Optimal Excitation of a High Speed Switched Reluctance Generator

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Abstract

This paper presents a new approach for controlling a switched-reluctance generator (SRG). The control objective is to produce the required power using the excitation that produces the highest efficiency. The SRG considered here operates above base speed. The turn-on and the conduction angles are the only control parameters that can be used to optimize the power conversion. The conventional control method that advances the turn-on angle as the speed increases is not enough to produce optimum performance. The turn-on and the conduction angles together are the key elements for optimal excitation. Optimization of the excitation angles is performed using a machine model based on finite element analysis. For all of the operating speeds, all possible turn-on and conduction angles are simulated to get the desired power output. The excitation angles using the minimum rms phase currents are chosen among those that give the desired output power. The control strategy is experimentally tested using a 6kW 5000 rpm SRG. The control algorithm is able to provide required power with very good generator efficiency.

1 Introduction

Switched-reluctance machines (SRM) operating both as motor and generator are receiving increased attention with the improvements of power electronics technology and machine design [1]. The advantages of the SRM are the absence of the rotor windings or permanent magnets on the rotor, brushes and independence of their phases. The advantages can make the SRM more efficient and less expensive in some applications. The efficiency of the motor is highly dependent on the motor design and the control strategy. There have been many studies on designing more efficient SRMs. This paper contributes to optimizing the switched reluctance generator excitation to produce high efficiency.

Efiiciency is important in any system, but particulary so in automotive systems where inefficiency either leads to reduced fuel economy or reduced battery life. Our work here is motivated by the development of a switched-reluctance starter/alternator system for automotive applications. While the relative merits of switched-reluctance machine in the starter/alternator application are subject to debate by some [2], we believe the work on all technologies should continue unabated until there is an independent, vehicle-based drive-off between the competing technologies.

The switched-reluctance machine discussed in this paper is a three-phase design. The specification upon which the design is based is shown in Fig 1. The low speed, high torque curve corresponds to motor operation. The high speed trajectory corresponds to 6 kW of shaft power. Motoring performance is met with a 250 V dc bus; generator performance is achieved with a 300 V dc bus.

Optimizing the machine efficiency at low speed, especially in motoring, is rather straightforward [3]. At low speed we always have control through actively shaping the current. Above base speed the machine starts operating in single-pulse mode and in generator mode phase currents can continue to increase even after the excitation is turned off. Because of the time-scale differences between the average power provided by the generator and the generator phase excitation, we have assumed the average power is constant throughout one electrical cycle [4]. The power delivered by the generator is directly mapped to the phase excitation. For any operating speed there have been many conduction angles providing the same dc link current. The excitation angles providing the same power with the minimum rms phase current are taken to be the optimum excitation

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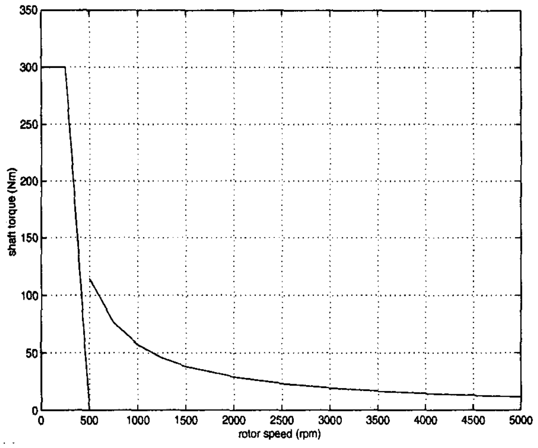

Figure 1: Operating point specifications of the investigated switched-reluctance machine.

angles. So the problem is reduced to generating a map linking dc link current to the commutation angles in the most efficient way. To accomplish this, we extensively modelled the switched-reluctance generator (SRG) using finite element analysis. For every operating point we have found the optimum excitation angles.

