Unity Power Factor Control of Sensorless Switched Reluctance Motor

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Abstract

Switched Reluctance Motors have an inexpensive, intrinsic simplicity and low cost that makes them well suited to home appliance and office applications. However the motor suffering with necessity of shaft position sensor, lead to non-linearity of operations. Further, the involvement of static converters deteriorates the operational power factor. Implementation of a sensorless algorithm, can remove the need of position sensors. Also, the drive includes a compact power factor control in the input stage by implementing Zero Current Switching Quasi-Resonant Boost Technology. This paper presented, aims at optimized low line current distortion, high power factor, low cost and a shaft position sensorless Switched Reluctance Motor drive.

Index Terms

Switched Reluctance Motor, Power Factor Control, Zero Current Switching, Quasi-Resonant Boost Converter, Sensorless Control.

I. INTRODUCTION

It is easy to predict an increasing use of small power, variable speed, electrical drives for household application, heating and air conditioning, and office automation systems in the near future. Most such domestic application does not require high dynamic performance, but instead, robustness and low cost. Therefore, the challenge in this field is not in terms of performance, but rather in terms of cost and size reduction.

The classical motor drive for household appliance is universal motor, directly fed from the main source. A number of apparent drawbacks in such solution are poor speed regulation, low efficiency, harmonic distortion, and electromagnetic emissions. For higher power application (such as washing machines), single-phase asynchronous and permanent magnet DC motors fed by controlled rectifier or choppers are also employed. The weakness of such traditional system has favored new solutions employed motors with no brushes, such as Induction, Synchronous PM Brushless, Variable Reluctance and Switched Reluctance Motors (SRM). Among several possible drive structures, a very promising solution consists in replacing universal motors with reliable and low-cost Switched Reluctance Motor drive.

Increased reliability, reduced cost and adaptability to operate under harsh conduction can be achieved by the drive, without the aid of any shaft position feedback. The “open-loop” mode of operation is not stable in SRM drive, but it is achieved with the help of an additional stabilization circuit [1].

On the other hand, some significant events have recently added other degree of freedom in this scenario, such as the power quality, electromagnetic compatibility, and energy consumption. The static power converters generate noticeable line current harmonic pollution as an unavoidable side effect which is responsible for poor power factor and causes the flowing current in neutral wire of the main power system. Due to the fast diffusion of small size power converters in industry, pollution levels of office and home, line-current have become unacceptable, claiming for regulation on current harmonics generation.

Line current pollution control must also be obtained with a minimum extra cost. Such a constraints, as well as low power of the proposed drive, claim for a single switch power factor control. In the proposed solution, Power Factor Control (PFC) boost stage based on a Zero Current Switching (ZCS) quasi-resonant topology[2] is used, that allows one to obtain a high power density. Moreover, an automatic line current shaping strategy is developed in order to obtain closed sinusoidal input current without a specific current control loop. This allows one to simplify the control circuit designed, although at the expense of slightly reduced performance. On the other hand, as the potential working conditions of home appliance drives are well known a priori, the control system can be optimized for the specific tasks.

Two approaches can be followed to reduce the line current pollution generated by electric drives, passive input filters and active power factor control. Although simple in principle, adaptation of existing drives to new standards by adding large input filters is often disadvantageous in terms of increased size and power loss. By contrast active line current control technique allows one to develop more effective and economic PFC that can advantageously replace traditional input stages. As a consequence, a large interest is presently shown in developing low-power, low-loss electric drives complying with the new standards by adopting active power factor control circuits.

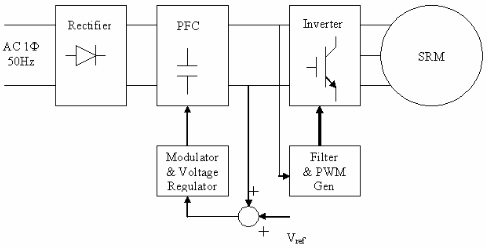

Fig 1, Block Diagram of Proposed SRM Drive.

This paper describes a low-power SRM drives aimed to equip home appliances, such as washing machines, vacuum cleaners and air conditioning systems. The proposed block diagram for this SRM drive has been presented in the fig.1. The drive design has been specifically optimized to low line current distortion, high power factor, low cost and a shaft position sensorless SRM drive.

II. SWITCHED RELUCTANCE MOTOR

A Reluctance Motor is an Electrical Motor, in which torque is produced by the tendency of its movable part, to move to a position, where the inductance of the excited winding is maximized [1].

The basic operation of the SRM is that, the current is passed through one of the stator winding, 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 flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position.

