International Journal of Soft Computing 9 (6): 391-400, 2014
ISSN: 1816-9503

Bus Synchronized Matrix Converter Fed Switched Reluctance Machine in Motoring and Generating Modes of Operation

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Abstract: This study presents a Novel Control System for three phases grid connected, switched reluctance machine operated in both the motoring and generating modes. The converter configuration is worked out to provide ac to ac power conversion without a need for an intermediate energy storage element. The converter is configured with bidirectional switches in the matrix fashion along with the freewheeling diodes. It has more number of switches than the conventional matrix converter in order to facilitate the regeneration and its feedback to the grid. At any point of time, only two switches will be conducting and hence switching losses are kept to the minimum. To reduce harmonics and improve the power factor at the ac terminals, LC filter are used. The control scheme ensures supply of sinusoidal current while the machine draws excitation current also from the same ac supply. Complete switching model of the SRM along with converters is presented for simulation. The feasibility and the effectiveness of the proposed method are assessed for various dwell angles of the SRM and various speeds of the prime mover.

Key words: Switched reluctance machine, matrix converter, freewheeling diode, grid supply, constant speed prime mover

INTRODUCTION

The Matrix Converter (MC) provides direct AC-AC conversion and is considered an emerging alternative to the conventional two-stage AC-DC-AC converter topology (Wheeler *et al*., 2002, 2003). A matrix converter provides a large number of control levels that allows for independent control on the output voltage magnitude, frequency and phase angle as well as the input power factor. When compared with the AC-DC-AC converter system, the bold feature of MC is elimination of the DC-link reactive elements, e.g., bulky capacitors and/or inductors. However, this topology has not yet found its appropriate place in industrial applications. The main reasons behind this are the potential commutation problems, requiring complex control and snubber circuits, unavailability of monolithic bi-directional switches, lack of decoupling between the two ac sides of the converter and low voltage gain. A novel MC topology with advantages over the conventional nine-bidirectional-switch topology has been developed by Wei and Lipo (Apap *et al*., 2003). The improved topology has the same performance as the conventional MC but does not have any commutation problems. In addition, voltage gain is improved and control is simplified. This study proposes a new matrix converter system in which the AC-DC-AC converter has been replaced by a matrix converter MC topology with bidirectional freewheeling diode and the switched reluctance machine operated in both the modes of operation as a motor and generator.

Switched Reluctance Generator (SRG) is an attractive solution for worldwide increasing demand of electrical energy. It is low cost, fault tolerant with a rugged structure and operates with high efficiency over a wide speed range. Merits of using SRG have been proved for some applications like starter/generator for gas turbine of aircrafts (Aten *et al*., 2006; Kim *et al*., 2000) windmill generator (Kim and Sul, 1993; Youm and Kwon, 1999) and as an alternator for automotive applications (Pan *et al*., 2004). The major issue in the stand-alone generator is power-density maximization that is maximum power throughput for a given power rating. In other words, minimal sizing and lighter weight in the same rated machine are the most important factors. Thus, understanding characteristics of SRG for maximization of output power of generator in design and control is a pivotal point for utilizing it for more and more applications. Generating mode of Switched Reluctance

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Machine has been one of the research topics recently (Aten *et al*., 2006; Kim *et al*., 2000; Kim and Sul, 1993; Youm and Kwon, 1999; Pan *et al*., 2004). In (Nassereddine *et al*., 2008a, b) principle of operation of SRG has been presented and the necessity for closed loop control is proved. According to Torrey (2002), the control of excitation of SRG for maximum efficiency at single pulse mode of operation has been presented. Turn on and turn off angles are defined as control variables, turn on angle is set based on the output power and the turn off angle is selected to achieve optimal efficiency at each power level and speed. According to Faiz (2006), a new performance criteria as productivity of generator is described, in this method, instead of two phase commutation steps which are on and off in single pulse mode, a freewheeling step is added. During this step, the phase is short circuited and the current increases due to back-emf voltage. This method produces more power than the conventional method, for the same turn on period and it reduces current ripple on DC link bus. Direct power transfer from SRM to grid has been not been attempted in literature. The reason for this could have been due to the excitation requirement of SRM. In every power transfer cycle of SRM, initially power is drawn from the source followed by regeneration. The period of excitation and regeneration depend on the turn ON and turn OFF angles of the phase excitations. An attempt has been made in this study to propose converter configuration and the control scheme for direct power transfer between grid and SRM.

MATHEMATICAL MODEL

In this study, researchers focus on the electro mechanics of Switched Reluctance Machines (SRM). The intent is to provide an understanding of energy conversion process. Switched reluctance machines can work as motor or as generator just by changing their switching angles and control the path of energy generated. Regarding the operation of the machine when rotor pole is in line with the energized stator pole, the position is said to be a stable equilibrium. When the rotor pole is not aligned with an energized stator pole is said to be an unstable equilibrium. Rotor will tend to turn to the position of balance featuring a motoring operation. Thus, in SRM, there is a natural tendency to align the rotor and the stator active poles in order to maximize the inductance of that phase. When a prime mover forces the aligned rotor pole to move from the equilibrium, work is done on the machine, resulting in generation of electric power. SRM acts as a generator (SRG) in this mode.