The control strategy is tested experimentally. We have used a 6 kW SRG for our test. The induction motor controlled by an adjustable speed drive provides mechanical power at constant speed. A digital signal processor is used to implement the control. Figure 2 shows the block diagram of the experimental system.

Section 2 provides background on the SRM and its model. The optimization and mapping process is described in Section 3. Section 4 provides the experimental testing of the SRG. Conclusions are given in Section 5.

2 Switched Reluctance Generator Model

The SRM consists of doubly salient stator and rotor laminations and electrical windings on the stator. Machine phases are properly wound over symmetrically located stator poles. Excitation of a phase winding magnetizes both stator and rotor poles. The magnetic circuit creates torque which tries to minimize the reluctance. The ideal torque production of the switched reluctance motor can be described as

$$T_e(i,\theta) = \frac{1}{2} i^2 \frac{d}{d\theta} L(\theta) \quad , \tag{1}$$

where $L(\theta)$ is phase inductance, i is motor phase current, and θ is mechanical rotor position. As we can see from this equation the change of phase inductance with the rotor position is the key element in torque production. The inductance of the magnetic circuit increases as the rotor poles approach alignment with the stator poles. The inductance decreases as the rotor poles move out of alignment with the stator poles. The machine produces positive torque if we excite the phases by applying current during the region of increasing inductance. It produces negative torque, working as generator, if we excite the phases during the decreasing inductance region. Figure 3 shows the ideal excitation and torque production of the SRM both in motoring and generating operation.

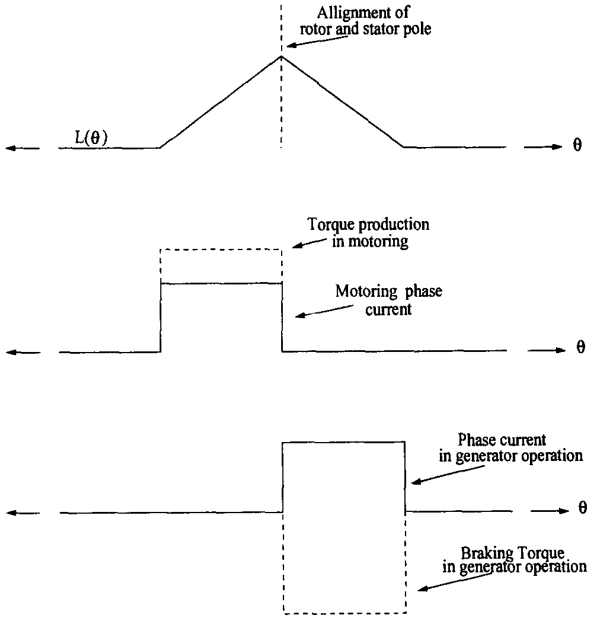

Figure 3: Ideal excitation of SRM and torque production.

The SRM exhibits spatial and magnetic nonlinearities in operation. The magnetic nonlinearities cause Eqn. 1 to be of limited applicability. The inductance of the magnetic circuit is a nonlinear function of the mechanical position [7]. In addition to the nonlinearity in the torque production, the inverter drive is not able to produce the desired square-wave currents as in Fig. 3. The

