Studying Different Types of Power Converters Fed Switched Reluctance Motor

Samia M. Mahmoud, Mohsen Z. El-Sherif, and Emad S. Abdel-Aliem
Shoubra Faculty of Engineering, Cairo, Egypt
Email: emad.atwa@feng.bu.edu.eg, emadsami7@gmail.com

Maged N. F. Nashed
Electronics Research Institute, Cairo, Egypt
Email: maged@eri.sci.eg

***Abstract*—This paper presents requirements, detailed analysis, and operation of six converter types used with 3-phase 6/4 switched reluctance motor (SRM). These converters are R-dump, C-dump, C-dump with freewheeling transistor, asymmetric, series, and parallel type. The simulation results are made by MATLAB/SIMULINK package. The paper also introduced why the asymmetric bridge converter type is the best one especially for high speeds.**

***Index Terms*—SRM, R-dump, C-dump, C-dump with freewheeling, asymmetric, series, parallel converter**

I. INTRODUCTION

The operation of SRM is quite simple because of its ability to operate efficiently from unidirectional winding currents, thus only one switch per phase is sufficient yielding a very economical brushless drive but in ac motor drives at least two switches per phase are required. Furthermore, a phase winding in series with a switch in the SRM but the windings are not in series with switches in ac drives that lead to irreparable damage in shoot-through faults. In the case of a shoot-through fault, the phase inductance limits the rate of rise in current and provides time to initiate protective relaying to isolate the faults. The SRM phases are independent and, in the case of one winding failure, uninterrupted operation of the motor drive operation is still possible although with reduced power output [1]. The drive system for 3-ph 6/4 SRM with *H*-bridge converter is shown in Fig. 1.

The power converter is a power supply unit that follows the commands of the controller to energize each phase of the motor at the appropriate times. It is required to activate and commutate the motor phases. Therefore, it does not only deliver energy to an electronic device from an electrical outlet, it also regulates the current to meet specific device requirements and should have the ability of regulation to provide increasing or decreasing of phase current. The position detector detects the rotor position because phase excitation pulses need to be properly synchronized to the rising region of the inductance profile for motoring operation. The controller regulates the motor performance. It has to posses the rotor position signal. It may be realized by a rotor position sensor or a sensorless control procedure, e.g. from analyzing induced voltages in the phase windings [2]-[4].

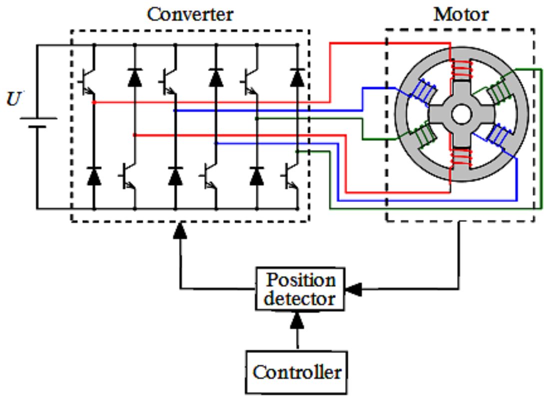

Figure 1. Basic configuration of 3-ph 6/4 SRM drive system.

The optimum performance of SRM depends upon the appropriate positioning of the currents relative to rotor position. At controlling the motor; as the current passes through one phase, the torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flowing through the phase winding. Continuous torque can be produced by synchronizing each phase's excitation with the rotor position. The amount of current flowing through motor windings is controlled by switching on and off by the power electronic switches.

The power converter is the heart of the motor drive. The performance, size, and the cost of the motor drive are mainly depends upon the selected converter type of the power converter circuit. So, this paper introduces a comparison between different converter types used with 3-ph 6/4 SRM. The motor parameters are presented in Appendix A.

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II. Requirements of SRM Converter

The selection of converter topology for a certain application is an important issue. Basically, the SRM converter has some requirements [5], such as:

- Each phase of motor has at least one switch to be able to conduct independently.
- The converter should be able to excite the phase before it enters the generating or demagnetizing region.

In order to improve converter performance; such as higher efficiency, faster excitation time, fast demagnetization time, high power, and fault tolerance. So, the converter must satisfy some additional requirements [3], [6]-[8]:

- The converter energy can be supplied to one phase while extracting it simultaneously from the other phase. So, the converter should be able to allow phase overlap control.
- For the phase current control; it is necessary to modulate the phase voltage using Pulse Width Modulation (PWM) technique at low speeds.
- Sufficiently high forcing voltage at each operation point so that the current is injected sufficiently quickly into the winding at high speed. The required control method may be single pulse or hysteresis current control. By this control; the demagnetization time is reduced for avoiding negative torque and / or permitting an extension of commutation period (i.e.; dwell angle).
- The demagnetization energy from the outgoing phase should be fed back to the dc source (dc-link capacitor) or using it in the incoming phase.
- The converter should be able freewheel during the chopping period to reduce the switching frequency. So the switching loss and hysteresis loss may be reduced.
- The converter has to be single rail of power source in order to reduce the voltage stress across the semiconductor switches.
- The converter should not require bifilar windings or rely upon the motor construction.
- The converter should have resonant circuit to apply zero-voltage or zero-current switching for reducing switching loss.
- A low number of semiconductor switches is desirable.
- Apply power factor correction circuit in order to improve the power factor.
- Little complexity of converter is required.

Selecting the proper switching strategy, dwell angle and control technique (usually hysteresis current control) will define the efficiency and application of this converter.

