Smooth Transition between Optimal Control Modes in Switched Reluctance Motoring and Generating Operation

Christos Mademlis and Iordanis Kioskeridis

Abstract—This paper presents the design and implementation of a control system for switched reluctance machines applicable over the entire speed range, for motoring and generating operation. The suggested control system achieves high performance and smooth transition between PWM-control to single-pulse control modes. The proposed controller on-line determines the optimal firing angles for all operating modes. The optimal condition of one operating mode is derived from the optimal condition of the other operating mode and thus smooth transition between the control modes is provided. The parameters of the optimal controller and the model of the test switched reluctance machine are determined experimentally. Simulation results under various operating conditions are presented to demonstrate the effectiveness of the proposed control scheme.

Keywords: Reluctance motor drives, reluctance generators, variable speed drives, optimal control, optimization methods.

NOMENCLATURE

θ	Mechanical angle at rotor position.
θ_α , θ_u	Aligned and unaligned rotor position, respectively.
θ_{1u} , θ'_{1u}	Rotor position at which stator and rotor pole corners start and complete overlap, respectively.
θ_{on} , θ_{off}	Turn-on and turn-off (commutation) rotor position, respectively.
θ_q	Rotor angle at which phase current extinguishes.
θ_s	Rotor position at which phase current reaches its reference value.
θ_{o1}^M	Rotor angle interval from turn-on to a position that current reaches its reference value (in motoring operation).
θ_{o1}^G	Rotor angle interval from a position at which stator and rotor pole corners complete overlap to an angle at which phase current extinguishes (in generating operation).
θ_{e1}	Rotor angle interval over which phase is excited (dwell period).
θ_{e2}	Rotor angle interval over which phase flux-linkage decays to zero (de-fluxing period).
θ_{rrp}	Rotor pole pitch.
L	Phase inductance.
L_a , L_u	Aligned and unaligned inductance, respectively.
λ	Phase flux-linkage.
λ_c	Peak phase flux-linkage.
i_{ph}	Phase current.
i_{ref}	Reference current in PWM-current control.
I_{bat}	Battery current.
u_{ph}	Phase voltage.
V_{dc}	Converter *dc*-link voltage.
ω_r	Angular speed.
ω_b	Base speed.

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Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

I. INTRODUCTION

A Switched Reluctance Machine (SRM) is capable of operating as a motor as well as a generator by adjusting the firing angles and thus changing the direction of the conversion power flow [1]. A SRM operates in motoring/generating mode by retarding the firing angles so that the bulk of the winding conduction period comes prior/after the aligned rotor position. In motoring operation, the power converter regulates the magnitude of the SRM current to meet the torque and speed requirements of the load. In generating operation, the converter excites the SRM phases to support continuous conversion from mechanical energy to electrical energy by extracting it from the prime mover [2].

The torque in a SRM is produced in pulses by the tendency of the rotor to move towards the position where the inductance of the excited stator pole winding is maximized. At low speeds, the torque is limited by the current that is controlled by either voltage-PWM or current regulation and is called '*PWM-control mode*'. At high speeds, the machine back-EMF is increased and the available voltage is insufficient to regulate the current. This is called '*single-pulse control mode*' and the torque is controlled by the duration of the current pulses [3].

The SRM has been built for drives ranging from a few watts up to hundreds of kilowatts and for various industrial applications operating over a wide speed range [4]. Due to its rugged brushless design, the low manufacturing cost and its capabilities of low inertia and fault tolerance, the SRM is ideally suitable for high performance applications at low cost [5].

Several research papers published in industry literature over the past decades report on high performance control

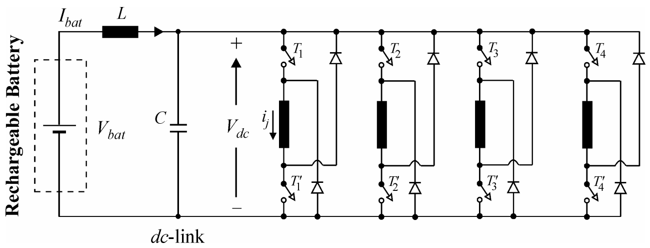

Fig. 1. Power converter topology of a 4-phase SRM.

methods for SRM drives [6]-[10]. The criteria that characterize the performance of a SRM drive are high efficiency, low torque ripple and low acoustic noise. The importance of each of these criteria depends on the drive application and is weighted according to the working area of the drive. Since the above objectives cannot be simultaneously satisfied, the optimal performance of a SRM is reached through an appropriate balance between them [4].

