

Switched Reluctance Generators and Their Control

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Abstract—This paper discusses how the switched reluctance generator (SRG) converts energy as directed by a controller. Beginning with a review of the electromechanics of generation, the paper identifies the implications of the energy conversion process on how the SRG is controlled. The structure of the SRG controller for speed-control and power-control applications is discussed. Practical implementation details for commutation of the SRG are reviewed. Concepts are illustrated with a 6-kW SRG designed to serve as a starter/alternator in automotive applications.

Index Terms—Generator control, switched reluctance, synchronous generators.

I. INTRODUCTION

THIS PAPER discusses the switched reluctance generator (SRG) and its control. The SRG can be considered the dual of the switched reluctance motor (SRM), although there are some important differences in control objectives and control implementation. The goal of this paper is to elucidate the control issues for the SRG and summarize typical SRG behavior. This is accomplished through a discussion of energy conversion in the SRG that identifies the important features of the SRG that must be considered in designing its control.

The SRG is under development for variable-speed applications where the inherent characteristics of the SRG make commercial sense. To date, these applications include sourcing aerospace power systems [1]–[3], starter/alternators for hybrid vehicles [4]–[6], and wind turbine applications [7], [8]. The aerospace and automotive applications are generally characterized by high-speed operation. The wind energy application is characterized by low-speed high-torque operation.

The SRG is compatible with demanding applications. The absence of windings and permanent magnets on the rotor support both high rotational speeds and high-temperature operation. Further, the absence of windings on the rotor helps to keep the majority of the losses within the stator, making the SRG relatively easy to cool. The switched nature of the SRG makes it compatible with any application that requires variable-speed operation. In the case of aerospace and automotive applications, variable-speed operation is needed for compatibility with the engine that drives the SRG. In wind energy applications, variable speed operation is needed to extract additional energy from the wind stream and to lessen the mechanical stresses within the system.

As with motor systems, the proper application of a generator to a system requires an understanding of the characteristics of

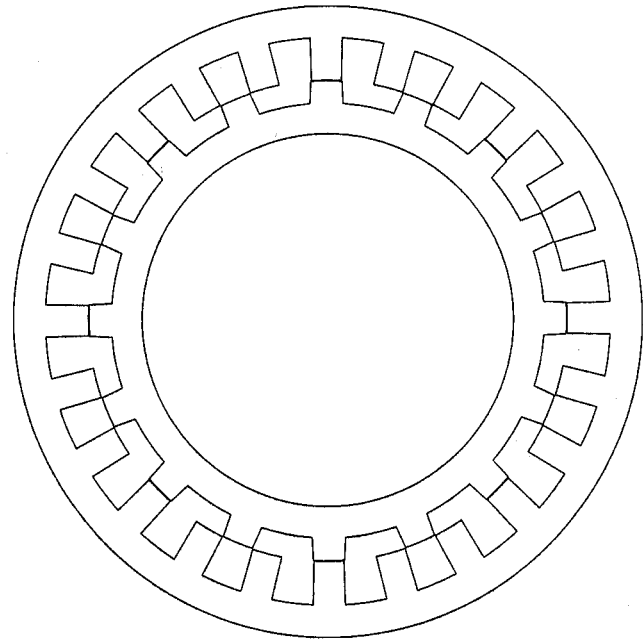


Fig. 1. Three-phase 24/16 SRG.

the prime mover. In the aerospace and automotive applications, the prime mover is able to provide essentially constant power over a wide speed range. In the wind energy application, the shaft power is proportional to the cube of speed, implying a substantial increase in torque and power as the speed increases. The prime mover torque–speed characteristic must be considered carefully when determining the electromechanical specifications of the generator. Equally important are the characteristics of the electric power system into which the SRG provides energy.

This paper is organized as follows. Section II focuses on the electromechanics of the SRG. This includes a short discussion of torque production and the energy conversion process. The intent is to provide insight into the operation of the SRG to illustrate control issues. Section III focuses on the control structure and its implementation. This builds on the electromechanical concepts developed in Section II. Many of the concepts discussed in the paper are illustrated through example with an SRG designed for an automotive starter/alternator.

II. SRG ELECTROMECHANICS

In this section, we focus on the electromechanics of the SRG. The intent is to provide an understanding of the energy conversion process so that we can better understand the control of the SRG. For illustrative purposes, we will use the SRG of Fig. 1 as a running example. The SRG of Fig. 1 is a three-phase design having 24 stator poles and 16 rotor poles, a 24/16 SRG

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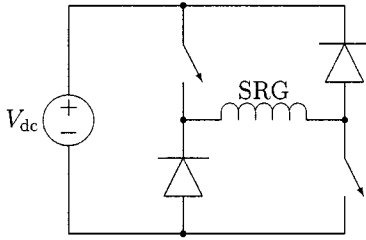


Fig. 2. One phase of the inverter used to excite the SRG of Fig. 1.

that has been developed for automotive applications. Its performance has been documented in [4] and [5]. From experience, it is known that this SRG is representative of typical SRG behavior.

The SRG of Fig. 1 has steel laminations on the rotor and stator. There are concentrated windings placed around each salient pole on the stator. The coils around the individual poles are connected to form the phase windings. There are no windings or permanent magnets on the rotor, making the structural integrity of the rotor compatible with operation at very high speeds. The design of the laminations and phase windings is beyond the scope of this paper. The interested reader is referred to [9] for a discussion of the issues related to magnetic design of the SRG; these issues are shared with the SRM.

As discussed in [4], the design of the SRG of Fig. 1 was the compromise of two competing functions. The first function is that of starting an internal combustion engine by providing high torques at low speeds. The second function is providing electrical energy through generation at speeds ranging from engine idle to maximum speed. The compromise of these two competing functions resulted in a magnetic design that supported generation from 500 through 5000 r/min at a maximum power of 6 kW. Because of the influence of the high starting torque requirement, generation between 500–1000 r/min required current regulation. Generation above 1000 r/min did not require current regulation.

The SRG of Fig. 1 is excited through a common asymmetric bridge. Fig. 2 shows one phase of this inverter that uses the same dc source for exciting each SRG phase through two controllable switches and demagnetizing the same phase through the diodes. There are other inverter topologies that may be useful for generator systems and typically involve segregating the excitation and demagnetization functions; see [2], [9], and the references therein for a description of these other topologies. The phase excitation is based on a turn-on angle (θ_{on}) and a turn-off angle (θ_{off}). The conduction angle (θ_{cond}) is the interval over which the phase is excited: $\theta_{cond} = \theta_{off} - \theta_{on}$; some authors refer to the conduction angle as the dwell angle.

