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Research paper

Simulation of Energy Dump Converter Topology for Switched Reluctance Motors

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Abstract

The switched reluctance machine (SRM) is the least expensive machine to produce yet it is very reliable. An SRM drive system has to be designed so that there is integration between the machine and the converter-controller configuration. This paper focuses on the resistor dump converter topology where most of the energy from the windings is dissipated in a resistor. A detailed analysis and simulation of the converter has been conducted and a design guideline for the proposed converter is laid out. The resistor dump converter has a low component count and this enables it to achieve a low cost converter. Simulation results show that for the resistor dump converter additional snubbers are required. This leads to an increase in complexity of the controller as more parameters need to be considered. Also, the addition of the passive components of the snubber makes the circuit less reliable and costly. For the purpose of just looking into detail on the behaviour of the converter, it is sufficient to look at the results of the simulation using a static inductor to model the SP-SRM. If cost is to be the priority, the most economical choice must be made but within limits of the application.

Keywords: *converters; resistor dump; switched reluctance motor;*

1. Introduction

Switched reluctance motors (SRMs) are motors which do not have any windings or magnets, whilst the stator is mostly made out of steel laminations forming poles on which series of coils are wound. A rotating magnetic field is produced when current is 'switched' between the phase coil windings in a sequential pattern. The magnetic circuit is subject to saturation and therefore the machine is highly non-linear. In order for the machine to rotate smoothly the current switching must be precisely timed with the rotor position. Therefore, for proper control, some form of rotor position feedback is required. The machine is capable of reaching high speed with high efficiency if the commutation is accurately controlled with respect to the rotor position angles [1]. The simple construction of the motor results in a machine that is low cost. However, the cost of the power electronics driving the SRM is high [2].

In this paper, the resistor dump converter is chosen for analysis. In this converter, part of the energy in the phase windings are either dissipated (or dumped) in a resistor. The detail description of the converter will include mathematical analysis of the equivalent circuit. For the equivalent circuit, it is assumed that all components are ideal except where specifically noted. From this point on, the equation used to model the SRM would be the general equation assuming the machine is linear.

The motor is represented by an inductance that is variable depending on rotor position, $L(\theta)$, machine back-EMF (produced by the current and the rate of change of inductance as a function of rotor position at an angular speed), $i\left(\frac{dL(\theta)}{d\theta}\right)\omega$, and an internal resistance, rint. All circuits use a constant voltage source, at the input side to represent the DC link voltage. This is equivalent to the peak voltage of the single phase mains supply.

The converter need to be controlled so that switching occurs only when the rotor is at the position of increasing inductance. Therefore, a position sensor will need to be used. This signal, combined with some defined hysteresis band will enable the SRM to pull the required current during operation. All converters are analysed based on using the same hysteresis current control.

This paper highlights the advances in SRM technologies, and briefly discusses the cost considerations of the converters. As cost becomes the main concern for SRM technologies, this paper focuses on the resistor dump converter as this is the most basic form of the converter which also has only one switch. For converters, the presence of only one switch indicates the low cost of the converter as the component count is low. The paper then discusses the simulation of the resistor dump converter to illustrate its operation and finally the advantages and disadvantages of the converter are highlighted in a summary table.

2. Advances in SRM Technologies

In the last decade there has been an increase in research to tackle the obstacles described above. Areas that have seen significant progress are in consumer products, automotive, aerospace, domestic appliances as well as amusement park rides [3]. The reason is due to the need for machines with high-grade performance, robustness to harsh conditions, rugged operation and economical prices [4, 5].

One of the growing markets for SRM technology is the automotive industry [6, 7, 8]. According to [6] the SRM is very prominent because it has a modular and rugged structure, wide speed range and insensitivity to high temperatures. The normally associated noise due to stator vibrations can be reduced by methods like high stiffness stator design [9] and active noise cancellation technique [10].

In the aerospace industry, the SRM is a main contender because it has the capability to achieve high rotational speed combined with high power density [11], reliability [12] and lower cost. There is an increasing interest in the concept of 'more-electric aircraft' due to commercial and environmental pressures. Once again, the simple SRM rotor design allows higher operating speeds and operation within harsh environment especially in high temperatures [13]. As far as power converters are concerned, weight, volume, efficiency and reliability are key considerations, and thus having the usual electrolytic capacitors becomes unsuitable [13].

