# SWITCHED RELUCTANCE MACHINE WITH ASYMMETRIC POWER CONVERTER IN GENERATING MODE

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**SUMMARY**

*Switched reluctance (SR) machine has various desirable features, which comes from its simple construction. They are the wide speed range, high temperature operation and small moment of inertia. But without any precise control technique no from these advantages could be utilised. SR machine in generating mode also starts to be used and its control technique can be even simpler than in motoring mode. In this paper a drive with a small 6/4 SR machine with an asymmetric half-bridge power converter produced as a motor, will be changed to generator. To obtain this the control technique based on DSP as well as the drive set-up will be modified. The appropriate control technique for obtaining generating mode will be designed and implemented for SR machine control. Generator operation will be tested by various load and speed conditions. Simulation results will be done for the purpose of comparing with those measured.*

***Keywords:*** *Switched reluctance generator, motor, machine, PWM control, DSP, phase current*

## 1. INTRODUCTION

Recently besides switched reluctance motors (SRM), the switched reluctance generators (SRG) has begun to be used for some variable-speed applications such as sourcing aerospace power systems, fuel pumps for airplanes, starter/alternator for hybrid vehicles and wind turbine applications [1].

These machines are investigated for their interested properties like the possibility to work by high speed and high temperature without problems because they have no permanent magnets and no winding on the rotor. SR machines have doubly salient design of the magnetic circuit. The excitation winding is placed on the stator poles while the rotor is without winding. It follows that the energy conversion is based on reluctance variation. The phase current pulse is controlled and synchronised with the rotor position feedback. SR machine has also disadvantages in producing acoustic noise and in complex control because they need power converter and rotor position sensor. With the advance in control techniques and power electronic technology, growing interest in this type of machine is expected.

In this paper a drive with a low power 6/4 SRM with an asymmetric half-bridge power converter (APC) and a brushless DC motor (BLDC) as a load will be introduced. But the aim is to modify the control technique and the drive set-up to activate SRM in generating mode. APC is a universal type of converter and is mostly used for applications with the SR machine both in motoring and in generating mode. The appropriate control technique based on Freescale's DSP 56F805 will be designed and implemented for SRG control. Also some simulation results will be carried out and compared with those measured ones.

## 2. DRIVE SET-UP

Demo-drive (Fig. 1) with the SRM, APC with 6 IGBT power transistors - 2 per phase, DSP board, optoisolation board and 3-phase BLDC motor was designed from Freescale Semiconductor Inc. Following modifications of the drive have been made to obtain a generating mode:

1. Mechanical energy supply connecting. SR machine, now SRG, was disassembled from the drive and coupled with an external DC machine. DC machine has been used in term of settings speed for wide range of generator's states.