The switches and diodes within the inverter of Fig. 2 must support the maximum dc-bus voltage and the maximum phase current. For the SRG of Fig. 1, the maximum phase currents occurred during motoring operation at low speeds where the phase currents are regulated. The maximum voltage occurs when the SRG is operating as a generator.

A. Energy Conversion

For an SRG, mechanical energy is converted to electrical form by virtue of proper synchronization of phase currents with

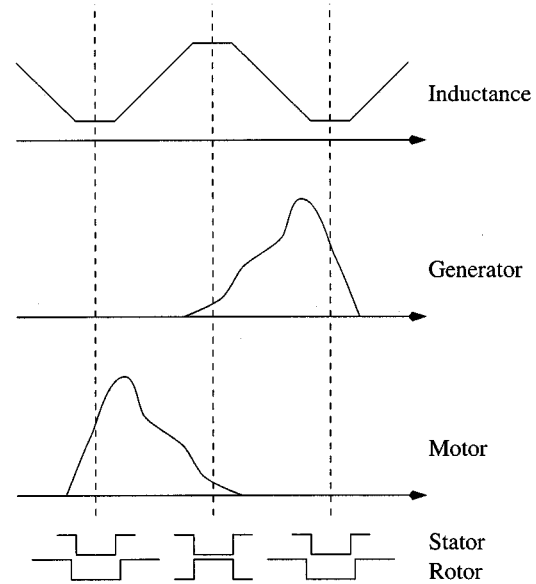


Fig. 3. Idealized inductance variation and the currents used to support motor and generator operation.

rotor position. During generation, the SRG produces negative torque that is trying to oppose rotation, thereby extracting energy from the prime mover. It is the responsibility of a commutator to excite the phases in proper order to support continuous energy conversion.

Torque in the SRG, as in the SRM, is created by the natural tendency of the stator poles to attract the nearest rotor poles. If the phase is excited before the rotor poles come into alignment with the stator poles, the rotor experiences torque in the direction of rotation consistent with operation as a motor. If the phase is excited as the rotor poles move through the aligned position, the rotor experiences torque opposing rotation consistent with generator operation. Fig. 3 shows the relationship between the idealized inductance profile and phase currents for motoring and generating above base speed. For both the SRG and the SRM, base speed is the speed at which phase currents are nominally constant without the need of current regulation. Base speed can be taken to be the speed where the phase back electromotive force (EMF) balances the source voltage and resistive drop. Base speed is slightly different for the SRM and SRG due to the different signs on the resistive drop. For the SRG, the nominally constant phase currents are supported by the diodes of Fig. 2 for reasons that will become clear below.

More generally, the SRG has both spatial and magnetic nonlinearities that must be considered when designing both the magnetic structure and the control. The flux linking a phase of the SRG of Fig. 1 is shown in Fig. 4 where phase flux linkage (λ) is shown as a function of phase current (i) for a number of different rotor positions. The rotor positions are given in mechanical measure, with 0° corresponding to alignment between stator and rotor for phase a . Rotor positions in electrical measure can be found by multiplying the mechanical position by the number of rotor poles (N_r), 16 in this case. The magnetic nonlinearity is evident particularly near the aligned position; there is no perceptible nonlinearity in the unaligned position.

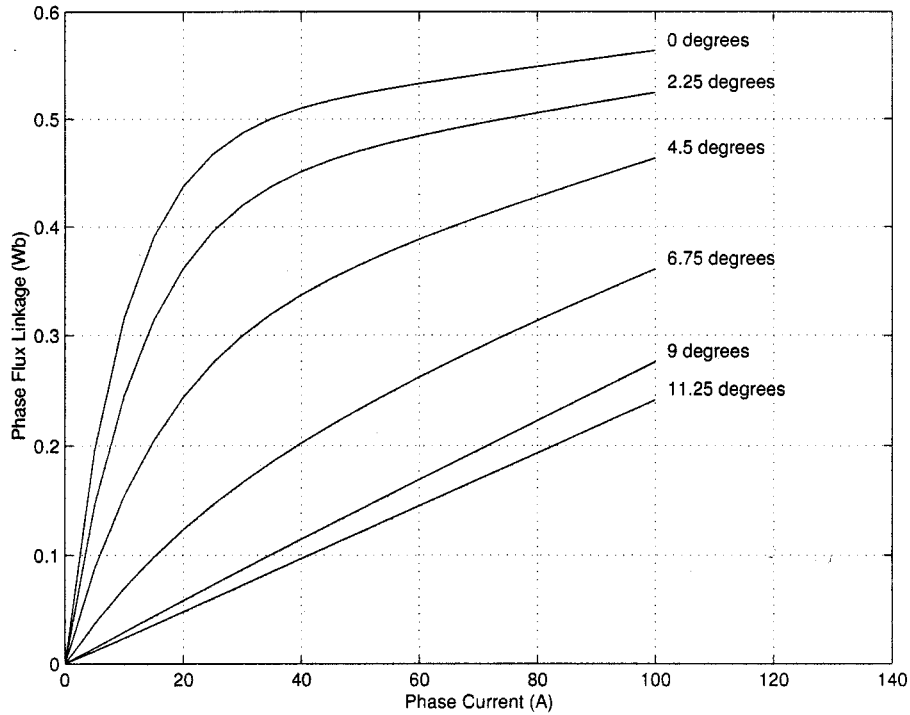


Fig. 4. Phase flux linkage as a function of current and rotor position for the SRG of Fig. 1.

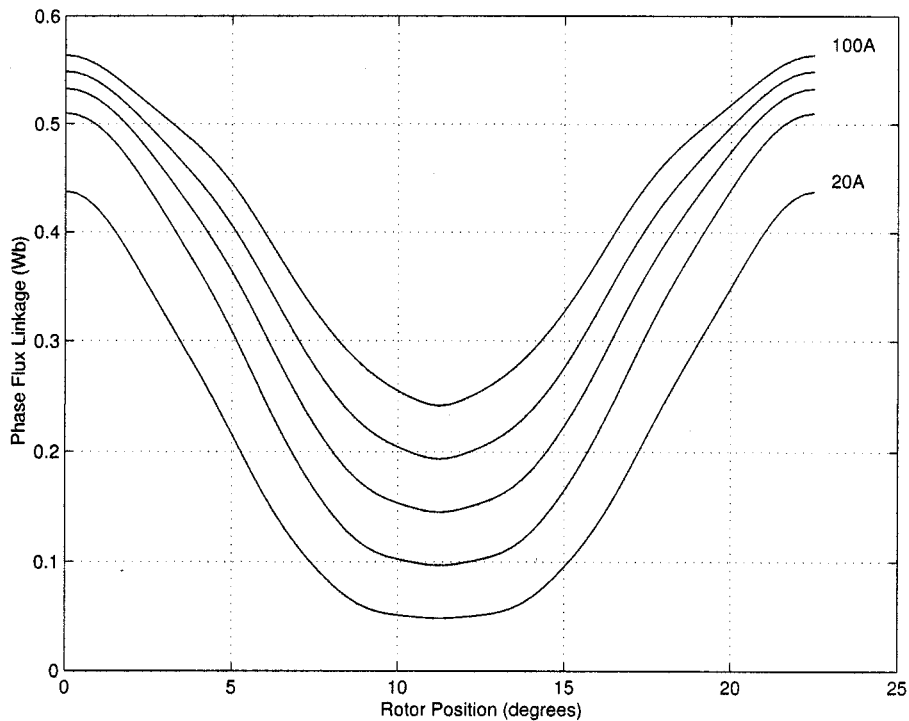


Fig. 5. Phase flux linkage as a function of rotor position and current for the SRG of Fig. 1.

