

EXPERIMENTAL VERIFICATION OF INDUCED VOLTAGE SELF-EXCITATION OF A SWITCHED RELUCTANCE GENERATOR

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Abstract – Switched reluctance machine does not have its own self-excitation capability. However, permanent magnets could be placed in various positions on the core of the switched reluctance machine to provide its excitation requirements during starting. This paper is devoted to the experimental verification of this new self-excitation principle. The complete power electronic controller for driving a self-excited switched reluctance generator as well as several different generator configurations have been implemented. Design details, operating principles and experimental results are presented.

I. INTRODUCTION

Switched reluctance machines have been found to offer important advantages over conventional AC machines in generating as well as motoring applications. For example, the phases of the switched reluctance machine are decoupled from each other under normal operation thereby improving reliability. This characteristic offers an advantage over more conventional machines (PM machines primarily) when the machine is used as a generator, since the faulted phase will not conduct current while the remaining phases continue to operate. However, the primary problem concerning effective employment of switched reluctance generator is the fact that such a machine is inherently completely passive and has no self-excitation capability so that some other source of power is necessary for excitation which consequently increases complexity and decreases reliability.

Computer simulations of a new self-excitation principle using a small permanent magnet were conducted in a previous study for WPAFB [2,3]. These simulations have demonstrated that permanent magnets could be placed on a small portion of the axial length of two poles of the switched reluctance machine to provide its excitation requirements during starting. In general, SR generator power is fed to a power controller and from there to a DC link capacitor. The change of the permanent magnet flux during the rotation of the rotor induces alternating voltages in the stator windings which can be rectified and which can be used to initially charge the DC link capacitor to a small voltage. Once excitation is supplied to the generator for a brief period using the energy stored on the dc link capacitor, the capacitor voltage can be built up to the rated voltage by extracting energy from the prime mover.

In general, the magnets can be placed in various positions in the magnetic flux path and may have various sizes and shapes. Simulation results [3] have shown that the required amount of the permanent magnet flux can probably be obtained by simply fixing the rectangular magnet pieces to each tooth of the machine poles. The purpose of this study is

to experimentally verify the utilization of the permanent magnets in self-exciting a switched reluctance generator and to determine the minimum amount of the required permanent magnet flux. In order to accomplish this task, a switched reluctance machine drive complete with the affixed permanent magnets and a power electronic controller have been implemented.

II. SELF-EXCITED SWITCHED RELUCTANCE GENERATOR

A. Switched Reluctance Machine Used

A commercially available switched reluctance machine was used for the experimental set-up consisting of a four-phase regular 8/6 machine with eight stator poles and six rotor poles. A cross section of the machine stator and rotor core is shown in Fig. 1. The picture shows also the permanent magnet pieces affixed to each pole of the one stator phase.

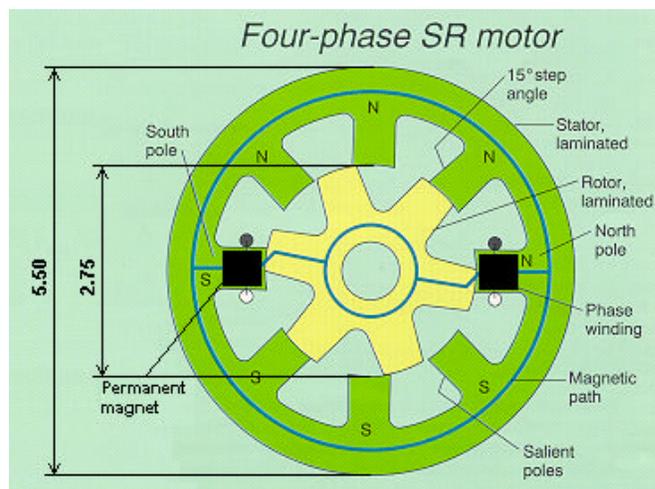


Fig. 1: Cross section of the switched reluctance machine with permanent magnets affixed to two stator poles.

B. Self-excited Generator Design

As demonstrated in the previous computer simulation study, self-excitation capability of the SR generator could potentially be obtained by simply attaching rectangular magnet pieces to each pole of the machine phase. This concept was implemented in three different means which will be shown and explained in the remainder of the text.

The permanent magnet material used is samarium cobalt. The shape and the dimensions of one permanent magnet

piece were chosen to fit the dimensions of the stator tooth and are shown in Fig. 2.