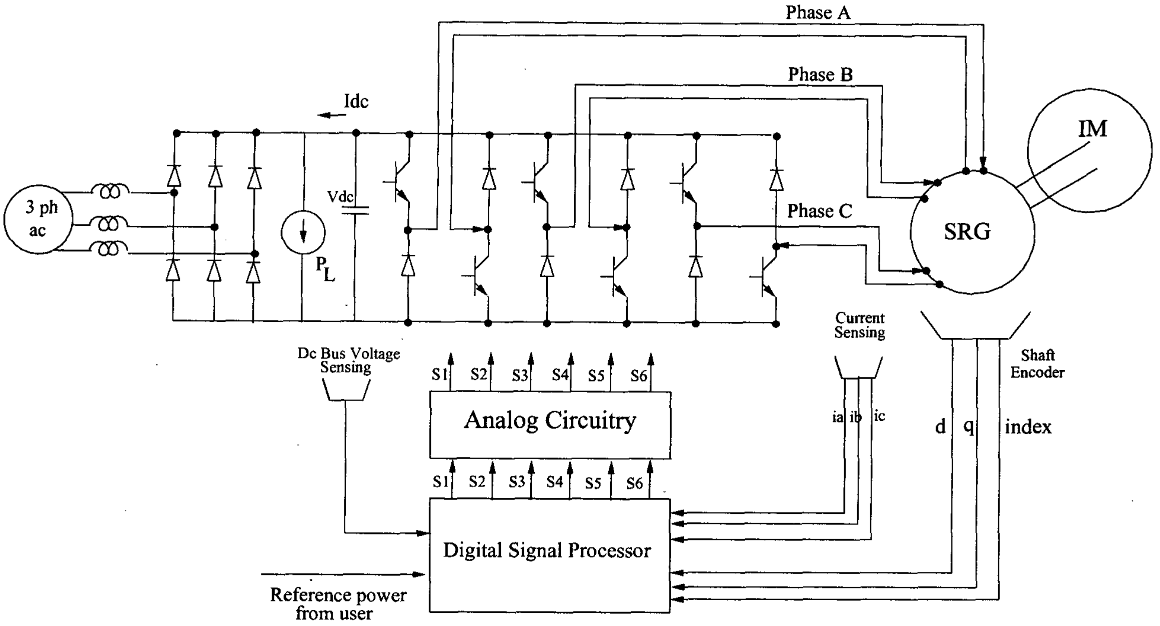

Figure 2: The block diagram of experimental SRG system.

electrical dynamics of SRM can be described as [5]

$$v = Ri + \frac{d\Psi(\theta,i)}{dt} \quad , \qquad (2)$$

where v is the phase voltage, R is the phase resistance, and i is the phase current, and Ψ is the phase flux linkage. Putting $\Psi(\theta,i) = iL(\theta,i)$ gives

$$v = Ri + L(\theta,i) + i\frac{dL(\theta,i)}{di} + i\frac{dL(\theta,i)}{d\theta}\omega \quad . \qquad (3)$$

The generator that is presented here operates above base speed. Generator operation is characterized by the single pulse mode rather than chopping mode. The dc bus voltage is kept constant throughout operation. These conditions and Eqn. 3 suggest that current production is very much dependent on the time of excitation according to rotor position and mechanical speed. Figure 4 shows the excitation of the experimental SRM as a generator. The applied voltage to the phase, current and braking torque production are shown in Fig. 4. The flux linkage (Ψ) characteristic, as function of current (i) is shown in Fig. 5 for two rotor positions.

The turn-on and the conduction angles are the only parameters available to control the generator efficiently and properly. Proper selection of these control angles is necessary to regulate the output power. In order to properly control the machine we have optimized

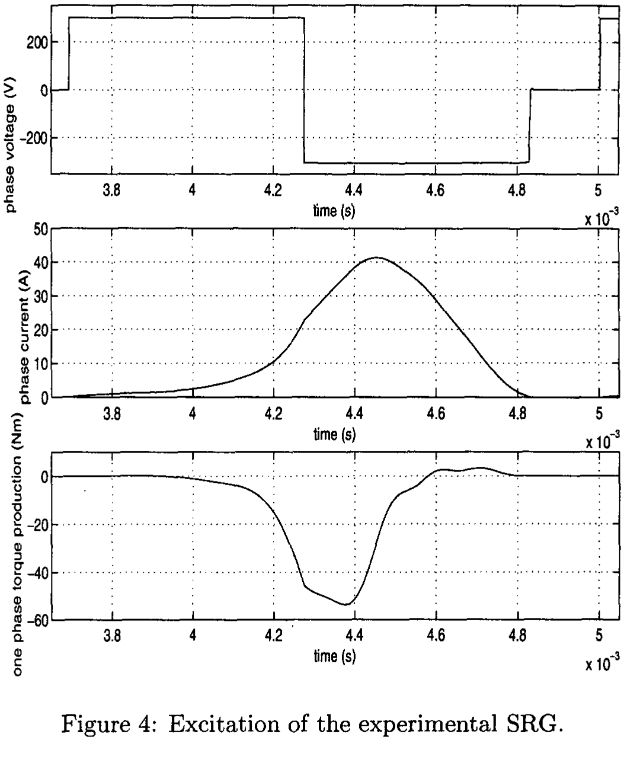

Figure 4: Excitation of the experimental SRG.

