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Matrix Converter fed Switched Reluctance Motor - An Experimental Investigation

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ABSTRACT: This paper presents an experimental investigation on performance of Switched Reluctance Motor (SRM) when directly fed from AC supply using a matrix converter. The converter has bidirectional switches in the matrix form to facilitate motoring and regeneration. The freedom provided by matrix converters to vary excitation voltage, phase current and dwell angle are studied. Further the influence of matrix converter control on torque ripple, speed ripple, acoustic noise and input power factor are investigated. A 4 phase 8/6 0.5kW SRM is used for experimentation. A hysteresis current control algorithm is used for analysis. Merits and demerits of matrix converter control are brought out.

Index Terms— Constant current reference, H bridge Matrix converter, hysteresis current control, sinusoidal current reference, torque ripple.

I. INTRODUCTION

The switched reluctance motor (SRM) is attracting researchers because of simple construction, low inertia and excellent fault tolerance [1]. SRM can operate as both motor and generator by suitably selecting the firing angles [2]. The entire SR drive includes a motor, position sensor, controller and converter. Several types of converter topologies are found in literature to meet objectives such as faster excitation, faster demagnetization, high efficiency, and to draw minimum reactive power [3-8].

In case of renewable energy sources converters can be directly fed from DC supply. For most of the applications they need to be supplied from utility AC source. In such cases DC supply is obtained with a rectifier coupled with a dc link capacitor. Single switch drive with R dump is suitable for low cost applications at the cost of poor current control resulting in large torque ripple. With an additional C dump or dual decay converter the driver can store energy and self excite to enhance the efficiency. It still suffers from torque ripple problem. The resonant converter serves to overcome the switching losses but introduce external inductances and increase the control complexity [9-10].

Matrix converters are used to directly convert AC-AC supply without need for a rectifier DC link capacitor and an inverter [11-14]. SRM is capable of operating with bidirectional current. Hence coupling an SRM with matrix converter provides the following advantages:

i. No necessity for bulky reactive elements
ii. Possibility of flow of bidirectional current
iii. Nearly sinusoidal input and output waveform
iv. Controllable input power factor.

Sinusoidal excitation with overlapped phase currents is shown to reduce torque ripple and iron losses [15-17]. Single sided matrix converter with unidirectional current is shown to have the advantage of self commutating in SRM [18]. Torque ripple can be minimized initially at the design stage itself and further by suitable control techniques. An inner current loop is introduced to have control over the torque. Hysteresis current control is the simple method but has the disadvantage of variable switching frequency high current ripple and consequent audible noise. PI/PID based fixed switching frequency control provides easier digital implementation with low current ripples and low audible noise. They show poor performance with varying operating conditions [11]. Fuzzy logic, neural network, adaptive and genetic algorithm based tuning of current shapes is shown to achieve less vibrations. [19-24].

This paper presents an experimental investigation of double sided matrix converter fed SRM. The experimental results are matched with simulated performance. Performances of hysteresis current control with constant and sinusoidal current references are studied.

II. MATHEMATICAL MODELLING

In this section, we 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. The block diagram for the system is shown in fig 1(a).

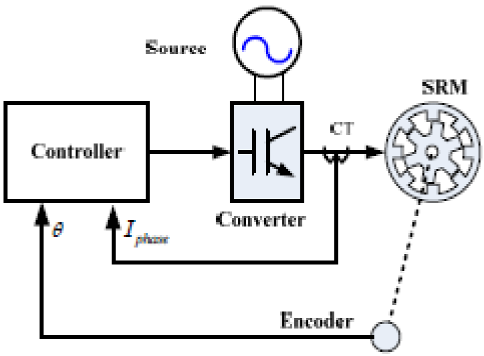

Fig 1(a). Block diagram of SRM fed matrix converter.

A per phase equivalent circuit for SRM can be derived neglecting the mutual inductance between the phases as follows which is shown in fig 1(b). 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 (1)

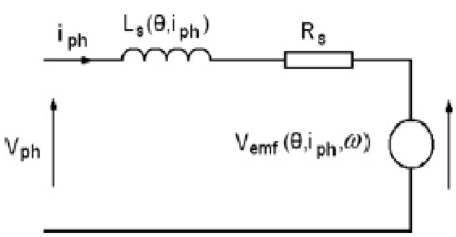

Fig 1(b). SRM per phase winding model.

$$V_{ph} = R_s i_{ph} + \frac{d\lambda(\theta, i_{ph})}{dt} \qquad \ldots(1)$$

Where R_s is the resistance per phase λ is the flux linkage per phase, given by, $\lambda = L(\theta, i_{ph}) i_{ph}$ and L is 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,

$$V_{ph} = R_S i_{ph} + L(\theta, i_{ph})\frac{di_{ph}}{dt} + i_{ph}\frac{d\theta}{dt}\frac{dL(\theta, i_{ph})}{d\theta} \qquad \ldots(2)$$