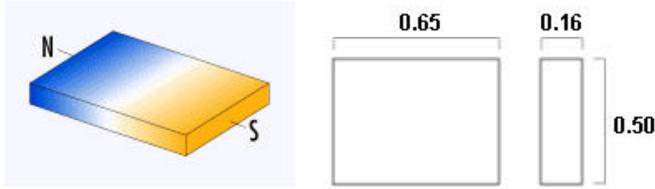


Fig. 2: Shape and the dimensions of the permanent magnet pieces utilized, inch units.

The first option of magnet placement that was implemented is shown in Fig. 3. In this case, the stator core was cut around the teeth of the one phase from top surface toward bottom of the core. Several lamination layers of each tooth were removed and room for the permanent magnets was provided. The permanent magnets were placed so as their top surfaces were aligned with the surface of the stator core. This was done on both sides of the stator core with four permanent magnet pieces (two permanent magnets per phase tooth on both stator sides) employed. The mounted permanent magnets can be clearly seen in Fig. 3 which shows only one side of the stator core.

The second option that has been implemented comprises only permanent magnets fastened to the stator poles without any cutting the stator core. The permanent magnet pieces were affixed in the available space between the stator winding and the pole tooth. Again, four permanent magnets were used, two pieces on both sides (top and bottom) of each phase pole.

The last option for a self-excited SR generator design was the same as the first case except that only two instead of four permanent magnet pieces were fastened on each phase tooth on only one side of the stator core.

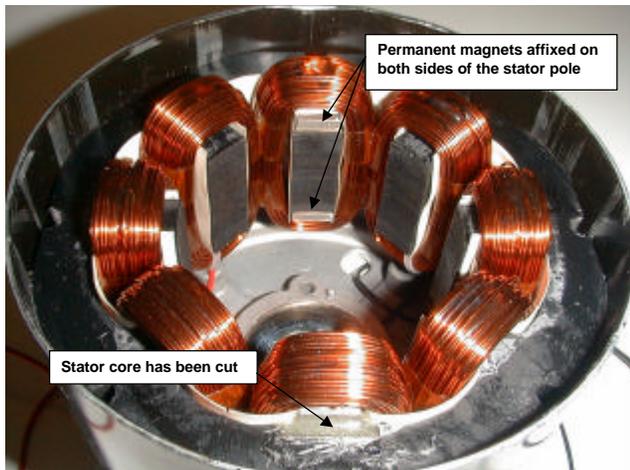


Fig. 3: Self-excited generator design for which stator teeth have been cut.

Normally, the strength of the permanent magnet flux that is closed through the stator and rotor core and the air gap depends on the position of the permanent magnets with respect to the rotor core. Therefore, to maximize the magnet flux, the permanent magnet pieces were placed to minimize

the air gap between the permanent magnets and rotor core as much as it is possible in all of the above mentioned options.

III. POWER ELECTRONIC CONTROLLER

The power electronic controller for the switched reluctance generator can be regarded as comprising the power converter and control circuitry. The controller configuration of the Fig.4 was chosen for this self-excited switched reluctance generator. The power circuit with two MOSFET transistor and two diodes per phase provides the maximum control flexibility and efficiency, with minimum passive elements. In addition, the body diodes of MOSFET switches establish a full bridge diode rectifier resulting in shorter charging time of the DC link capacitor. This circuit operates in the single-pulse mode with a current-regulated control loop.

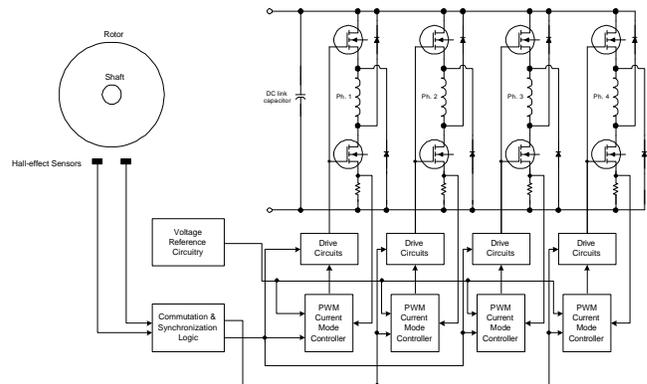


Fig. 4: Block diagram of the power electronic controller.