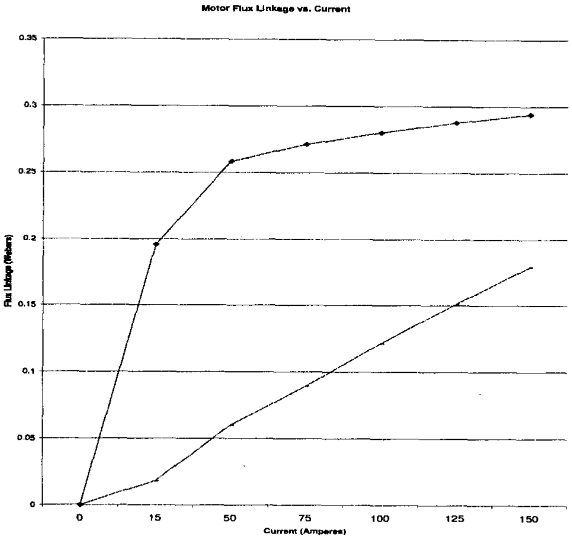

Figure 5: Ψ vs. i characteristic for the experimental SRG at the aligned and unaligned positions.

the turn-on and conduction angles to produce required power throughout the operating speeds. These angles provide the required power with minimum rms phase currents. We have performed the optimization using the motor model based on finite element analysis. The following section provides the optimization procedure for the turn-on and conduction angles.

3 Mapping

Efficient operation of the SRG is highly complicated given its nonlinear behavior. It is difficult to achieve optimal operation by using feedback control rules. A mapping strategy, on the other hand, can offer a much simpler and efficient solution to the problem. A map can be constructed in order to relate the dc link current with commutation angles, dc bus voltage and generator shaft speed. In order to generate any desired dc link current for given shaft speed and bus voltage, the map is used to find the optimum commutation angles.

Since the goal of the mapping is to provide efficient operation, it will be sufficient to consider the average value of the dc link current rather than its instantaneous value. This is a legitimate simplification as long as the averaging is done through one electrical cycle of the SRG because this is the smallest incremental step over which commanded commutation angles are effective [4].

$$\bar{i}(t) = \frac{1}{\tau}\int_{t-\tau}^{t} i(\sigma)\,d\sigma \quad . \tag{4}$$

Here, τ is defined as the time spent during one electrical cycle of the SRG and given by

$$\tau = \frac{2\pi}{\omega N_p N_r} \quad , \tag{5}$$

where ω is the rotor speed, N_p number of the stator phases and N_r is the number of rotor poles.

By using the SRG model mentioned in the previous section, a map is constructed for the following conditions:

1. For different speeds between 1000-5000 rpm in 200 rpm increments.
2. For different dc bus voltages between 275-325 V in 25 V increments.
3. For different turn-on angles between -90 and 145 electrical degrees in 5 electrical degree increments.
4. For different conduction angles between 90 and 180 electrical degrees in 5 electrical degree increments.

Figures 6 and 7 show how the dc link current and rms phase current vary with the commutation angles at 3000 rpm based on the simulated model. Figure 6 shows that there are multiple combinations of turn-on angle and conduction angle that yield the same output current. Given this, it makes sense to choose the pair that yields highest efficiency.

