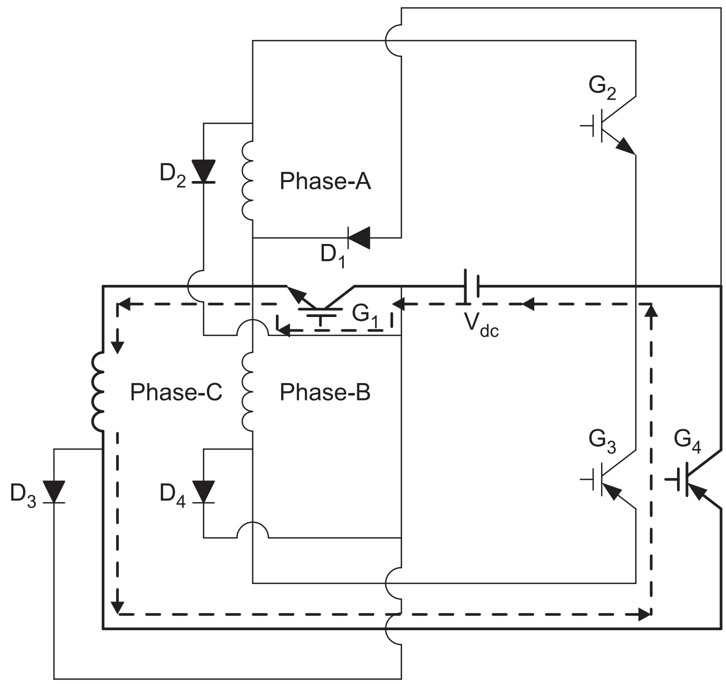


Figure 12: Phase-C excitation mode

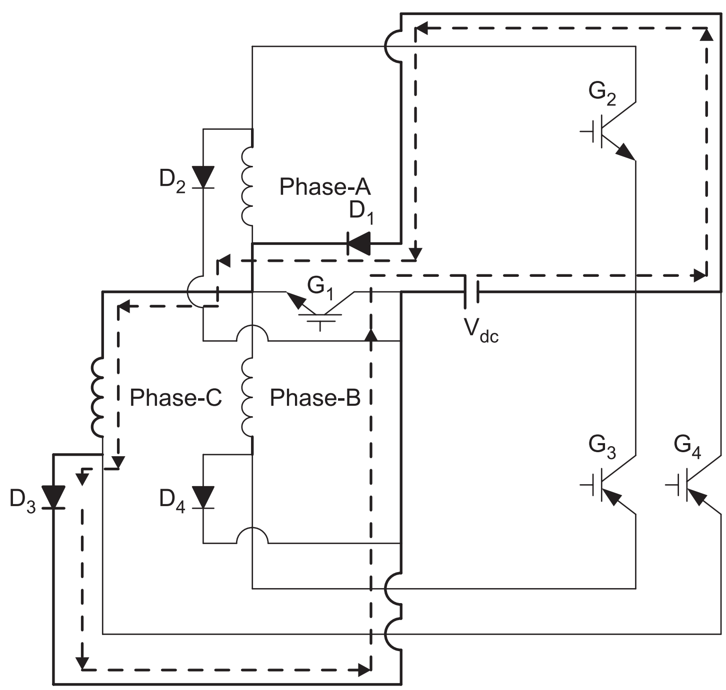


Figure 13: Phase-C de-excitation mode

Excitation mode of phase-C and de-energizing mode of phase-C is shown in Figure 12 and Figure 13 respectively. The mode of operations in phase-C is similar to that of phase-A but with different power switches and diodes for its operation in phase-C. For energizing mode of phase-C, power switches G_1

and G_4 are ON. Phase-C excites through source, G_1 and G_4 storing some energy in phase winding while producing low reluctance path. The stored energy in phase winding of phase-C is de-energized through diode D_1 and diode D_3 through source and the current path is shown.