The data for Fig. 4 were obtained through finite-element analysis and subsequently modeled using the method described in [11] using the relationships

$$\lambda(i, \theta) = a_1(\theta) \left(1 - e^{a_2(\theta)i} \right) + a_3(\theta)i \quad (1)$$

$$a_j(\theta) = \sum_{k=0}^N A_{jk} \cos(kN_r\theta), \quad (2)$$

Another insightful way of representing the data of Fig. 4 is shown in Fig. 5 where the flux linkage is shown as a function

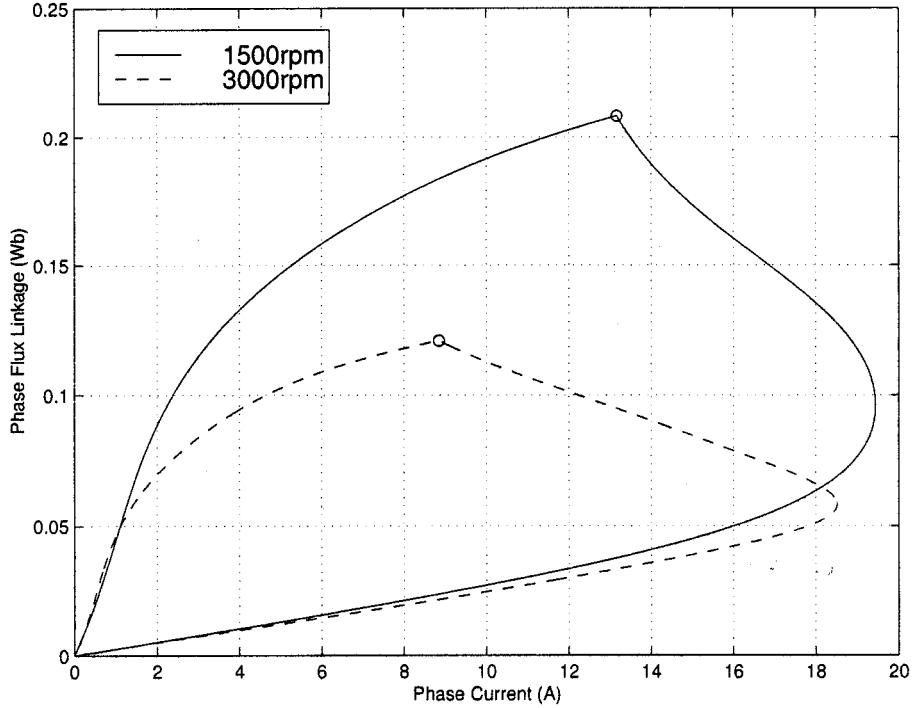


Fig. 6. Energy conversion cycles for the SRG of Fig. 1 at 1500 and 3000 r/min. Circles indicate where the controllable switches are turned off.

of rotor position for a number of different phase currents [10]. Fig. 5 shows both the spatial and magnetic nonlinearities found in a practical SRG.

B. Excitation and Generation

The SRG requires a source of excitation in order to generate electrical energy. This excitation is derived from a switching inverter, such as that shown in Fig. 2. When the controllable switches are closed, current builds in the SRG phase winding. For generator operation, excitation generally begins near the aligned position for relatively low-speed operation. The excitation is often advanced with increasing speed so that excitation begins before the aligned position. This is analogous to the advance introduced in the control of the SRM. After the controllable switches are turned off, more energy is returned to the source than was provided for excitation.

Fig. 6 shows two energy conversion cycles for the SRG of Fig. 1 operating at two different speeds. Each loop is traversed in a clockwise manner. The areas enclosed by the loops correspond to the energy converted from mechanical to electrical form for the two cases. There are qN_r energy conversion cycles in each revolution of the rotor; q is the number of phases. The circles in Fig. 6 indicate the point where the controllable switches are turned off and phase current is supported by the diodes of Fig. 2.

To better understand the issues in exciting the SRG and extracting energy through the phase winding, it is instructive to look at the back-EMF coefficient of the SRG. To begin, the electrical dynamics of an SRG phase are

$$\frac{d\lambda}{dt} = v - Ri. \quad (3)$$

Because phase flux linkage is a function of current and position, (3) can be expanded and rewritten as

$$v = \frac{\partial \lambda}{\partial \theta} \frac{d\theta}{dt} + \frac{\partial \lambda}{\partial i} \frac{di}{dt} + Ri \quad (4)$$

or

$$v = \omega \frac{\partial \lambda}{\partial \theta} + \frac{\partial \lambda}{\partial i} \frac{di}{dt} + Ri. \quad (5)$$

The first term on the right side of (5) represents the back-EMF presented by the phase winding. The second term on the right side of (5) represents the voltage dropped across the phase inductance. The back-EMF coefficient for the SRG is $\partial \lambda / \partial \theta$ where it is implied that the partial derivative is taken with current held constant. It follows that the back-EMF coefficient of the SRG is the slope of the flux linkage versus position information given in Fig. 5. Fig. 7 gives the back-EMF coefficient for the SRG for three values of phase current. In other machines, such as a brushless dc motor, this $\partial \lambda / \partial \theta$ term is sometimes called the back-EMF constant; this terminology is not used here because it is hard to consider this term constant in view of Fig. 7.

There are several features of Fig. 7 that are worthy of note. First, the back-EMF coefficient is negative during the region of decreasing phase inductance and positive during the region of increasing phase inductance. Second, the back-EMF coefficient retains the spatial and magnetic nonlinearities that are present in the flux linkage data of Figs. 4 and 5. Third, the peak back-EMF coefficient increases with current up to a certain point; additional increases in phase current actually serve to reduce the back-EMF coefficient.