III. Types of SRM Converters

The converter fed SRM is powered from fixed voltage dc-link, which is established by an ac/dc converter or directly by a battery bank. The selection of suited converter and control scheme depends on the performance and the requirements of the specified SRM application [3], [9]. The SRM features of operation must be pointed out before determining the converter types used. These features can be summarized in three tasks [5]:

- The current must be supplied into the phase only in the positive gradient period of its inductance profile.
- The torque should be maximized during phase energizing of the motor phase. This is achieved by shaping the phase current by maximize its amount at rise time period and minimize it at fall time period.
- The stored magnetic energy during the commutation period should be freewheeled or returned to the dc source.

A. R-Dump Converter

The *R*-dump converter type is shown in Fig. 2. It is one of the configurations which have one switch (i.e., transistor) and one diode per phase. The value of resistance *R* determines the power dissipation and also the switch voltage. The change in the value of *R* should be done to achieve both reasonable stress on the switch (increases with higher *R*), and appropriate fall time of the current (increases with lower *R*). When the switch T_1 is turned off, the current freewheels through diode D_1, charging C_s, and later flows through the external resistor *R*. This resistor partially dissipates the energy stored in the energized phase [10], [11].

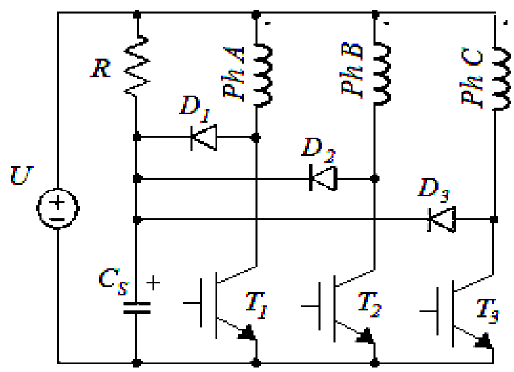

Figure 2. R-dump converter.

The design considerations such as the turn-off transient voltage have to be included in rating of the switch T_1. If the current comes under the negative slope region of the phase inductance, negative torque will be generated, decreasing the average motoring torque. This converter has the disadvantage that the current in any of phases will take longer to extinguish compared to recharging the source and also the energy is dissipated in a resistor; thus reducing the overall efficiency of the motor drive [10].

B. C-Dump Converter

This converter type is considered as a converter of auxiliary voltage supply [1]; because the demagnetization energy of a phase is fed into an auxiliary voltage supply which is a dump capacitor in order to restore the intermediate circuit or for directly energizing the succeeding phase. This converter circuit is shown in Fig. 3. In that converter, assume that T_1 is turned on to energize the phase a. When the phase current i_a exceeds the reference value, T_1 is turned off, this enables the diode D_1 to be forward biased, and the current path is closed through the dump capacitor C_d which increases the voltage across it in order to achieve fast demagnetization as asymmetric converter. Then the excess energy from the dump capacitor is transferred into the dc source via L_r by turning on the dump switch T_r. The voltage of the capacitor is regulated to be maintained at twice the supply voltage ($2U$) in order to apply ($-U$) across the outgoing phase for yielding faster demagnetization. The dump switch T_r is operated at a higher frequency than the phase switches [12], [13].

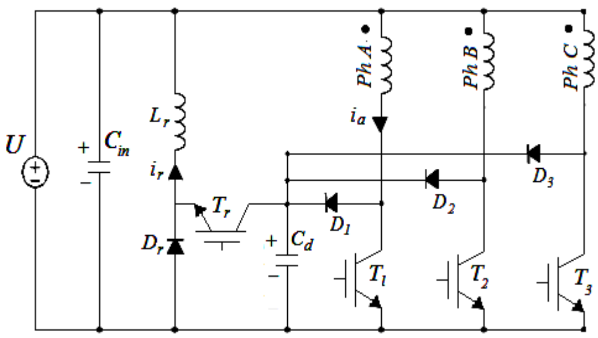

Figure 3. C-dump converter.

The advantages of C-dump converter are; uses lower number of switching devices allowing phase independent current control, has full regenerative capability, fast winding demagnetization during commutation, and phase commutation advancing is allowed. The major disadvantages of that converter are; the use of a capacitor and an inductor in the dump circuit, the voltage rating of the devices is twice the dc link voltage, since the capacitor voltage must be maintained at $2U$ to allow fast demagnetization, and the converter does not allow freewheeling [1], [10]. The C-dump SRM converters are hard switching topologies because the power switches and diodes are switched on and off while their voltages and currents are nonzero. Further, the energy circulating between C_d and the dc link results in additional losses in the machine, thereby decreases the efficiency of the motor drive [14].

C. C-Dump with Freewheeling Converter

The problems of conventional C-dump converter can be overcome by adding a freewheeling transistor T_f as shown in Fig. 4. The inductor L_r is not used, which amounts to considerable savings in the drive system cost [16]. For energizing of the phase a; transistor T_1 is turned on. When the phase current i_a exceeds a set value, T_1 is turned off, then C_d will be charged. When the voltage of the capacitor C_d exceeds the dc source voltage, T_f conducts and current takes the path of machine phase, diode D_1, and T_f (see, the voltage across the machine phase is almost zero).

When the current in phase A has to be commutated, T_1 is turned off without turning on T_f which enables the transfer of the energy from the machine partially to C_d and partially for power conversion in the machine. During the commutation of T_1, the voltage across the machine phase is ($U-v_o$). When the diode D_s is reversed biased; the voltage v_o will be applied across the conducting phase. For example, The energy accumulated in C_d during commutation of phase a, is used in phase b for faster current rise at the time of initiating the current i_b. Alternatively, the energy could be used in the latter during rising phase inductance (say, at higher speeds) for good current and torque control.