4. PROPOSED CONVERTER FOR SRM WITH CONTROL CIRCUIT

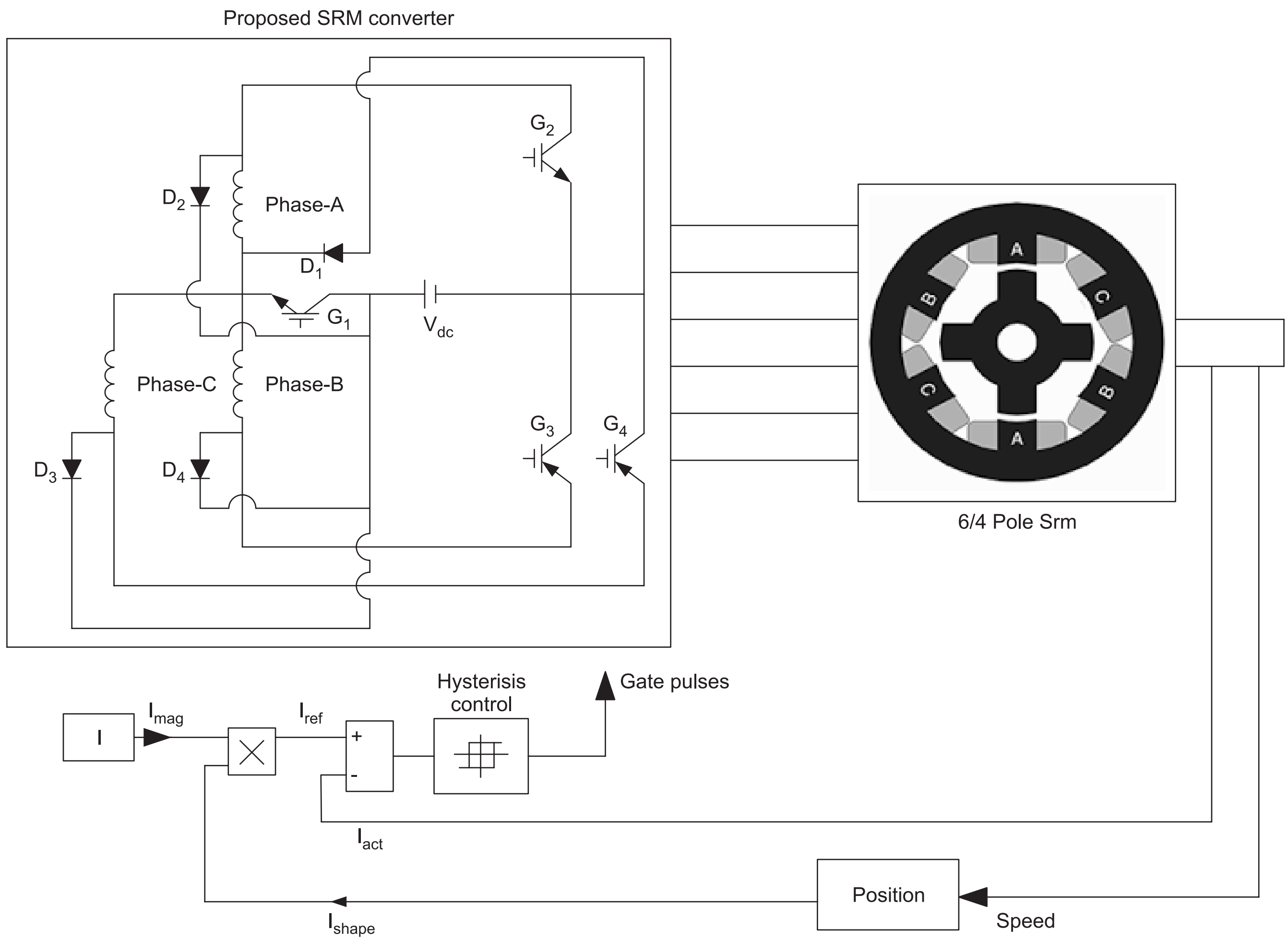


Figure 14: Proposed novel converter driving SRM

Proposed converter with SRM drive is shown in Figure 14. The phases are excited from the converter and phase windings of SRM produces low reluctance path for rotor to align producing reluctance torque. The speed is sensed and is converted to current shape signal. The current shape signal is multiplied to current magnitude signal to obtain reference current signal. Reference current is compared with the actual current from stator currents and the error signal is sent to hysteresis current controller. Hysteresis current controller produces gate pulses to the power switches in proposed converter thus operating the phase windings of SRM. At a time only one phase will be active while the other phase windings are kept inactive.

5. MATHEMATICAL MODELING OF SRM

A mathematical model is a description of a system using mathematical terminology. The process of developing a mathematical model is termed mathematical modelling. A model may help to explain a system and to study the effects of different components, and to make predictions about behaviour.

The voltage equation can be written for one phase of SRM drive, by assuming that other phases have no mutual coupling.

$$\mathrm{V} = \mathrm{R}_s i + \frac{d\lambda(\theta, i)}{dt} \tag{1}$$

Where i represent the phase current, R_s represents the phase resistance, V represents the voltage across the phase winding and $\lambda(\theta, i)$ represents the phase-flux-linkage for a respective rotor position (θ) and current (i).

The rate of change of flux-linkages with time is as follows;

$$\lambda(\theta, i) = \mathrm{L}(\theta, i)i \tag{2}$$

$$p\lambda(\theta, i) = \mathrm{L}(\theta, i)i at\ \theta = \text{constant}$$

$$\frac{di}{dt} + i\frac{d\mathrm{L}(\theta, i)}{dt}\ ati\ = \text{constant} \tag{3}$$

Where p represents the derivative operator, d/dt, L represents the machine self-inductance of respective phase; it is a function of rotor position and excitation current. By using partial derivation the derivative of flux linkage can be obtained as follows.

$$p\lambda(\theta, i) = \frac{\partial\lambda(\theta, i)}{\partial i}\frac{di}{dt} + \frac{\partial\lambda(\theta, i)}{\partial\theta}\frac{d\theta}{dt} = l(\theta, i)\frac{di}{dt} + \omega_m\frac{\partial\lambda(\theta, i)}{\partial\theta} \tag{4}$$

Where $l(\theta, i)$ represents incremental inductance, as it is the ratio of incremental flux-linkages and incremental excited current. The relation of increment inductance and self-inductance is represented as,

$$\mathrm{L}(\theta, i) = \frac{1}{i}\int_0^i l(\theta, i)\, di \tag{5}$$

The self-inductance is differentiated over the incremental inductance. Generally in a SR drive system operating conditions are non-linear, so the change in co-energy leads to the electro-magnetic torque determination, which is the next following step.

$$\delta \mathrm{W}'_f(\theta, i) = \int_{i_1}^{i_2} \lambda(\theta, i)\, di \tag{6}$$

The flux linkages are integrated. For a constant current the air gap torque is calculated as follows.

$$\mathrm{T}_e = \frac{\partial \mathrm{W}'_f(\theta, i)}{\partial\theta} \tag{7}$$

Where T_e is the total torque.

