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Exploring the Behavior of Switched Reluctance Generator under Normal and Field Weakening Mode of Operation

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Abstract

This paper investigates the influence of advance switching angle control to enhance voltage generation in Switched Reluctance Generator. The concept of field weakening mode of operation with advance dwell angle is achieved with turn-on and turn-off angles as the control parameters. The voltage-current characteristics are essentially programmable and determined almost entirely by the angle control. It identifies the implication of five operating regions adapted to achieve control over the magnitude of the generated voltage. Detailed implementation of the proposed switching strategy is described. Simulation results have been explained through theoretical evaluation over various modes of operation.

Keywords: Control, Field Weakening, Phase Advancing, Switched Reluctance, Voltage, Generation.

Introduction

Switched Reluctance machine (SRM) is a highly efficient , electronically commutated brushless DC machine. The SRM as a generator(SRG) is the dual of SRM as a motor with respect to the varying inductance and the resulting torque. To take advantage of the machine's dynamic capability, it calls for three major control loops - (i) Rotor position is very crucial in SR Machines, the innermost element of control being position and determines the appropriate turn on and turn off angles. (ii) Second inner control loop is current, the position and current regulator operate on a very short time scale (iii) the outer loop is concerned with regulating the average power supplied to the load with highest degree of flexibility and control [1,2]. Thus, the simple structure of SRM demands a complex control design making the selection of suitable control gains problematic at each operating point of the drive. SRG under study is compatible with applications demanding multi-level power sources.

The existing literature focuses on the many angle control algorithms for SR motors. But not enough work has been carried out with switched reluctance generator [3] introduces a range of strategies necessary to accommodate sensor less control for four quadrant operation in SRM drives.[4] Presents optimal control of a switched reluctance machine in a four-quadrant drive with smooth transition with the firing angle conditions of one operating mode are derived from the other operating mode without the knowledge of the machine magnetization curves. A detailed study of Switched Reluctance Machines with Electronic Control is highlighted in [5]. [6] Identifies the implications of the energy conversion process in SRG as directed by a controller for speed-control and power-control applications to serve as a starter/alternator in automotive applications. In [7] an inverse machine model of SRG is developed and optimal efficiency control scheme is designed for operation at a constant voltage. Investigating the problem of accomplishing maximum energy conversion in SRG with optimal turn-on and turn-off angles in single-pulse operation in a wide speed range and provides constant dc-link voltage at a desired value is discussed in [8].Almost all these findings focus on the derivation of angle control or suboptimal control variable employing either fixed turn on or turn off angle. However, these models have not discussed the effect of phase advancing to maximize voltage generation in SRG.

This paper investigates the dynamic behavior of SRG under the influence of advance switching angle to gain control over the output voltage. As an example, study is carried out for a lab prototype model of a three phase, 6/4 configuration to exploit its unique voltage-current characteristics. Once the optimal motional back-EMF is established, by proper synchronization of the excitation with respect to the rotor position, SRG series wound characteristics are exploited to enhance the productivity. The proposed switching strategy of the SRG operating in the normal and field weakening mode is supported by regulating angle control parameters to extend the voltage range. Thus, the impact of the five operating regions on dynamic behavior of the SRG is established with a one-to-one correspondence between magnetic status of the SRM, along with excitation and commutation at proper rotor positions. To prove the feasibility of the proposed technique, simulation results are presented. We have also included initial experimental results to validate our claims.

Organization of the paper is as follows. Section 2 focuses on basic structure of SRM under study. It also discusses on the energy-conversion process. Section 3 focuses on the proposed five regions of operation and the switching strategy to enhance the output voltage in SRG. This builds on the mathematical model of SRG proposed elsewhere, includes a switching model, time average model and a detailed small-signal model to achieve overall system stability and control design. Section 4 focuses on hardware implementation with simulation and experimental results. Section 5 concludes the paper.