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,

$$V_{emf} = i_{ph}\omega \frac{dL(\theta, i_{ph})}{d\theta} \qquad \ldots(3)$$

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

$$T_d - T_L - J\frac{d\omega}{dt} - B\omega = 0 \qquad \ldots(4)$$

Where T_d is the total torque developed T_L is the load torque ω is the angular speed J is the moment of inertia and B is the frictional coefficient. The resultant electromagnetic torque is the composition of contribution of four phases where each one has its own instantaneous inductance voltage and current.

$$T_d = \frac{1}{2}\left(i_a^{\,2}\frac{\partial L_a}{\partial\theta} + i_b^{\,2}\frac{\partial L_b}{\partial\theta} + i_c^{\,2}\frac{\partial L_c}{\partial\theta} + i_d^{\,2}\frac{\partial L_d}{\partial\theta} \right) \qquad \ldots(5)$$

Considering equations (1) – (5) the mathematical model for the SRM is made which explains the complete dynamic behavior of the machine.

III. THE MATRIX CONVERTER AND CONTROL ALGORITHM

The chosen single phase to four phase H bridge matrix converter is shown for only one phase of the SRM in Fig 2. It contains 16 bidirectional switches. As in any matrix converter only few switches conduct at a time, though there is more number of switches. An AC capacitor and suitable freewheeling diodes are used in the converter.

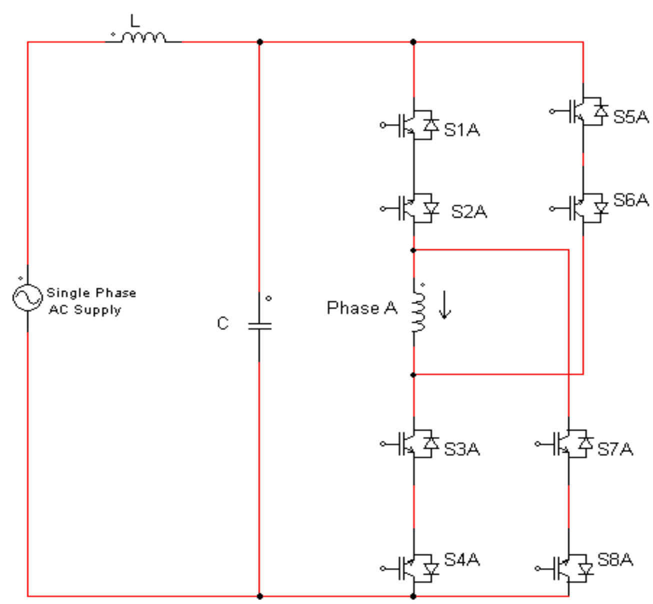

Fig 2. H Bridge matrix converter topology.

(A). Operating modes of converter

In every switching period each phase encounters two modes namely excitation mode (θ_{on} -θ_{off}) and freewheeling mode ($\theta > \theta_{off}$).

i. Excitation mode:
During positive half cycle and in excitation mode the switches S1A and S3A are turned on, the energy is drawn from the supply which magnetizes the phase a winding. During negative half cycle and in excitation mode the switches S2A and S4A are turned on. Even the current direction reverses SRM has a positive torque hence the motor rotates.
ii. Freewheeling mode:
S6A and S8A are turned on during the regeneration mode of positive cycle and S5A and S7A are turned on during the regeneration mode of negative half cycle. During this period the emf stored in the phase winding is pumped back into the supply.

(B) Control algorithm for matrix converter
Hysteresis current control algorithm is used to control the SRM. In the hysteresis current control method, the current is allowed to chop within a tolerance band; around the desired level of current. This produces a waveform with high switching components.
The following control algorithms are analysed using a matrix converter.

1. Constant current reference
2. Sinusoidal current reference

In constant current reference control the supply is sinusoidal and the hysteresis control is done based on constant current reference. The fixed θon and θoff control is used. The switches are turned on based on position encoder information and they are turned off based on hysteresis current control technique. In sinusoidal current reference the supply as well as reference current both are sinusoidal, which also uses the hysteresis current control.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A Matlab/Simulink is used to simulate the converter of fig 2 with hysteresis current control. The performance of SRM with this converter is analysed. Both constant current reference and sine reference are implemented using hardware.

A. 30V ac supply and 0.8 A constant current reference
Fig 3(a) shows the phase currents of SRM when feeding with ac supply. Fig 3(b) shows the supply voltage and supply current wave forms. We can find the power factor has got affected.