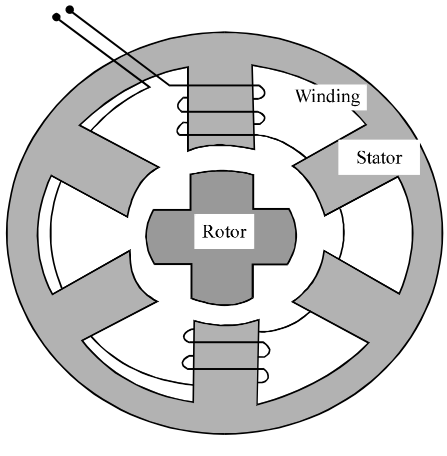

Fig. 1: Structure of 6/4 SRM

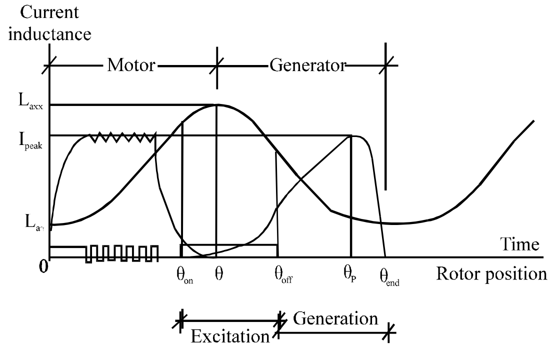

Fig. 2: Idealized inductance profile of SRG

A cross section view of three-phase 6/4 poles SRG is shown in Fig. 1. Figure 2 shows idealized inductance profile of SRG. When ignoring saturation, the inductance varies linearly with respect to the rotor position. As for three-phase 6/4 poles SRG, the inductance is minimum when stator and rotor poles are completely unaligned (0°) and maximum when poles are fully aligned (45°). Motoring status is obtained when the stator is excited during the positive slope in the inductance profile. And for generator, the stator phases are excited during the negative slope in the inductance profile. Figure 2 shows the current behaviour for motor and generator models.

A per phase equivalent circuit for SRM can be derived neglecting the mutual inductance between the phases shown in Fig. 3. The voltage applied to each phase is equal to the sum of resistive voltage drop and the rate of change of flux linkages in the corresponding phase and is given by Eq. 1:

$$V_{ph} = R_S i_{ph} + \frac{d\lambda\left(\theta, i_{ph}\right)}{dt} \tag{1}$$

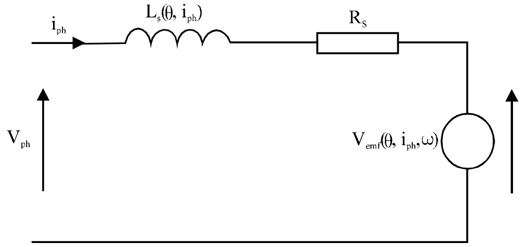

Fig. 3: SRM Winding Model

Where:

R_s = The resistance per phase

λ = The flux linkage per phase, given by $\lambda = L_{ph}(\theta, i_{ph})i_{ph}$

Ls = The inductance per phase which is dependent on the rotor position and phase current

Expanding the inductance term, the phase voltage equation is given by:

$$V_{ph} = R_S i_{ph} + L_s\left(\theta, i_{ph}\right)\frac{di}{dt} + i_{ph}\frac{d\theta}{dt}\frac{dL\left(\theta, i\right)}{d\theta} \tag{2}$$

$$V_{ph} = R_S i_{ph} + L\left(\theta, i_{ph}\right)\frac{di}{dt} + i_{ph}\omega\frac{dL\left(\theta, i_{ph}\right)}{d\theta} \tag{3}$$

The three terms on the right hand side of the equation represents the resistive voltage drop, inductive voltage drop and the induced emf, respectively. The induced emf is given by:

$$V_{emf} = i_{ph}\omega\frac{dL\left(\theta, i\right)}{d\theta} \tag{4}$$

For a given sign of ω and i, the sign of induced emf e is defined by the sign of $\partial L/\partial\theta$. It can be seen that when $(\partial L/\partial\theta)<0$ the back EMF is negative, the mechanical power is converted to electrical power resulting in generating mode. When $(\partial L/\partial\theta)>0$, the back emf is positive resulting in the motoring mode. The rotor's motion dynamics is governed by the Eq. 5:

$$C_m + C_{emag} - J\frac{d\omega}{dt} - B\omega = 0 \tag{5}$$

Where:

C_m = The applied mechanical torque

C_{emag} = The electromagnetic torque

ω = The angular speed

J = The moment of inertia

B = The frictional coefficient

The resultant electromagnetic torque is the composition of the contributions of three phases where each one has its own instantaneous inductance, voltage and current.

$$C_{emag} = \frac{1}{2}\left(i_a{}^2\frac{\partial L}{\partial\theta} + i_b{}^2\frac{\partial L_b}{\partial\theta} + i_c{}^2\frac{\partial L_c}{\partial\theta}\right) \tag{6}$$

Considering Eq. 1-6, the mathematical model for this SRG is made which explains the complete dynamic behavior of the machine.