System Description

Fig.1 shows the Switched Reluctance machine under study. It has 6 stator poles with concentric windings connected to dc supply and 4 rotor poles, rotating by sequentially exciting the stator phases with asymmetrical power inverter. Fig 2 shows one phase of the asymmetrical power inverter with two controlled switches S_1 and S_2 with two feedback diodes D_1 and D_2 in magnetizing and demagnetizing modes. L_{ph} are the three machine windings, the currents through them is controlled by the turn-on and turn-off angles of the controllable switches. The diodes serve to freewheel the winding currents when the switches are turned-off during current regulation and phase commutation. The output of the inverter is used to energize the three phases of the machine and the voltage of the capacitor is used to demagnetize the phases during turn-off and current regulation. Reversal of stator field is achieved by transferring current to the next winding [9,10].The current is determined by the motor winding resistance, applied voltage and excitation angles. Parameters of SRM and DC motor are given in Appendix 1.

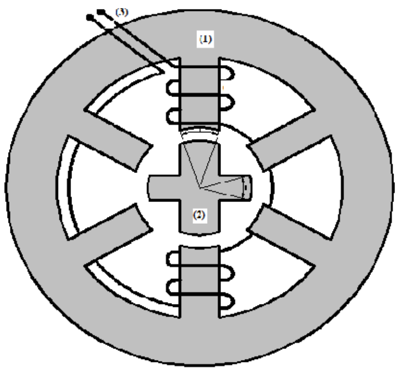

Figure 1: Cross –section view of 6/4 configuration

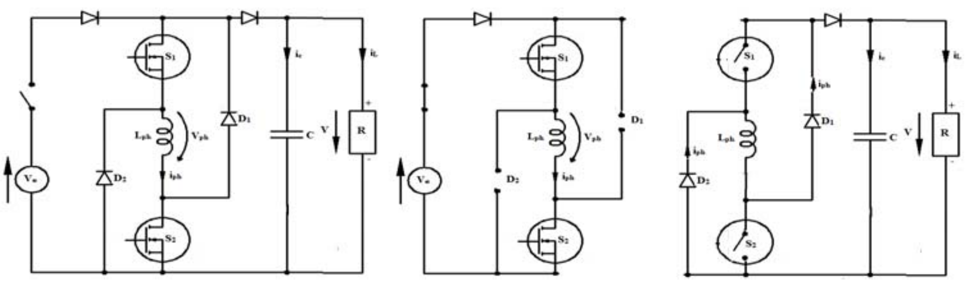

Figure 2: (a) One phase of Asymmetrical Power Bridge (b) Magnetizing (c) Demagnetizing mode

When the stator phases are excited during the descending portion of the inductance profile, magnetizing current will be established creating a magnetic flux in the core and generates a braking torque working against the torque developed by the prime mover as shown in Fig 3. After completion of the magnetizing process, a substantial back emf will continue to increase the phase current as the motional emf is the product of electromechanical energy conversion. In the second portion, back emf works against a negative bus voltage and tends to eliminate the phase current. Fig 4. Shows one complete energy conversion cycle in SRG. Area A represents the excitation energy and B represents the energy converted into electric power. The ratio between the generating energy and the excitation energy will determine if the machine is more suitable to operate as a motor or generator. If B/A ≤1 the machine can perform better under the motoring stage and if B/A ≥ 1 the machine perform better under the generating stage [13].

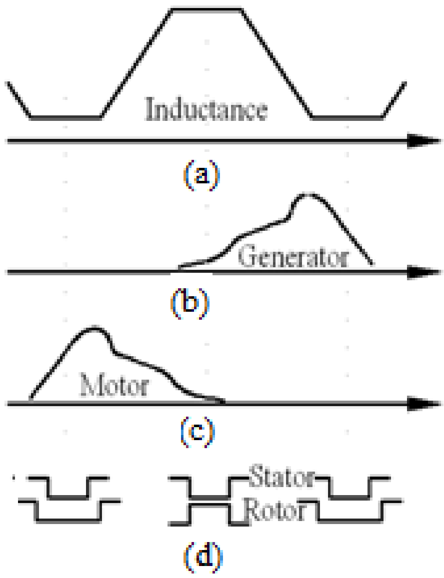

Figure 3: (a) Inductance profile (b) Generating current(c)Motoring current(d) Tooth alignment