Since the operating points summarized by the SRG model are not optimized, a heuristic selection algorithm is employed based on the copper losses of each operating point. It can also be argued that minimizing the rms current also minimizes the switching and conduction losses within the inverter. This gives us the most efficient commutation angles for the desired average dc link current. Figure 8 shows the relationship between average dc link and rms phase current for all simulated operating points along with optimized points for average dc link currents smaller than 20A.

In order to demonstrate how the suggested method helped to improve the efficiency, certain operating points for 10 A and 20 A dc link current from Fig. 8 are selected and used in the experimental drive system to see the associated efficiencies. Figures 9 and 10 show the efficiencies for 10 A and 20 A dc link current, respectively. As seen from the figures, generator, inverter

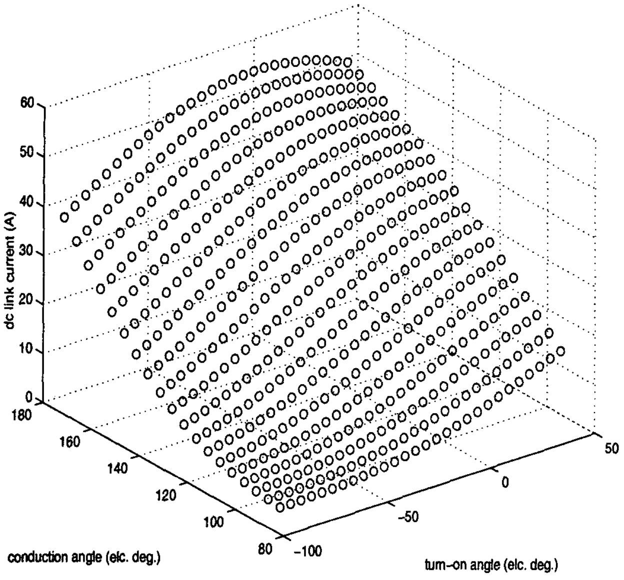

Figure 6: Relationship between average dc link current and commutation angles at 3000 rpm.

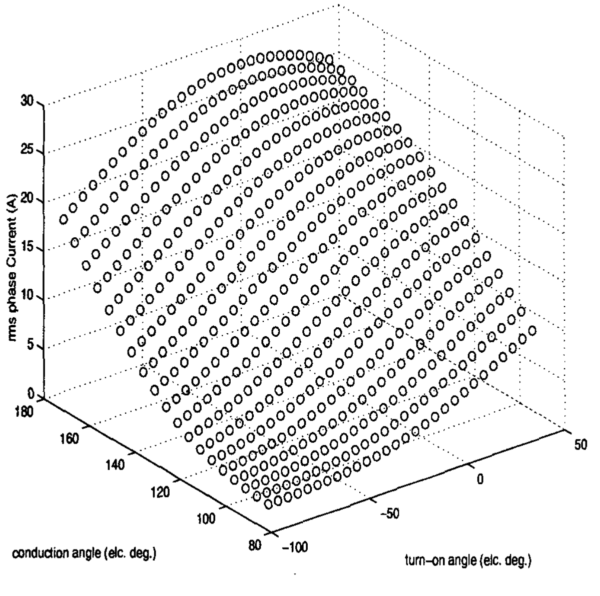

Figure 7: Relationship between rms phase current and commutation angles at 3000 rpm.

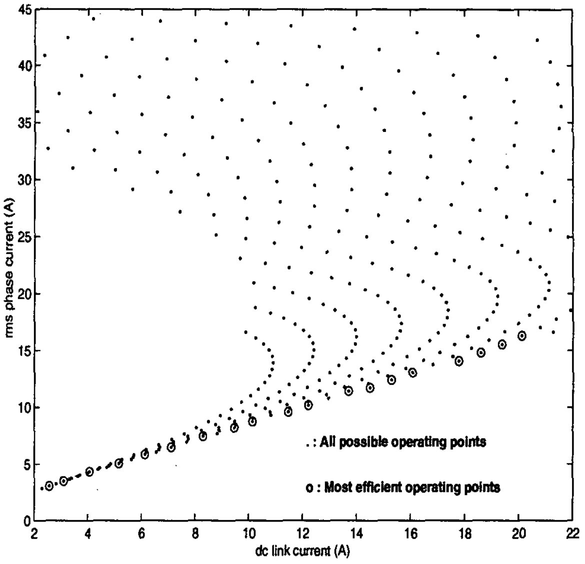

Figure 8: The relationship between dc link current and rms phase current before and after optimization.

and system efficiencies drops significantly as rms phase current increases. The proposed optimization method selects the excitation angles with minimum rms phase current so that the maximum system efficiency is assured.

