

Comparative Analysis of Control Algorithms for a Power Source - Power Converter - Switched Reluctance Motor System in Generator Mode

Dimitar Yankov

Department of Electronics, Faculty of Electronics and Automation
Technical University of Sofia, Plovdiv Branch
Plovdiv, Bulgaria
d.yankov@tu-plovdiv.bg

Ivan Maradzhiev

Department of Electronics, Faculty of Electronics and Automation
Technical University of Sofia, Plovdiv Branch
Plovdiv, Bulgaria
iv_mar@tu-plovdiv.bg

Abstract—This paper presents a study of motor and converter power losses, efficiency, and torque ripple in a power source- converter -switched reluctance motor system, in generator mode operation, using unipolar modulation and different types of control algorithms. In the MATLAB/Simulink environment, for each of the selected algorithms, the converter and motor power losses, efficiency, and torque ripple are investigated while varying different input parameters. Based on the simulation results obtained, the different control algorithms of the system are compared and the most efficient one is selected.

Keywords— switched reluctance motor, iron loss, efficiency, torque ripple, MATLAB/Simulink

I. INTRODUCTION

The switched reluctance motors (SRM's) robust design and ease of starting without drag torque make it suitable for power generation applications (wind turbines, hydroelectric plants, electric vehicles, etc.). Despite these advantages, there are many critical characteristics that affect the generator operation of the SRM. The biggest negative effect on the machine performance is the applied e.m.f., which is negative in this mode to help reduce the magnitude of the current in the demagnetizing mode. In order to increase the efficiency of the motor in generator mode, there are some key factors that need to be improved, namely: the mode of phase excitation, the setting and switching of the power semiconductor switches, the current magnitude control, the switching voltage control, etc.[1].

After the literature analysis of different control algorithms for the power source - converter - SRM system in generator mode [1], based on their advantages and disadvantages, the following algorithms are studied in this paper: control by current regulation; hysteresis current control; control by pulse width modulation (PWM) control by optimal switching angles and PWM.

The purpose of this paper is to perform a comparative analysis of the above algorithms for controlling a power source - converter - SRM system in generator mode, in terms of motor and converter power losses, efficiency, and torque ripple.

II. CONTROL ALGORITHMS FOR A CONVERTER-SWITCHED RELUCTANCE MOTOR SYSTEM OPERATING IN GENERATING MODE

In this section, the block diagrams of the above

algorithms are presented to investigate the operation of a power source – converter - switched reluctance motor system in generator mode, the SRM is of type 12/8 model H55PWBKM-1844. The nonlinear mathematical model of the SRM and the topology of an asymmetric bridge converter presented in [2] were used for the simulation studies.

A. Power converter - SRM system control via independent current regulators

The principle block diagram and the sequence of steps for controlling a converter-SRM system in generator mode by means of independent current regulators is shown in Fig.1.

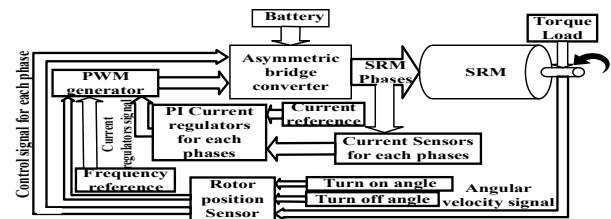


Fig. 1. Block diagram of an SRM control with three current regulators in generator mode.

The essence of this algorithm is as follows: the magnitude of the phase current is monitored by an independent current sensor (shunt resistor) for each phase, and the switching of the upper transistors is performed by a PWM generator with a fixed frequency and a variable duty cycle, the magnitude of which depends on the resulting error at the output of the regulators. The speed to be studied is kept constant by means of a load torque unit, which simulates the operation of the machine in generator mode and acts as a load machine during the simulation.

B. Hysteresis current control of the converter-SRM system

The basic block diagram for controlling a converter-SRM system in generator mode with hysteresis current control is shown in Fig.2.

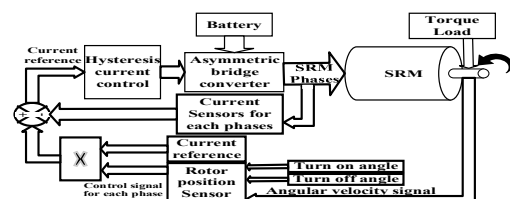


Fig. 2. Block diagram of an SRM drive with hysteresis current control in generator mode.

Bulgarian Ministry of Education and Science and "Research and Development" Sector of the Technical University of Sofia.