The problem of the performance optimization of a SRM drive was examined in [10]-[13] where optimal control schemes are proposed for low to high speed operation and for motoring and generating operation. In this paper, the design and implementation of a universal SRM average torque controlled system is presented that is based on the above control methods and provides smooth transition between PWM to single-pulse control for both motoring and generating operation. The suggested controller on-line determines the optimal turn-on and turn-off angles for attaining high performance at all operating modes, through simple formulas that could serve as optimal conditions. The implementation of the controller is simple, since no additional feedback signals from the machine are required. The parameters of the optimal controller and the model of the test switched reluctance machine are experimentally determined. Several simulation results are presented to demonstrate the effectiveness of the proposed control scheme.

II. Analysis of SRM operation

The power converter topology of a 4-phase SRM drive with two controlled power switches and two free-wheeling diodes per phase is illustrated in Fig. 1. In motoring operation, the electrical power of the source is converted to mechanical power to sustain the load torque. In generating operation, the direction of the power flow is reversed and the mechanical power provided by an active load is converted to electrical power for charging the battery.

In a SRM, torque is produced by phase current pulses properly synchronized with rotor position. The behavior of the phase current depends on the relationship between the back-emf and the source voltage. At low and medium speeds, the phase current is regulated to a desired value by PWM control, since the back-emf is quite smaller than dc-link voltage. At high speeds, the SRM turns to single pulse mode, as there is no control over the phase current after turning off the converter switches, since the back-emf is larger than the dc-link voltage.

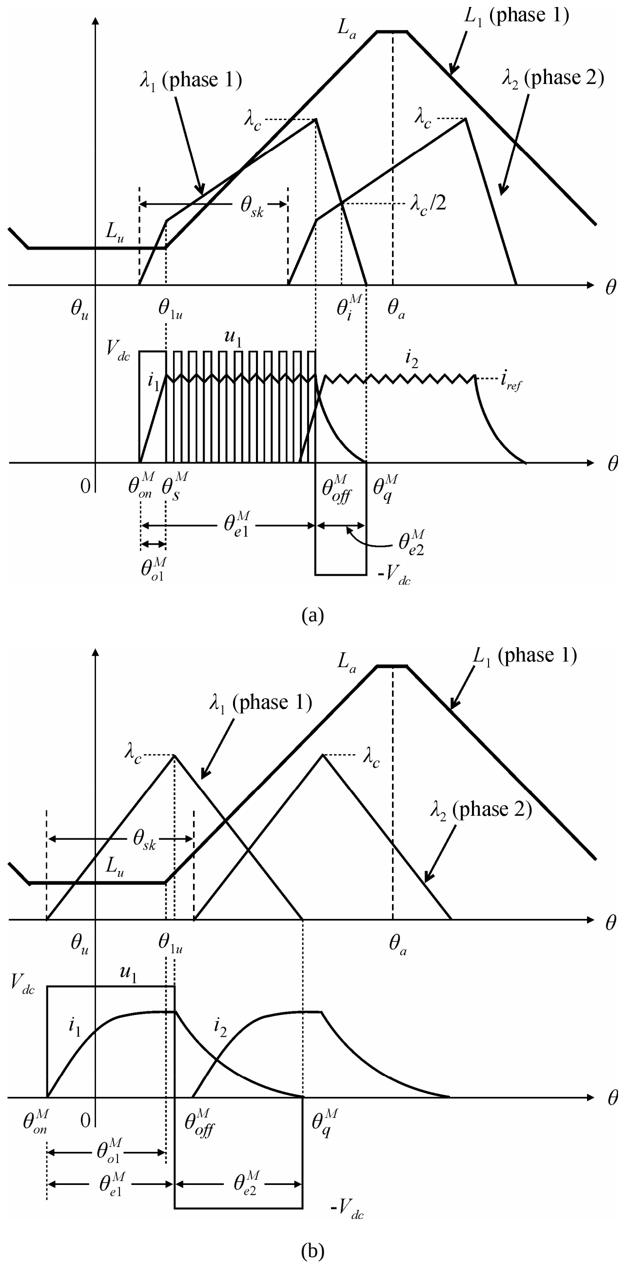

Fig. 2. Typical SRM waveforms in motoring operation considering the overlapping flux-linkage and current profiles of two neighboring phases: (a) PWM-current control and (b) single pulse control.

The objective of the motoring control is to keep constant the rotor speed at a desired value. In generating operation, the control objective depends on the drive application. The aircraft power systems and automotive applications require regulation of average power (or current) output [2], while constant dc-link voltage is needed in the case of a passive electrical load [1]. In this paper, the case of an automotive application is examined and the current that charges the battery is controlled.

The control key in SRM motoring and generating operation is to precisely synchronize the phase current pulses with the rotor position, in order to accomplish maximum machine efficiency with reduced torque ripple.