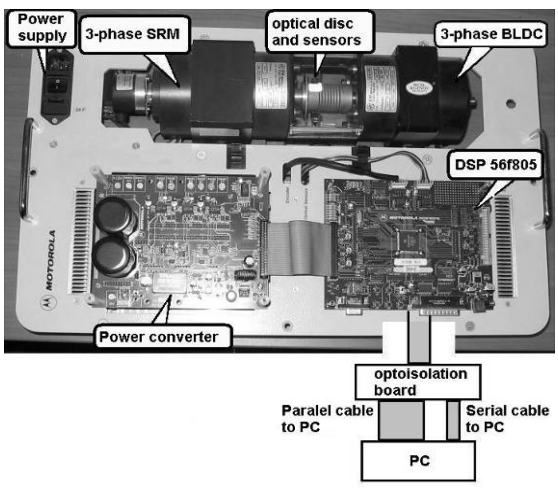



**Fig. 1** Demo-drive with a 3-phase SRM developed by Freescale Semiconductor Inc

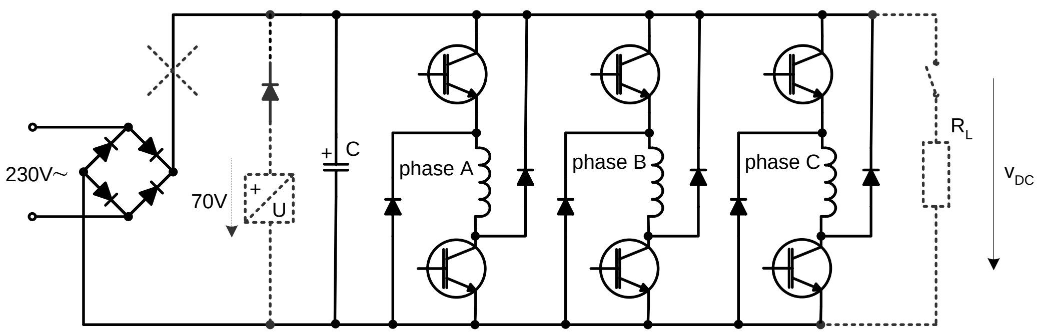



**Fig. 2** Power scheme of the APC for the SR machine. Dotted line means modifications needed to change motoring mode to generating mode

2. Power converter modification. APC is a converter with one DC bus providing both the phase excitation as well as generation. That is why the load resistance as well as excitation source were connected across the same DC bus (Fig. 2). SRG is an independent source of electrical energy but the external source 70V DC has two main functions: First to provide electrical energy for excitation when the drive starts and no voltage on the DC bus is available. Second to supply additional logical circuits of the converter until the DC bus voltage increase above the level of 70V. Diode D1 connected in series prevents the external source from overvoltages and disconnect the DC source when the generated voltage is greater then DC source voltage. The detailed description of SRG operation with the APC is explained in [3], [4].

| | $P_N$ [W] | $v_N$ [V] | $i_N$ [A] | $n_N$ [min$^{-1}$] |
|---|---|---|---|---|
| **SRM** | 180 | 300 | 3 x 1,2 | <5000 |
| DC machine | - | 24 | 15 | 3000 |

**Tab. 1** Rating of the used SRM and DC machine

| | | |
|---|---|---|
| Number of phases | $q$ | 3 |
| Number of rotor poles | $N_r$ / $N_s$ | 6 / 4 |
| Rotor and stator pole arcs | $\beta_r$ / $\beta_s$ | 30° / 30° * |
| Stroke angle | $\varepsilon_m$ | 30° * |
| Effective overlap ratio | $\rho_e$ | 1 * |
| Phase resistance | $R_f$ | 22 Ω |
| Unaligned phase inductance | $L_{min}$ | 0,1 H |
| Aligned phase inductance | $L_{max}$ | 0,66 H |

* Approximate value

**Tab. 2** Measured and calculated SRM parameters

## 3. SR MACHINE PARAMETERS

The both SRM and driving DC machine rated parameters are shown in the Tab. 1. The parameters of SR machine are given for the motoring mode. As you can see the output power is relatively low but the DC bus voltage $v_{DC}$ is relatively high 300V. That corresponds also to measured phase parameters shown in Tab. 2. Phase resistance $R_{ph}$ and also aligned $L_{max}$ and unaligned inductance $L_{min}$ are relatively high. Parameters regarding the machine construction are also shown in Tab. 2 and they are explained in [5]. The cross-section of the magnetic circuit is shown in Fig. 3 and the profile of the phase inductance as a function of the rotor position $\theta$ in mech. degrees is in Fig. 4.

## 4. USED CONTROL STRATEGY

In the Fig. 5 there is a block diagram of the experimental setup. The input power on the SRG rotor shaft is given by DC machine and is supplied by a regulated DC source. Blafl and white disc with 3 optical sensors mounted on SRG's rotor shaft are used to obtain the rotor position signal. Above mentioned load resistance and external source are connected across the DC bus. SRG is controlled by means of the 16 bit fixed point DSP 56f805. As input parameters for control strategy are used measured phase currents $i_{phA}$, $i_{phB}$,, $i_{phC}$, DC bus voltage $v_{DC}$, demanded DC bus voltage $v_{DC}$* and rotor position $\theta$ is needed for commutation between phases.