In this algorithm, similar to the previous one, the magnitude of the phase currents is monitored by means of three independent current sensors; the switching of the upper transistors of the converter is done by means of a relay with a hysteresis band in the range $\pm 0.1A$ and varying frequency; the difference between the current reference and the actual measured phase current is the input signal to the relay.

C. Converter-SRM system control via PWM

The basic block diagram for PWM control of a converter-SRM system in generator mode is shown in Fig.3. Soft switching (modulated upper transistor, switched lower transistor of the asymmetric bridge converter) is implemented.

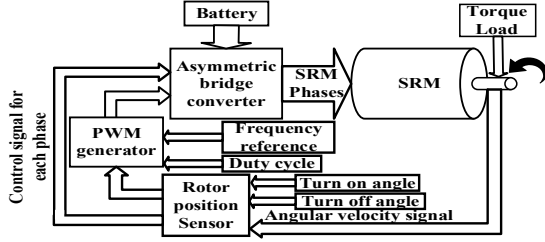


Fig. 3. Block diagram of an SRM drive system and PWM modulation.

In this algorithm, the switching of the upper transistors of the converter is done by a PWM generator with a fixed frequency and duty cycle, unlike the previous two algorithms. The operation of the machine in generator mode is simulated by a load torque block similar to the previous control algorithms.

D. Control via optimum switching angles and PWM modulation

After the analytical study of the control algorithm of the optimal switching angles and PWM presented in [3,4], the asymmetrical bridge converter-SRM system is simulated in the MATLAB/Simulink software simulator using a structured nonlinear motor model presented in [2]. The block diagram used to implement the study is shown in Fig. 4.

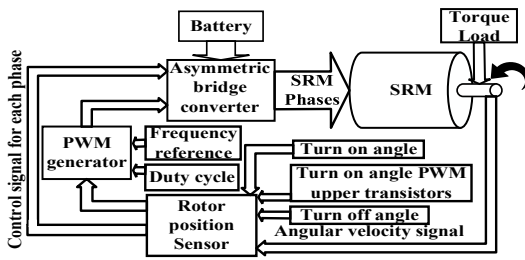


Fig. 4. Block diagram of an SRM drive controlled through optimum switching angle and PWM modulation.

In this algorithm, the assignments for the switch-on angles, PWM switch-on for the upper transistors and switch-off, as well as the frequency and duty cycle of the PWM signal are entered analytically using the parameters calculated in the [3,4]. In contrast to the algorithms presented so far, in this one all input parameters are fixed values. The simulation of the system operation in generator mode is implemented by a load torque block.

III. COMPARATIVE ANALYSIS OF CONTROL ALGORITHMS BASED ON POWER LOSSES, EFFICIENCY AND TORQUE RIPPLE WHEN THE SYSTEM OPERATES IN GENERATOR MODE

This section of the paper presents a comparative analysis of the investigated control algorithms under unipolar modulation in the machine generator mode. A comparison is made based on converter and motor power losses, efficiency, and torque ripple. The graphical and tabular results are presented depending on the change of various input parameters.

A. Comparison of unipolar modulation control algorithms based on power losses

Since the asymmetrical converter-SRM system is complex to analyze, the losses in the converter and motor are studied by varying various parameters. The variation of losses under the impact of motor speed n , turn-on angle θ_{on} , turn-off angle θ_{off} , modulation frequency f and duty cycle D is studied.

The losses in the converter are studied as a function of the variation of various parameters using the relationships summarized in Table 1, where: N_r is the number of rotor poles, θ_{ph} is the rotor position, E_{onT} and E_{offT} are the energy losses when turn on and off respectively the transistors and f_{sw} is the switching frequency of the transistors [5,6,7].

TABLE I. LOSSES IN THE CONVERTER

Nº	Name of losses	Equation
1	Transistor conduction losses P_{conT}	$P_{conT} = \frac{N_r}{2\pi} \int_0^{2\pi/N_r} p_{conT}(\theta_{ph}) d\theta_{ph}$
2	Diode conduction losses P_{conD}	$P_{conD} = \frac{N_r}{2\pi} \int_0^{2\pi/N_r} p_{conD}(\theta_{ph}) d\theta_{ph}$
3	Switch-on losses P_{onT}	$P_{onT} = E_{onT}(i, v) f_{sw}$
4	Switch-off losses P_{offT}	$P_{offT} = E_{offT}(i, v) f_{sw}$
5	Total power losses in transistors P_{totT}	$P_{totT} = P_{conT} + P_{onT} + P_{offT}$

Motor losses are calculated using the relationships given in [8].