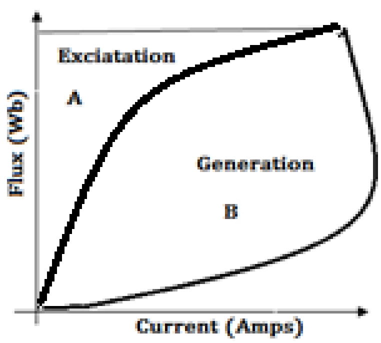

Figure 4: Energy conversion cycle in SRG

Five Operating Regions of SRG

SRG being highly dynamic system with variable structure, its dynamics undergoes a significant change as voltage and current of the generator vary. Fig 5 shows the characteristics in five different operating regions in SRG stemming from the minor role of motional emf. Investigations on the fundamental characteristics of SRG and control issues indicate that it is a controllable current source with pulsed operation and becomes a DC voltage source with filter capacitor or storage battery. Its series wound characteristics is used to operate in field weakening mode to generate very high voltages.

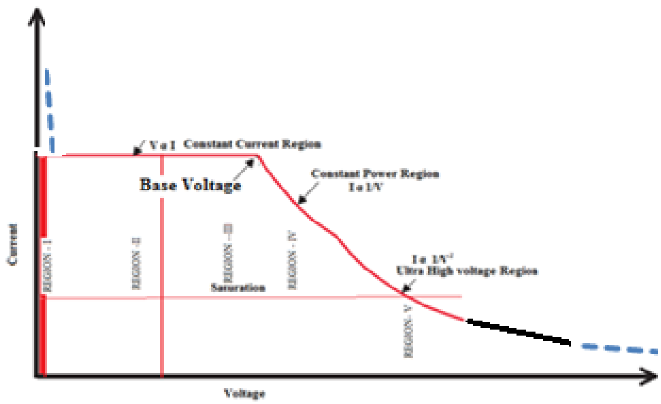

Figure 5: SRG Voltage-Current Characteristics

Region II reflects a range of generated voltages within which the induced voltage is less than the dc-link voltage and the ability to shape and regulate the current pulse. The non-linear effects of saturation are noticed in region-III with current being proportional to voltage. This point is also referred to as base voltage where the back –emf is such that there is no more current in the windings hence no more increase in load, and beyond this point the output power remains constant at its maximum. Region-IV represents constant power region and is characterized by the product of current and square of voltage remaining constant. This also refers to range of voltages where the back-emf is greater than the dc-link voltage with Current turning into single pulse mode. Unsaturated operation along with significant contribution of mutual inductance at high voltages is observed in region-V generating very high voltages. Operational voltage thus acts as a multiplier to the current component, resulting in high impact in induced voltages. These trends contribute to significant changes in dynamic behavior of SRG. Evaluating the weight of different criteria leads to distinguished areas over the voltage –current range as shown in Fig 5. Here, only the first quadrant is shown. The boundaries between these areas are obviously not very clear, but can be identified satisfactorily. To enhance the compactness and effectiveness of the SRG drive potentially used in generating units, magnetizing current can be boosted further by proper timing in intermediate freewheeling mode [14].

Proposed Switching Strategy

SRG possess a unique relationship between phase voltage, commanded current, resistance, inductance and rotor position, making use of the machine's magnetic characteristics in one way or the other[15,16]. SRG can be designed to possess a significant field weakening mode of operation above base voltage, when the smallest amount of current is used to weaken the magnetic flux of the stator. Thus, setting magnetic flux as the function of the operating region.