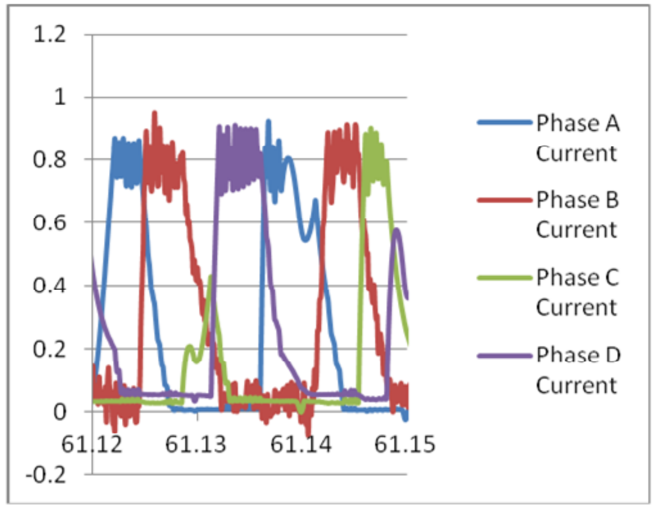

Fig. 3(a). Phase currents of 8/6 SRM with 30v Peak ac supply constant current reference of 0.8A.

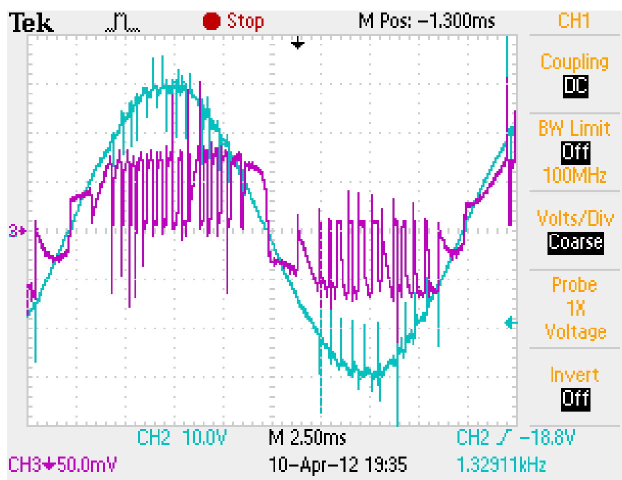

Fig. 3 (b). supply voltage and current.

The SRM is tested under various voltage and current reference levels and performance analysis is carried out. The speed ripple, torque ripple power factor and THD are tabulated.

Table 1. Performance with Constant current reference (30 V sinusoidal supply).

Constant current reference (A)	Speed ripple (Rpm)	Torque ripple (%)	Power factor	THD (%)
0.6	2.92408	135.3103	0.5	86.2
0.7	7.3237	101.53	0.55	83.2
0.8	10.2046	85.1869	0.62	77.5
0.9	14.1611	73.592	0.7	70.3
1	11.5214	61.6876	0.74	64.8
1.1	23.7167	62.4672	0.78	59.4
1.2	14.934	59.7569	0.83	51.1

Table 2. Performance with Constant current reference (100 V sinusoidal supplies).

Constant current reference (A)	Speed ripple Rpm	Torque ripple %	Power factor	THD (%)
0.35	5.482	206.09	0.258	96.5
0.4	4.974	183.3677	0.278	95.2
0.45	10.761	138.7581	0.336	94.7
0.5	22.3082	117.135	0.359	93.2
0.55	10.1333	93.368	0.398	91.6
0.6	57.146	85.5086	0.445	89.5
0.7	21.73	69.6915	0.523	84.7
0.8	25.4765	47.0565	0.572	82.1
0.9	53.4045	37.4526	0.619	79.6
1.0	52.4116	32.4602	0.636	76.9
1.2	26.4504	22.1815	0.696	71.6
1.5	22.1043	16.3165	0.75	65.3
2	41.6692	12.2135	0.823	56.2

Table 3. Performance with Constant current reference (1A) (different sine voltages).

Supply voltage (volts)	Speed ripple Rpm	Torque ripple (%)	Power factor	THD (%)
50	12.81	43.1804	0.746	66.7
100	18.75	32.6839	0.648	75.9
150	51.44	23.1812	0.587	80.7
175	60.06	19.3439	0.572	81.3

Table 4. Performance with Constant current reference (3A) with different sine voltages.

Supply voltage (volts)	Speed ripple rpm	Torque ripple (%)	Power factor	THD (%)
50	38.704	14.0624	0.908	40.3
100	19.35	6.6584	0.864	49.8
150	79.372	4.2764	0.743	66.7

B. With 30V ac supply and 0.8A sinusoidal current reference

Fig 4 (a) shows the phase currents of SRM, when feeding with ac supply with sinusoidal current reference. Fig 4 (b) shows the supply current and supply voltage wave forms. The performance of SRM is observed for various reference levels. The torque ripple, speed ripple, power factor and THD are tabulated.