The studies were carried out at a supply voltage of $V=170.2V$ for the different control algorithms and unipolar modulation, varies:

- motor speed n - from 500 to 10000 rpm in increments of 500 rpm;
- the turn-on angle θ_{on} - in a range of 24.29° with a step increase or decrease of $\pm 2.5^\circ$, and the PWM turn-on angle θ_{swon} for the optimal angle and PWM control algorithm;
- the turn-off angle θ_{off} - by increasing or decreasing in steps of $\pm 2.5^\circ$ from the original value $\theta_{off}=42.43^\circ$;
- the switching frequency f of the upper transistors - varies from 1kHz to 10kHz with a 1kHz step between measurements.
- the duty cycle D - analysis was carried out by varying D in the range 0.1 to 1 with a step of 0.1 between measurements.
- the battery is composed of 46 cells with a nominal voltage of 3.7V or the supply voltage of the converter is $V=170.2V$. Li-ion cells of the Samsung model INR18650-25R are used in the battery. The

equivalent replacement circuit according to its technical documentation was used to structure the battery[9].

- the asymmetric bridge converter feeding the SRM is implemented by IRFP460 MOS transistors and FR604 reverse current diodes.

The following notations are used to summarize and visualize losses in the converter-SRM system: Motor control via independent current regulators $P_{cont1}[W]$; Hysteresis current motor control with independent current sensors $P_{cont2}[W]$; PWM control $P_{cont3}[W]$; Control by optimal switching angles and PWM $P_{cont4}[W]$; Power losses when conducting the transistors in the arm A of the converter $P_{contT}[W]$; Power losses when conducting the diodes in the arm A of the converter $P_{conD}[W]$; Power losses when switching on the transistors in arm A of the converter $P_{on}[W]$; Power losses when switching off the transistors in arm A of the converter $P_{off}[W]$; Total power losses of transistors in converter arm A $P_{totalT}[W]$; Total power losses in converter arm A $P_{totalC}[W]$; Power losses in motor steel $P_c[W]$; Power losses in motor stator windings $P_{el}[W]$; Mechanical losses in motor $P_{mech}[W]$ and Total power losses in motor $P_{Total_loss}[W]$.

The losses in the other converter arms (Arm B and Arm C) are equal to the losses in Arm A, and the losses associated with diode turn-off are ignored as fast recovery diodes are used.

a) Power losses P_{contT} when conducting the transistors in the converter's arm A under unipolar modulation.

Fig.5 shows the power losses of the transistors in the converter arm A at $P_{contT}[W]$ under unipolar modulation as a function of the motor speed n .

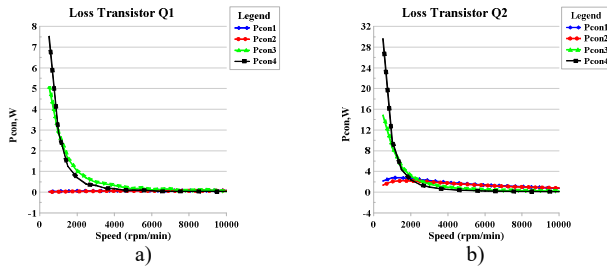


Fig. 5. Conduction losses of the transistors in arm A of an asymmetrical converter as a function of the motor rotation speed n : a) transistor Q1, b) transistor Q2.

From the given graphs, it can be seen that the losses on both transistors decrease as the motor speed decreases.

b) Power losses P_{conD} when conducting the diodes in the arm A of the converter under unipolar modulation.

The conduction loss results for diodes D1 and D2 as a function of the turn-on angle θ_{on} are given in Table 2.

TABLE II. DIODE CONDUCTION LOSSES IN THE CONVERTER ARM AS TURN-ON ANGLE VARIOUS

Turn-on angle [deg.]	16,79		21,79		26,79		31,79	
Diodes	D1	D2	D1	D2	D1	D2	D1	D2
$P_{conD1,W}$	1,44	3,04	0,97	1,97	0,55	1,17	0,32	0,60
$P_{conD2,W}$	1,41	2,98	0,96	2,01	0,58	1,20	0,29	0,58
$P_{conD3,W}$	0,56	1,04	0,39	0,39	0,22	0,47	0,10	0,26
$P_{conD4,W}$	0,40	0,65	0,28	0,49	0,11	0,25	0,01	0,01

The conduction losses of the diodes in the converter arm decrease as the turn-on angle increases.

c) Total power losses of the transistors in the A-arm of the P_{totalT} converter under unipolar modulation.