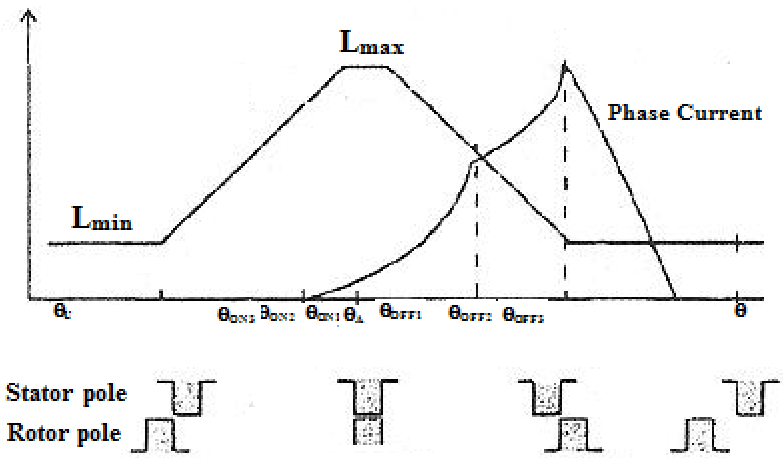

Figure 6: Proposed Switching Strategy

The proposed study ensures the uniqueness of switching strategy to effectively enhance the productivity of the SRG. The multilevel modeling and simulation of the entire system comprising of the power converters, srg and dc motor, load a high level programming language for the control, is carried out in one mode. The controller input variables are typically speed and dc-link voltage. The output of the voltage controller is a current command or a duty ratio used to drive the switches [17]. The study is first conducted without any voltage controller in the control loop, subsequently extended with different controllers and operated in self-excited mode. With turn-off angle θ_{OFF} fixed at 90^0-unaligned position, the turn-on angle θ_{ON} is advanced in the motoring region in the steps of 1^0 from the aligned region i.e at 45^0as in Fig 6. SRG performance is studied with different loads and different switching angles. But only those cases which are necessary for performance analysis are reported Fig 7 shows the response of SRG when θ_{OFF} is fixed at 80^0mechanical degrees while θ_{ON} is varied in the range of 45^0 to 30^0. Table–I shows the summary of the unique Voltage- Current characteristics possessed by SRG.These Voltage- Current characteristics are analogous to Speed –Torque characteristics possessed by SRM [18, 19]. Hence, it can be concluded that the electrical power output of SRG is equal to Mechanical power output in SRM for the same machine, where speed is equal to voltage and torque is equal to current. Another very significant factor noticed in region –V with high advance angle θ_{ON} at 25^0 with a low load of 10,000 ohms, the generated voltage is 900V; voltage is five times the machine rating.

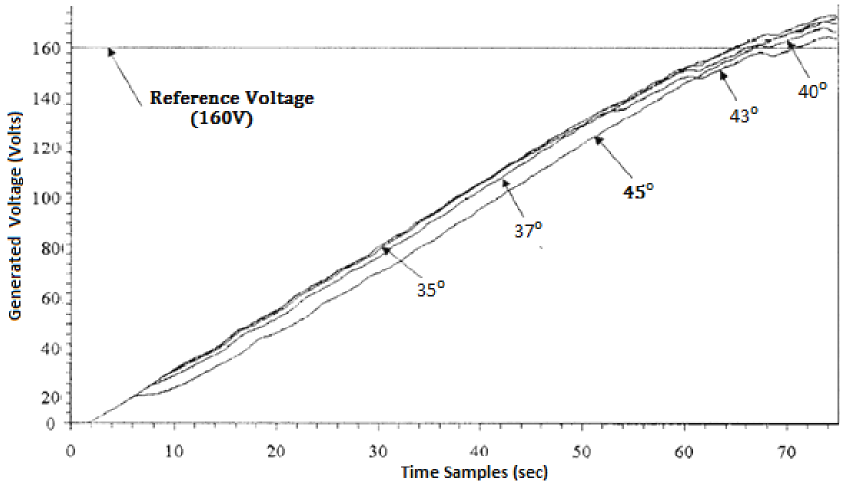

Figure 7: Transient response of SRG when θ_{OFF} is fixed at 80^0mechanical degrees while θ_{ON} is varied in the range of 45^0 to 30^0

Table 1: Voltage- Current Characteristics Of SRG Connected With Different Loads With Different Advanced Turn-On Angles