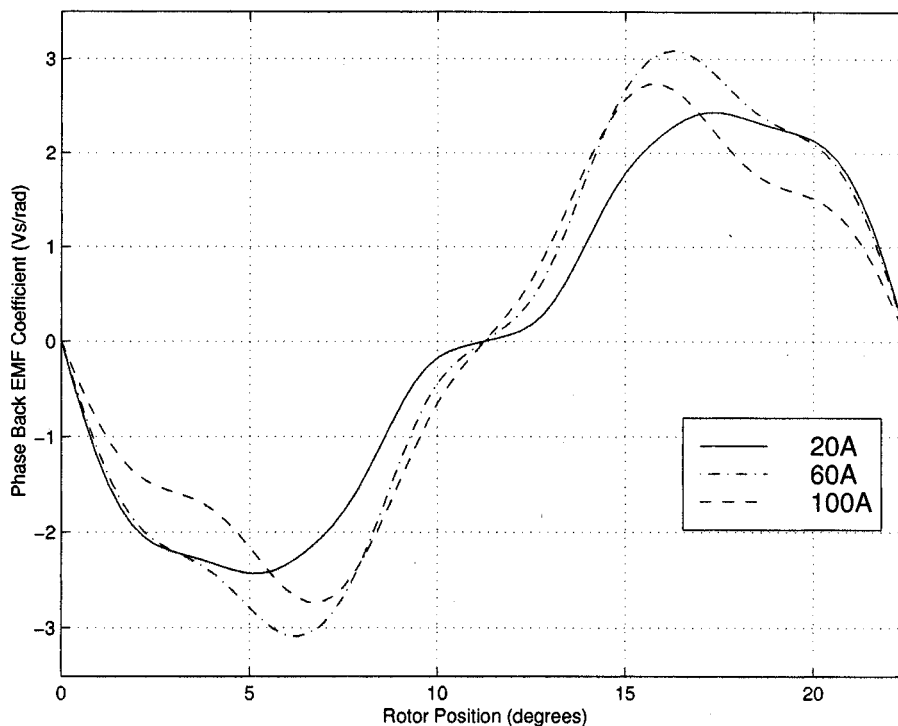


Fig. 7. Back-EMF coefficient for the SRG of Fig. 1 for three levels of phase current.

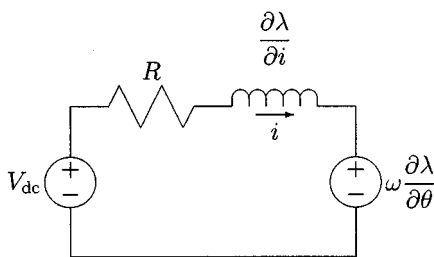


Fig. 8. Inverter topology during phase excitation.

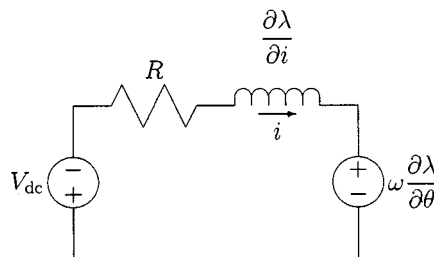


Fig. 9. Inverter topology during phase demagnetization.

Figs. 8 and 9 show the inverter circuit topologies for the excitation interval and demagnetization interval, respectively. The dynamics of the phase current can be inferred from the relative sign and magnitude of the back EMF compared to the applied voltage. For example, during excitation prior to the aligned position, phase current is building up in the face of the back EMF, reducing the effectiveness of the source voltage. This drives significant advancement in θ_{on} to have adequate phase current as the rotor enters the region of decreasing phase inductance.

Behavior during demagnetization can be assessed by comparing the relative magnitude of the back EMF and the source voltage. If the source voltage has larger magnitude than the back EMF, the phase current will decrease. This may necessitate multiple periods of excitation when generating at low speed, leading to a current waveform that is regulated to maintain adequate excitation as the rotor moves from the aligned position to the unaligned position. At high speeds, the back EMF can serve to drive increases in phase current in the face of negative source voltage and decreasing flux linkage after the controllable switches have been turned off. This occurs when $\omega (\partial \lambda / \partial \theta) < -V_{dc}$.

Phase current waveforms tend toward exacerbated peaks at increasing speeds. Fig. 10 shows the phase current waveforms for the energy conversion cycles given in Fig. 6. The waveform for operation at 3000 r/min has a higher crest factor than the waveform at 1500 r/min due to the back EMF being substantially higher; the crest factor for operation at 1500 r/min is 2.22 versus 2.36 for operation at 3000 r/min. The crest factor is defined as the ratio of the peak phase current to the rms phase current. Note that the rotor position of the peak current varies relatively little despite the large difference in speed and corresponds to a rotor position just before the idealized phase inductance decreases into the minimum inductance region. This characteristic is typical in the SRG, just as the peak phase current for motoring operation above base speed is always located near the position where the phase inductance begins increasing from its minimum value. This phenomena has its origins in the rapid change in back-EMF coefficient on either side of the aligned and unaligned positions as shown in Fig. 7.

In addition to increased crest factor at higher speeds, the SRG has a tendency toward open-loop instability when the back-EMF magnitude is sufficiently larger than the source voltage. The

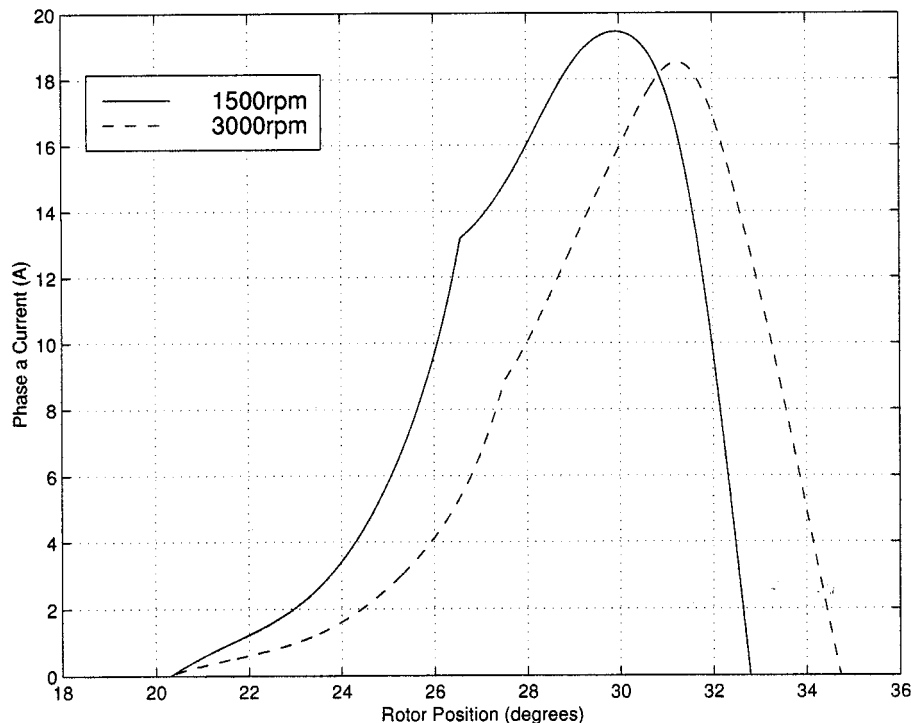


Fig. 10. Phase current waveforms as a function of rotor position for the energy conversion cycles of Fig. 6.

essence of the instability is that increased source voltage tends to increase the excitation current, thereby increasing the energy extracted from the prime mover. The increased energy conversion typically outpaces the increase in load associated with the increase in excitation voltage. Depending on the nature of the load, this extra energy conversion may go into further increasing the excitation voltage. This phenomenon is discussed in [2] and [3]. The SRG of Fig. 1 has been found unstable, even with a resistive load where the power consumed is proportional to the square of the excitation voltage.