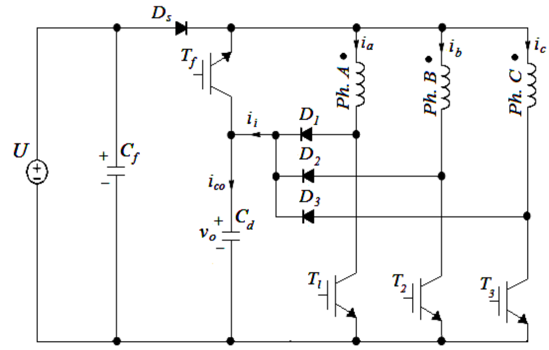

Figure 4. C-dump converter with freewheeling transistor.

The advantages of this converter topology includes; no energy transfer from the machine to the dc source, achieves zero voltage across the machine phase to give higher control flexibility, lower acoustic noise, lower dielectric losses in the machine, and longer life of the insulation, higher voltage of C_d could be used to greater benefit in current and torque control at higher speeds. The limitations in this converter are; only motoring operation is possible, the rating of T_f is very much higher than that of phase switches, control coordination between the freewheeling switch and main phase switches during commutation with overlapping phase currents restricts control flexibility [10], [15].

D. Asymmetric, Classic, or Conventional Converter

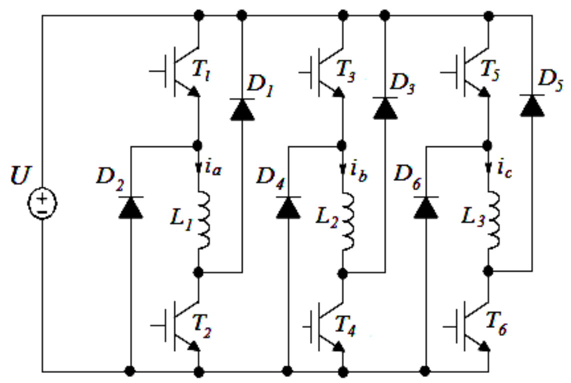

Figure 5. Asymmetric bridge converter.

In order to have a fast built-up of the excitation current, high switching voltage is required; the asymmetric bridge converter (H-bridge) is used. Fig. 5, shows the asymmetric bridge converter for 3-phase SRM drive. The unipolar switching strategy can be achieved by that converter which consists of two power switches and two diodes per phase. In each phase, the upper switch is used to perform the PWM switching control, while the lower one is used in charge of commutation. Each phase can be controlled independently. The three current modes of operation, defined as magnetization, freewheeling, and demagnetization mode [3]. The benefit of using unipolar switching strategy is to obtain less current ripple and a better frequency response in the inner current control loop of the drive system [17], [18].

With the asymmetric converter, the SRM is usually controlled by either current control or voltage control. The main advantage of current control over voltage control is that the phase current can be controlled precisely, which means that torque is properly controlled and the reduction of torque ripple or noise is possible. In the SRM drive system, the current reference value is enforced with a current feedback loop where it is compared with the phase current. The current error is presumed to be processed through a hysteresis controller with a current window of the value (Δi). When the current error exceeds the value ($-\Delta i$), the phase switches are turned off simultaneously. At that time the phase diodes complete the path through the dc source [19], [20].

The advantages of a classic converter are; allows greater flexibility in controlling the machine current because the converter is capable of applying the values of supply voltages (U, $-U$, and 0), all the phases can be controlled independently which is very essential for very high speed operation, so, if one switch is damaged, the drive can still with reduced power level, provides the maximum control flexibility, fault tolerance capability, the voltage stresses across the switching element is restricted to supply voltage value, and also the least noise is produced [1], [10], [21]. The disadvantages are; one switch is always in the current conduction path, thus increasing the losses in the converter and requiring a larger heat sink for cooling. This would further reduce the system efficiency. Two devices are always in series with the motor winding, which increases the conduction loss, size of the drive as well as cost increases because three switches and three diodes are used for 3-ph SRM drive. This converter produces a relatively low demagnetizing voltage at high speeds [10], [19], [22], [23].

Through complete the reading of that paper, it is found that the asymmetric converter topology is suitable for high speed operation due to the fast fall and rise times of current and also provide negligible shoot through faults. In the asymmetric bridge converter; there is no presence of high heat or copper losses because the absence of the resistance commutation circuit or any coil added to the converter topology. So, it is considered as the most suitable converter for high power SRM drives [19], [24].

E. Series Passive Converter

As mentioned in [3], [25], [26]; the passive converter of series capacitor is modified from the classical bridge converter by adding one diode and one boosting capacitor in series with the phase windings as shown in Fig. 6; to achieve voltage boosting capability. In this circuit, the boosting capacitor is charged resonantly by the use of motor phase windings during the phase turn off periods.

The maximum boost voltage can be obtained by a suitable size of the capacitor. Because the discharge of the boost capacitor is not controllable in the passive converter, the voltage of the boost capacitor is changed by the stored magnetic energy during different operating condition. When the phase switch is turned on, the voltage of the boost capacitor may fall very fast until the voltage reaches the dc link voltage ($+U$).

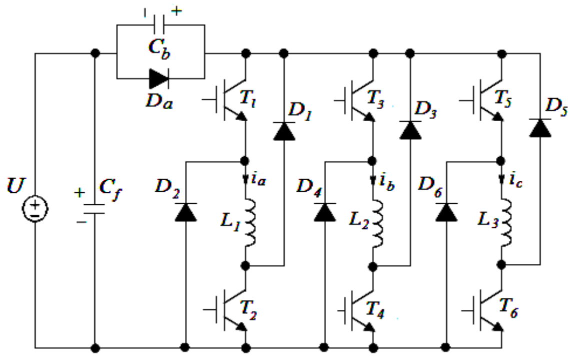

Figure 6. Series converter.