Between the adjacent phases there are mutual flux linkages. The mutual components of non-adjacent phase inductances like as *ac* & *bd* are eliminated as the phase currents of *a* & *c* as well as *b* & *d* never overlaps. Though they overlap for a small duration of time for small currents due to this the mutual flux linkages are very low compared to adjacent phases. The flux & voltage equations for 6/4 pole SR drive can be expressed in the form of phase currents, inductances, resistances with respect to position of current & rotor as follows;

$$\begin{bmatrix} \mathrm{V}_a \\ \mathrm{V}_b \\ \mathrm{V}_c \end{bmatrix} = \begin{bmatrix} \mathrm{R}_s & 0 & 0 & 0 \\ 0 & \mathrm{R}_s & 0 & 0 \\ 0 & 0 & \mathrm{R}_s & 0 \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} \tag{8}$$

Where

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} = \begin{bmatrix} L_a & M_{ba} & 0 \\ M_{ab} & L_b & M_{cb} \\ 0 & M_{bc} & L_c \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{9}$$

And $M_{ab} = M_{ba}$, $M_{bc} = M_{cb}$ and $M_{ca} = M_{ac}$

Where R_s represents the phase stator resistance, L specifies the per phase self-inductance, M represents the mutual inductance between phase components. I, V & λ are specifies the current, voltage, flux-linkages respectively in the respective phases. These are evaluated as a 6/4 pole SR drive system

6. RESULTS AND ANALYSIS

Results and Discussions for Asymmetrical Converter fed SRM

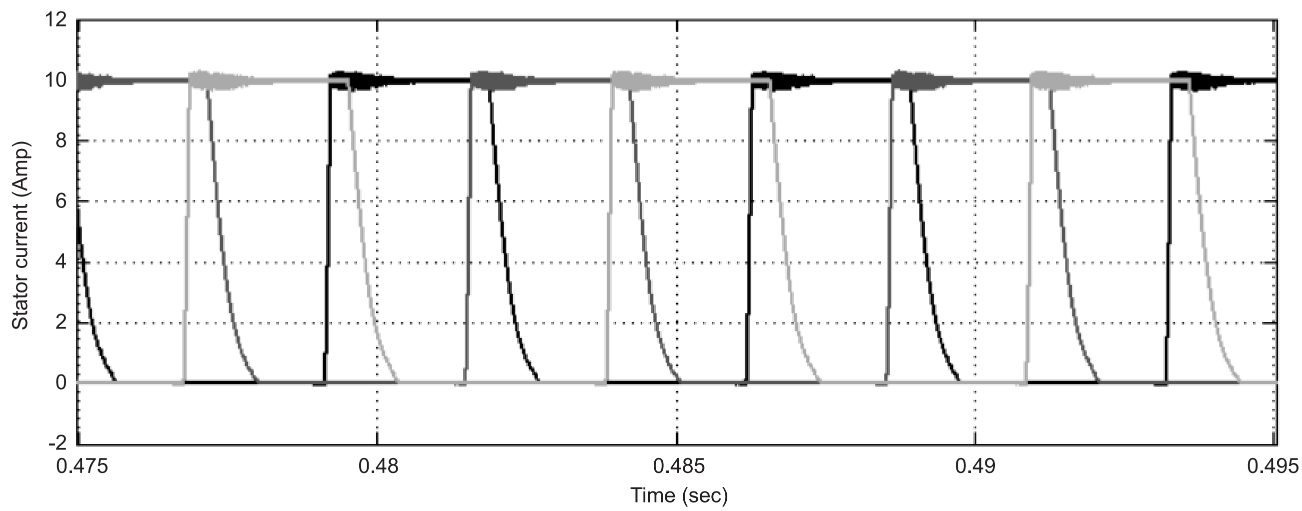


Figure 15: Phase stator currents in asymmetrical converter fed SRM

Three phase stator currents fed to SRM is shown in Figure 15. Stator currents produced with asymmetrical converter with magnitude of 10A is shown. All three phases are have magnitude of 10A. Only one phase is excited at a time but a small overlap is observed. Overlap angle can be reduced with some control techniques.