There is also a rapid increase in SRM-based domestic products. Some popular ones are 'Maytag Neptune' washing machine by Emerson Electric Co. and 'DC05' vacuum cleaner by Dyson. Significant cost savings can be achieved at higher operating speeds.

An SRM cannot produce motion when it is directly connected to a voltage supply line, but instead rely on intelligent control for electronic commutation. The performance of an SRM is very much dependent on the applied control. For any specific application, the machine design and power converter must be designed as a whole [14]. The integration of SRM and the control devices is termed Switched Reluctance Drive (SRD) [15]. In a typical SRD, control of the machine torque is achieved by setting control variables according to calculated or measured functions [16].

Well known methods to control SRM current are hysteresis control (HCR), delta modulation (DCR) and voltage PWM control [17]. Many variations exist on these basic schemes. In all cases, the most important variable is the turn-on and turn-off angles. During this period, the flux builds up from zero to its peak value.

As far as the switching devices are concerned, the choice of which to use depends on the requirement of the application. Generally, for applications requiring higher switching frequencies, MOSFETs are used. However, quite recent progress power electronics devices means there are MOSFETs that can operate at very high voltage ratings.

2.1. Costs Considerations for SRM Drives

In the selection of an SRM motor and drive for any application, the main concerns are performance and costs. Many novel approaches to SRM drives has focused on reducing the cost through topological and control modifications [18]. Topological modifications involve the reduction in the number of components namely the switches in the converter circuit. New control algorithms are then proposed which takes into account the reduced number of components, to produce the desired speed-torque output.

Some of the common features of low cost motor drives that would be desirable by industry would be minimal number of controllable switches, thus minimal cost of the attendant circuits such as gate drives and logic power supplies, and cooling mechanisms [19]. Low cost motor drives would also be required to have the smallest volume, weight and cost of the power electronics and controller.

To address this issue, single-switch-per-phase converters have been proposed [20-24] and are most suitable for low cost applications due to the relatively low component count and drive simplicity [25]. While being the most cost effective circuit, single-switch-per-phase converters face challenges such as unability to provide four quadrant operation as well as wide variable speed control. To achieve this, two-switch-per-phase converters have also been proposed [26].

One of the topologies which has only one switch per phase is the resistor dump converter. Part of the stored energy is dissipated in a resistor (R_{dump}) instead of being regenerated into the DC link. A diode is also needed for freewheeling. The significant cost reduction in this topology is because a resistor is used in place of the extra semiconductors for the regeneration path. Although this circuit has been available for some time, it was first analysed by Krishnan in [27]. The main advantage of this converter topology is the simple configuration since there is only one switch per phase. The switch driving requirement is minimal as the switch shares a common source (emitter) connection.

The major drawback of this circuit is that the energy is simply dumped during each commutation process resulting in a low efficiency converter. This inefficiency is, however, more than compensated by their simplicity, low cost and low component count. Also, as the dissipative component is a resistor, the defluxing voltage will tend to drop as the current decreases. The resistor will also need to have a high power rating, which will create the necessity for adequate cooling of the resistor.

The converter with such drawbacks makes it undesirable. However, it is considered suitable for low cost variable speed applications that require intermittent use such as hand tools [27].

3. Research Method

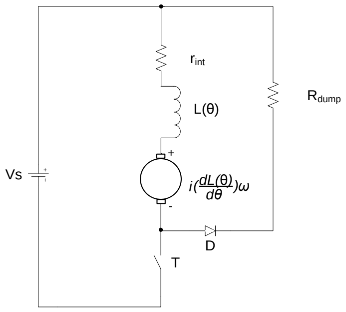

Figure 1: Resistor dump converter

Figure 1 shows the resistor dump converter. The resistor dump converter topology is simulated in Orcad/Pspice. All test circuits use a voltage source at the input side to represent the DC link. Usually, this would be equivalent to an ideal voltage supply, a full wave diode bridge rectifier and DC link capacitor. However, in the resistor dump topology, the DC link voltage is set to be 600V.