Reference current is calculated by means of P-regulator from the difference between actual $v_{DC}$ and demanded $v_{DC}$* voltage. Active phase is chosen in the block commutator 1 by means of $\theta$ value.

The current of the active phase is compared with the reference current and their difference is leaded into the hysteresis comparator.

Hysteresis output determines output value 1 what means the both switches of the active phase are in active state or 0 what means they are off. When the switches are active it means they are switched with PWM with frequency 8kHz and pulse width 80÷98%. Block commutator 2 determines which phase and pair of switches are active.

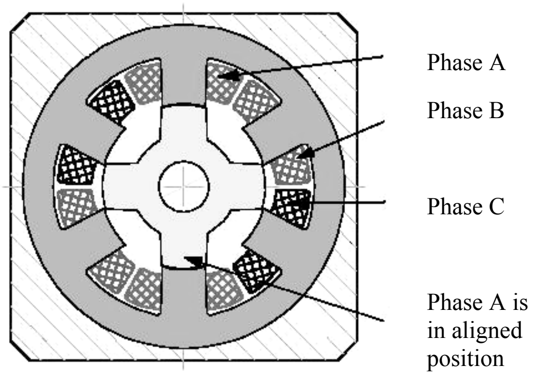



**Fig. 3** Cross-section of the investigated SR machine

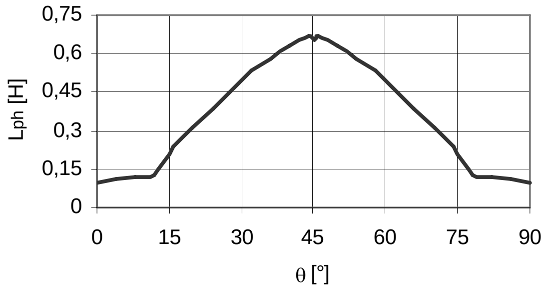



**Fig. 4** Phase inductance profile of the investigated SR machine

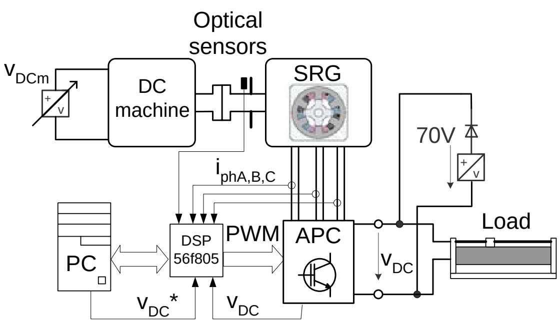



**Fig. 5** Block diagram of the SRG drive set-up

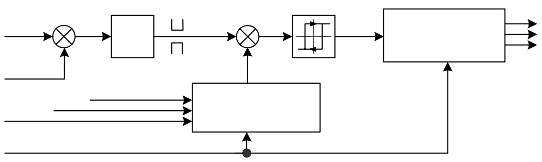


**Fig. 6** Block diagram of the control strategy

Control gate signals of the phase switches are explicitly determined by the various combinations of phase optical sensor signals and each phase sensor signal is determined by its actual rotor position, as it is represented by Fig. 7. When some of the switches control signals is 1, it means the appropriate phase is active. Note in Fig 7. each phase is active at interval of 30ºmech., what corresponds with interval of machine torque zone when phase inductance decreases. At each moment just one phase is active, when some inaccuracy of the sensors position is not taken into account.