To handle the charging of the boosting capacitor (C_b) in the beginning of the conduction period, one diode is needed to series or parallel with the power switch to protect the power switch [3]. After charging of the capacitor (C_b), there are three modes of operation; in the magnetization mode, T_1 and T_2 are turned on, the charging across the capacitor (C_b) is discharged and decreased down to zero, the voltage ($+U$) is applied to the phase winding, then, the phase-A winding is energized with the current flow through the path of U, D_a, T_1, L_1, T_2, and U. In the freewheeling mode where the winding voltage is zero; if the current in the winding exceeds the reference value, either T_1 or T_2 is turned off, the current that is flowing in the winding is free-wheeling through one path, either the path of L_1, T_2, D_2 or the path of L_1, D_1, and T_1. In the demagnetization mode, the stored magnetic energy of the energized winding also charges the incoming phase winding. Also, that the stored magnetic energy may use to charge the two capacitors (C_b & C_f) in series, so, a part of the energy is stored in the boost capacitor to build up a boost voltage [3], [8].

F. Parallel passive converter

As mentioned in [3], [25], [26]; the passive converter of parallel capacitor is modified from the classical bridge converter by adding one boosting capacitor in parallel with the phase windings to achieve voltage boosting capability. The parallel type converter for 3-ph SRM is shown in Fig. 7. Due to the direction of diode (D_a), the stored magnetic energy is only feed back to the boost capacitor (C_b). The maximum boost voltage can be obtained by a suitable size of the capacitor. Because the discharge of the boost capacitor is not controllable in the passive converter, the voltage of the boost capacitor is changed by the stored magnetic energy during different operating condition. When the phase switch is turned on, the voltage of the boost capacitor may fall very fast until the voltage reaches the dc link voltage (+*U*). The boost capacitor as in [8] increases the turn-on and turn-off voltage applied to the motor phases for motoring action. All the semiconductor devices except (D_a) must be rated for the boost voltage plus transients [27].

After charging of the capacitor (C_b) through the diode (D_a), there are three modes of operation; in the magnetization mode, T_1 and T_2 are turned on, the charging across the capacitor (C_b) is discharged and decreased down to zero, the voltage (+*U*) is applied to the phase winding, then, the phase-*A* winding is energized with the current flow through the path of *U*, D_a, T_1, L_1, T_2, and *U*. In the freewheeling mode where the winding voltage is zero; if the current in the winding exceeds the reference value, either T_1 or T_2 is turned off, the current that is flowing in the winding is free-wheeling through one path, either the path of L_1, T_2, and D_2 or the path of L_1, D_1, and T_1. In the demagnetization mode, the stored magnetic energy of the energized winding also charges the incoming phase winding. Also, that the stored magnetic energy may use to charge the boost capacitors, so, a part of the energy is stored in the boost capacitor to build up a boost voltage [3], [8].

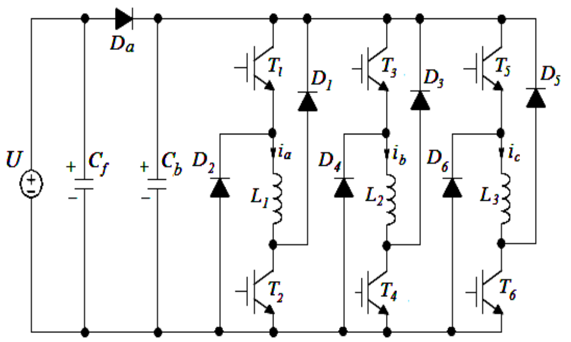

Figure 7. Series converter.

TABLE I. COMPARISON BETWEEN THE SIX POWER CONVERTERS

Features	R-dump	C-dump & C-dump with freewheeling	Asymmetric, Series & Parallel
Phase Independence	complete	partial	complete
Freewheeling	allowed	allowed	allowed
No. of devices	low (N)	low (N+1)	high (2N)
Performance	fair	very good	very good
Control	simple	complex	simple
Efficiency	low	high	high
Torque per ampere	low	high	medium
Fault tolerance	low	low	high

A comparison of the above discussed topologies used for 3-ph 6/4 SRM is summarized in Table I. The selection of a converter, in most of the cases, depends upon the application. For low performance applications where precise control of torque is not required, low cost converters can be employed. For applications, which require precise and simple control and where efficiency and reliability are important, a high performance converter which can provide fast demagnetization of phases is required.

IV. Simulink Models and Simulation Results for SRM Converters

A. Results for R-Dump Converter

The complete model using *R*-dump converter is shown in Fig. 8. The inductances, currents, total torque, and motor speed are shown in Fig. 9. Where; L_a, I_a are solid lines & L_b, I_b are dashed lines & L_c, I_c are dotted lines. The system reaches its steady speed at angle 3 rad.. During steady state operation, the maximum phase current is 2.435 A, the average phase current is 1.231 A, and the average total torque developed by motor is 1.797 Nm at 940 rpm. The evolution of energy conversion for calculating the work done and motor average torque can be represented for phase *a* by Fig. 10.

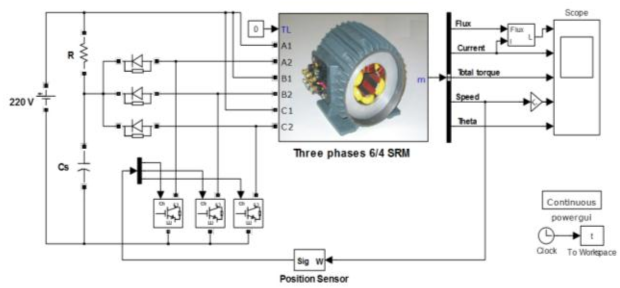

Figure 8. Simulink model of 3-ph 6/4 SRM using R-dump converter

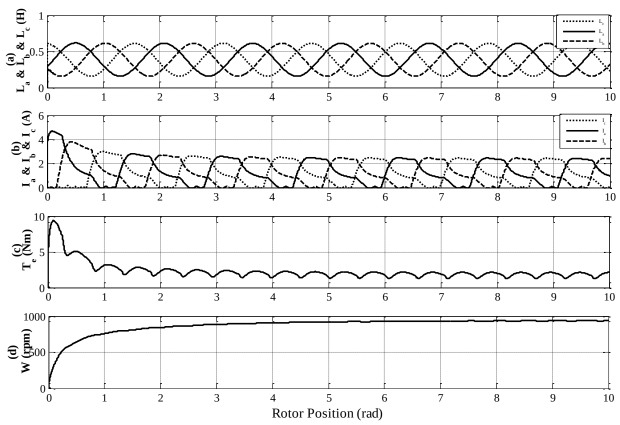

Figure 9. Simulation results versus rotor position for R-dump: (a)Inductances (b)Currents (c)Total torque (d)Speed