The structure of the power electronic controller ensures proper driving of the self-excited switched reluctance generator. A control system was designed consisting of position sensing elements, synchronization circuitry, commutation logic and PWM generators. Each block of the drive system can be recognized in Fig. 4. The position detection block of this figure has been realized by a magnetic encoder consisting of a magnet ring commutator mounted on the machine shaft and two Hall-sensor ICs. The synchronization and commutation circuits are implemented by several standard CMOS digital chips. PWM generators are standard analogue current-mode controllers which are synchronized with digital circuitry and with generator voltage reference.

As can be noted, each generator phase has its own PWM controller. This makes it possible for the self-excited generator to operate with only one excited phase. Current-mode controllers have been chosen since they are suitable for the flyback converter structure which can be recognized in the per-phase power circuit. The only fundamental difference is that the inductance is not constant but varies with rotor position.

The converter has three different operating modes: charging mode, voltage build-up mode and generating mode. In charging mode, the DC link capacitor is charged by the alternating emf of the permanent magnet flux through the diode rectifier circuit. The power converter operates completely passively in this mode of operation. The passive

diode circuit rectifies the induced voltage of the phase where the permanent magnets are placed. The DC link capacitor is charged up to the peak value of this induced emf (minus the diode forward voltage drop). This voltage may be few volts depending on the machine speed and permanent magnet flux power. Fig. 5 illustrates the corresponding waveforms of this mode of operation.

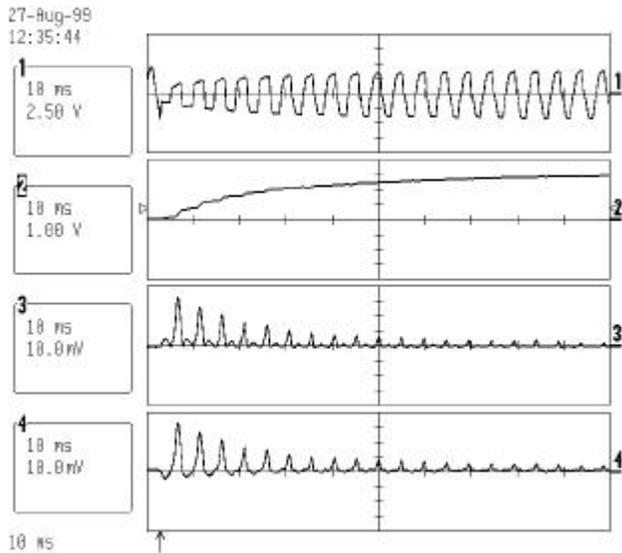


Fig. 5: Waveforms during the charging mode of operation. The waveforms from top to bottom: induced alternating voltage, capacitor voltage and charging current, and phase current. The scale for the bottom two traces is 0.2A/div.

During the voltage build-up mode the capacitor voltage is increased up to the rated voltage. This is accomplished by actively switching of the power transistors. The switching action is similar to the regular generating mode, except that a duty-cycle which is too lengthy may completely discharge the capacitor when its voltage is still fairly low. In general, the excitation power is first supplied from the DC link capacitor while the transistors are conducting. The DC link voltage turns on at a point near the aligned position (slightly before or after) so that the bulk of the winding conduction period comes after the aligned position. Current begins to rise as the rotor poles approach the stator poles of the next phase to be excited. The phase current increases utilizing the energy from the capacitor until the switches are turned off at the commutation angle defined by the control circuit.

When the switches are turned off, the current in the switches is commutated to the diodes and continues to flow until it reduces to zero. The terminal voltage reverses which is also handled by the freewheeling diodes. Generating power is now returned to the DC link capacitor during this de-fluxing period. Therefore, the direction of the energy flow is changed from the machine to the capacitor and hence, the capacitor voltage increases. Fig. 6 illustrates the waveforms of the voltage build-up mode when only one generator phase is excited.

For generator action to be sustained as well as produce a voltage increase during the build-up mode, the energy returned during the de-fluxing period must exceed the

excitation energy supplied when the switches are on. The difference between electrical input energy and electrical output energy is provided by the prime mover. The amount of energy flow can be controlled by regulating the turn-on instants of the switches.