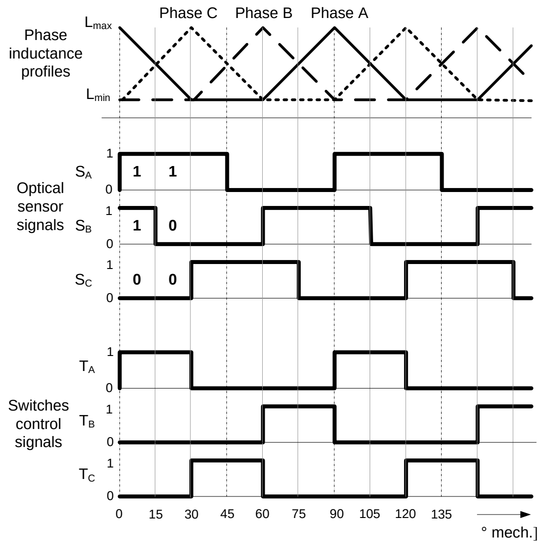



**Fig. 7** Switches control strategy vs. rotor position and inductance profiles

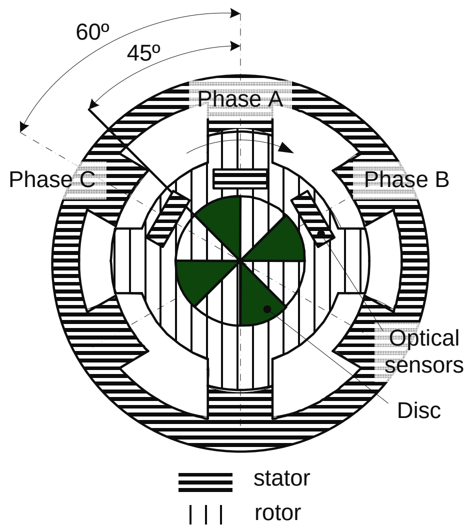



**Fig. 8** Optical sensors on the stator and black/white disc on the rotor configuration

Configuration of the phase optical sensors is in Figh. 8. Each phase optical sensor position is synchronized with phase stator pole, so the distance between them is 60º. The optical disc has four black and white segments with angle 45º and the position of segments is synchronized with four rotor poles. Then the rotor position can be unequivocally determined.

For example if the rotor position is as in Fig. 8 and the rotor turns in clockwise direction the optical sensors signals are as in Fig. 7 when $\theta$=0º or 90º. Phase A starts to be active because it is now in its aligned position. Sensor signal $S_A$ will be logical 1 for the next 45º as it is seen from Fig. 7 and also from Fig. 8, because black segment of the disc turns along the sensor A. Each phase starts to be active when its optical sensor evaluates the colour change of the disc segment from white to black, and its sensor signal turns from 0 to 1. Each phase stops to be active at the moment when the next phase sensor evaluates the colour change of the disc segment from white to black. (Fig. 7 and Fig. 8).

The position control of SRG can be simpler than that of SRM because there is no need to launch start-up routine. Start-up routine sets some demanded start rotor position in order to get reference speed and rotation direction. But in SRG the speed and direction is established by prime mover.

## 5. MEASURED AND SIMULATED RESULTS

SRG was started as no-loaded with the 70V on the DC bus from external source and the speed 2000rpm. The voltage reached the desired value 180V after 0.7s (Fig. 9).

Measured and simulated phase current and DC bus voltage profiles are in Fig. 10a÷d. The first two pictures represent no-load state where generated power is used only for losses covering and for supplying of converter control circuits.

When the speed decreased below 1500rpm the generator performance was very unstable which caused even weakly loaded generator under low excitation. and $v_{DC}$ decreased to zero.

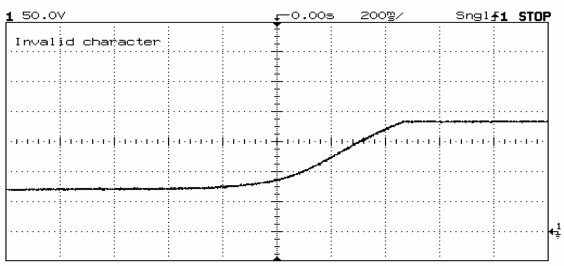



**Fig. 9** Starting excitation of the no-loaded SRG, measured $v_{DC}$ raises from 70V to 180V

On the other hand SRG worked better and more stable with increasing speed. But high-speed operation was limited by DC motor because its rated speed was only 3000rpm. Measured and simulated phase current and DC bus voltage by speed 3500rpm are in Fig. 11.