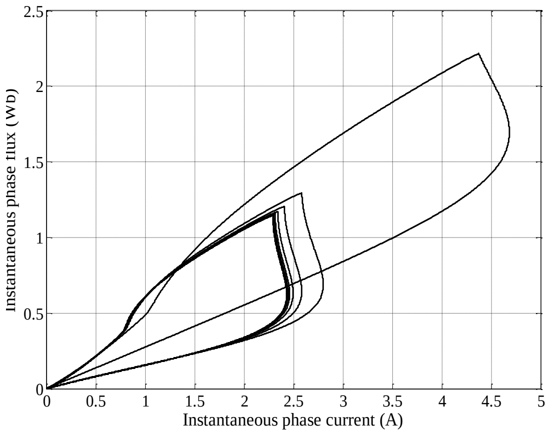

Figure 10. Evolution of energy conversion at using R-dump converter

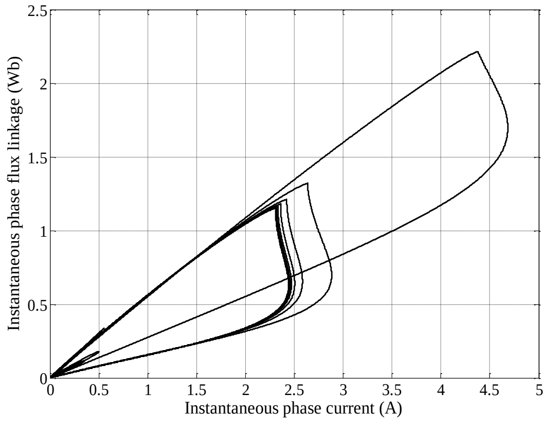

Figure 13. Evolution of energy conversion at using C-dump converter

B. *Results for C-Dump Converter*

The simulation model using *C*-dump converter is shown in Fig. 11. The simulink results are shown in Fig. 12. The system reaches its steady speed at a step angle about 3 rad. The simulation results during steady state shows that the shape of phase inductance is not distorted. During steady state operation, the maximum phase current is 2.443 A, the average phase current is 0.9053 A, and the average total torque developed by motor is 1.759 Nm at 927 rpm. The evolution of energy conversion for calculating the work done and motor average torque can be represented for phase *a* by Fig. 13.

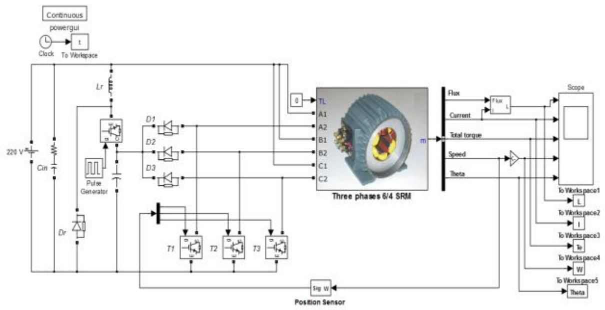

Figure 11. Simulink model of 3-ph 6/4 SRM using C-dump converter

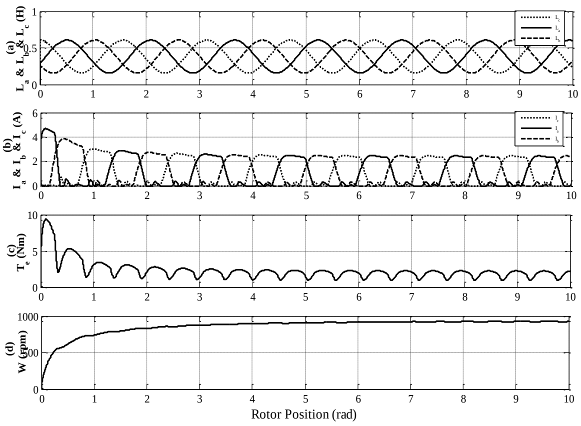

Figure 12. Simulation results versus rotor position for C-dump: (a)inductances (b)currents (c)total torque (d)speed

C. *Results for C-Dump with Freewheeling Converter*

The complete simulation model using the *C*-dump converter with freewheeling transistor is shown in Fig. 14. The simulink results of phases inductance, phases current, total torque, and motor speed are shown in Fig. 15. The system reachs its steady speed at a step angle about 6 rad. The simulation results during steady state shows that the shape of phase inductance is not distorted. During steady state operation, the maximum phase current is 2.724 A, the average phase current is 1.028 A, and the average total torque is 2.099 Nm at 1090 rpm. The evolution of energy conversion for phase *a;* is shown in Fig. 16.