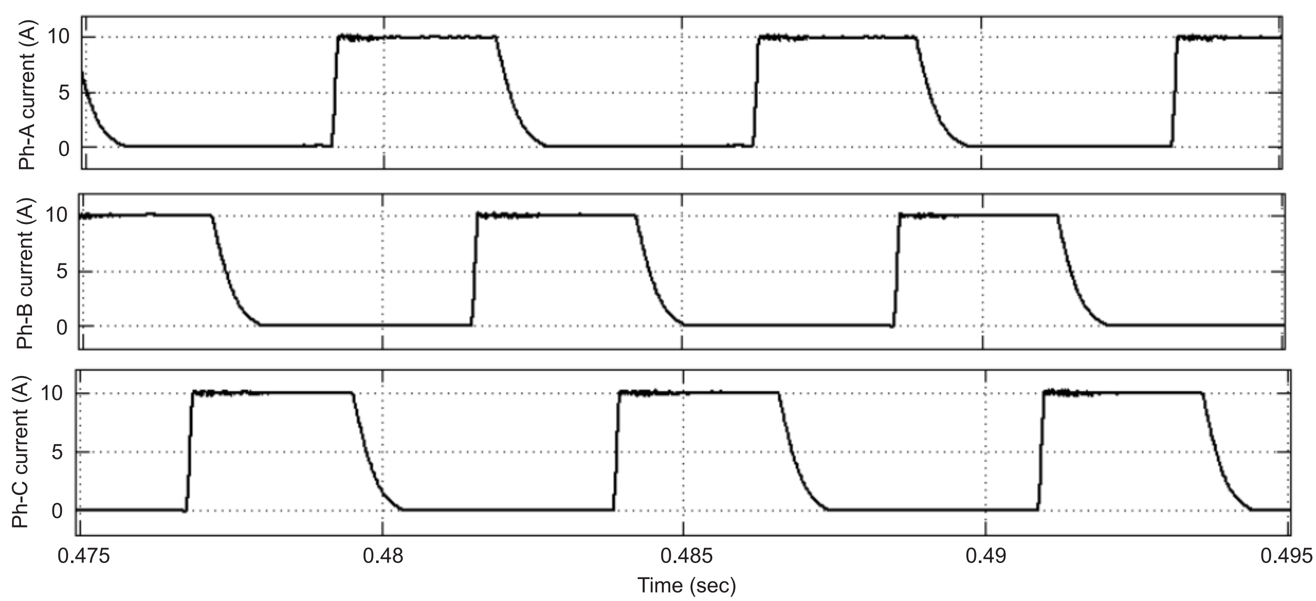


Figure 16: Phase currents in individual phases of asymmetrical converter fed SRM

Phase current in individual phases of SRM fed from asymmetrical converter is shown in Figure 16. Each phase winding carries a current of 10A. Clearly phase currents drawn by SRM fed from asymmetrical converter are depicted.

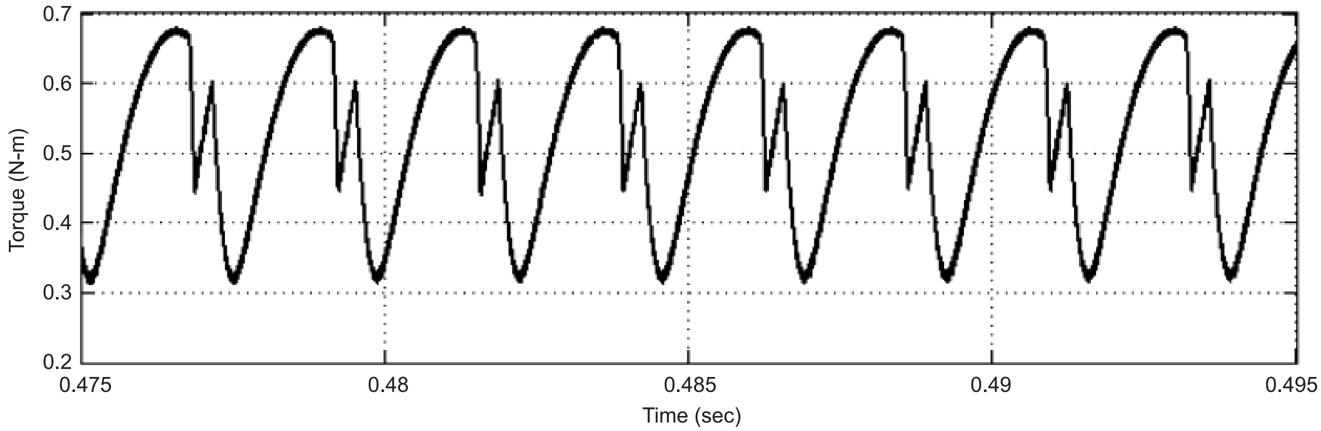


Figure 17: Torque in SRM fed with asymmetrical converter

Reluctance torque produced in SRM when fed from asymmetrical converter is shown in Figure 17. Torque ripples are observed in torque waveform and torque ripple of 0.4 Nm is present when SRM is fed from asymmetrical converter.