Measured and simulated phase voltage $v_{phA}$ and current by speed 2000rpm and two load conditions are in Fig. 12. By smaller load $R_L$=2200Ω phase is switched with 8kHz PWM with duty cycle $D$=90%. By higher load $R_L$=1200Ω, $D$ had to be increased to 98% in order to get sufficient generated power for stable SRG operation. With $D$ almost 100% this operation was very close to one-pulse operation. DC bus voltage was kept only in 150V in order to fit the whole curves to oscilloscope screen.

It can be declared that measured and simulated results are in a good agreement and the reasons of differences are in not precise mechanical configuration of sensors, optical disc and in neglecting of magnetic circuit saturation.

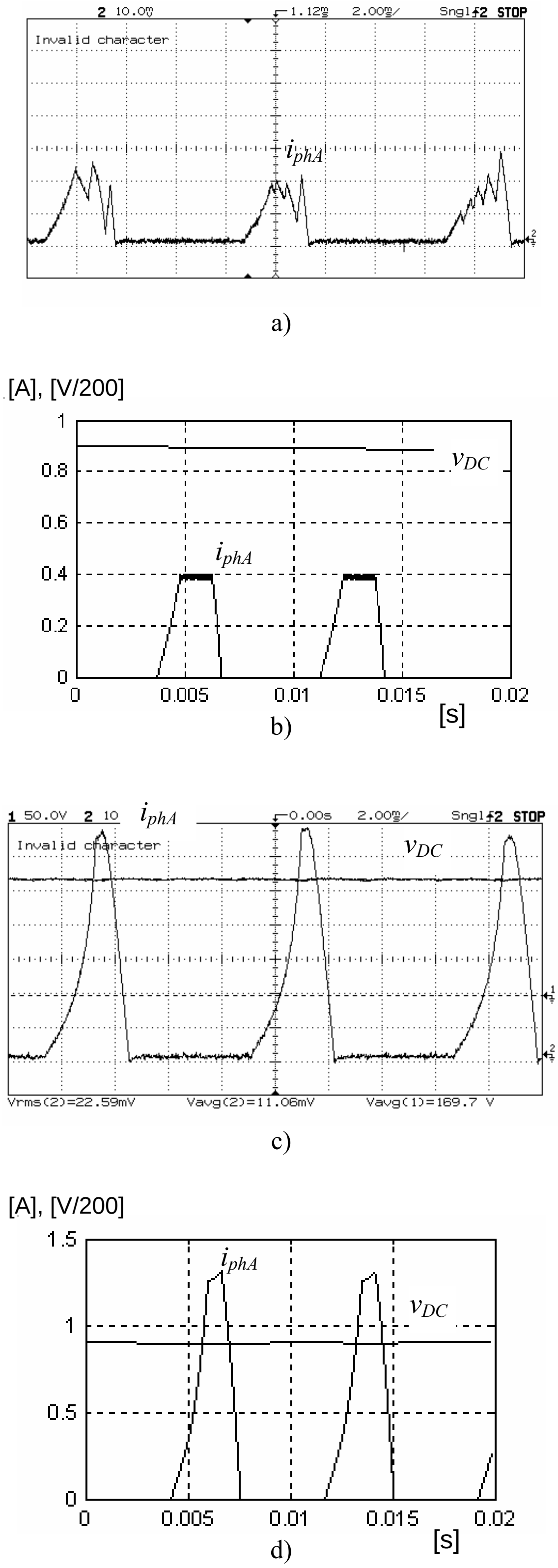
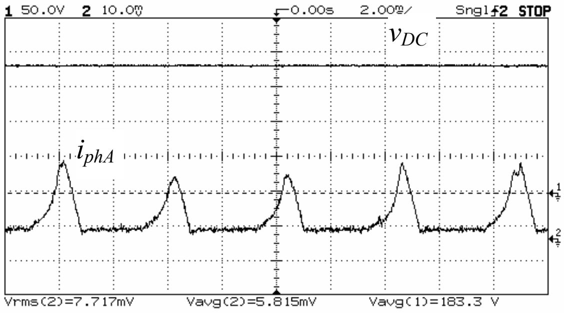
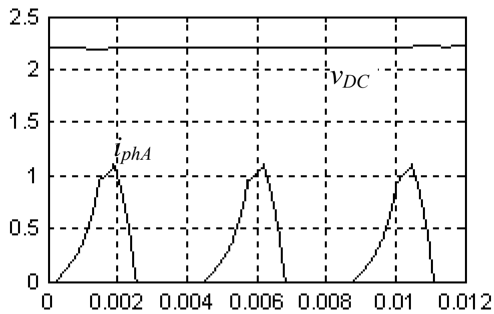