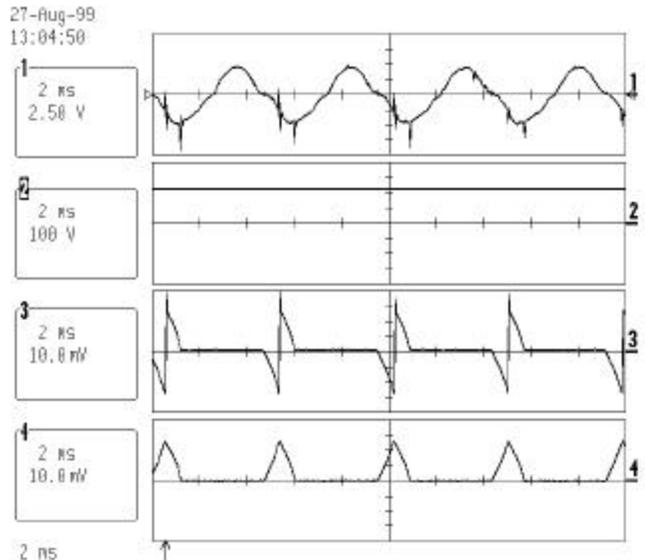


Fig. 6: Waveforms of the voltage build-up mode of operation. The waveforms from top to bottom: induced alternating voltage, capacitor voltage and current, and phase current. The scale for the two bottom traces is 1A/div.

IV. EXPERIMENTAL RESULTS FOR CHARGING THE LINK

A. No-Load Conditions

The tests were done for three different configurations of the self-excited SR generator described in section II. In all three cases, the DC link capacitor of 680 μ F was charged by passive action of the converter circuit at the start. Once the capacitor was initially charged the driving pulses for the active switches were applied by manually presetting the voltage command reference. It should be noted that control system was implemented in open-loop mode without providing a control signal of the DC link voltage. Hence, the DC voltage build up was "open loop" and the process controlled manually by control of the firing pulses. It can be noted that the DC link capacitor voltage readily builds up to the rated value which is 240 V. The machine speed was 2000 rpm, only half of the maximum speed, for each self-excited generator configuration.

Experimental waveforms of the charging operation for configuration #1 are shown in Fig. 7. Fig. 8 shows experimental waveforms during the start of the voltage build-up operation for configuration #1.

The process of a gradual increase of the DC link capacitor voltage for configuration #1 is shown in Fig. 9. Charging continues until the capacitor voltage reaches the rated value of 240 V, which lasts less than one second. From Fig. 9, a changing build-up rate can be recognized. This appears because the DC link voltage command signal is changed manually, as already mentioned. More physical insight of the process could be obtained by referring to Fig. 10 which

shows the same build-up mode, but only during first 200 ms. The natural generator-circuit response, after a step change in voltage command has performed, is shown in this Figure.

In practice, faster system response can be achieved by feeding back and regulating the DC link voltage. With a closed-loop control system, it would be possible to achieve automatic duty cycle adjustment, and therefore the machine is supplied with required excitation power. Further, it should be mentioned that this open loop build-up rate is not defined by the current limit setpoint of the current mode controllers in the control circuit rather by the excitation instant during the rotor transition between aligned and unaligned position and circuit itself. By shifting the moment when the gate pulses of the converter switches are applied it is possible to change the excitation and thus generated power, which defines the build-up voltage rate.

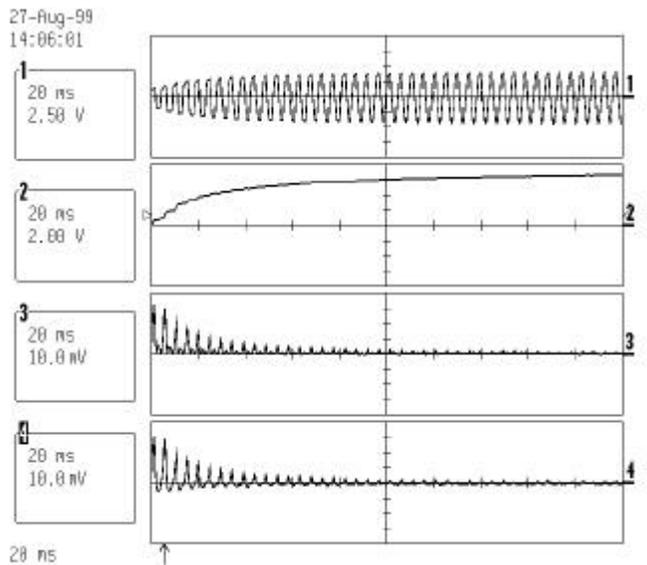


Fig. 7: Waveforms during charging mode of operation, configuration #1. The waveforms from top to bottom: induced alternating voltage, capacitor voltage and current, and phase current. The range for the two bottom traces is 0.2A/div.