Non-linear model of inductance: To simulate the dynamic performance accurately the relational expression of position, angle of rotor and phase current must be described exactly. The magnetic circuit of the SRM is saturated and non-linear, its inductance can be approximated by Fourier series. The harmonic component of the inductance is further less than the fundamental component so the phase inductance can be expressed as follows:

$$L_k(\theta, i_k) = L_o(i) + L_1(i)\cos(N_r\theta) \tag{7}$$

$$L_o(i) = \frac{L_{max}(i) + L_{min}(i)}{2} \tag{8}$$

$$L_1(i) = \frac{L_{max}(i) - L_{min}(i)}{2} \tag{9}$$

Where:

L_{max} = The aligned position inductance

L_{min} = The unaligned position inductance

These self inductances of the machine windings are measured using a LCR meter by rotating the rotor in steps. The mutual inductances of phases are neglected.

MATRIX CONVERTER WITH FREEWHEELING DIODE

The matrix converter represents a new generation of AC-AC converters with a compact design due to lack of large energy storage elements.

Conventional matrix converter topology: The conventional matrix converter topology is composed of an array of nine bidirectional switches connecting each phase of input to each phase of output. By properly operating the switches in the matrix converter one can achieve control on the output voltage magnitude, frequency and phase angle as well as control on the input displacement angle. Matrix converter is a bidirectional power flow device with the capability of producing high quality input and output waveforms. Figure 4 shows the schematic diagram of conventional matrix converter.

New matrix converter with freewheeling diode: Figure 5 shows the schematic diagram of the new matrix converter topology with anti parallel freewheeling diodes where BDS are the bidirectional switches and FD are the freewheeling diodes. For a controlled regeneration the anti parallel freewheeling diodes can be replaced by bidirectional switches. The new converter is based on the concept of making the regenerating energy to flow back to the grid by the freewheeling path provided. However, there is no energy storage element between the line side and load side. This proposed matrix converter provides the advantage of utilizing the three phase supply as an input to the SRG phases in the excitation period and is fed back during the generating period.

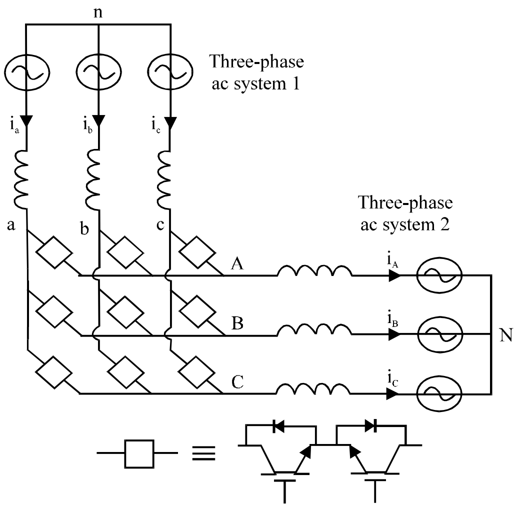

Fig. 4: Schematic diagram of a conventional matrix converter

Computing model of the proposed system: The block diagram of matrix converter fed grid connected SRG for a single phase is shown in Fig. 6. The literature reveals that the SRG is normally excited by a dc source. In the proposed method, the SRG phase windings are excited by the three phase AC source. All the power that comes from the ac source is again pushed back from the SRG windings and the freewheeling diodes.

The excitation period begins when the controlled switch is turned on the inductance is still increasing, the diodes off and the phase winding generates a positive counter emf which is shown in Fig. 7a. The bidirectional switches operates for both positive and negative half cycles of the sinusoidal supply. The generating period begins when the controlled switch is turned off, the inductance is now decreasing, the diode is on and the phase winding generates a negative counter emf which is explained in Fig. 7b. The decreasing inductance results in the negative motional back emf that in turn intensifies the establishment of magnetizing current. After completion of magnetization process a substantial back emf will continue to increase the phase current. In second portion the back emf works against the negative bus voltage which tends to eliminate the phase current. The maximum current will be determined by turn on and turn off instants. This is in odds with motoring mode of operation in which only turn on instant plays a major role in determination of maximum current at high speeds. Here, θ_{on} is the position at which both the bidirectional switches are closed allowing the magnetizing current to be injected into the machine. Correspondingly, θ_{off} depicts the