III. Defining the SRM Optimal Conditions

The average torque control is an easily implemented and cost-effective control method that is based on time-averaged analysis of machine operation and the control is developed on per-stroke basis [1]. The efficiency can be improved and torque ripple can be reduced by controlling the flux-linkage level of the machine, so that an appropriate balance between the contributions of each phase to the total flux is accomplished. Therefore, high efficiency with reduced torque ripple is achieved by on-line controlling the SRM turn-on and turn-off angles [10]-[13].

In PWM-controlled motoring operation, the turn-on angle is selected so that the phase current acquires its reference value i_{ref} at the angle θ_{1u} just when the stator and rotor poles start to overlap and the inductance starts rising [4], [10]. Thus, the optimal turn-on angle is determined by

$$\theta^M_{on_{opt}} = \theta_{1u} - \theta^M_{o1} = \theta_{1u} - \frac{L_u i_{ref}\,\omega_r}{V_{dc}} \tag{1}$$

The above condition allows the current to increase up to its reference value while the inductance is still low and there is no back-emf that would oppose the current increase.

The turn-off angle is specified so that the flux-linkages of two neighboring phases are equal to half of the peak flux-linkage λ_c on their intersection angle θ^M_i [10], and is given by

$$\theta^M_{off_{opt}} = \theta_{1u} + (2\theta_{sk} - \theta^M_{e2})\left[1 - \frac{\theta^M_{o1}}{\theta^M_{e2}}\right] \tag{2}$$

The above condition provides SRM performance optimization through a correct balance between criteria of maximum efficiency and minimum torque ripple. Fig. 2(a) illustrates the flux-linkage and current profiles of two neighboring phases in PWM-current control mode, where the overlapping region is considered.

In high speeds, the motor back-emf is increased and the available voltage may be insufficient for chopping. The chopping interval $\theta^M_{off} - \theta^M_s$ of PWM current control does not exist and the torque is controlled by varying the firing angles of current single pulse. Thus, the optimal turn-off angle θ^M_{off} approaches θ_{1u} and the θ^M_{o1} interval should be proportional to the dwell period θ^M_{e1} [11]

$$\theta^M_{o1} = c^M_\lambda \theta^M_{e1} = c^M_\lambda \frac{\lambda_c \omega_r}{V_{dc}} \tag{3}$$

where c^M_λ is the optimization parameter that could be determined experimentally ($c^M_\lambda \le 1$). Substituting (3) in (1), the optimal condition of turn-on angle for the single pulse mode is derived