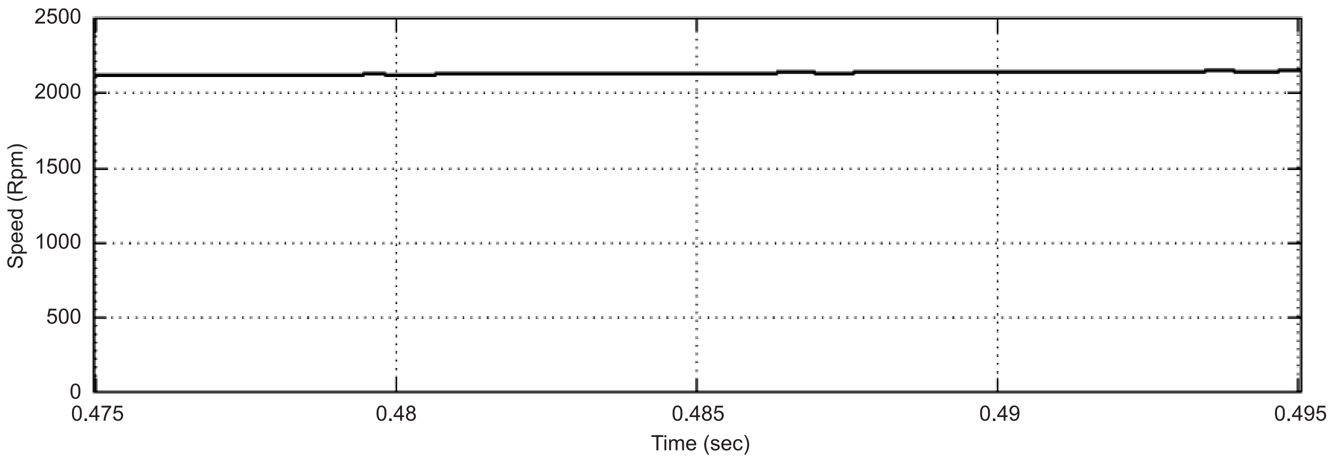


Figure 18: Speed of SRM drive fed from asymmetrical converter

Speed at which SRM is running at is shown in Figure 18. SRM when fed from asymmetrical converter runs at 2200 is shown. Speed of SRM is maintained constant.

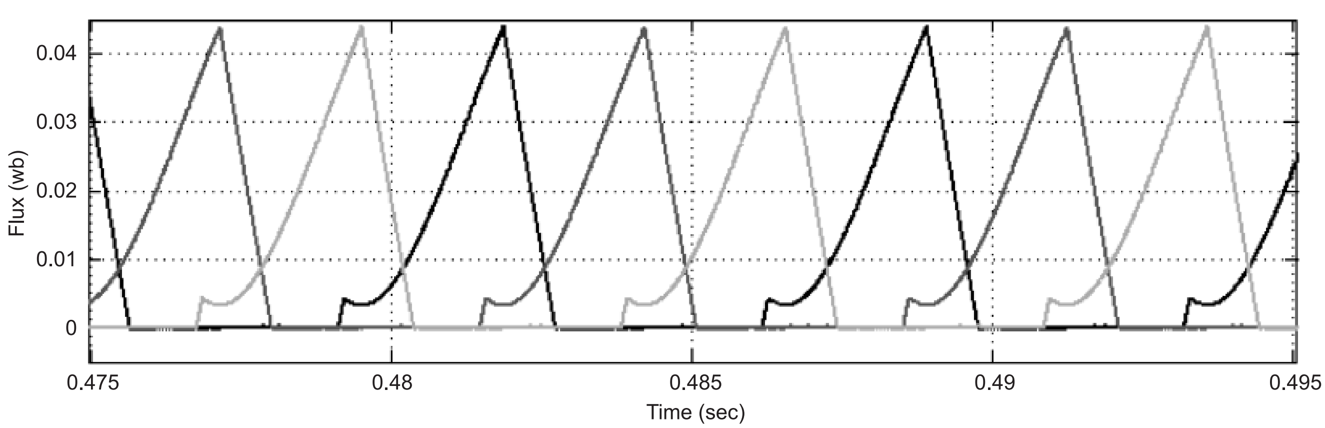


Figure 19: Flux produced due to phases of SRM

Flux that is produced in SRM due to phase windings fed from asymmetrical converter is depicted in Figure 19. Peak flux of 15 mWb is produced by each phase of SRM when fed from asymmetrical converter. Non-linear nature of flux is observed.

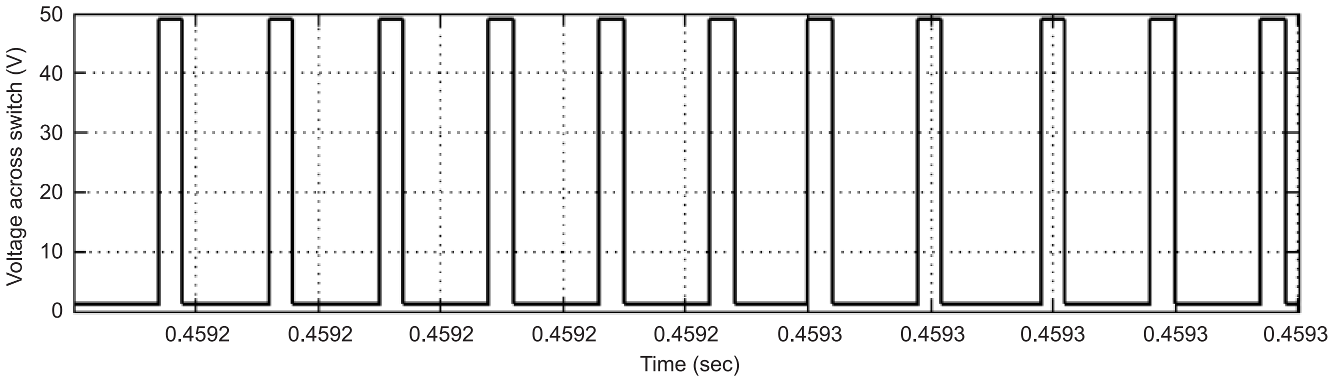


Figure 20: Voltage across switch in asymmetrical converter

Voltage present across switch during operation in asymmetrical converter is shown in Figure 20. Each switch is subjected to a peak voltage of 100V during their operation.