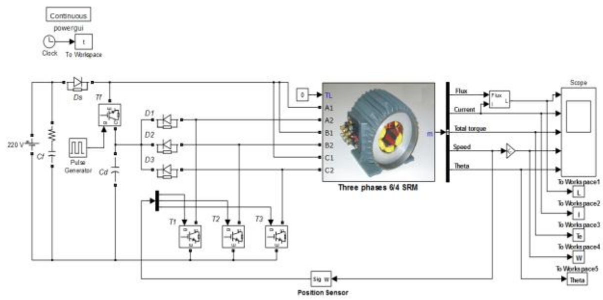

Figure 14. Simulink model of 3-ph 6/4 SRM using C-dump converter type with freewheeling transistor

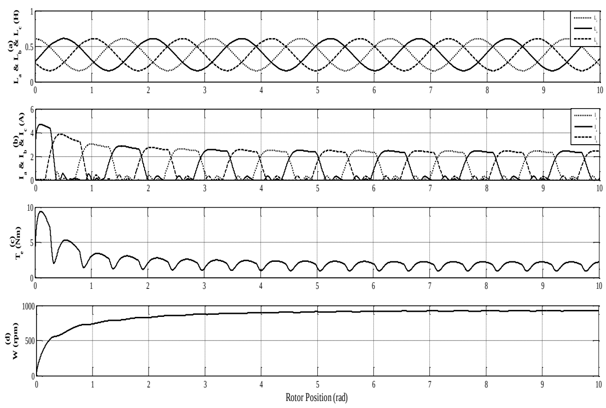

Figure 15. Simulation results versus rotor position for C-dump with freewheeling transistor: (a)Inductances (b)Currents (c)Total torque (d)Speed

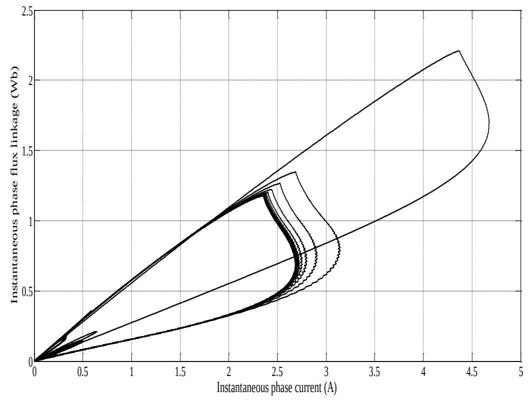

Figure 16. Evolution of energy conversion at using C-dump converter with freewheeling transistor

D. Results for Asymmetric Bridge Converter

The complete simulation model using the asymmetric bridge (*H*-bridge) converter is shown in Fig. 17. The simulink results of phases inductance, phases current, total torque, and motor speed are shown in Fig. 18. The system reachs its steady speed at a step angle about 5 rad. The simulation results during steady state shows that the shape of phase inductance is not distorted. During steady state operation, the maximum phase current is 2.379 A, the average phase current is 0.953 A, and the average total torque developed by motor is 1.756 Nm at 946 rpm. The evolution of energy conversion for phase *a* is shown in Fig. 19.

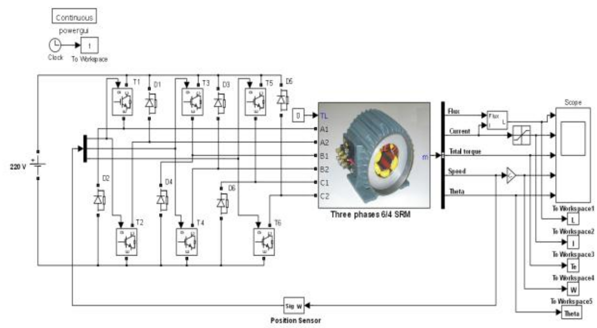

Figure 17. Simulink model of 3-ph 6/4 SRM using H-bridge converter

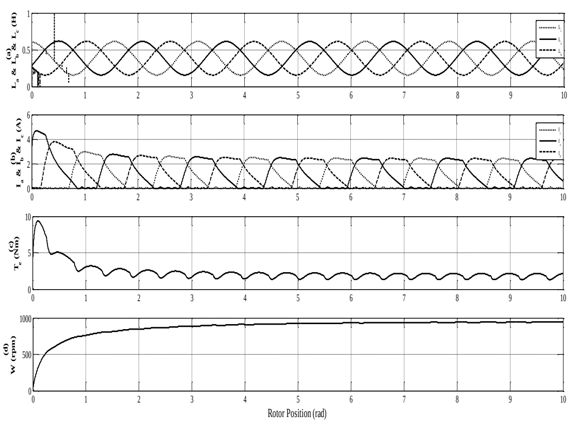

Figure 18. Simulation results versus rotor position for H-bridge converter: (a)Inductances (b)Currents (c)Total torque (d)Speed

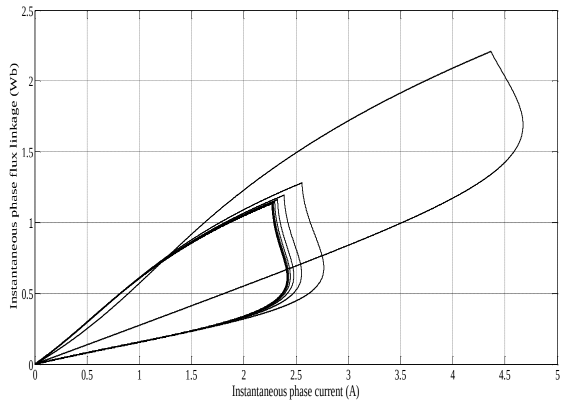

Figure 19. Evolution of energy conversion at using asymmetric converter

E. Results for Series Converter

The complete simulation model using the series converter is shown in Fig. 20. The simulink results of phases inductance, phases current, total torque, and motor speed are shown in Fig. 21. The system reachs its steady speed at a step angle about 4 rad. The simulation results during steady state shows that the shape of phase inductance is not distorted. During steady state operation, the maximum phase current is 2.575 A, the average phase current is 1.073 A, and the average total torque developed by motor is 1.92 Nm at 1000 rpm. The evolution of energy conversion for phase *a* shown in Fig. 22.