**Fig. 10** Measured (a,c) and simulated (b,d) phase current and DC bus voltage, no-load conditions (a,b), by $R_L$=1200Ω (c,d) and $n$=2000rpm

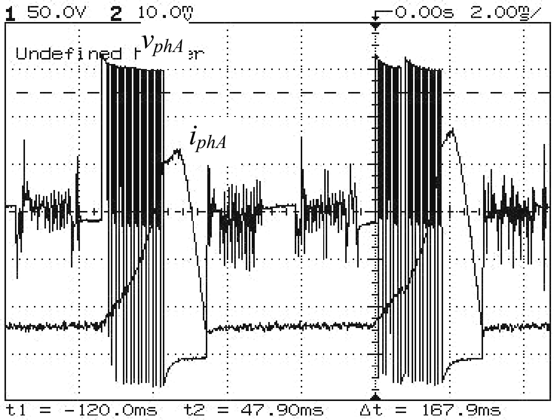



a)

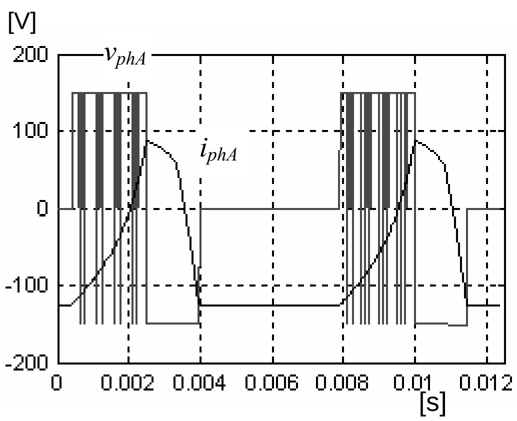



b)

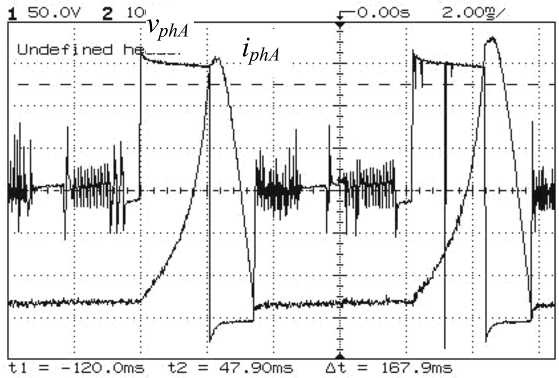
**Fig. 11** Measured (a) and simulated (b) phase current and DC bus voltage of no-loaded SRG by 3500rpm and $v_{DC}$=220V



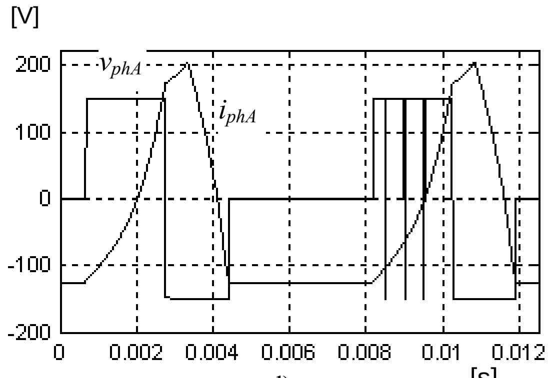

a)




b)




c)




d)