Results and Discussions for Proposed Converter fed SRM

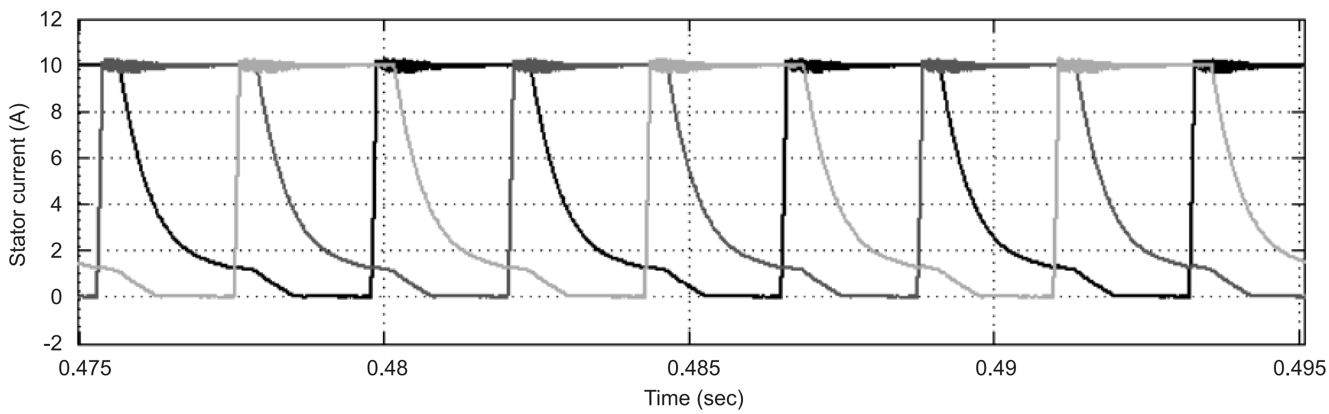
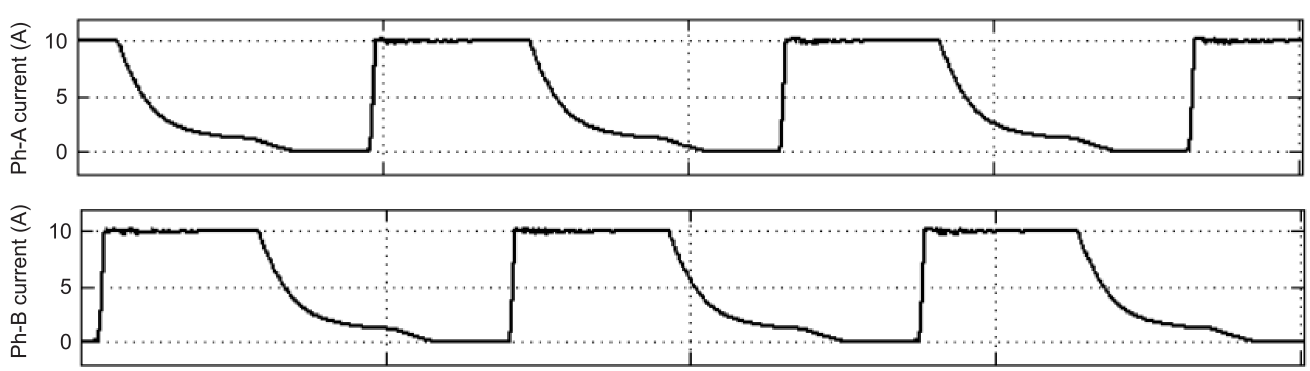


Figure 21: Three-phase stator currents in proposed converter fed SRM

Three phase stator currents fed to SRM is shown in Figure 21. Stator currents produced with asymmetrical converter with magnitude of 10A is shown. All three phases have magnitude of 10A. Only one phase is excited at a time but a small overlap is observed. Overlap angle can be reduced with some control techniques.



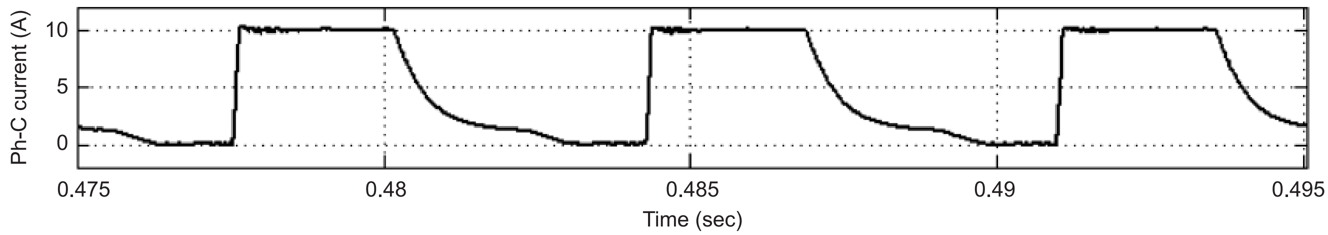


Figure 22: Phase currents in individual phases of proposed converter fed SRM

Phase current in individual phases of SRM fed from asymmetrical converter is shown in Figure 22. Each phase winding carries a current of 10A. Clearly phase currents drawn by SRM fed from asymmetrical converter are depicted.