$$\theta^M_{on_{opt}} = \theta_{1u} - c^M_\lambda \theta^M_{e1} \tag{4}$$

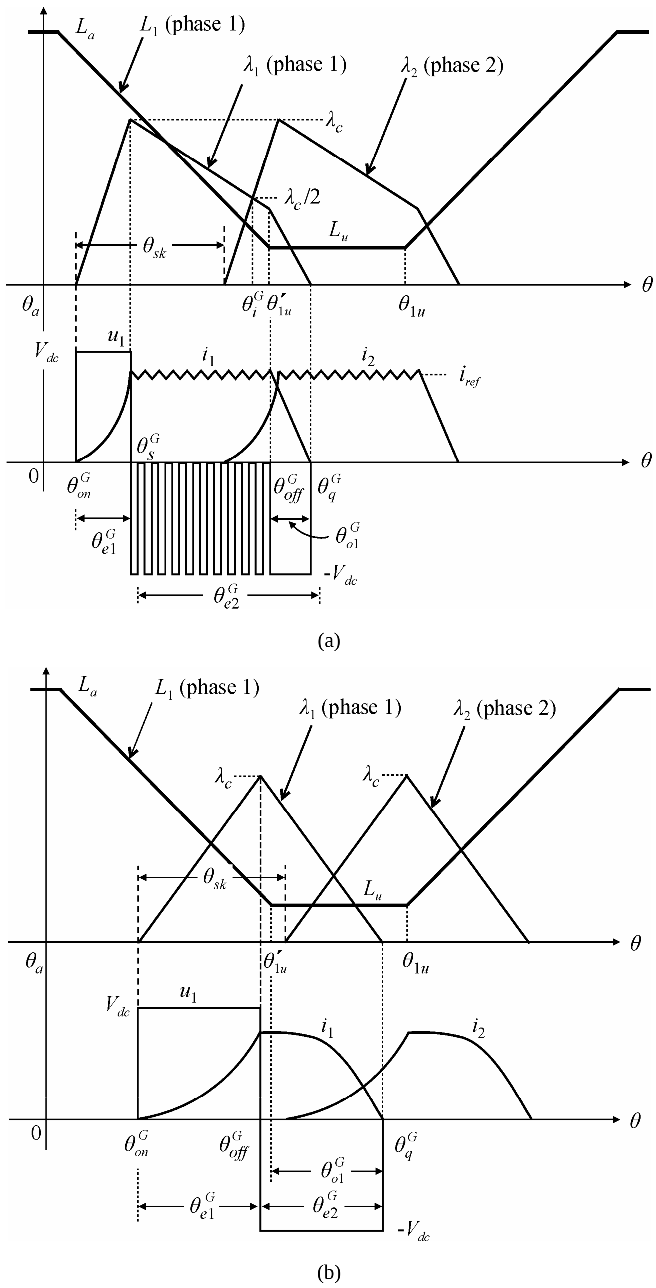

Fig. 3. Typical SRM waveforms in generating operation considering the overlapping flux-linkage and current profiles of two neighboring phases: (a) PWM-current control and (b) single pulse control.

and consequently, the optimal turn-off angle condition is given by [Fig. 2(b)]

$$\theta^M_{off_{opt}} = \theta^M_{on_{opt}} + \theta^M_{e1} = \theta_{1u} + (1 - c^M_\lambda)\theta^M_{e1} \tag{5}$$

In PWM current controlled generating operation, the optimal turn-on angle at which the flux-linkages of two neighboring phases are equal on their intersection angle θ^G_i [Fig. 3(a)] is defined by [12]

$$\theta^G_{on_{opt}} = \theta'_{1u} - \left[\theta^G_{o1} + 2\theta_{sk}\left(1 - \frac{\theta^G_{o1}}{\theta^G_{e1}}\right)\right] \tag{6}$$

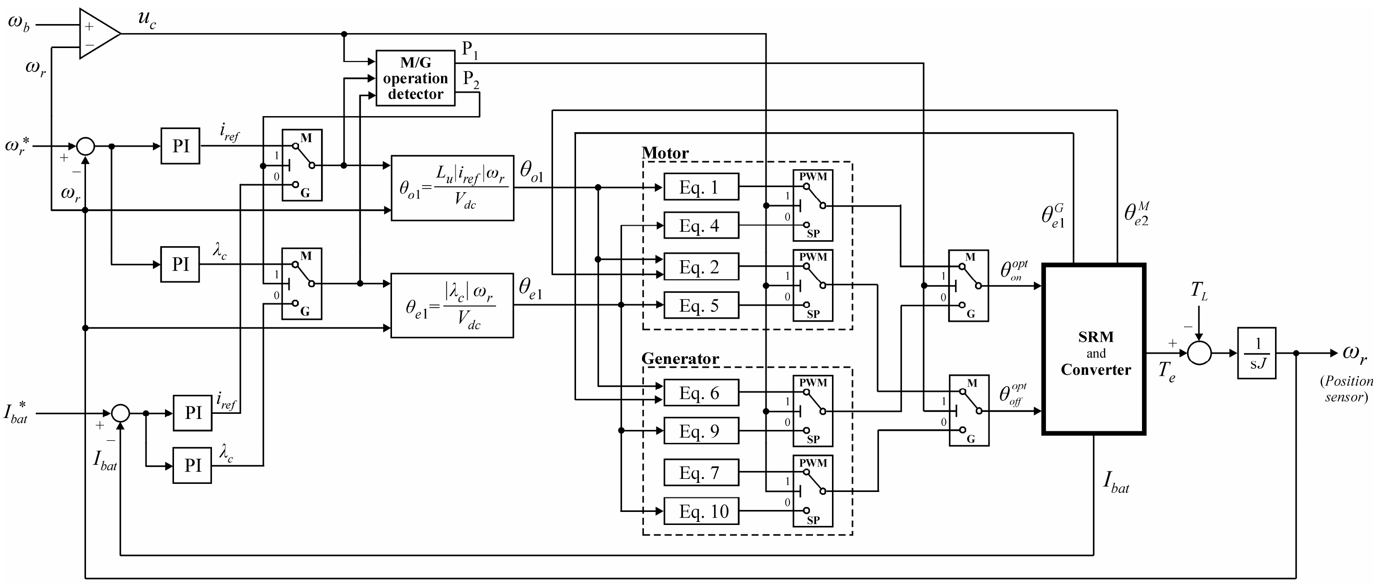

Fig. 4 Block diagram of a universal SRM control system for optimal motoring and generating operation.

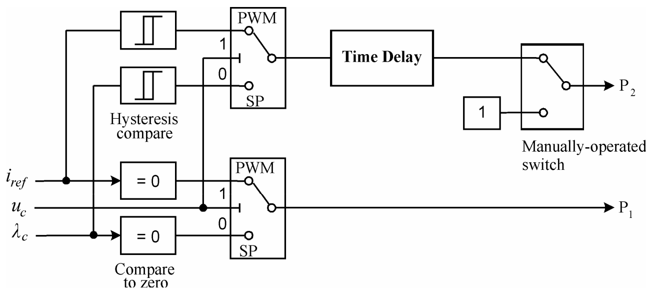

Fig. 5. M/G operation detector control scheme.