**Fig. 12** Measured (a,c) and simulated (b,d) phase current and voltage of SRG by 2000rpm and $R_L$=2200Ω (a,b) and $R_L$=1200Ω (c,d)

## 6. OUTPUT POWER AND EFFICIENCY MEASUREMENT

Output power was measured for comparing with the motoring operation. Output power was calculated simply as the power consumed by load resistance:

$$P_{out} = v_{DC} i_L \tag{1}$$

where $i_L$ is load current.

Input power $P_{in}$ was needed to calculate drive efficiency. It was taken as an output power of DC driving motor:

$$P_{in} = P_{out\_DCm} \tag{2}$$

Output power of the DC motor was taken as the whole system input power times its efficiency which was estimated to 70%:

$$P_{out\_DCm} = P_{in\_DCm} * 70\% \tag{3}$$

The efficiency was calculated as the ratio of $P_{out}$ and $P_{in}$:

$$\eta = \frac{P_{out}}{P_{in}} 100 \tag{4}$$

Output power and also efficiency were maximal by maximum $v_{DC}$=220V and therefore only characteristics for this voltage are in Fig. 13. SRG was started in no-load condition simulated by variable resistor 2200Ω connected as a load to the terminals. Then it was decreased step by step to increase the load of SRG. The maximum output power achieved in generating mode was 51W. This value is considerably lower than 180W, which is rated output power of the SR machine in original motoring mode. There are several reasons for this:

The DC bus voltage 220V is lover than rated value 300V for motor. Some filter circuits had to be used for filtering overvoltage peaks on the phase switches to allow the operation by 300V.

The control was not ideal because it was determined with the main focus on the simplicity and functionality to apply the generating operation in SR machine. For increase the output power the excitation angle should be enhanced from 30º to maximum 45º, which is half of the rotor pole distance 90º and the beginning of excitation period should be shifted before the aligned position as more as speed increases.

From the Fig. 13 is clear, that the efficiency of SRG with converter is around 65%. If the converter efficiency is taken about 85%, then the SRG efficiency is 75%. This result for such small machine is quite good.

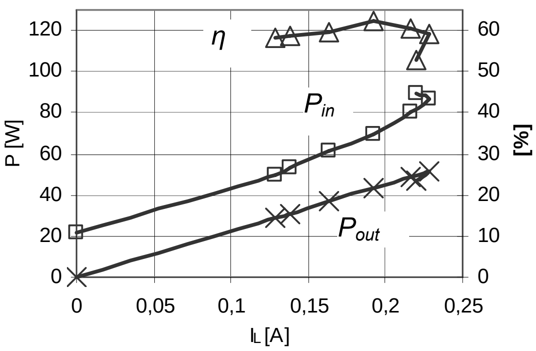



**Fig. 13** Measured input and output power and efficiency vs. load current by 2000rpm

## 7. CONCLUSION

In spite of not ideal values of output power and efficiency the main task: to obtain a generating mode of SRM with an asymmetric power converter was completed. Some changes on drive set-up were done and the new control algorithm for generating operation was carried out. Even with this really simple control strategy we have been able to control output voltage and to get limited currents. Generating operation was tested by some speeds and load conditions. The highest measured output power was 51W. The achieved efficiency of SRG is around 75% if efficiency of its converter is supposed about 85%.

## ACKNOWLEDGMENT

This work was supported by Science and Technology Assistance Agency of Slovak Republic under the contract No. APVT-20-39602, and by VEGA No. 1/2052/05 and VEGA No.1/3086/06 and by Freescale Semiconductor Inc.

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## BIOGRAPHIES

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