Further, the tendency toward instability contributes to the self-excitation of the SRG. Residual magnetism is often sufficient to start the self-excitation process. With the controllable switches disabled, the SRG of Fig. 1 was able to charge the dc bus to a small voltage, typically less than 10 V for an SRG intended to feed power into a 300-V dc bus. Enabling the controllable switches applies the small bus voltage to developing excitation current which, in conjunction with the open-loop instability, quickly charged the dc bus to its intended operating voltage. There are abundant anecdotal data that confirm self-excitation of the SRG, although there has not been careful analysis of this phenomenon. More work is necessary to thoroughly characterize the conditions under which the SRG can self-excite.

C. Control Implications

Section II-B alluded to several excitation issues that have implications for the control implementation. This section summarizes these points for clarity as we prepare to discuss how the SRG is controlled. These points have duals with regard to the control of the SRM.

- 1) We have no control over where the peak phase current occurs once the SRG has entered single-pulse operation above base speed. This leaves us with many combinations of turn-on angle and conduction angle that will yield the same output power. An important issue is how to best choose the excitation parameters. This is more challenging for the SRG than the SRM because the peak phase current for the SRG occurs while both controllable switches are off. For the SRM, the turn-on angle can be used to directly control the peak current, thereby partitioning the responsibilities of the turn-on angle and conduction angle. For the SRG, the turn-on angle and conduction angle control the peak phase current jointly and severally.
- 2) For operation below base speed, it is necessary to regulate the phase currents. It is usual to use unison operation of the phase switches to regulate phase currents during generation. There is little value in having the SRG generate into its phase windings.
- 3) The turn-on and turn-off angles must be advanced to support constant power operation above base speed. The rate of advance is generally different for turn-on and turn-off until the maximum conduction angle is reached.

III. SRG CONTROL

Building upon the electromechanics of the SRG and the energy conversion principles discussed in the previous section, we can now examine the control of the SRG. We begin this examination with a discussion of how a typical SRG controller is structured. We then turn our attention to methods for choosing “op-

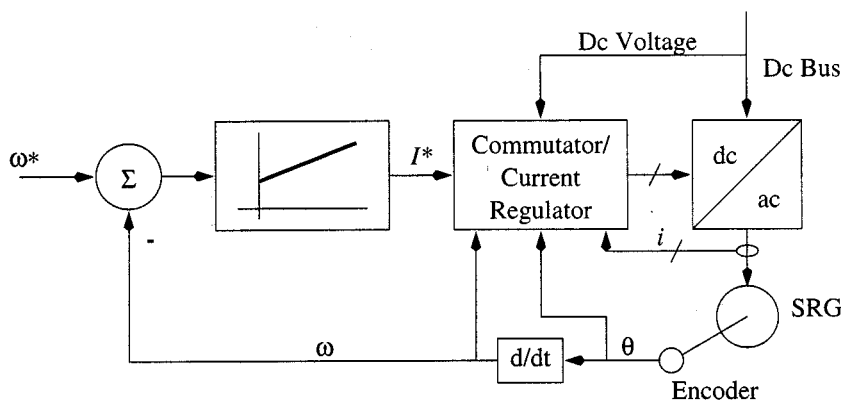


Fig. 11. Structure of the controller for regulating SRG speed.

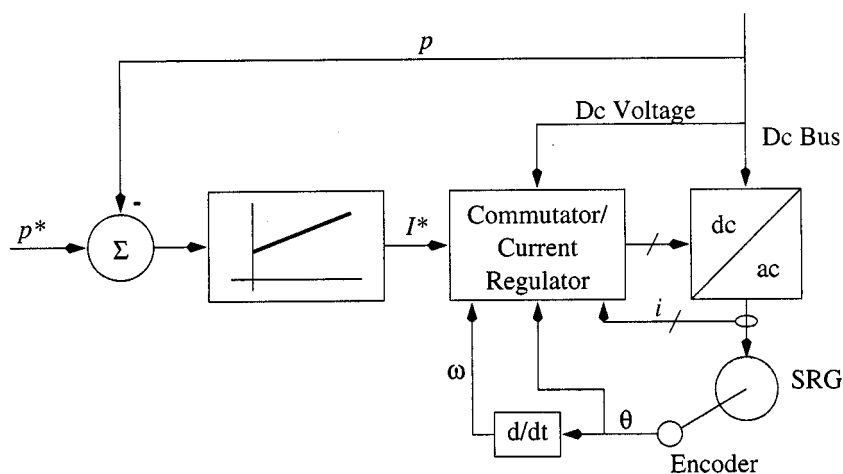


Fig. 12. Structure of the controller for regulating SRG power.

timal” excitation parameters. Finally, we discuss some specific control implementations.

A. Controller Structures

The structure of the SRG controller is similar in nature to that of the SRM. For operation from below base speed to above base speed, there must be a commutator that determines the appropriate turn-on and turn-off angles. Below base speed, current regulation is required; this is generally accomplished by logically combining the commutation signals with a signal that reflects the relative relationship between the desired current and the actual current. The commutator and the current regulator operate on a very short time scale, suggesting these loops constitute the innermost elements of the control.

The outer loop is usually concerned with either regulating the speed of the SRG, or in regulating the average power supplied by the SRG. An application such as wind energy would focus on regulating the speed of the SRG relative to that of the wind stream in order to force peak aerodynamic efficiency [7], [8]. An application such as an aircraft power system would require regulation of average power (or current) output. Figs. 11 and 12 summarize the structure of controllers for regulating SRG speed and power, respectively.

The design of the controller for the SRG is challenging for three reasons. First, the output of the SRG tends to be open-loop

unstable. As discussed above, as the speed of the SRG increases beyond the base speed, the output dc current increases with increasing voltage. Such a situation demands stabilization through application of closed-loop control. Second, the SRG system is highly nonlinear, making the selection of suitable control gains problematic. Third, the excitation parameters needed to support a particular output power are not unique.