Fig.6 shows the variation of the total losses of the transistors in converter arm A with the turn-off angle θ_{off} .

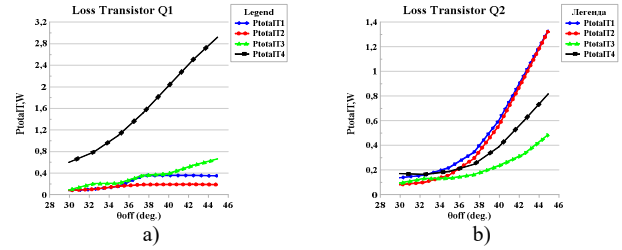


Fig. 6. Variation of the total losses of the transistors in the converter arm as a function of the turn-off angle θ_{off} : a) transistor Q1, b) transistor Q2.

There is a decrease in the total transistor losses in the A-arm of the converter as the magnitude of the turn-off angle θ_{off} increases.

d) Total power losses in the converter arm A P_{totalC} .

A study of the total losses in the A-arm of the converter P_{totalC} was carried out, similar to other loss studies, when various parameters were varied.

The results obtained for the total losses in the converter arm when the turn-off angle θ_{off} is varied are given in Table 3.

TABLE III. RESULTS FOR TOTAL LOSSES IN THE CONVERTER ARM WHEN CHANGING THE TURN OFF ANGLE

Turn-off angle [deg.]	29,93	32,43	34,93	37,43	39,93	42,43	44,93
$P_{totalC1,W}$	0,33	0,62	1,35	2,22	2,90	3,58	4,15
$P_{totalC2,W}$	0,27	0,56	1,32	2,06	2,75	3,47	4,06
$P_{totalC3,W}$	0,21	0,43	0,51	0,87	1,24	1,69	2,29
$P_{totalC4,W}$	0,60	0,79	1,10	1,52	2,00	2,50	2,92

It can be concluded that as the turn-off angle θ_{off} increases, the total losses in converter arm A also increase.

e) Power losses in the motor stator windings P_{el} and total power losses in the motor P_{Total_loss} .

The comparison of the motor winding losses and the total motor power losses for the investigated control and unipolar modulation algorithms, as a function of the motor speed n and the switching frequency f of the upper transistors, respectively, is shown in Fig.7a) and Fig. 7b).

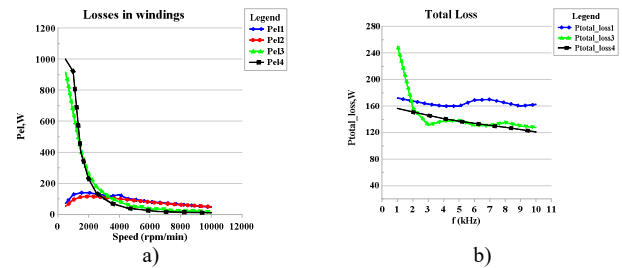


Fig. 7. a) Motor winding losses as a function of motor speed, b) total motor power losses as a function of switching frequency of upper transistors.

The study of the losses in the windings as the speed of the machine changes shows that their value increases as the speed decreases.

on the basis of the study and the results presented hereof, it can be concluded that as the switching frequency of the upper transistors f increases, the total losses in the motor decrease.

B. Comparison of unipolar modulation control algorithms based on efficiency.

The graphical results presented in this paragraph are correlated with the system performance η for the investigated control algorithms, unipolar modulation and generator mode of machine operation. The investigations were carried out as a function of the motor speed variation n and the turn-on angle θ_{on} .

Fig.8a) and Fig.8b) graphically show the efficiency dependence η as the machine speed n and the turn-on angle θ_{on} vary.

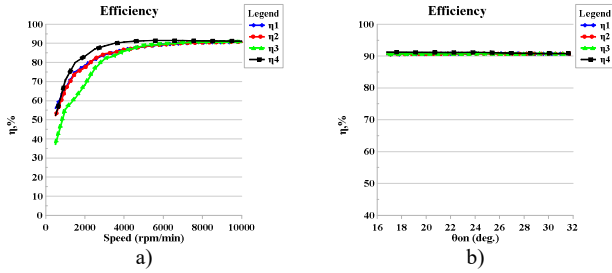


Fig. 8. Efficiency versus: a) speed, b) turn-on angle θ_{on} .

The research results show that efficiency increases as the speed of the machine increases. The turn-on angle has no significant effect on the efficiency of the system.