The main focus of this work is to obtain a detailed analysis of the resistor dump converter topology. Throughout the simulation, the 1kW motor is modelled by an inductor value and a small winding resistance. The simulation is performed with the minimum inductance value of a 1kW single phase SRM. The low inductance value was chosen to simulate the worst case scenario, where smaller inductance will generate larger current and voltage stresses across the components. The value of the inductor initially used for the purpose of the simulation is 17mH. This was selected based on the practical values used in the references [4,5,7]. The equivalent model for the single phase SRM for simulation purposes is shown in Figure 2. The 1Ω resistor is used as the voltage drop across it represents the current that is flowing through the load.

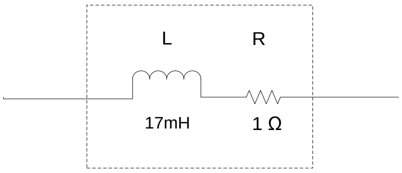

Figure 2: SP-SRM model used in the simulation

In a real machine, switching only occurs during the dwell angle, of the rotor. The dwell angle is defined as the angle between the turn-on angle and the commutation angle (or turn-off angle). In the simulation, where the rotor signal is not present, this can be implemented by a clock signal. To determine the frequency of the clock signal, the following assumptions have been made on the machine:

SP-SRM type: 2/2 motor (two stator and two rotor poles)
SP-SRM speed: 1500 rpm

The entire conduction must be completed during one rotor pole pitch, α_P , and for this machine, the value is:

$$\alpha_P = \frac{2\pi}{N_r} = \pi = 180^{\circ} \tag{1}$$

where N_r = number of rotor poles = 2

In this pole pitch, the permissible θ_D can be calculated as follows:

$$\theta_D = \alpha_P \cdot \frac{(1+\rho)}{2} = 90^{\circ} \tag{2}$$

where ρ is the mean resistive volt drops due to resistance during, θ_D , assumed to be zero.

Therefore, the time, t, needed to provide 90° of dwell angle for a 1500 rpm machine is:

$$t = \frac{60}{1500} \times \frac{90^{\circ}}{360^{\circ}} = 10ms \tag{3}$$

Based on this calculation, the clock signal needs to have a frequency of 50Hz (period of 20ms) with 50% duty cycle. This is taken as the worst case.

The converter is simulated using a hysteresis current controller. An upper band and a lower band are set as reference values. The current through the single phase SRM is measured and compared with the reference. The current value is obtained by reading the voltage drop across the 1Ω resistor shown in Figure 2. Based on Ohm's Law, any voltage across a unit value of resistor will be equal to the current. The power switches are turned off when the upper band is reached, and turned on when the lower band is reached.

The calculation of the hysteresis window size is based on the pulsed current rating of the single phase SRM [8]. This is at least equal to the value of the maximum peak current of the drive. During chopping, the current can be approximated by periodically rectangular blocks of current. For a 1kW SP-SRM, the peak current per phase, I_p is calculated by:

$$I_p = \frac{P_d}{m\eta k_d V_N} = 5.88A \tag{4}$$

where,
P_d = power output = 1kW
m = number of phase = 1
η = efficiency of the machine = assumed at 100%
k_d = duty cycle = 50%
V_N = nominal DC supply voltage

Therefore, for the simulation, I_p is used as the average value of the hysteresis window. For the simulation, the value of 6% ripple has been chosen for the hysteresis band as a compromise to limit torque ripple, switching losses, conduction losses and core losses [9].

For the purpose of simulation of each circuit, it is assumed that all components are ideal except where specifically noted. The simulation is done using a static inductance.

4. Results and Analysis

The size of the resistor in the converter determines the demagnetisation current fall time, the current through the freewheeling diode, switch stresses, and the power dissipation across the resistor. The power rating of the resistor is calculated at the worst case where all the energy from the winding is dissipated in the dump resistor.

As the value of the resistor increases, the current decays faster and vice versa. Therefore, as the switching frequency increases, the resistor value has to be increased to match the switching frequency increase.

The simulation result is shown in Figure 3. Here, two values of resistance have been provided for comparison. The figure shows the associated phase current waveforms for the two resistor values. Smaller resistances will cause longer switching current fall time. As discussed in the previous chapter, during the demagnetisation mode, the current decays with a time constant of , τ where:

$$\tau = \frac{L(\theta)}{R_W + \frac{dL(\theta)\omega}{d\theta} + R_D} \tag{5}$$

$L(\theta)$ is the inductance, ω is the angular speed and R_D is the dump resistance. From this, it can be seen that small values of R_D will result in longer decay times.