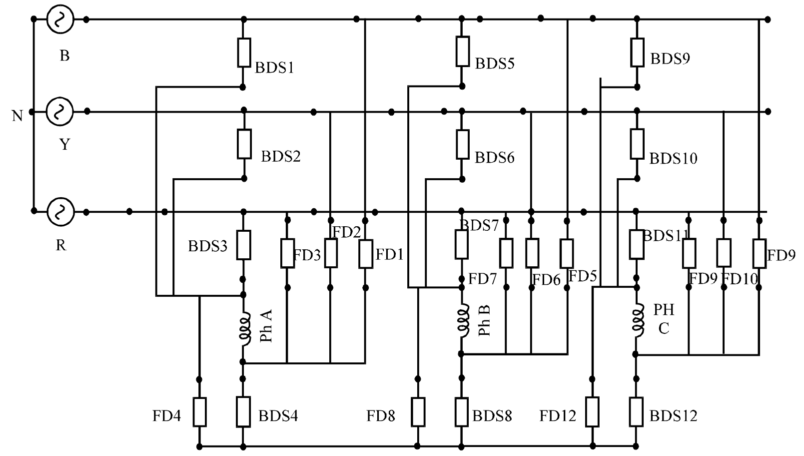

Fig. 5: Schematic diagram of the matrix converter with freewheeling diodes

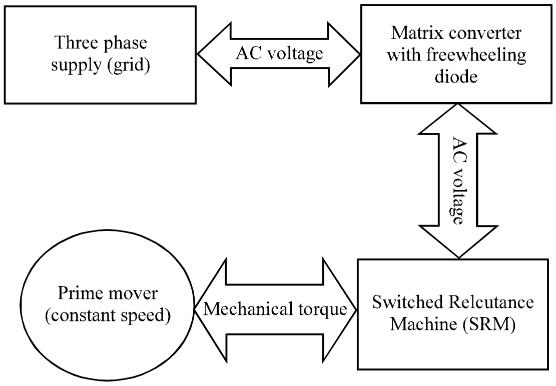

Fig. 6: Block diagram matrix of converter fed grid connected SRG

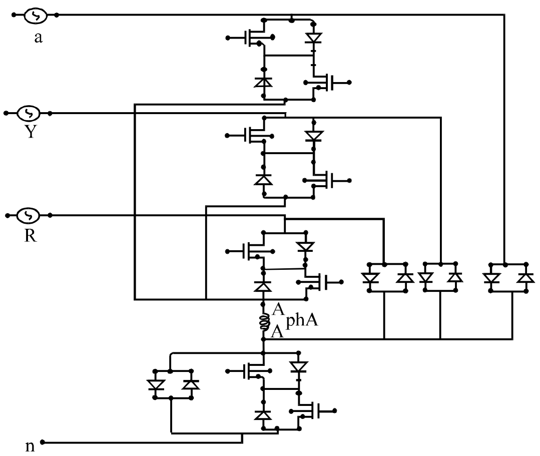

Fig. 7: Matrix converter configuration for one phase winding

position at which both the switches are open allowing the generator current to follow through the diodes and back to the grid.

Freewheeling switching strategy: In order to make the emf generated to be fed to the grid a new switching strategy of matrix converter is provided. Once in the descending portion of the inductance profile the stator phases can be excited by selecting the corresponding supply phase. It is noted that the motional back emf is the product of electromechanical energy conversion the turn on instant will be selected in the neighbourhood of aligned position. Notably the turn on instant will be used for phase advancing at higher speed to allow enough time for build-up of magnetizing current. This phase advancing may as well be extended into the motoring region to allow for a satisfactory operation at very high speeds.

Once the magnetizing current reaches its targeted value, i.e., θ_{off} the bi-directional switches will be opened.

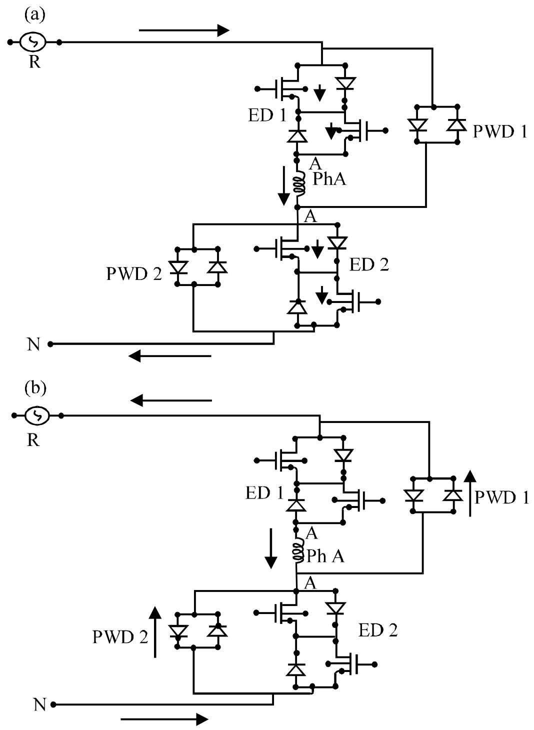

Fig. 8: SRM phase A winding operating modes; a) switches turned on (excitation mode); b) Switches turned off (generating mode)

At this time the converted mechanical energy of the rotor into electrical form is pumped back to the supply. This trend continues until a drastic change in the slope of the inductance occurs resulting in a significant reduction in the motional back emf. At this time the next phase voltage dominates the dynamics of the coil and phase currents starts its downhill path. This process will quickly clear the respective stator phase from any residual current.