If the SRG is supplying energy to a sufficiently stiff voltage source, it may not be necessary to close the outer control loop that regulates the average power delivered to the load. For example, the battery in an automotive application is sufficiently stiff to prevent the system voltage from running away. Proper charge control of the battery, however, would dictate that some effort be taken to control the average power generated by the SRG.

B. Optimal Selection of Excitation Parameters

The most challenging piece within the controllers of Figs. 11 and 12 is the commutator that is responsible for selecting the turn-on and turn-off (or conduction) angles. While this is challenging for the SRM as well, the optimization is more straightforward because only the turn-on angle dictates the peak phase current; see [12] for a discussion of excitation optimization for the SRM. For the SRG, both turn-on and turn-off angles contribute to peak phase current above base speed.

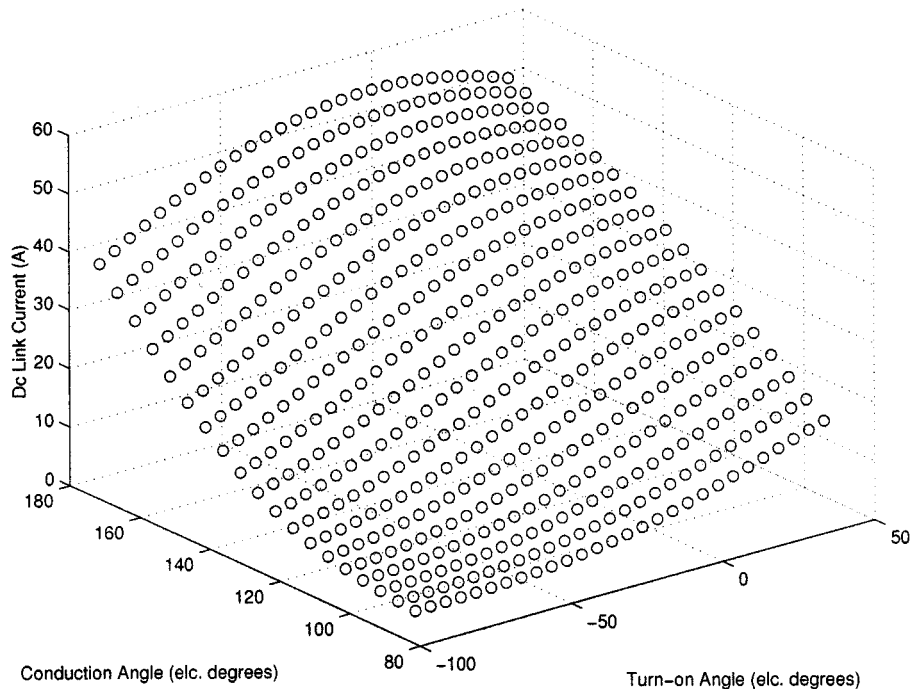


Fig. 13. Average dc-link current as a function of excitation parameters for the SRG of Fig. 1 for operation at 3000 r/min.

For operation below base speed, SRG operation is very similar to that of the SRM. In particular, the phase currents would be regulated to follow a prescribed value as a function of rotor position. The value is nominally constant unless very low torque ripple is part of the objective. Conduction would be carried out over the region of decreasing inductance. The determination of the turn-on angle is based on providing adequate time to build up the phase current before entering the torque production region. Current regulation for the SRG is usually based on unison operation of both controllable switches in Fig. 2.

To illustrate the optimization problem, Fig. 13 shows the average dc-link current as a function of excitation angles for the SRG of Fig. 1 for operation at 3000 r/min and a fixed 300-V dc bus. The data suggest that there are multiple combinations of excitation parameters that provide the average same dc-link current. Typical performance metrics such as efficiency, torque ripple, rms dc-link current, etc., can be dramatically different for the various combinations of excitation parameters that yield the same power output. Fig. 14 shows the rms phase current for the SRG of Fig. 1 as a function of average dc-link current for operation at 3000 r/min [5]. Each point corresponds to a different combination of turn-on and turn-off angle; the circled points correspond to the minimum rms phase current for a specific value of dc-link current.

Where maximization of efficiency at each operating point is the optimization objective, minimization of rms phase current is a reasonably pragmatic approach. Minimizing the rms phase current implies minimizing the resistive losses in the SRG, minimizing the peak flux in the SRG, thereby minimizing core losses and minimizing conduction losses within the inverter. A more precise optimization would require very detailed models for

every loss mechanism within the SRG system and would be difficult to enforce in practice [13]. Minimization of rms phase currents is a reasonable objective of, for example, self-tuning control [14], [15].

It is certainly possible to perform the optimization experimentally in order to build up a table of excitation parameters based on speed and required dc-bus current. Figs. 15 and 16 show the turn-on and conduction angles for the SRG of Fig. 1 that result in maximum system efficiency as a function of operating speed and average dc-link current. It is possible to fit functions to the data of Figs. 15 and 16 to calculate the excitation parameters, rather than use a table. This is the approach taken in [1] to handle operation in the motor mode. Figs. 15 and 16 show the tendency to advance turn-on and extend conduction for higher output current (power).

Other optimization criteria might include minimization of torque ripple or rms dc-link current. While these criteria could lead to a different choice of excitation parameters than minimization of rms phase currents, minimization of rms phase currents would tend to reduce both torque ripple and rms dc-link current because minimizing rms phase currents would reduce the current peaks and positive torque production that lead to large rms dc-link current and large torque ripple.

In applications where the SRG system is used to regulate the voltage used to excite the SRG, linearization of the SRG control characteristic may be the preferred optimization goal. These applications include aerospace power systems. Control linearization is discussed in [1] and [3]. In [1], the authors report linearizing the control characteristic of the SRG by fixing the phase current at turn-off. Advances in turn-on angle then produced increased dc-bus current. At low power levels, the turn-on angle