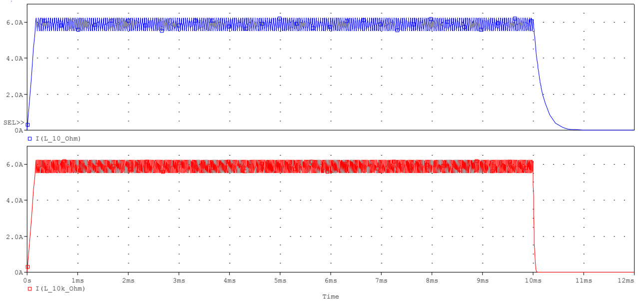

Figure 3: Phase current waveform using two values of resistors;

(top) 100Ω (bottom) 1kΩ

From the figure, the smaller resistor results in a lower switching frequency of 24.73 kHz compared to a frequency of 44.84 kHz using a ten times larger resistor. Also, the 100Ω resistor has a longer current turn-off time.

Figure 4 shows the relationship between resistor size and length of phase turn-off tail current. This clearly demonstrates that higher resistor value results in shorter current turn-off times. The next graph in Figure 5 shows the relationship between resistor sizes to the switching frequency. As the resistor size increases, the switching frequency will increase as well.

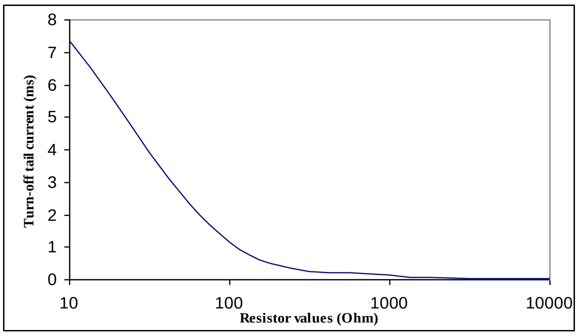

Figure 4: Graph of resistance against length of turn-off tail current

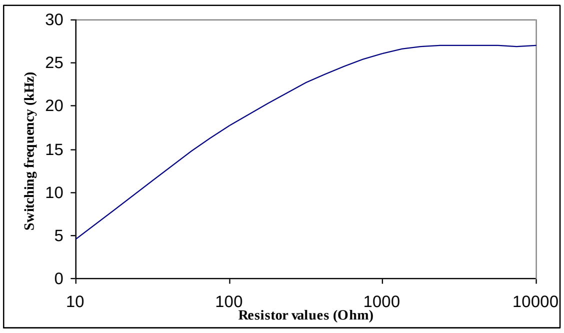

Figure 5: Graph of resistance against switching frequency

When the switch is on, the freewheeling diode is reverse biased by voltages from the DC link and the dump resistor volt drop. During turn-off, the switch voltage stresses can be obtained by this equation [25]:

$$V_{stress} = V_S + V_D + I_P R_D \tag{6}$$

where V_S is the DC link voltage, V_D is the forward drop of the freewheeling diode, and $I_P R_D$ is the volt drop across the dump resistor.

Figure 6 shows the voltage across the switches when two different resistors are used. When a 100Ω resistor is used, the voltage is approximately twice the DC link voltage, but when a 1kΩ resistor is used, the voltage is nearly 7kV. From the waveforms it is clear that the voltage across the switch is larger if a larger resistor is used. It can be concluded that the use of a larger resistor results in higher voltage stresses across the switch and the freewheeling diode. The graph in Figure 7 shows the relationship between resistor size and the switch voltage stress (calculated as the percentage of the DC link voltage).