CONTROL ALGORITHM FOR MATRIX CONVERTER

Hysteresis Control algorithm is used when simulating the operation of the matrix converter. The first, single band hysteresis control uses the supply phases with the most positive and most negative voltages to control the SRM phase currents. This effectively rectifies the supply to produce an un-smoothed dc output voltage to the SRM phases (Fig. 8). The rectified voltage is applied to the phase in either direction such that the current is maintained at the reference level. This produces supply current waveforms comparable with those of a diode bridge rectifier but with high frequency switching components.

SIMULATION RESULTS AND ANALYSIS

The matrix converter was simulated in the MATLAB/SIMULINK environment driving the generator model described previously. Both the single band and double band methods were simulated at 500 rpm. The SRG mathematical model is evaluated for the matrix converter using a computing program which inputs are the three phase voltages, θ_{on}, θ_{off} and the prime mover speed. The outputs are the currents at the phases, switching voltages. Each new set of values for the phase voltages and for the torque is used to feedback the program in order to evaluate the next state. The computing program uses dynamic values from the relations among the matrix converter, ac source and the SRG. Such a modelling strategy for simulation allows an evaluation of converters behaviour under different conditions like speed and excitation voltages. As a result this converter can be used in grid connection without power interruptions. The MATLAB/SIMULINK model developed for this proposed method is shown in Fig. 9.

Simulation results at constant speed of 500 rpm, θ_{on} = 3 deg and θ_{off} = 15 deg using the matrix converter topology are presented here. Figure 10 shows the phase winding currents of the SRG under this condition. Figure 11 and 12 shows the switching voltages of the supply and the grid current pushed back to the supply. During the excitation process the phase switch is conducting and the diode is not conducting because the less impedance path for the current crosses the switch. As a result the voltage at the winding terminals is a negative back emf which is pushed back to the supply. The developed torque which is shown in Fig. 13 is negative which confirms that the machine is running as generator. At this speed harmonic content is also reduced which is shown in Fig. 14. Figure 15 shows the input voltage and the regenerative current.

By keeping the turn on angle constant and varying the turn off angle at a speed of 500 rpm the developed torque, amount of grid current are increased. As turn off angle increases the harmonic are also increased.

At speed of 5000 rpm the switching frequency increases and a smooth sine wave for the grid current is obtained. The THD is also reduced to a lower level and the negative torque also increases. But the settling time increased since amount of transients at starting is more. The simulation results are tabulated as shown below. The turn on, turn off angles, the speed of the prime mover are taken as the control variables. The generated voltage and the THD are tabulated for the fixed dwell angle and variable prime mover speed is varied. Table 1 shows that as the speed of the prime mover increases the induced emf is also increased. The total harmonic distortion is also reducing as the speed increases. But the amount of harmonic present is high because of the switching of the converters.