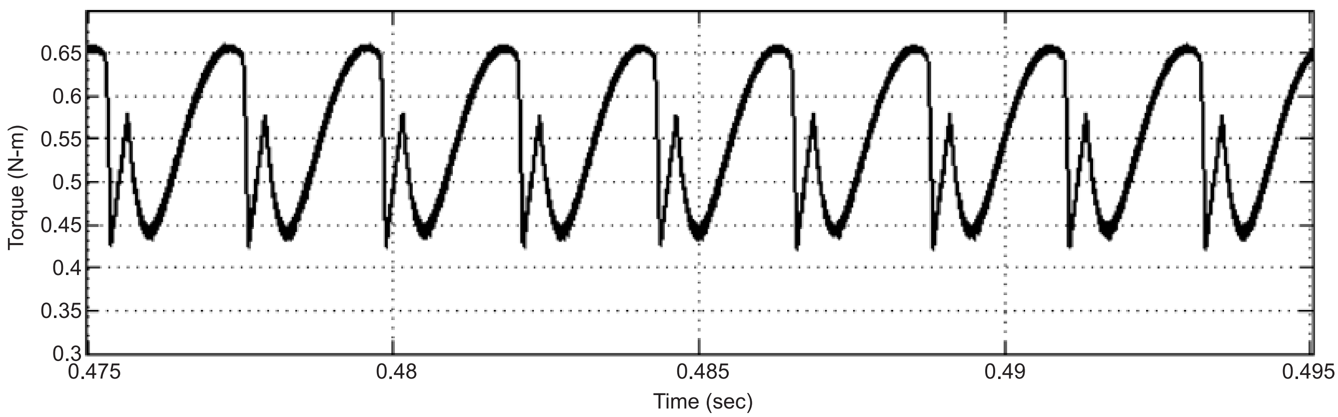


Figure 23: Torque in SRM fed with proposed converter

Reluctance torque produced in SRM when fed from asymmetrical converter is shown in Figure 23. Torque ripples are observed in torque waveform and torque ripple of 0.3 Nm is present when SRM is fed from asymmetrical converter. Ripple is reduced when SRM is fed from proposed converter when compared to SRM fed from asymmetrical converter.

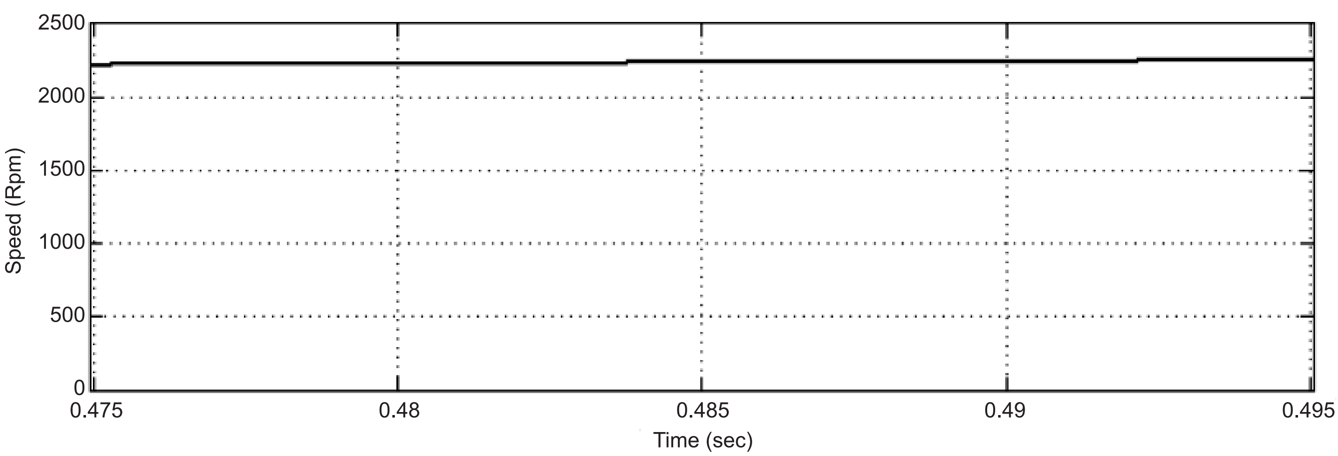


Figure 24: Speed of SRM drive fed from proposed converter

Speed at which SRM is running at is shown in Figure 24. SRM when fed from asymmetrical converter runs at 2200 is shown. Speed of SRM is maintained constant.

Flux that is produced in SRM due to phase windings fed from asymmetrical converter is depicted in Figure 25. Peak flux of 15 mWb is produced by each phase of SRM when fed from asymmetrical converter. Non-linear nature of flux is observed.