4 Experimental Results

The performance of the controller is experimentally verified on a 6 kW SRG. The control for the generator is implemented using a Texas Instrument TMS320F240 digital signal processor. The SRG is coupled to an induction motor, which provides the constant speed mechanical power using an adjustable speed drive. A shaft encoder provides direct, quadrature and index pulses to the quadrature encoder pulse unit of the DSP. The control algorithm programmed in the DSP estimates the motor speed. Based on the estimated speed and reference power provided by the user, the controller finds the appropriate excitation angles from the look-up table. Based on the excitation angles and the rotor position, the controller outputs the switching decisions for each generator phase. The dc bus voltage is kept constant throughout the operation. The algorithm is tested for 3 kW and 6 kW points between 1000 and 5000 rpm. Figure 11 shows the generator phase current and voltage at 3000 rpm and 3 kW.

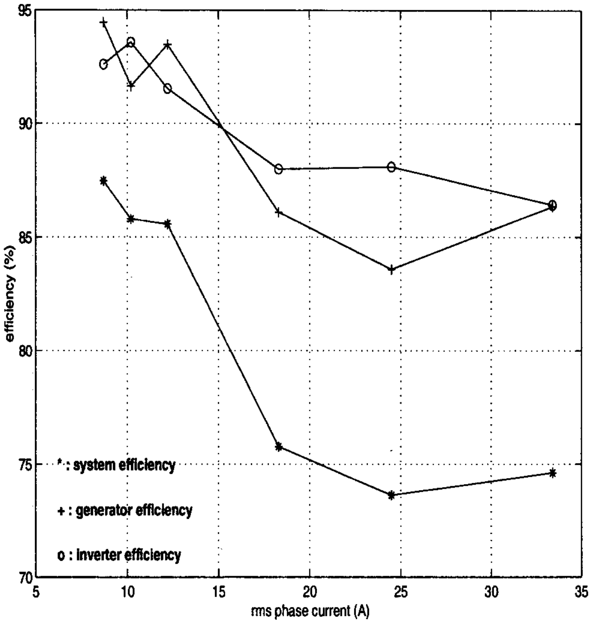

Figure 9: Generator, inverter and system efficiencies for different excitation angles providing 10 A dc link current at 2000 rpm.

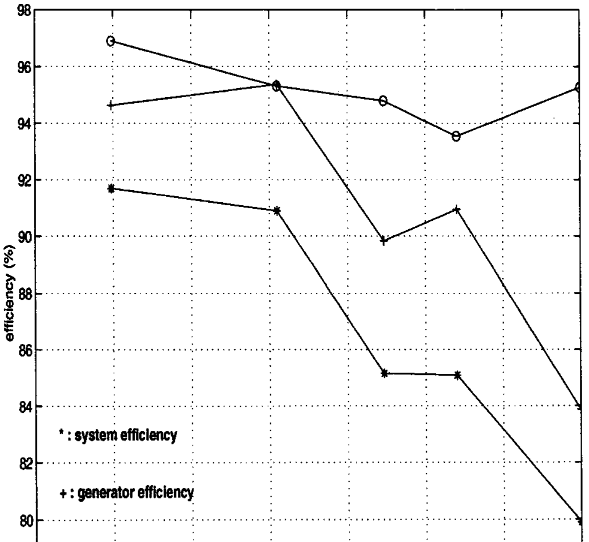

Figure 10: Generator, inverter and system efficiencies for different excitation angles providing 20 A dc link current at 2000 rpm.