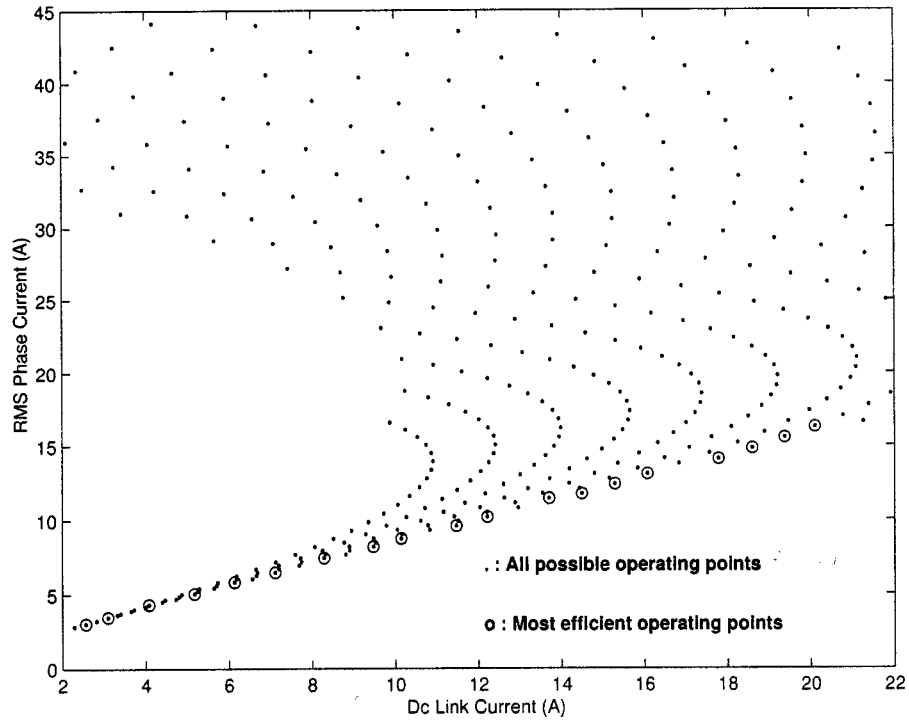


Fig. 14. RMS phase current as a function of average dc-link current for the SRG of Fig. 1 for operation at 3000 r/min.

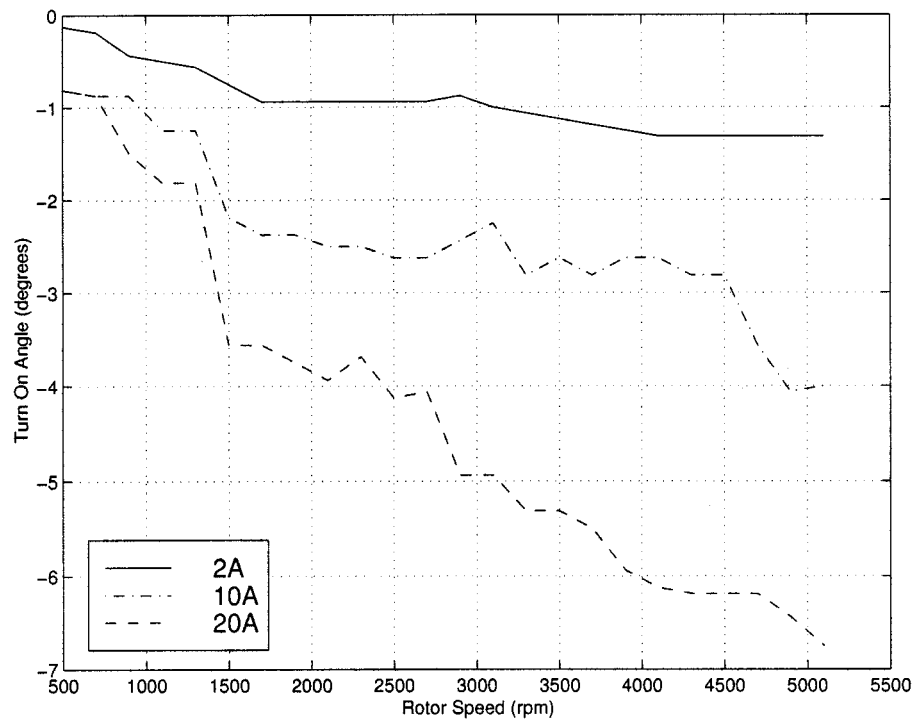


Fig. 15. Efficiency-optimal turn-on angle as a function of speed and average dc-link current for the SRG of Fig. 1.

is fixed and the turn-off angle is used to control the average current in order to increase system efficiency. In [3], the authors fix the turn-on angle and use a map of average dc-link current as a function of conduction angle to globally linearize the control characteristic.

C. Control Implementation

Control of the SRG is usually accomplished via a computer, whether it be a microcontroller, digital signal processor (DSP), or something more sophisticated. Consistent with Figs. 11 and 12, there are several tasks that must be handled by the controller.

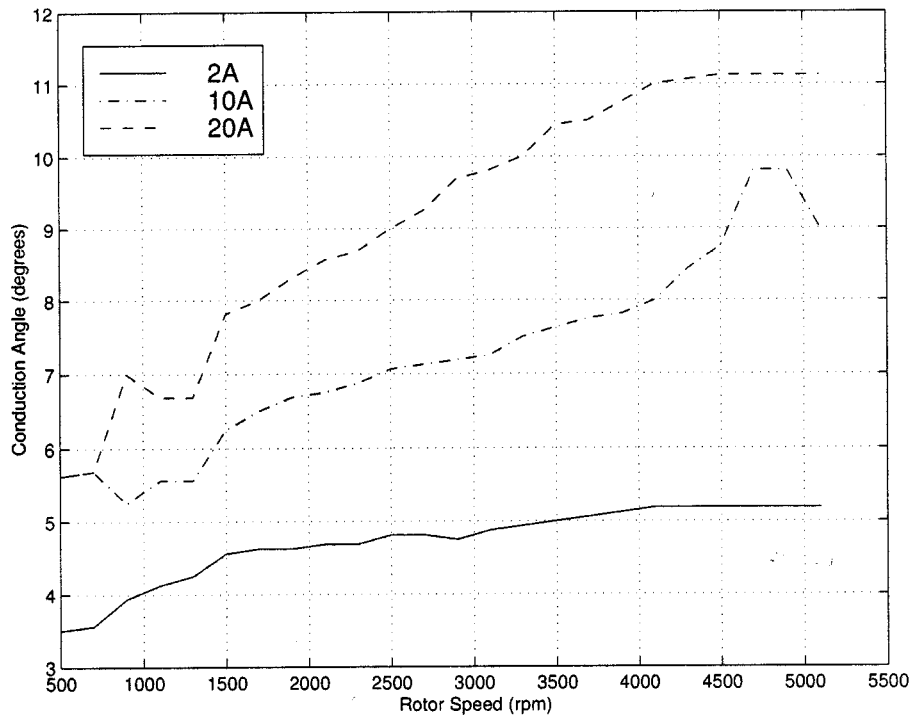


Fig. 16. Efficiency-optimal conduction angle as a function of speed and average dc-link current for the SRG of Fig. 1.