<table>
<tr><th rowspan="2">Resistive Load in ohms</th><th colspan="2">Dwell Angle</th><th rowspan="2">Generated voltage V volts</th><th rowspan="2">Phase Current I amps</th><th rowspan="2">Load Current I amps</th><th rowspan="2">VαI</th><th rowspan="2">Iα1/V</th><th rowspan="2">Iα1/V2</th></tr>
<tr><th>θON</th><th>θOFF</th></tr>
<tr><td>10</td><td>20</td><td>90</td><td>483</td><td>30</td><td>4.83</td><td>14490</td><td colspan="2" rowspan="4">REGION - II</td></tr>
<tr><td></td><td>25</td><td></td><td>500</td><td>30</td><td>5</td><td>15000</td></tr>
<tr><td></td><td>30</td><td></td><td>500</td><td>26</td><td>5</td><td>13000</td></tr>
<tr><td></td><td>35</td><td></td><td>492</td><td>25</td><td>4.92</td><td>12300</td></tr>
<tr><td>100</td><td>20</td><td>90</td><td>680</td><td>24</td><td>6.8</td><td rowspan="9"></td><td>16320</td><td rowspan="6">REGION-III</td></tr>
<tr><td></td><td>25</td><td></td><td>700</td><td>21</td><td>7</td><td>14780</td></tr>
<tr><td></td><td>30</td><td></td><td>700</td><td>20</td><td>7</td><td>14000</td></tr>
<tr><td></td><td>35</td><td></td><td>662</td><td>22</td><td>6.62</td><td>15224</td></tr>
<tr><td></td><td>40</td><td></td><td>680</td><td>23</td><td>6.8</td><td>15640</td></tr>
<tr><td></td><td>45</td><td></td><td>680</td><td>23</td><td>6.8</td><td>15640</td></tr>
<tr><td>1000</td><td>25</td><td>90</td><td>700</td><td>18</td><td>0.7</td><td rowspan="5">REGION-IV</td><td>10290000</td></tr>
<tr><td></td><td>30</td><td></td><td>712</td><td>17.5</td><td>0.712</td><td>9875800</td></tr>
<tr><td></td><td>35</td><td></td><td>720</td><td>17</td><td>0.72</td><td>9897728</td></tr>
<tr><td></td><td>40</td><td></td><td>723</td><td>16.4</td><td colspan="2">0.723</td><td>9890302</td></tr>
<tr><td></td><td>45</td><td></td><td>722</td><td>15.8</td><td colspan="2">0.722</td><td>9807407</td></tr>
<tr><td>10000</td><td>25</td><td>90</td><td>900</td><td>11.2</td><td colspan="2">.09</td><td colspan="2" rowspan="2">REGION-V</td></tr>
<tr><td></td><td>27</td><td></td><td>820</td><td>13.7</td><td colspan="2">.082</td></tr>
</table>

Table 2: Steady- S.tate Characteristics of 1.2 KW, three phase,6/4 SRG at 380rpm with Ve=20Vin Self-excited mode of operation

Generated Voltage(Volts)	31.5	39.5	51.2	87.8
Output Power(Watts)	18.9	24.095	38.4	66.72
Lamp Load(watts)	200	160	100	40
Load Current (Amps)	0.6	0.61	0.75	0.76
Ripple Voltage(volts)	1.7	1.8	1.78	8.0

Simulation Results and Discussions

A detailed simulation study of very precise lab prototype model of SRG in MATLAB/SIMULINK environment[20] is carried out. The performance of SRG starting from standstill (Region-I) up to maximum generated voltage (Region-V) on different loads with different advance switching angles is simulated. Voltage is set to the rated value of the machine of 160 volts with excitation current set to 16 amps, running at a constant speed of 1000 rpm. The effect of variation of switching angles is evaluated in terms of generated voltage; load supplied and load current in different region of operation. Table–I shows the summary of the unique Voltage- Current characteristics possessed by SRG as shown in Fig 5. Fig 8. illustrates the phase current overlap at ⍰$_{ON}$ at 30^0 and ⍰$_{OFF}$ at 75^0 in region -5 because of the presence of mutual inductance ,two current pulses appear per stroke, one from the previous phase to be turned –off and another from the incoming phase to be turned –on, defined as the region of magnetic overlap.