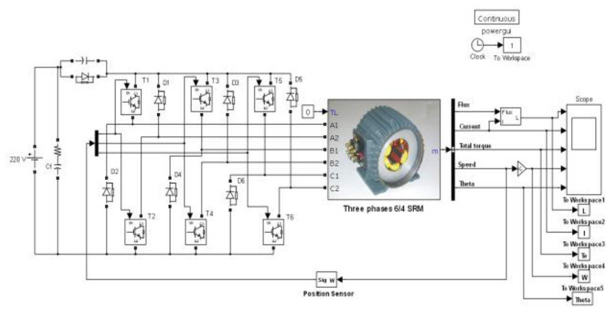

Figure 20. Simulink model of 3-ph 6/4 SRM using series converter

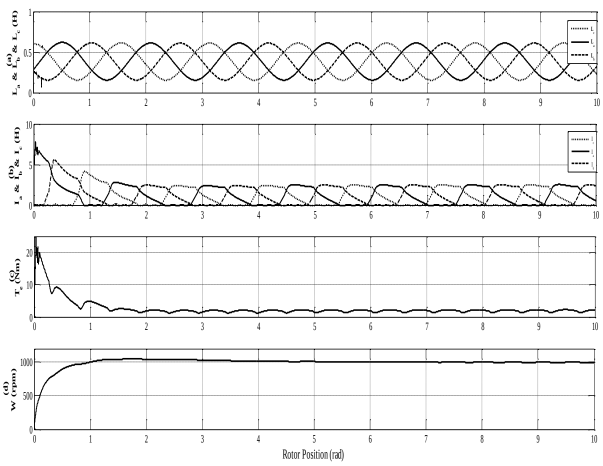

Figure 21. Simulation results versus rotor position for series converter: (a)Inductances (b)Currents (c)Total torque (d)Speed

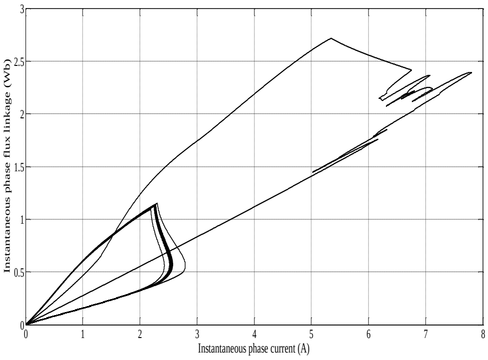

Figure 22. Evolution of energy conversion at using series converter

F. *Results for Parallel Converter*

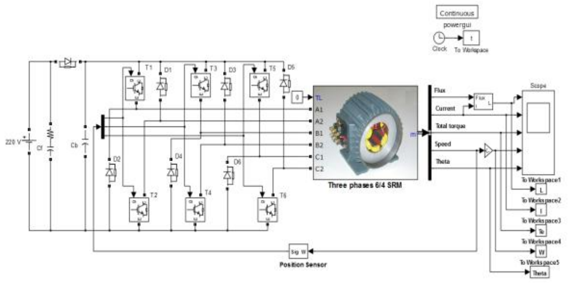

Figure 23. Simulink model of 3-ph 6/4 SRM using parallel converter

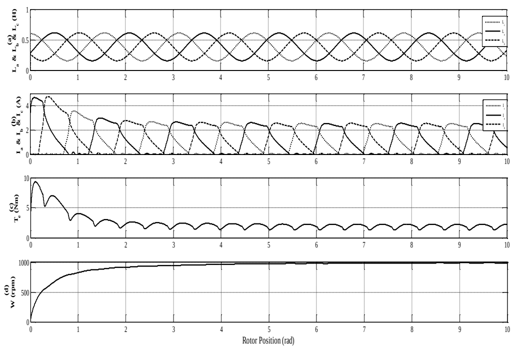

Figure 24. Simulation result versus rotor position for parallel converter: (a)Inductances (b)Currents (c)Total torque (d)speed

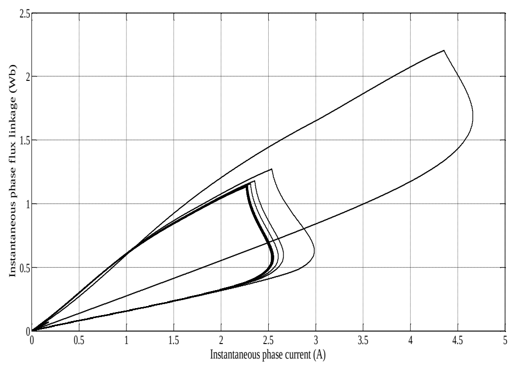

Figure 25. Evolution of energy conversion at using series converter

The complete simulation model using the parallel converter is shown in Fig. 23. The simulink results of phases inductance, phases current, total torque, and motor speed are shown in Fig. 24. The system reaches its steady speed at a step angle about 5 rad. The simulation results during steady state shows that the shape of phase inductance is not distorted. During steady state operation, the maximum phase current is 2.551 A, the average phase current is 1.075 A, and the average total torque developed by motor is 1.904 Nm at 1000 rpm. The evolution of energy conversion can be represented for phase *a* by Fig. 25. In both series or parallel converter; the stored energy of the de-magnetized outgoing winding charges the incoming phase winding and also the two converter performances are similar.

The work done and the torque can be evaluated from the area enclosed between the aligned and unaligned flux linkages versus excitation current characteristics [28], [4]. The average torque at high speed is reduced and is deduced from the size of the enclosed surface area generated by the corresponding flux linkage-current characteristics. The included area for each speed is directly proportional to the average torque per phase. Consequently, an indication of the change in the average torque with increasing speed may be found by observing the change of area obtained at any speed. If phase current or flux linkage ripple is halved, the torque ripple caused by this current or flux linkage ripple is reduced to one fourth of the original one because the generated torque is proportional to the square of the current or the flux linkage [10], [29].