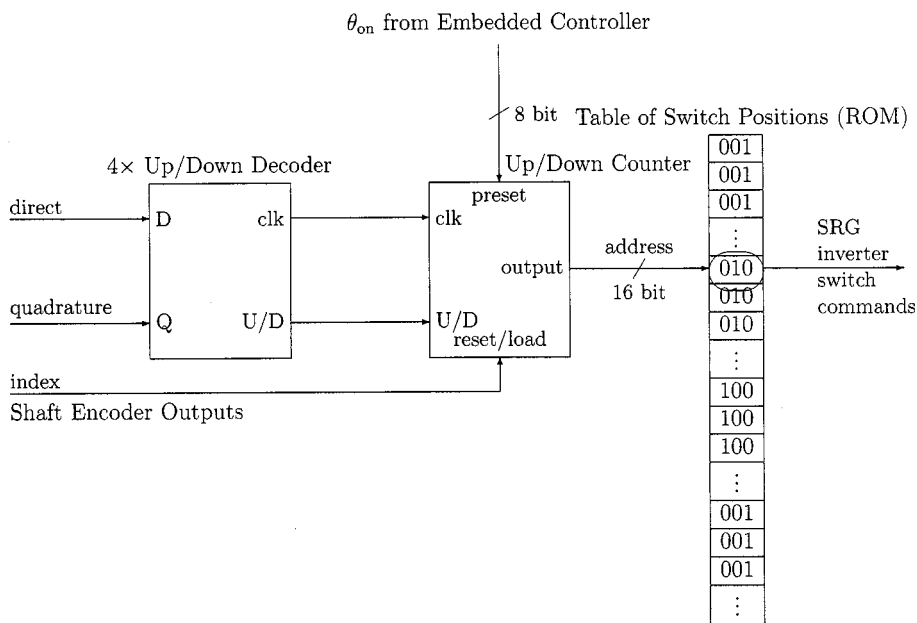


Fig. 17. Method of implementing excitation angles using a ROM-based table of switch positions. Multiple tables are used to accommodate different conduction angles.

Implementation of the excitation parameters and current regulation are the most time critical because small implementation errors in excitation angles can have a significant impact on the electromechanical performance [13]. The commutator and current regulator typically operate on very short time scales. The outer control loop generally operates on a much longer time scale. A separation of time scales can often be employed to aid with the design of the outer control loop [3].

For an SRG that must operate at very high speed, it may be necessary to implement the commutator in hardware based on parameters determined by software. This is the approach taken in [1], where rotor position is used to index through a ROM-based table of switch states. Adjustment of the turn-on angle is accomplished by shifting the base pointer to the table. The essence of the concept is shown in Fig. 17 for a fixed conduction angle. Adjustment of conduction angle is accomplished

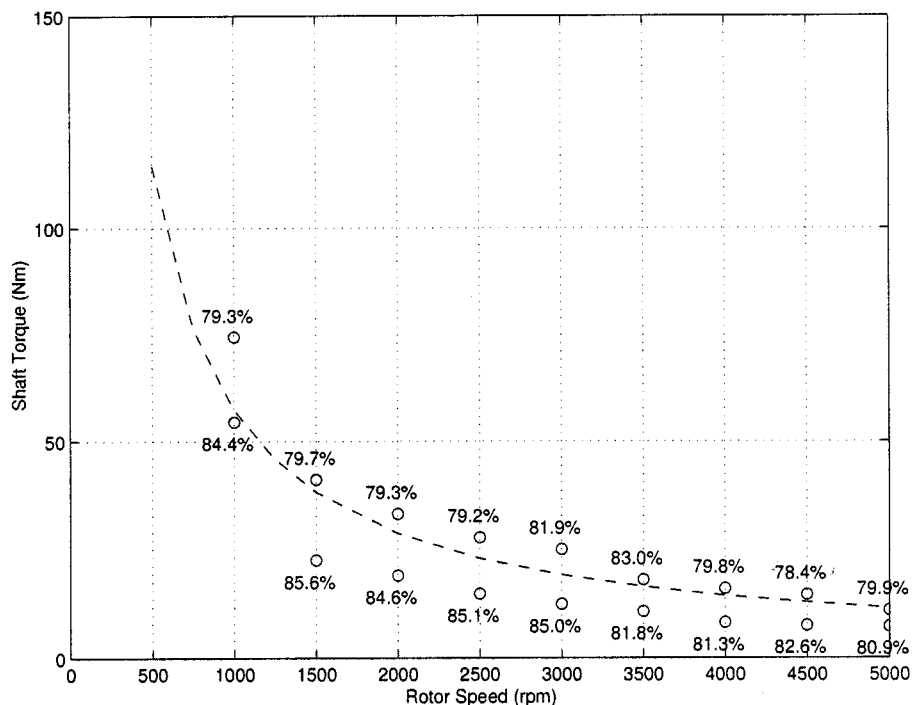


Fig. 18. System efficiency as a function of torque and speed, based upon the SRG of Fig. 1.

by having multiple tables in the ROM, each based on a different conduction angle. Because of the spatial periodicity of the SRG, the ROM table needs only to be large enough to service one electrical cycle with each table entry being accessed N_r times per revolution.

With the DSPs optimized for motor control, it is possible to integrate commutation and current regulation algorithms directly into the processor, thereby simplifying the system hardware. These DSPs generally have pulsewidth modulation (PWM) generators, analog-to-digital converters, and incremental encoder interface units available on-chip. For this type of implementation, commutation decisions can be implemented with lookup tables and if-then-else comparisons. This is the approach taken for the SRG of Fig. 1. Acceptable efficiency is achieved with a rotor position resolution of 5° (electrical); see [4] and [5] for component and system performance data associated with this system. System (combined SRG and inverter) efficiency for the SRG of Fig. 1 is given in Fig. 18.

IV. SUMMARY

This paper has concerned itself with the SRG and its control. While sharing many common features with the SRM, there are some important differences. First, most applications of the SRG are oriented toward constant power output, thereby placing substantial interest in SRG operation above base speed. Second, for operation above base speed, the SRG system produces increasing average dc-bus current for increasing excitation voltage. In certain systems, this suggests open-loop instability for which closed-loop control must be used. Third, operation above base speed results in two excitation parameters impacting the peak phase current. This allows satisfying the required electromechanical performance along with another

control objective. For SRG systems that deliver energy to a dc bus of fixed voltage, efficiency is commonly optimized. For SRG systems that deliver energy to a dc bus of variable voltage, control linearity is commonly optimized. This can be accomplished through use of a fixed turn-off current or global linearization through inverse mapping to achieve a known relationship between the average dc-link current and a $(\theta_{on}, \theta_{off})$ combination.

The SRG is capable of supporting high system efficiencies over a wide speed range. Essentially constant system efficiency for constant power output is typically achievable over a 3:1 speed range, with acceptable system efficiency over a 10:1 speed range. The SRG can offer high efficiency over a very wide speed range with a rotor structure that is compatible with high speeds and an overall structure that is tolerant of extreme environments.

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