TABLE I

FOUR-PHASE, 1-hp, 8/6 SRM AND DRIVE PARAMETERS

Output power 1-hp at 4,000 rpm (motoring operation)	
Inertia 0.0004 Kg·m^2	
θ_{rrp}= 2π/N_r=60^0	R_{ph}=1.3 Ω
L_a= 52.7 mH	L_u= 9.1 mH
Controller parameters:	
c_λ^M= 0.92	c_λ^G= 0.91

During the de-fluxing interval θ_{o1}^G, the stored field energy is returned to the dc-link and the flux and phase current are extinguished. If the de-fluxing interval exploits the unaligned region, the stored field energy is released without extracting mechanical energy from the prime mover. Then, the optimal turn-off angle is selected at the rotor position that stator and rotor pole corners complete overlap

$$\theta_{off_{opt}}^G = \theta_{1u}' \tag{7}$$

As for the motoring operation, in single pulse controlled SRM generating operation the θ_{o1}^G interval should be proportional to the de-fluxing period θ_{e2}^G [Fig. 3(b)]

$$\theta_{o1}^G = c_\lambda^G \theta_{e2}^G = c_\lambda^G \frac{\lambda_c \omega_r}{V_{dc}} \tag{8}$$

where c_λ^G is the optimization parameter that could be determined experimentally ($c_\lambda^G \le 1$). Since in single pulse mode, the dwell period is almost equal to the de-fluxing period ($\theta_{e1}^G \approx \theta_{e2}^G$), the optimal turn-on angle in generating operation is given by [13]

$$\theta_{on_{opt}}^G = \theta_{1u}' - 2\theta_{e1}^G + \theta_{o1}^G = \theta_{1u}' - (2 - c_\lambda)\theta_{e1}^G \tag{9}$$

and consequently the optimal turn-off angle condition is defined by

$$\theta_{off_{opt}}^G = \theta_{on_{opt}}^G + \theta_{e1}^G = \theta_{1u}' - (1 - c_\lambda)\theta_{e1}^G \tag{10}$$

From the above analysis it is concluded that, the optimal conditions for the turn-on and turn-off angles of the one control mode can be derived from the optimal conditions of the other control mode and vise-versa. This validates the generic nature of the proposed control theory while it appears to be the base for the implementation of a universal control scheme that provides smooth transition between the two control modes for both motoring and generating operations.

IV. IMPLEMENTATION OF THE OPTIMAL CONTROLLER

The block diagram of a universal SRM control system for optimal motoring and generating operation is illustrated in Fig. 4. The control system contains four proportional-integral (PI) controllers. The current PI controllers are used in the PWM control, for determining the reference current i_{ref}. The flux linkage PI controllers are used in the single pulse control, for determining the peak flux linkage λ_c. In motoring and regenerative braking operation, the PI controllers are used for speed control, while in generating operation the PI controllers are used for battery current control. Additionally, a follow-up

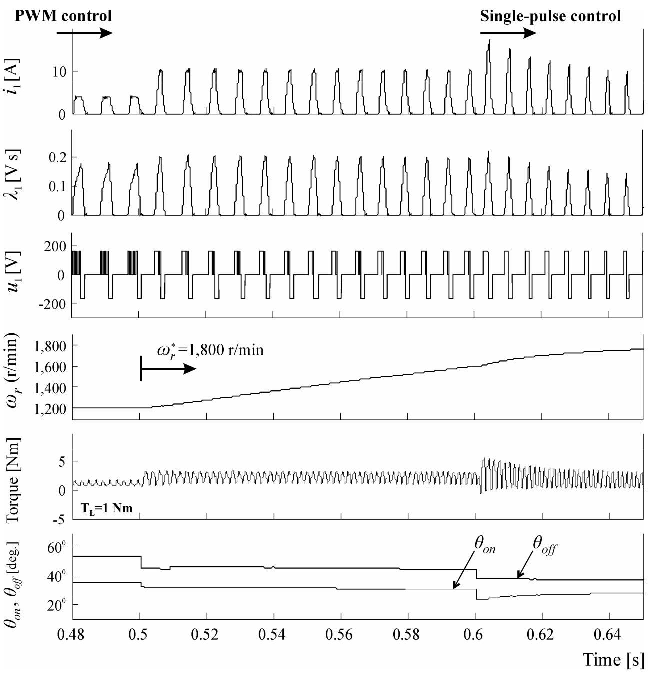

Fig. 6. Dynamic response of the optimal SRM drive to command speed step increase from 1,200 to 1,800 r/min, for load torque 1 Nm (current, flux-linkage and voltage of ph. 1, rotor speed, electromagnetic torque, turn-on and turn-off angles). The angles are counted from the aligned rotor position θ_a.