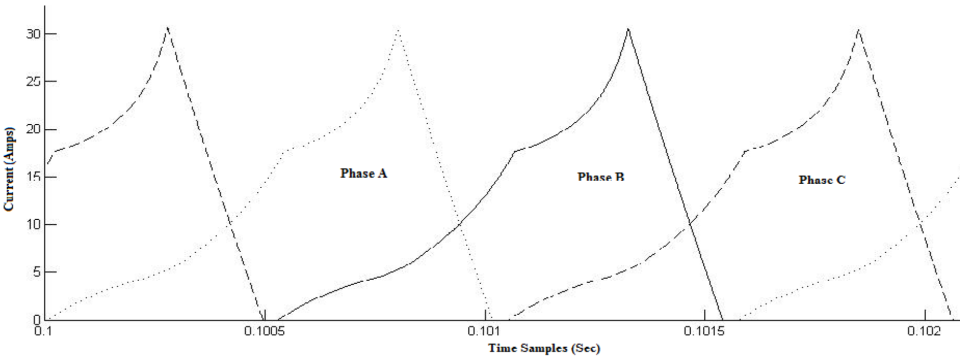

Figure 8: Phase currents waveforms with magnetic overlap at ⍰$_{ON}$ = 30^0 and ⍰$_{OFF}$ = 75^0.

Hardware Set-up

The SRG system under control consists of a lab prototype model of 1.2 KW, 160 volts, 6/4, three phases SR motor, a personal PC, the driver circuit and 6259 NI-DAQ card as in the Fig 9. The generator is fed by power inverter utilizing 6 MOSFETs (IRFP460) and six freewheeling diodes (MUR3040). The rotor positions are sensed by three encoders. An NI based data acquisition system is used to interface the rotor position encoder signals to MATLAB based real time workshop on a PC. The trigger pulses are generated from the same card and provided to the inverter with proper driver and isolation. The. 6259 NI-DAQ card has a sampling frequency of 1.25 MS/s with 16 differential or 32 single ended analog inputs and 24 digital input and output channels working for +/-11volts. The ADC has a resolution of 16 bits. A totem pole gate driver is used to turn ON the MOSFET as shown in the Fig 10. The input-output isolation is achieved using high speed HCPL-4503 opto-coupler to transfer the control signal from the input stage to the gate driver stage. The control architecture consists of a three-layer structure. In the upper level of the control system, the controller design is based state feedback strategy and generates the required voltage for each phase. In the middle level, the current controller generates pulses of required duty cycle to achieve the desired current demanded by the upper level. The phase currents are sensed by using a .01 ohm,10W resistor and voltage by voltage divider circuit, are fed back to ADC channel of the DAQ The current controller in turn depends on the rotor position information to trigger the gate pulses of the three-phase inverter connected to the generator phases. The rotor speed is determined by encoder pulses and rotor angle is obtained by integrating rotor speed. The firing angles are programmable and can be varied easily to control the generated voltage. The real no load state is defined as SRG generates energy consumed by the control, logic circuits, Leakage capacitor resistance, core, windings, and mechanical losses.