Finally, the waveforms for the self-excited generator, using configuration #1 when operating in the continuous generating mode are shown in Fig. 11.

Experimental results for the three different configurations can be summarized by referring to Table I which contains the corresponding measured results. It can be recalled that configuration #1 was realized with stator teeth that have been cut, configuration #2 is realized without cutting the stator core and with four permanent magnets, and configuration #3 is realized with only two permanent magnets and without cutting the stator core. The amplitude of the alternating voltage induced by the permanent magnets, the DC voltage of the initially charged capacitor and the time to initially charge the capacitor are shown. Again, the machine speed was 2000 rpm in all cases.

The experimental results demonstrate that successful operation of the described self-excited switched reluctance generator is possible. An inexpensive redesign of the standard

switched reluctance machine by using the permanent magnet pieces could provide the machine with self-excitation capability. This is especially true for the self-excited generator configuration realized without cutting the stator core and with only two permanent magnets simply fastened onto the phase teeth.

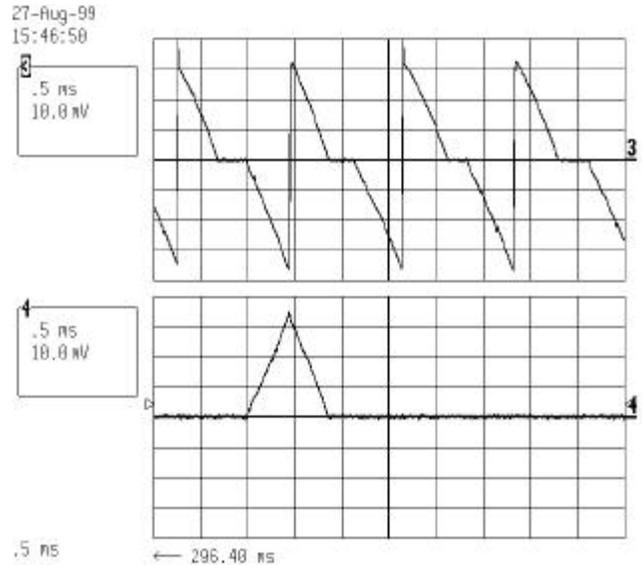


Fig. 8: Waveforms during voltage build-up mode of operation, configuration #1. The top waveform is capacitor current and the bottom waveform is phase current. The range for both traces is 1A/div.

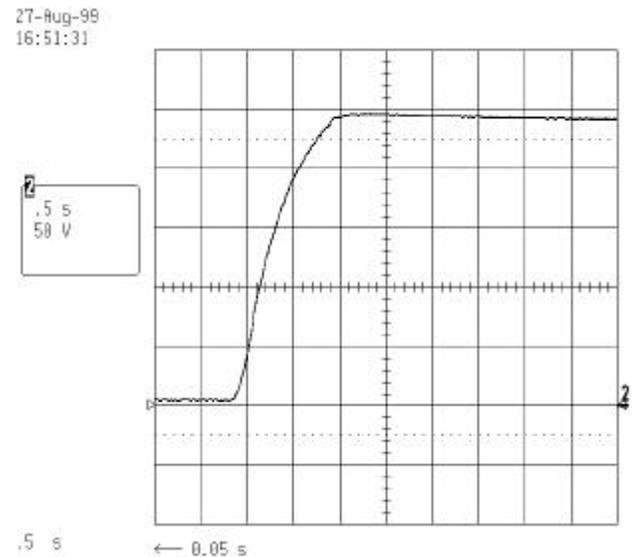


Fig. 9: Build-up of the DC link capacitor voltage, configuration #1.

B. Resistive Load Case

Tests were also carried out for various load conditions. To simulate a load, a resistor of 300 W was connected to the output of the self-excited generator, across the DC link capacitor terminals. Experimental waveforms for the start of

the build-up and continuous generating modes are shown in Figs. 12 and 13 respectively.