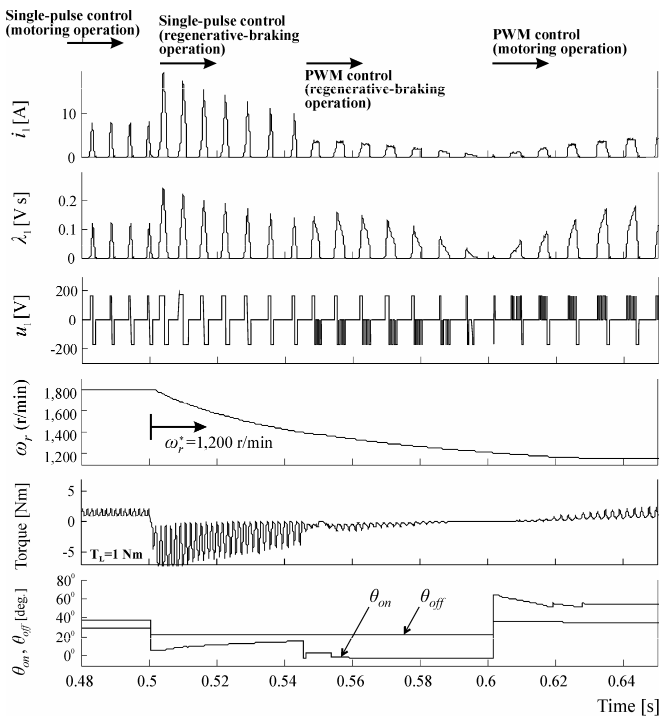

Fig. 7. Dynamic response of the optimal SRM drive to command speed step decrease from 1,800 r/min to 1,200 r/min, for load torque 1 Nm (current, flux-linkage and voltage of ph. 1, rotor speed, electromagnetic torque, and turn-on and turn-off angles). The angles are counted from the aligned rotor position θ_a.

technique is included in the PI controllers to achieve smooth transition between motoring and generating operation.

The appropriate PI controller and the relevant conditions for determining the optimal turn-on and turn-off angles according to the SRM operation mode are selected from the "M/G operation detector". Specifically, the SRM operation mode (i.e. motoring, regenerative braking and generating) is detected from the sign of the reference current i_{ref} or the peak flux-linkage λ_c. The decision between PWM and single pulse control is determined from the comparator output u_c, which compares the rotor speed ω_r and base speed ω_b. According to the SRM operation mode, the turn-on and turn-off angles are determined from the relevant optimal conditions using the measured θ_{e2}^{M} or θ_{e1}^{G} intervals for motoring or generating operation, respectively, and the calculated θ_{o1} or θ_{e1} angles for PWM or single pulse control, respectively.

The control scheme of the "M/G operation detector" is illustrated in Fig. 5. If either the reference current or the peak flux-linkage is positive, motoring operation is detected and a speed PI controller is used (control signals P$_1$ and P$_2$ are both high). If the reference speed is abruptly reduced ($\omega_r^* < \omega_r$) or if an active load ($T_L < 0$) is applied, the SRM turns to regenerative braking operation. This is detected from the negative values of the reference current or the peak flux-linkage, through the two zero and two hysteresis comparators (signal P$_1$ is low and signal P$_2$ is high). In the regenerative braking, the SRM operates as a generator and converts mechanical energy to electrical energy, which is fed to the battery. The speed control is employed and the turn-on and turn-off angles are determined from the generating optimal conditions. If the regenerative braking is caused for holding an active load and if this operation is continued after a predefined time delay interval, the battery current control is employed for regulating the average power generated by the SRM (signals P$_1$ and P$_2$ are both low). The generating operation could be also automatically or manually returned to motoring operation.

V. Simulation Results

The machine used to validate the effectiveness of the proposed control scheme was a 4-phase, 1-hp, 8/6 SRM. The experimentally determined parameters of the machine and the optimal controller are recorded in Table I. The nonlinear model of the test SRM drive that was used for obtaining the simulation results was developed in the Simulink environment (Matlab R2006a).