C. Comparison of control algorithms based on torque ripple in generator mode under unipolar modulation.

This section presents a comparative analysis of the control algorithms and unipolar modulation investigated in terms of torque ripple. The summarized torque ripple data is shown in Table 4. The results are obtained through the difference between the maximum and minimum torque values at two time intervals, when the phase is conducting and when switching between two separate phases. The control algorithms are numbered as follows: A1 - Motor control with independent current regulators; A2 - Hysteresis current control with independent current sensors; A3 - PWM control; A4 - Control via optimum switching angles and PWM modulation.

TABLE IV. COMPARISON OF TORQUE RIPPLE WITH UNIPOLAR MODULATION

Torque ripple during phase conduction in unipolar modulation				
	A1	A2	A3	A4
Max(Nm)	-0,65	-0,67	-0,05	-0,69
Min(Nm)	-0,65	-0,67	-0,17	-0,69
Torque ripple (Nm)	0	0	0,165	0
Torque ripple during phase switching in unipolar modulation				
	A1	A2	A3	A4
Max(Nm)	-0,02	-0,02	-0,002	-0,02
Min(Nm)	-0,65	-0,67	-0,05	-0,69
Torque ripple (Nm)	0,63	0,65	0,048	0,67

After the analysis, it can be said that with unipolar modulation there is no torque ripple when the phase is conducted. It is only in the case of PWM control that such pulsations are noticeable. At the time of switching between the phases, they are very large and it is most appropriate to control the system using algorithms 1, 2 and 4.

IV. CONCLUSION

This paper presents a simulation study and comparative analysis of control algorithms using a unipolar modulation of a power source – converter - switched reluctance motor system in generator mode. A detailed comparative analysis of the mentioned control algorithms is carried out, considering the factors of torque ripple, power losses and efficiency under the impact of different input parameters, in generator mode, for the converter and the machine. It is shown that the scheme, controlled by optimal switching angles and PWM and hysteresis current control, has a better energy performance compared to the other studied algorithms. In terms of motor losses, hysteresis current control is characterized by the lowest losses. From the study carried out on the basis of the efficiency in generator mode, it can be concluded that the most suitable control algorithms are: the algorithm with optimal switching angles and PWM, the control by means of current regulators and the hysteresis current control. With regard to the torque ripple, the most efficient control algorithms for the system are the optimum switching angle and PWM algorithm, the current regulators control and the hysteresis current controller.

The study carried out on the operation of the scheme in generator mode, taking into account the factors of converter and motor losses, efficiency and torque ripple, shows that the most suitable control algorithms are the algorithm with optimal switching angles and PWM and control with current regulators at a higher frequency.

ACKNOWLEDGMENT

This research is supported by the Bulgarian Ministry of Education and Science under National Program “Young Scientists and Postdoctoral Students - 2”. The authors would like to thank the "Research and Development" Sector of the Technical University of Sofia for the financial support provided during the publication.

REFERENCES

- [1] R. Krishnan, “Switched reluctance motor drives, modeling, simulation, analysis, design, and applications,” ISBN 0-8493-0838-0, CRC press, 2001.
- [2] D. K. Yankov and T. G. Grigorova, “A nonlinear model for a three-phase 12/8 switched reluctance machine,” International Journal of Power Electronics and Drive Systems, Vol 13, No 3, September 2022, pp. 1576-1587.
- [3] D. Yankov and T. Grigorova, “Analysis and Investigation of an Asymmetric Bridge Converter for a Three-Phase 12/8 SRM in Generating Mode,” 2020 XI National Conference with International Participation (ELECTRONICA), 2020, pp. 1-4.
- [4] D. Yankov, T. Grigorova and A. Pavlova, “A Study of Energy Recovery in an Asymmetric Bridge Converter for a Three-Phase 12/8 SRM in Generating Mode,” X International Scientific Conference "Technology, technologies and systems" (TechSys 2021), pp.1-8.
- [5] D. Yankov, T. Grigorova and E. Dinkov, “A Power Loss Analysis of a Three-Phase 12/8 Switched Reluctance Motor Fed from Asymmetric Power Converter in MATLAB/SIMULINK,” 2020 21st International Symposium on Electrical Apparatus & Technologies (SIELA), 2020, pp. 1-4.
- [6] D. Yankov, “Investigation of a reversible converter fed a switched reluctance motor (SRM),” Thesis for the PhD, Technical University of Sofia, Plovdiv Branch, 2022.
- [7] D. Yankov, T. Grigorova and I. Maradzhiev, “Analytical and simulation study of the power losses of a switched reluctance motor,” unpublished.
- [8] INR18650-25R-datasheet, SAMSUNG SDI, Oct.2013.