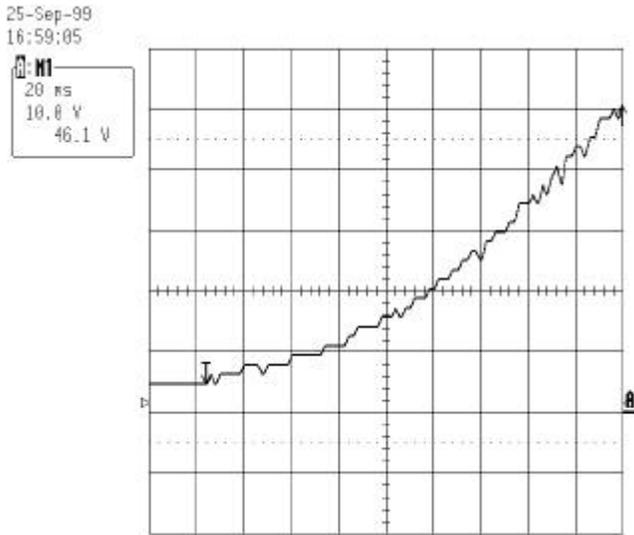


Fig. 10: Build-up of the DC link capacitor voltage during first 200 ms.

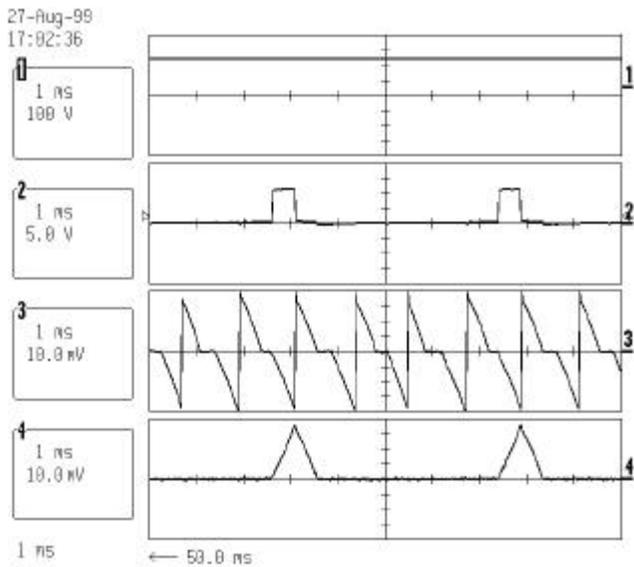


Fig. 11: Waveforms during continuous generating mode of operation, configuration #1. The waveforms from top to bottom: capacitor voltage, gate drive pulses, capacitor current and generator phase current. The scale for the two bottom traces is 1A/div.

TABLE I
SUMMARY OF EXPERIMENTAL RESULTS

	ZERO-TO-PEAK AC VOLTAGE [V]	INITIAL DC VOLTAGE [V]	CHARGE TIME [S]
CONFIG. #1	4.36	3.72	0.40
CONFIG. #2	1.76	1.23	3.22
CONFIG. #3	1.09	0.71	11.87

From Fig. 12 and 13 it can be seen that self-excited generator operates successfully again, supplying 150 W of

output power. As expected, the starting build-up rate is now less than that for the no-load conditions. Further, slightly less (≈ 210 V) steady state generator voltage is obtained, since the current reference in the control circuitry has not been changed.

C. Short-circuit Test

Finally, the short circuit condition on generator's DC bus was checked. Experimental results obtained are shown in Fig. 14. The self-excited generator is capable to produce and supply the short circuit current through the passive diode circuit. Once the short circuit conditions were released, the raise of the DC link voltage was possible.

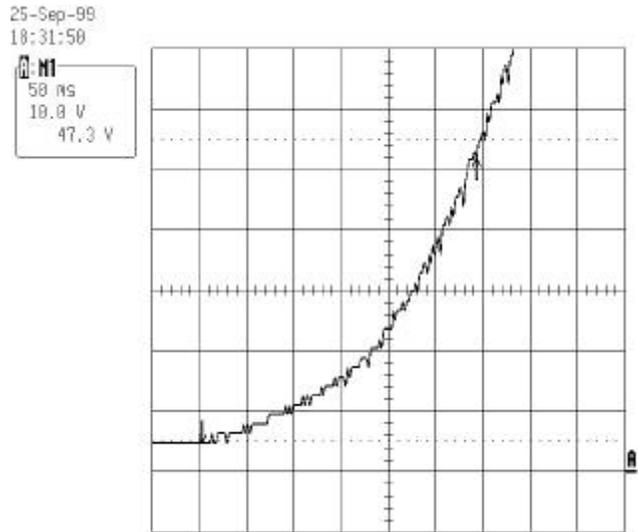


Fig. 12: Build-up of the DC link capacitor voltage for the loaded generator.