Fig. 6 and 7 illustrate the dynamic response of the optimal SRM drive to a command speed step increase from 1,200 r/min to 1,800 r/min and a command speed step decrease from 1,800 r/min to 1,200 r/min, respectively, for load torque 1 Nm. In Fig. 6, the dynamic response of the drive results to transition from PWM to single pulse control, which occurs when the rotor speed exceeds the base speed (1,600 r/min). In Fig. 7, the machine initially operates as a motor with single pulse control and turns to regenerative braking operation when the decrease of the command speed is applied. Then, when the rotor speed drops below the base speed, the control

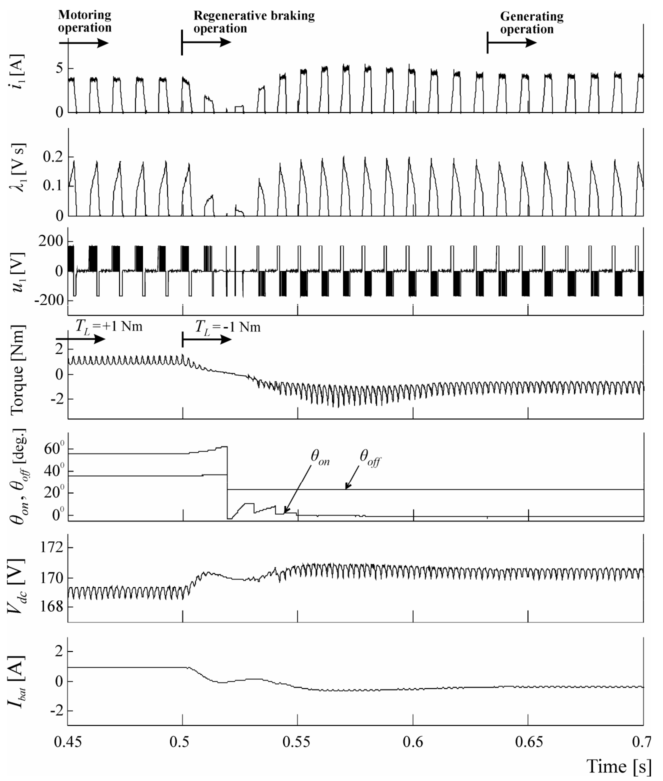

Fig. 8. Transient operation of the optimal SRM drive at 1,200 r/min with PWM control for a step change of applied torque from +1 Nm to -1 Nm (current, flux-linkage and voltage of ph. 1, electromagnetic torque, turn-on and turn-off angles, dc-link voltage and battery current). The angles are counted from the aligned rotor position θ_a.

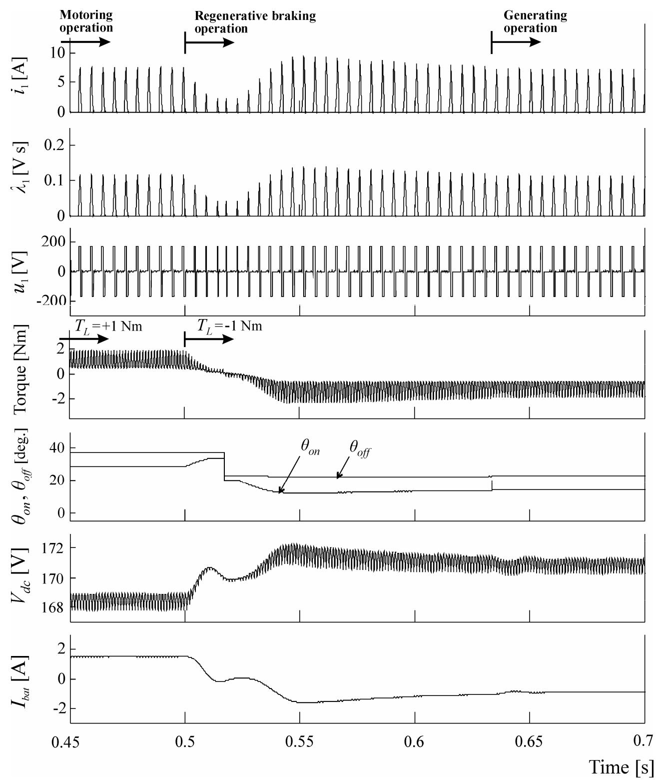

Fig. 9. Transient operation of the optimal SRM drive at 2,000 r/min with single pulse control for a step change of applied torque from +1 Nm to -1 Nm (current, flux-linkage and voltage of phase 1, electromagnetic torque, turn-on and turn-off angles, dc-link voltage and battery current). The angles are counted from the aligned rotor position θ_a.

mode changes from single pulse to PWM control and finally, the machine returns to motoring operation when the rotor speed reaches its new command value.

Figs. 8 and 9 show the transient operation of the optimal SRM drive at PWM and single pulse control, respectively, for a step change of the applied mechanical torque from +1 Nm (that corresponds to motoring operation) to -1 Nm (that corresponds to generating operation). The machine operation turns to regenerative braking when the applied torque becomes negative. Since this negative torque holds for more than a time interval of approximately 0.14 s, the SRM changes to generating operation.