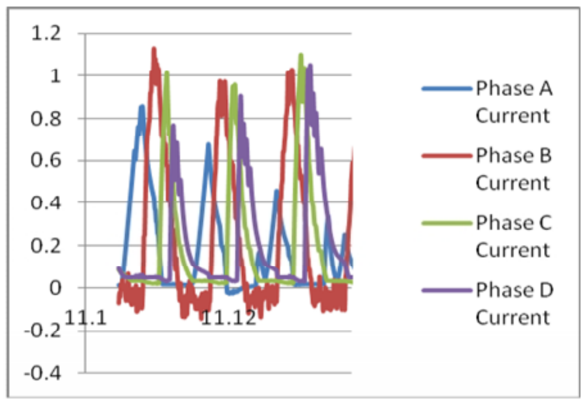

Fig. 4(a). Phase currents of 8/6 SRM with 30V ac supply sinusoidal current reference of 1A.

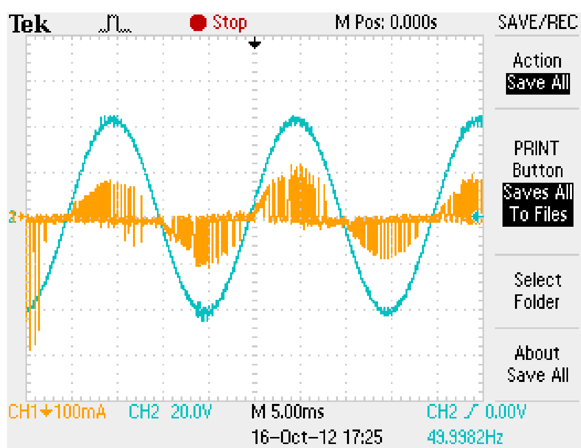

Fig. 4 (b). supply voltage and current for sinusoidal current reference.

Table 5. Performance Sinusoidal current reference (30v ac supply) .

Sinusoidal current reference (A)	W ripple (rpm)	Torque ripple	Power factor	THD (%)
0.7	11.95	208.49	0.544	83.3
0.8	6.8	163.34	0.608	78.3
1	10.307	93.68	0.815	59.7

Table 6. Performance with sinusoidal current reference (3A) with different sine voltages.

Supply voltage (volts)	W ripple (rpm)	Torque ripple	Power factor	THD (%)
50	10.69	0.08705	0.831	55.9
100	6.45	0.171005	0.879	47.0
150	26.954	0.105786	0.618	71.2
175	29.708	0.094342	0.565	82.2

From the above tables we can find that torque ripple is less in case of sinusoidal current reference. The acoustic noise also reduced because of overlapping of phases. The speed ripple is also reduced.

(A) Experimental setup

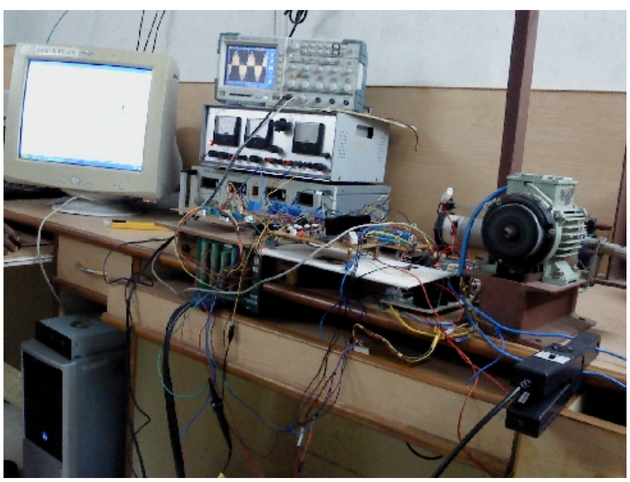

Fig. 5. Experimental setup.

Fig. 5 shows the experimental setup for the matrix converter fed 6/4 SRM. Control part is organized through MATLAB/Simulink model. Commutations pulsed are generated based on the information from discrete position sensor information are acquired through the National Instrumentation Data Acquisition (NI DAQ) card PCI 6251. An H bridge converter with necessary isolation and gate drivers are used to commutate the phase current. Hall Effect current and voltage sensors are used for measuring the active phase voltage and current respectively.

V. CONCLUSION

This paper presents a direct excitation of SRM with ac supply using a matrix converter. The SRM control is studied with two types of current references. The constant current reference is simple to implement but it will introduce third harmonics. The speed and torque ripple are found to minimize at higher speeds and over lapped phase excitation. The power factor is shown to improve with sinusoidal current reference. Hence it can be concluded that direct matrix converter fed SRM with sinusoidal current reference is most suited configuration for low cost high speed applications.

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