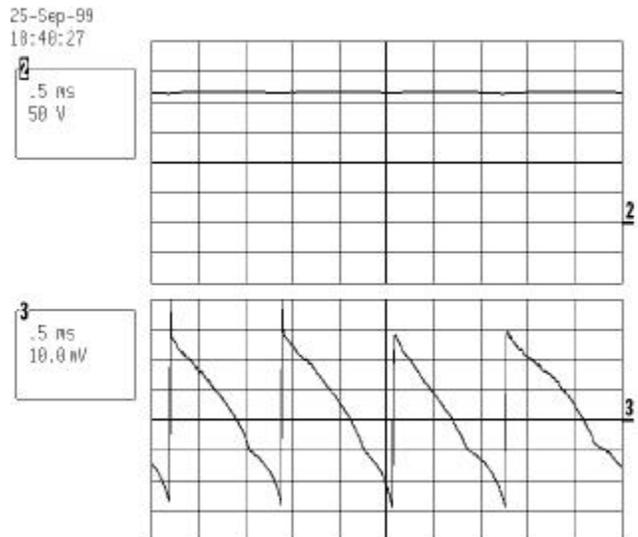


Fig. 13: Waveforms during continuous generating mode of operation for the loaded conditions. The top and bottom waveforms are capacitor voltage and current. The range for the current trace is 2A/div.

V. CONCLUSION

The purpose of this study was to experimentally verify the use of the permanent magnets for self-excitation of a switched reluctance generator. While the previous simulation study completed an analytical investigation of this concept, this work extended the investigation to a complete working experimental mode. Tests made have confirmed the validity of the existing computer simulation. In particular, a switched reluctance machine drive complete with affixed permanent magnets and a power electronic controller have been implemented. The tests were done on a small commercially available 1 HP switched reluctance machine. A standard converter configuration with two power transistor and two diodes per phase was chosen for this self-excited switched reluctance generator. The converter control circuit was realized with minimum necessary components making overall design simply and accurate.

It is important to note that the power converter control circuit was implemented in open-loop mode without feedback of the DC link voltage. Instead, a simple reference circuitry was used in the control system. It is reasonable to expect that faster build-up of the DC link voltage can be achieved with a control system when closed-loop control of the DC link voltage is implemented. Such a controller should be readily able to automatically adjust the duty-cycle of the active switches and provide the machine with its required excitation power.

The tests have been carried out for three different configurations of the self-excited switched reluctance generator which are described in the preceding text and for the no-load as well as for the loaded condition. The experimental results have demonstrated that successful operation of the proposed self-excited switched reluctance generator is possible and have confirmed the necessary realism needed to accurately predict the self-excitation concept.

The self excitation process was successful even for a self-excited generator configuration realized without cutting the stator core and with only two permanent magnets simply fastened onto the phase teeth. For this configuration, the initial charging of the DC link capacitor was only 0.7 V showing that an inexpensive, reliable modification of the standard switched reluctance machine by using the permanent magnet pieces provides the machine with self-excitation capability.

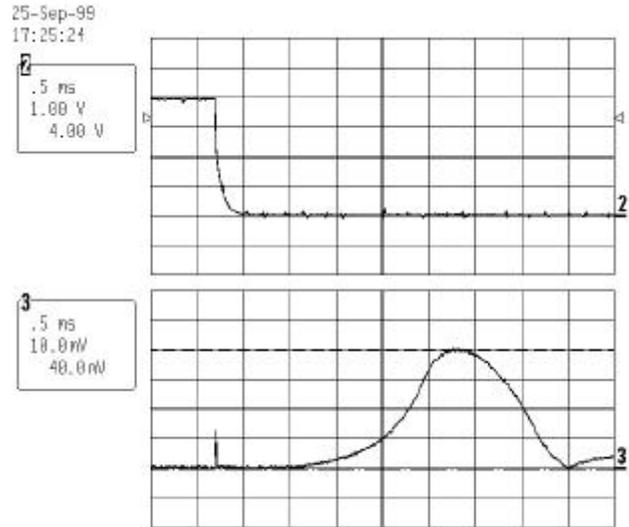


Fig. 14: Waveforms during one cycle of the short circuit conditions. The top and bottom waveforms are capacitor voltage and current. The scale for the current trace is 0.1A/div.

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