From the above it is concluded that in both cases, the controller reacts very fast and obtains the new optimal turn-on and turn-off angles. Moreover, the SRM drive changes smoothly from one control mode to the other and from one operating condition to the other.

VI. Conclusions

In this paper, a control system for SRMs that provides high performance and is applicable over the entire speed range, for motoring and generating operation was presented. The suggested controller on-line determines the optimal turn-on and turn-off angles for providing high efficiency and low torque ripple of the SRM drive. Moreover, it provides smooth transition between the control modes and operating conditions. Therefore, high performance transient operation of the SRM drive is accomplished. For validating the effectiveness of the proposed system drive, the non-linear model of the test 4-phase, 1-hp, 8/6 SRM was built in Simulink environment, using experimentally determined parameters of the machine and the controller.

References

[1] T. J . E. Miller, *Electronic control of switched reluctance machines*, Oxford, U.K.: Newnes, 2001.

[2] D. A. Torrey, "Switched reluctance generators and their control", *IEEE Trans. Ind. Electron.*, vol. 49, no. 1, pp. 3-14, Feb. 2002.

[3] W.F. Ray, P.J. Lawrenson, R.M. Davis, M. Stephenson, N.N. Fulton, and R.J. Blake, "High-performance switched reluctance brushless drives", *IEEE Trans. Ind. Appl.*, vol. IA-22, pp. 722-730, July/ Aug. 1986.

[4] J. Reinert, R. Inderka, M. Menne, and R.W. De Doncker, "Optimizing performance in switched reluctance drives", *IEEE Ind. Appl. Magazine*, vol. 6, pp. 63-70, July/Aug. 2000.

[5] K.M. Rahman, B. Fahimi, G. Suresh, A.V. Rajarathnam, and M. Ehsani, "Advantages of switched reluctance motor applications to EV and HEV: Design and control issues", *IEEE Trans. Ind. Appl.*, vol. 36, pp. 111-121, Jan./ Feb. 2000.

[6] B. K. Bose, T. J. E. Miller, P. M. Szczesny, and W. H. Bicknell, "Microcomputer control of switched reluctance motor", *IEEE Trans. Ind. Appl.*, vol. IA-22, pp. 708-715, July/Aug. 1986.

[7] P. C. Kjaer, P. Nielsen, L. Andersen, and F. Blaabjerg, 'A new energy optimizing control strategy for switched reluctance motors', *IEEE Trans. Ind. Applicat.*, vol. 31, pp. 1088-1095, Sept./Oct. 1995.

[8] J. J. Gribble, P. C. Kjaer, and T. J. E. Miller, 'Optimal commutation in

average torque control of switched reluctance motors', *Proc. Inst. Elect. Eng.-Elect. Power Applicat.*, vol. 146, no. 1, pp. 2-10, Jan. 1999.

[9] T. Sawata, P. C. Kjaer, C. Cossar, and T. J. E. Miller, 'A control strategy for the switched reluctance generator', in *Proc. Conf. ICEM'98*, Instanbul, Turkey, 1998, vol. 3, pp. 2131-2136.

[10] C. Mademlis and I. Kioskeridis, "Performance optimization in switched reluctance motor drives with online commutation angle control", *IEEE Trans. Energy Conversion*, vol. 18, pp. 448-457, Sept. 2003.

[11] I. Kioskeridis and C. Mademlis, "Maximum efficiency in single-pulse controlled switched reluctance motor drives", *IEEE Trans. Energy Convers.*, vol.. 20, pp. 809-817, Dec. 2005.

[12] C. Mademlis and I. Kioskeridis, "Optimizing performance in current-controlled switched reluctance generators", *IEEE Trans. Energy Convers.*, vol. 20, pp. 556-565, Sept. 2005.

[13] I. Kioskeridis and C. Mademlis, "Optimal efficiency control of switched reluctance regenerators", *IEEE Trans. Power Electron.*, vol. 21, pp. 1062-1072, July 2006.

BIOGRAPHIES

Christos Mademlis was born in Arnea Chalkidikis, Greece, on February 7, 1964. He received the Diploma degree in Electrical Engineering (1st class Hons.) and the Ph.D. degree in electrical machines from the Aristotle University of Thessaloniki, Greece, in 1987 and 1997, respectively.

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From 1995 to 2000 he worked as Superintendent Engineer in the Natural Gas of Greece Project. Since 2001, he has been with the Department of Electronics, Technological Educational Institute of Thessaloniki and he has been engaged in teaching power electronics and measuring systems. In 2003 he has been elected as an Associate Professor in the same Department. His primary research activities include power electronic converters, control and modeling of adjustable speed drives.