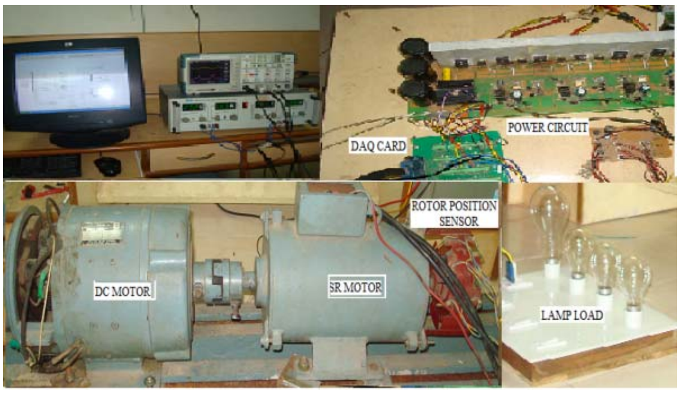

Figure 9: Photograph of hardware implementation

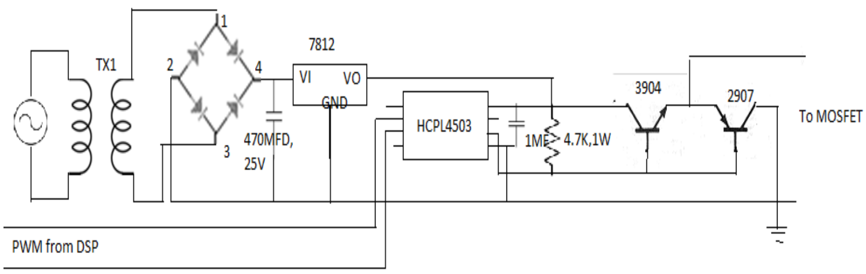

Figure 10: Drivers and Isolation Circuit

Experimental Results

Fig 11&12. shows the experimental results of a 1.2kW, 6/4 SRG loaded with variable resistive load. Stable output voltage is achieved by optimizing θ_{ON} and θ_{OFF}. The output voltage ripple is small under no-load and varies as the load increases with generator running at a speed of 380 rpm, connected with a capacitance of 4800µF. Increasing the value of filter capacitance can decrease ripple voltage but it degrades the SRG dynamic performance. The controller is programmed with different firing angles and its response is studied on the output of the SRG.

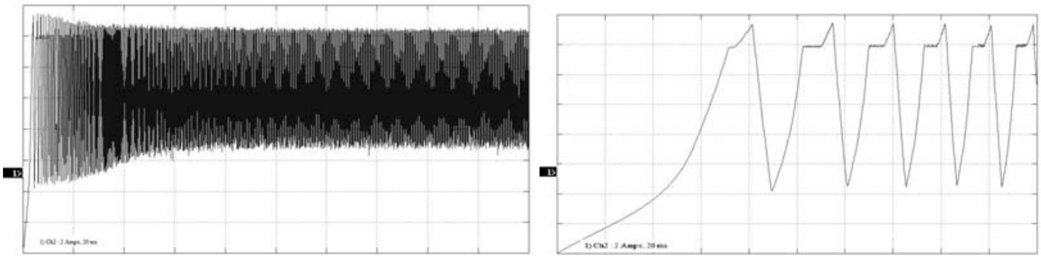

Figure 11: (a) Winding Current (b) Starting process (measurement)

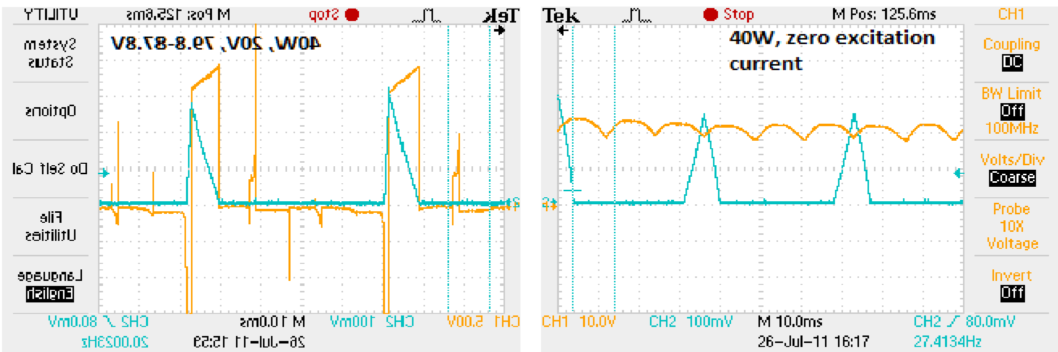

Figure 12: Voltage generated in SRG at a load of (a) 200W (b) 140 W (measurement).

Conclusion

By optimal selection of θ_{ON} and θ_{OFF}, iref the capacity of SRG system can be enhanced potentially as represented by the five operating regions. In realizing the optimal current control, proper modeling and comprehensive understanding of the entire SRG system is required. The turn-on and turn-off angles of phase current have been found to be very critical for energy conversion and generator performance. However, theoretical and experimental results have indicated that phase angle control of SRG current is closely related to the load level, rotor speed, rotor position, etc., and precise control of the firing angle requires an accurate model to fully account for their complicated relations. Simulation and experimental results are presented to validate the effectiveness of the proposed control scheme.

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Appendix 1

Parameter	Switched Reluctance Generator	Units
Voltage	160	volts
Current	16	amps
Base speed	1750	rpm
Stator poles	6	
Rotor poles	4	
Inductance	L_{min}=8m/L_{max}=60m	henries
Resistance/phase	1.3	ohms
Moment of Inertia	0.0013	Kgm^2
Friction co-efficient	0.0183	Nm-sec