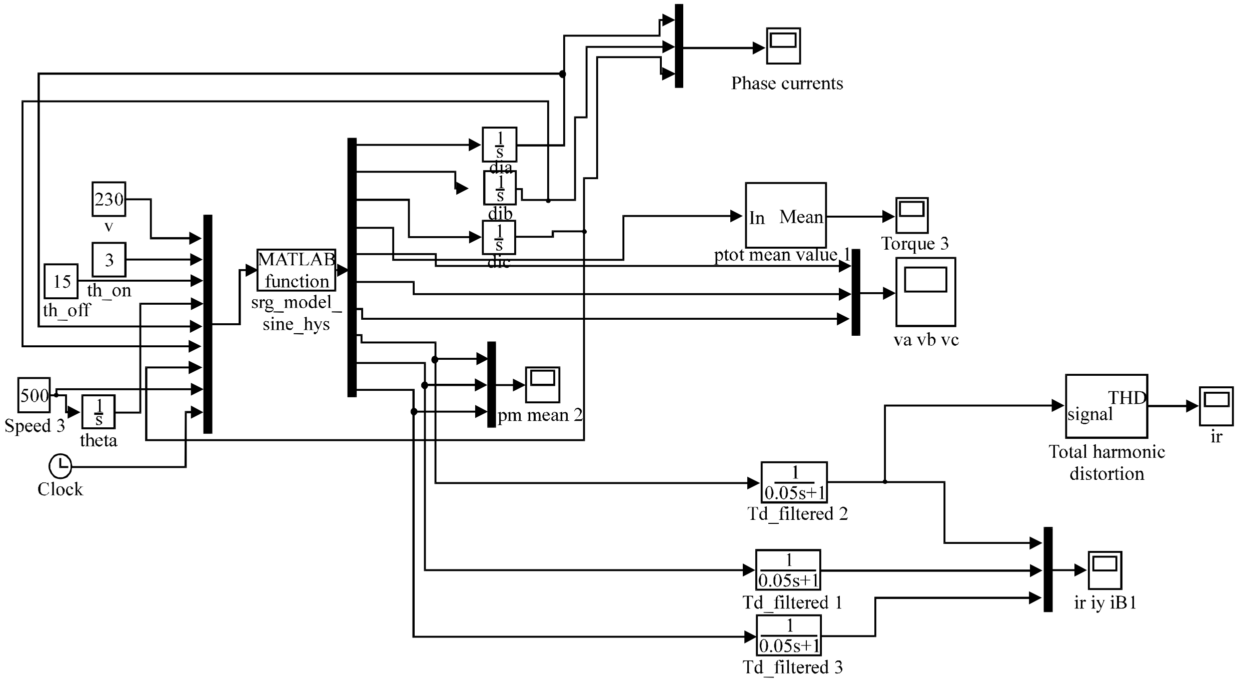

Fig. 9: Simulink model of the proposed method

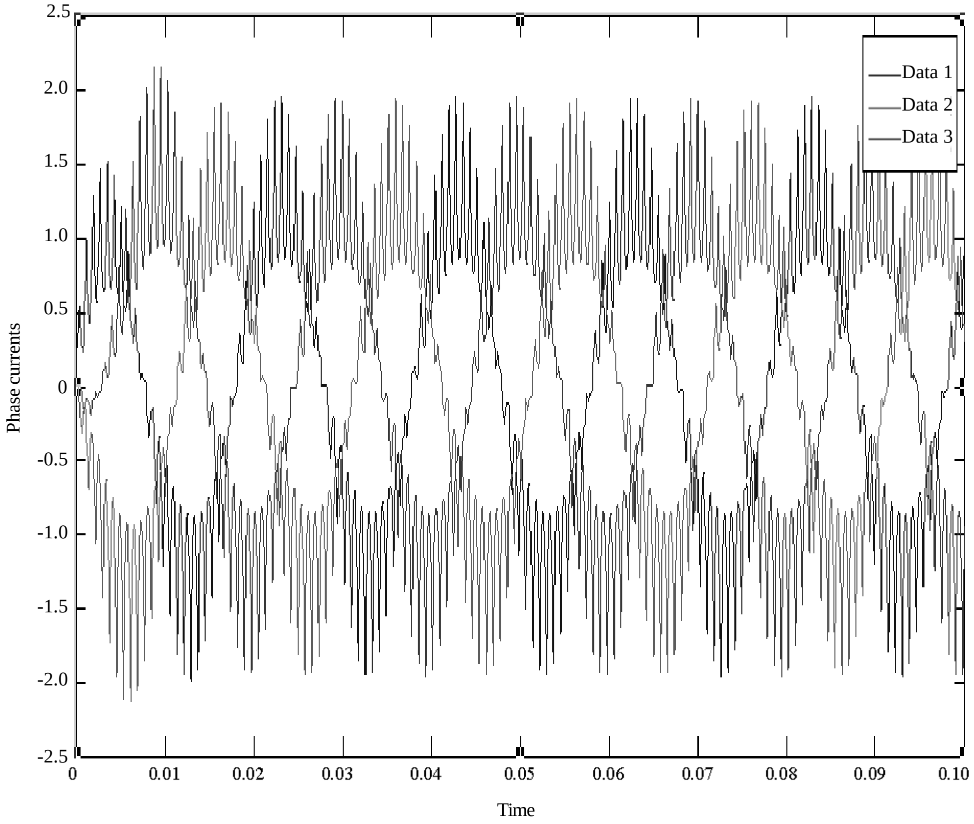

Fig. 10: Phase currents when speed is 500 rpm

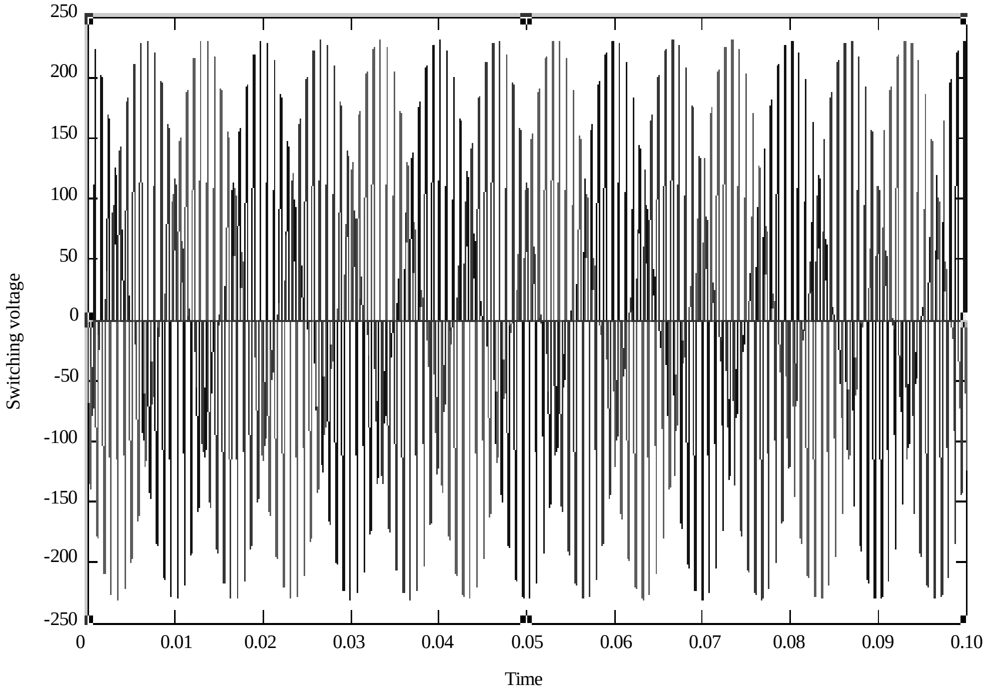

Fig. 11: Switching voltages of SRG

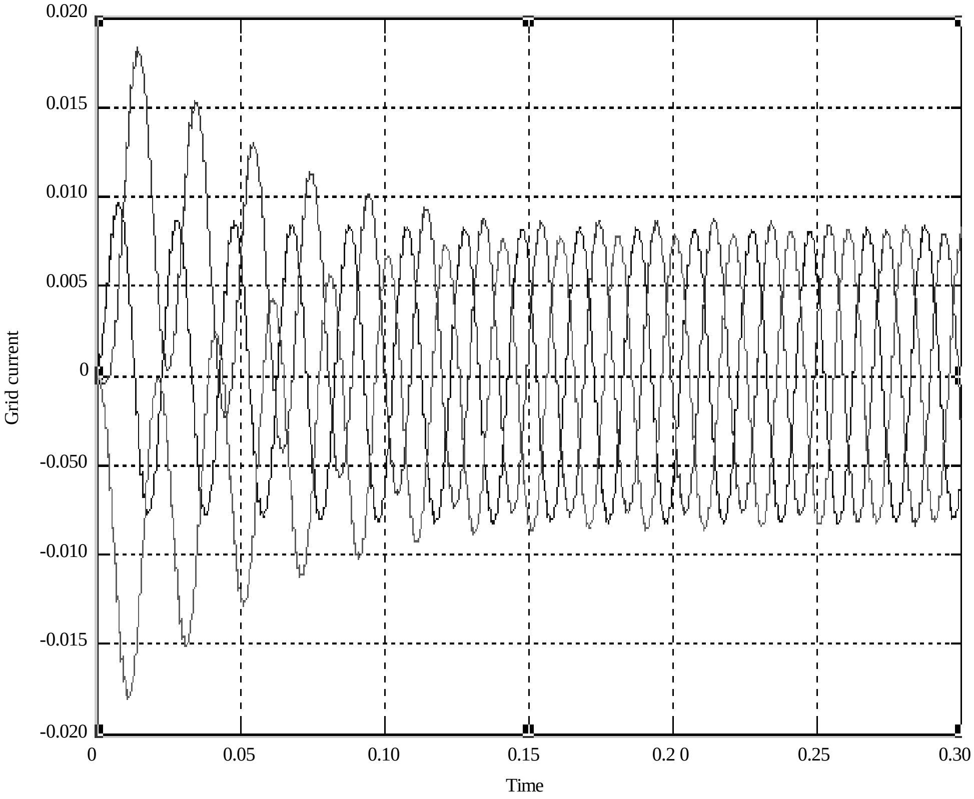

Fig. 12: Grid current of SRG

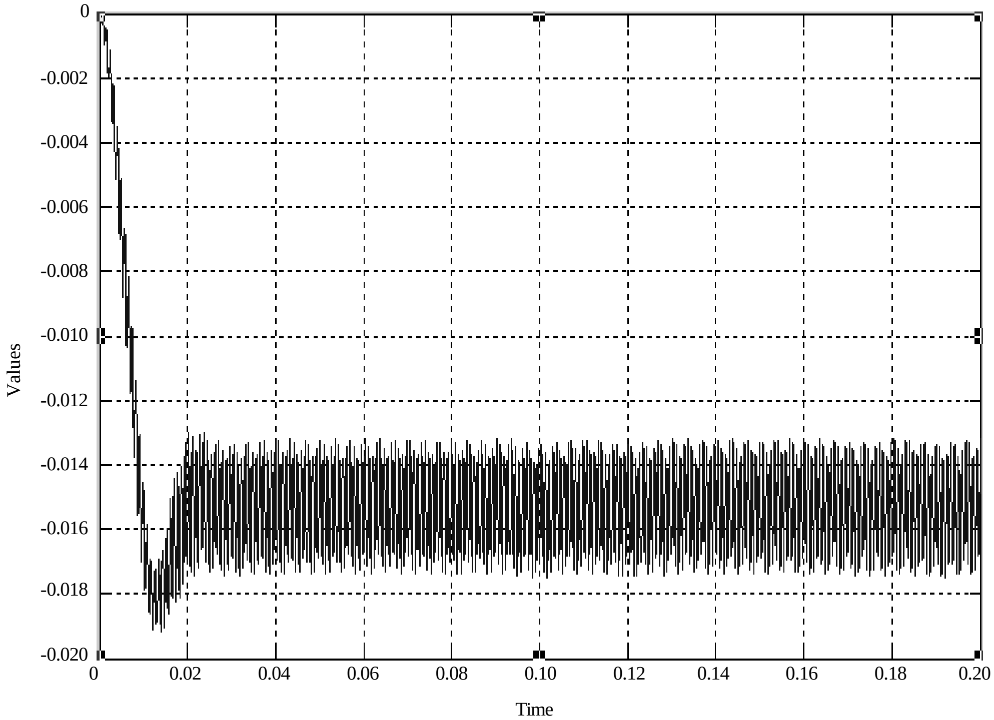

Fig. 13: Developed torque

Table 1: Generated emf at fixed $\theta_{on} = 0°$ and $\theta_{off} = 15°$

Speed of the prime mover (Rad sec^{-1})	Induced emf in SRG (Volts)	Total harmonic distortion in supply current (%)
100	50	2.373
200	80	2.317
300	125	2.268
400	150	2.265
500	200	2.256
600	215	2.231
700	250	2.228
1000	400	2.212

Table 2: Generated emf at fixed $\theta_{off} = 15°$ and constant speed 500 rad sec^{-1}

Turn on angle θ on (deg)	Induced emf in SRG (Volts)	Total harmonic distortion in supply current (%)
0	200	2.272
1	190	2.374
2	180	2.502
3	165	2.583
4	151	2.727
5	140	2.897

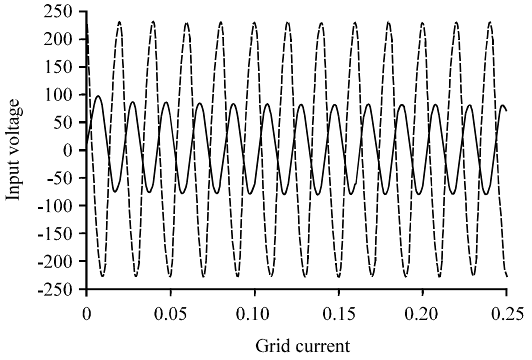

Fig. 14: Input voltage and grid current

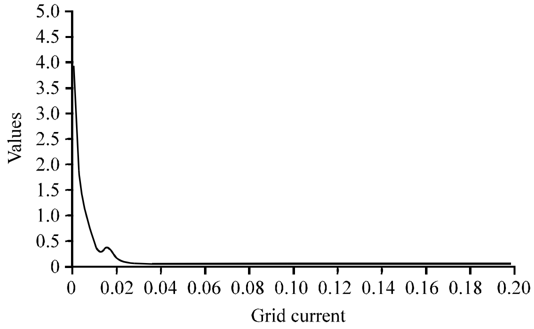

Fig. 15: Total harmonic distortion