TABLE II. COMPARISON BETWEEN THE SIMULATION RESULTS

Parameter	Max. phase current (A)	Average phase current (A)	Average total torque (Nm)	Torque per ampere	Speed (rpm)
R-dump	2.435	1.231	1.797	1.460	940
C-dump	2.443	0.905	1.759	1.943	927
C-dump with freewheel	2.724	1.028	2.099	2.042	1090
Asymmetric	2.379	0.953	1.756	1.843	946
Series	2.575	1.073	1.920	1.789	1000
Parallel	2.551	1.075	1.904	1.771	1000

In all the simulated converters, there is a comparative evaluation mentioned in Table II. The selection of a converter, in most of the cases, depends upon the application. As shown from the comparison of converters in Table I and the simulation reuslts in Table II. For low performance applications where precise control of torque is not required, the low cost dissipative converters; *R*-dump, *C*-dump, and *C*-dump with freewheeling can be employed. For high performance and precise applications where precise torque control and efficiency are important, the high performance voltage boosting converters; asymmetric, series, parallel types are used which can provide fast demagnetization of phases. In the aircraft applications where the precise operartion is required; the asymmetric bridge is preferred.

In spite of the properity of torque per ampere for asymmetric bridge type have intermediate value, but that converter is the preferred type, because it has the big benefits over other types as mentioned in Table I, specially the fault tolerance capability. So, it is choosen as the best in aerospace applications to give more safety for pepole life.

V. Conclusions

The most flexible and versatile four-quadrant SRM converter is the asymmetric (classical) converter, which has the capability of fault tolerance; in the case of one winding failure, uninterrupted operation with reduced power output of the motor drive is still possible. By comparing various converter topologies; it is found that the asymmetric converter with MOSFETs are suitable for high speed operation at low power due to the fast fall and rise time of current and also provide negligible shoot through fault. But, IGBTs power switches are preferable for medium speed operation at high power due to their high input impedance and due to low conduction losses.

Appendix A : Motor data

The parameters of the three phase 6/4 poles SRM are:

Number of motor phases : $K = 3$
Number of stator poles : $N_S = 6$
Number of rotor poles : $N_R = 4$
Stator pole arc (mech. deg.): $\beta_S = 40^o$
Rotor pole arc (mech. deg.): $\beta_R = 45^o$
DC voltage rating : $U = 220$ V
Stator phase resistance : $R = 17\ \Omega$
Aligned inductance : $L_{al} = 0.605$ H
Unaligned inductance : $L_{ul} = 0.155$ H
Inertia constant : $J = 0.0013$ Kg.m^2
Viscous friction coefficient : $B = 0.0183$ N.m.Sec^2
Rated speed : $n_r = 1000$ rpm
Rated phase current : $I_{ph} = 3$ A
Rated Torque : $T_e = 1$ Nm
Number of turns per phase : $N_{ph} = 600$
Winding wire diameter : $d = 0.5$ mm
Step angle (mech. deg.) : $\theta_r = 30^o$

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Mohsen Z. El-Sherif received his B.S. degree in 1970 from Electrical Engineering from El-Mansoura University, Egypt. In 1975, he worked as an engineer in Higher-Technical Institute at Shoubra, Egypt. In 1982, he received his M.S. degree from Cairo University, Egypt. From November 1985 untill May 1987, he worked as a guest researcher at Kyushu Institute of Technology, Japan. In December 1987 he received Ph.D. degree inElectrical drives from Cairo University, Egypt. In 1987- 1993, he worked as a Lecturer of Electrical Engineering and Electrical Machines at Zagazig University, Egypt. In 1993, he worked as Associate Professor at Shoubra Faculty of Engineering, Zagazig University. In December 1999 he was promoted to Professor's degree in the same Faculty of Engineering. In 2000 – up till now, he works as a Professor of Electrical Machines at Shoubra Faculty of Engineering, Benha university, Cairo, Egypt. His current research interests include electrical engineering, power electronics, electrical machines and drives.

Maged N. F. Nashed received his B.S. degree in Electrical Engineering, from Menoufia University, Egypt, in May 1983, his Diploma of Higher Studies from Cairo University, May 1990, his M.SC. degree in Electrical Engineering, from Ain Shams University, Cairo, Egypt, in April 1995 and his Ph.D. in Electrical Engineering, from Ain Shams University, Cairo, Egypt, in January 2001. He was a researcher for Fukuoka Institute of Technology, Japan, 2005. Since 1989, he has been a researcher with the Department of Power Electronic and Energy Conversion, Electronic Research Institute. Now he works as associate professor in the same Institute. He is engaged in research on power electronics; drive circuit, control of drives and renewable energy.

Samia M. Mahmoud received her B.S. degree in 1984 from faculty of Electrical Engineering, Benha University, Egypt. In November 11, 1999, she received her M.S. from Electrical Engineering and Electrical Machines at Zagazig University, Egypt. In October, 2004, she received Ph.D. degree in Electrical Engineering from Benha University, Egypt. In 2005- till now, she works as a lecturer of Electrical Engineering at Shobra Faculty of Engineering, Benha University, Cairo, Egypt. Her current research interests include wind turbine energy, electrical machines and drives.

Emad S. Abdel-Aliem received his B.S. & M.Sc. degree in Electrical Engineering, from Benha University, Cairo, Egypt, in May 2006 and December 2011 respectively. He works now on Ph.D. degree from Benha University, Cairo, Egypt. In 2006–2012 & from 2012 up till now, he works as a demonstrator and an Assistant Lecturer at Shoubra faculty of engineering, Benha University, Cairo, Egypt respectively. He has worked extensively in the modeling and studying of stepping motor drives. His research interests include modeling and control of switched reluctance motor drives, power electronics, and variable speed drives.