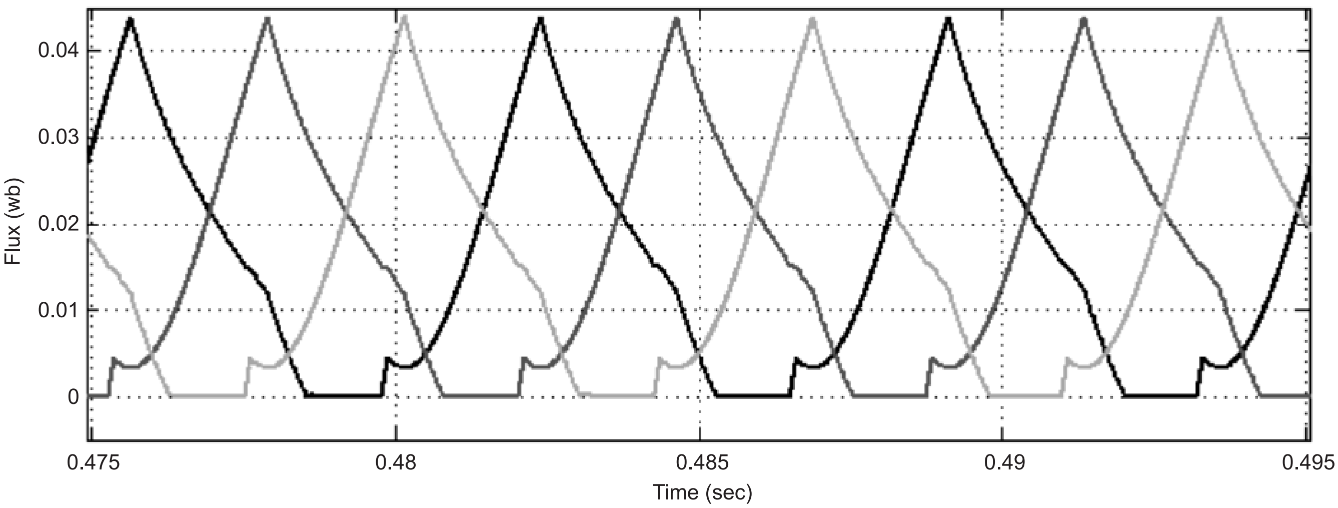


Figure 25: Flux produced due to three phases of SRM

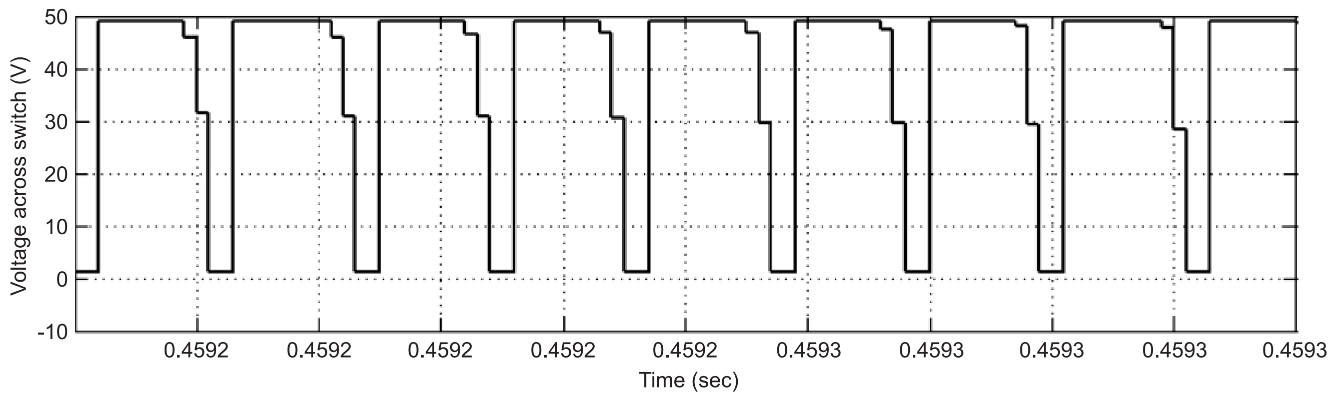


Figure 26: Voltage across switch in proposed converter

Voltage present across switch during operation in asymmetrical converter is shown in Figure 26. Each switch is subjected to a peak voltage of 100V during their operation. Comparative analysis of proposed converter with asymmetrical converter was depicted in table 1. From table 1 number of power switches in proposed converter is less compared to asymmetrical converter. Number of diodes requirement in proposed converter is less than asymmetrical converter. As numbers of components are reduced switching losses are less in proposed converter. Heat sink requirement is also less comparatively since only four switches are used. Numbers of gate drivers are also reduced in proposed converter.

Table 1
Comparative analysis between proposed converter and asymmetrical converter

Component	*Proposed Converter*	*Asymmetrical Converter*
Number of power switches	4	6
Number of diodes	4	6
Switching losses	Comparatively low	Comparatively high
Number of gate drivers	4	6
Heat sink volume	Low	high

7. CONCLUSION

Fault tolerant switched reluctance motor having simple and rugged construction is used for many applications in industries, EV applications, automobile industry, aerospace and many more. SRM is lightly constructed with no rotor windings but only with stator windings. When phases of SRM stator are excited, stator poles produces low reluctance path aligning rotor in the direction of stator flux axis. By sequential switching of stator windings of SRM, reluctance torque is produced to rum SRM. Sequential switching of SRM phases is fed from converter. Many converter topologies are available to feed SRM windings. A novel converter is proposed in this paper with minimum number of switches thus reducing the switching losses and number of accessory components required. The proposed converter is compared with asymmetrical converter and merits of proposed converter were tabled. Results were explained for SRM fed from asymmetrical converter and SRM fed from proposed converter. Characteristics remain same but number of components required is less in proposed converter. This paper depicts the suitability of proposed converter for SRM drive system with reduction in number of components for its operation.

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