The values of generated emf and THD for varying the dwell angle by varying the turn on angle are tabulated in Table 2. The prime mover speed is chosen to be 500 rad sec^{-1}. the generated voltage seem to be decreasing due to increase in turn on angle. Obviously, the excitation period is reduced hence the generated emf also decreasing. Table 3 depicts the values for the prime mover speed of 1000 rad sec^{-1} which is ~10000 rpm.

Table 3: Generated emf at fixed $\theta_{off} = 15°$ and constant speed 1000 rad sec^{-1}

Turn on angle θ on (deg)	Induced emf in SRG (Volts)	Total harmonic distortion in supply current (%)
0	410	2.241
1	380	2.355
2	350	2.436
3	330	2.553
4	304	2.686
5	280	2.831

Table 4: Generated emf at fixed $\theta_{on} = 0°$ and constant speed 500 rad sec^{-1}

Turn on angle θ off (deg)	Induced emf in SRG (Volts)	Total harmonic distortion in supply current (%)
15	205	2.267
16	230	2.161
17	250	2.092
18	260	2.025
19	275	1.963
20	300	1.875

Table 5: Generated emf at fixed $\theta_{on} = 0°$ and constant speed 1000 rad sec^{-1}

Turn off angle θ off (deg)	Induced emf in SRG (Volts)	Total harmonic distortion in supply current (%)
15	410	2.212
16	440	2.155
17	500	2.076
18	510	2.005
19	535	1.934
20	580	1.874

The dwell angle can also be varied by keeping the turn on angle fixed and varying the turn off. The performance of the SRG is tabulated in the Table 4 for a prime mover speed of 500 rad sec^{-1} and in Table 5 for 1000 rad sec^{-1}. Table 5 reveals that the generated emf increases with the increase in dwell angle.

CONCLUSION

This research introduces the matrix converter as a novel approach to driving the Switched Reluctance Machine as generating and motoring mode from a three phase sinusoidal supply. The basic operation of a switched reluctance machine is reviewed for the motor as well the generator operation, control techniques have been simulated using a Reliable Motor Model, demonstrating the effectiveness of the converter for controlling the phase currents. The single band and double band hysteretic approaches to current control require limited processing capability and so could be used in inexpensive drive systems.

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