By using the excitation angles found in Section 3, the generator produces desired output power with high efficiency. The input mechanical torque is measured by a strain gauge torque sensor. The output generator power is calculated by measuring generator phase current and voltages. For all operating points the generator efficiencies are calculated. Figure 12 shows the generator efficiencies at 3 kW and 6 kW points. As we see from this figure, the SRG offers high efficiency over wide duty.

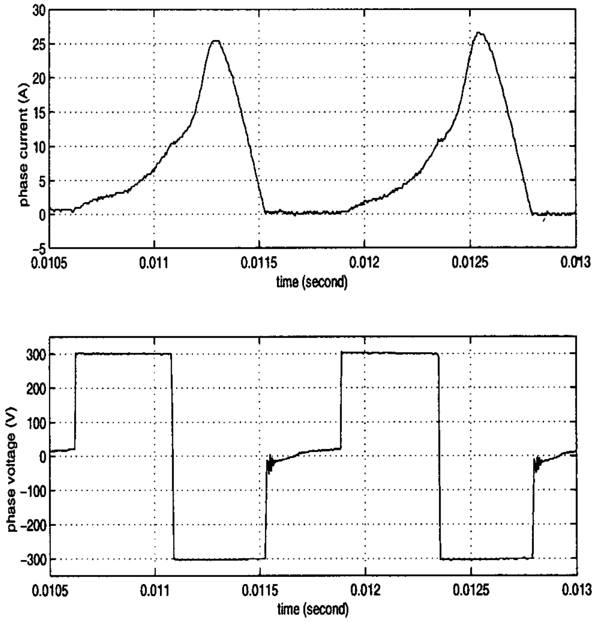

Figure 11: Motor phase current and voltage at 3000 rpm and 3 kW.

5 Conclusions

A novel excitation strategy is developed for a high-speed switched-reluctance generator. The aim is not only to provide stable commutation angles over a wide speed and power range but also to minimize the copper losses of the SRG and improve the generator efficiency. For this purpose, an SRG model is used to simulate various operating points for incrementally different turn-on angles, conduction angles, average dc link current, rotor speed and dc bus voltages. After that, a simple optimization is performed among these points to find most efficient point based on minimum copper losses within the windings. In the end, various maps were

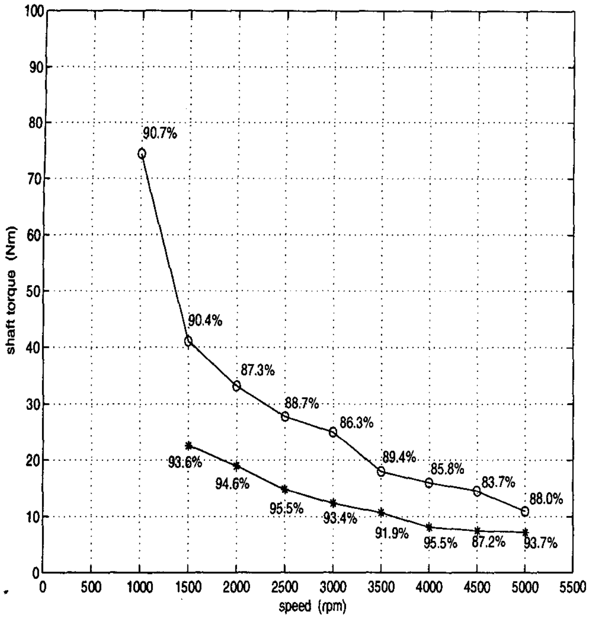

Figure 12: Measured generator efficiencies from 1000-5000 rpm at 3kW and 6kW.

obtained such that commutation angles are linked with averaged dc link current.

The maps constructed by simulation were then used in an experimental SRG drive. Experimental study shows that using these maps result in highly efficient operation of the SRG.

Acknowledgement

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