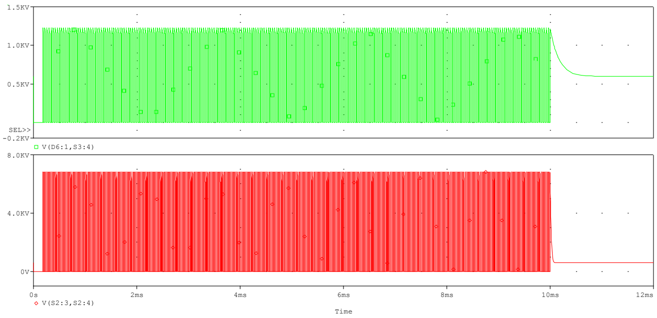

Figure 6: Voltage across the switches; (top) 100Ω (bottom) 1kΩ

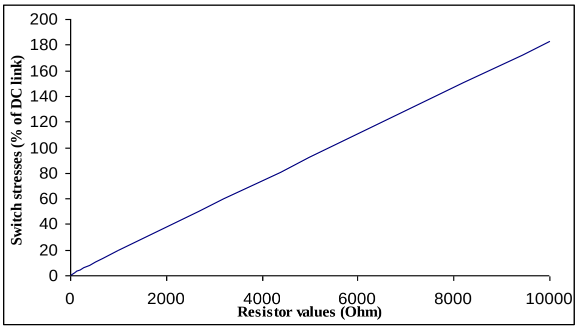

Figure 7: Relationship between dump resistance and switch voltage stresses

The average power rating, P_D of the resistor is calculated when the stored energy is dissipated in the dump resistor during every switch turn-off. It can be calculated as:

$$P_D = I^2 R_D \tag{7}$$

where I is the average demagnetising current and R_D is the dump resistance.

The graph in Figure 8 shows the relationship between resistor sizes and the dumped power based on the simulated values. The bigger the resistor, the larger power can be dumped.

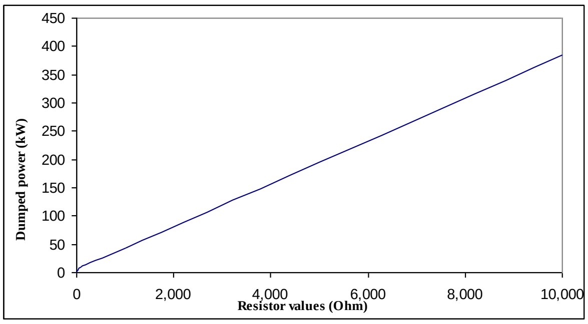

Figure 8: Relationship between dump resistance and dumped power

These results show that careful consideration of the size of the resistor is very critical to the efficiency and torque production, the voltage ratings and the power dissipation of the switching components.

In [6] it was found that adding a snubber capacitor (circuit shown in Figure 9) will significantly reduce the voltage stress across the switch. This snubber capacitor will limit the voltage rise and the maximum voltage across the switch. When the switch is on, the voltage across the capacitor is equal to the DC link voltage. After switch turn off, the energy from the winding is channelled to the snubber capacitor, and only when the capacitor voltage becomes higher than the DC link voltage, the remaining energy will be dumped into the resistor. Therefore, the circuit limits the switch stress because the voltage across the switch is now the voltage across the snubber capacitor plus the forward volt drop of the diode.

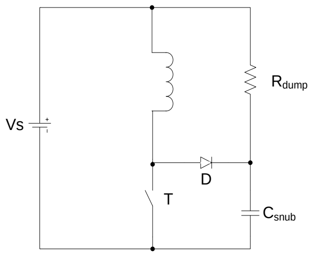

Figure 9: Resistor dump circuit with snubber capacitor

One drawback is that immediately after turn-off the circuit is effectively an RLC circuit and the rate of de-energising the inductor will depend on the RLC time constant.

5. Conclusion

Table 1 below is a summary of the advantages and disadvantages of the resistor dump converter. From this table, it can be concluded that although the converter has many advantages, there are also significant disadvantages which may hinder its application in mainstream products.

Table 1: Summary of advantages and drawbacks

Advantages	Disadvantages
• simple configuration • one switch	• energy wasted • low efficiency • additional snubber may be required

The resistor dump converter has a low component count and this enables it to achieve a low cost converter. In terms of the control drives, control for the converter is easily achieved. This could mean controller using analog devices or basic microprocessors e.g. PICs may be implemented.

It was seen in the simulation results that for the resistor dump converter additional snubbers are required. This leads to an increase in complexity of the controller as more parameters need to be considered. Also, the addition of the passive components of the snubber makes the circuit less reliable and costly.

For the purpose of just looking into detail on the behaviour of the converter, it is sufficient to look at the results of the simulation using a static inductor to model the SP-SRM. If cost is to be the priority, the most economical choice must be made but still within limits of the application.

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