The fig.2 shows an SRM machine with 3-phase, 6-stator poles and 4-rotor poles, which is in aligned position. The rotor pole's axis is aligned with the stator pole axis, where the inductance is maximum. This is said to be an aligned position. The rotor pole axis is aligned with the interpolar axis of the stator which is said to be at an unaligned position. In this position the inductance is minimum.

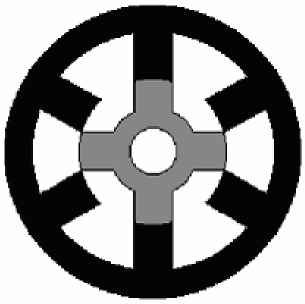

Fig 2 6/4 Switched Reluctance Motor

It is used widely in all area in the industrial as well as the domestic applications, such as home appliances, industrial blower and compressor, factory automation, variable speed-adjustable RPM drives, Battery powered Electric vehicles and Electric traction drives. The motors are available at ratings up to 350 kW.

SRM is inherently brushless, that avoids the electromagnetic pollution due to the mechanical commutation, low manufacturing cost, simple in construction, minimal temperature effects, low inertia, and wide speed range at constant power, low rotor losses and allow one to design low-cost power converters with a minimum count of switches per phase.

Three and four-phase machines are normally preferred to single and two phase motors since at the expense of a small increase of size and cost they allow one to obtain higher efficiency and flexibility[2].

The proposed SRM drive, based on a three-phase machine supplied by a split DC voltage inverter, uses an inverter topology with only a diode and an IGBT per phase. Such inverter topology needs SRM with bifilar windings in order to control the phase current.

As it has already been pointed out, a precise speed control of the proposed SRM drive is not required by the addressed application, while simplicity and low cost are mandatory. Therefore, a simplified torque control strategy is applied, switching the motor phase at programmed phase angles and controlling the motor torque in an open-loop fashion by chopping the phase voltage.

For the proposed application, the selected SRM is a 3-phase 6/4 machine, the characteristic of which has been given in the Table.1

Table 1 SRM Specifications

S.No	SRM Specifications	Values
1	No. of Phase	3
2	No. of Stator Poles	6
3	No. of Rotor Poles	4
4	Average Phase Resistance	0.522mÙ
5	Average Inductance (aligned)	80 mH
6	Average Inductance (unaligned)	8 mH
7	DC bus voltage	300 Volts
8	Rated Max. Speed	1500 rpm
9	Rated Power	750Watts

III. POWER FACTOR CONTROL

The basic scheme for a single switch PFC with a capacitive energy storage block consists of a diode bridge, a DC-DC converter and energy storage block and an output voltage control block. In order to control the power factor, the DC-DC converter must operate with a sinusoidal average input current in-phase with the input voltage [2].

Energy storage block, working as a flywheel, allows the PFC to absorb AC power from the main while delivering DC power to the output. Among PFC topologies, boost-based circuits are the most suitable for low power and low cost drives, since they are very simple, flexible, and cost efficient. The main drawback of boost-based PFC is that, the output voltage is always greater than the input voltage. It is an advantageous feature in the present system. In fact, since the split DC voltage inverter used to power the SRM delivers a phase voltage that is only half of the input voltage. Motor voltage, can be increased by simply increasing the boost output voltage.

Quasi-resonant techniques allow one to increase the switching frequency, reduce the size of the boost input inductance. In particular, Zero Voltage Switching (ZVS) Quasi-resonant topologies are well suited for high frequency applications, but they are affected by minimum load constraints that make their use difficult in the considered applications. On the contrary, ZCS topologies require that the load does not exceed a maximum value given by the input voltage level and the circuit parameters. This limitation fits very well with the features of a motor drive, making ZCS converters the topologies of choice. The fig.3 shoes such a PFC boost-based topology. And the parameters are given in the Table.2.

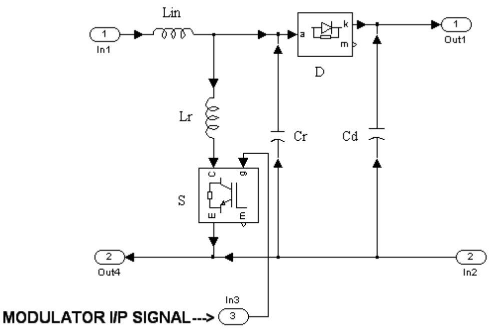

Fig 3, ZCS Quasi-Resonant Boost Converter

Table 2, ZCS Quasi-Resonant Boost Parameters

f_r	P_{max}	V_{out}	f_{smax}	C_r	L_r	C_{out}	L_{in}
170 kHz	1 kw	350 v	85 kHz	47 nF	18.8 µF	6.8 µF	2 mH

In PFC boost-based topologies, sinusoidal input current and unity power factor can be obtained by two different strategies. In the former, called the "multiplier approach", an output voltage control loop drives an inner input current control loop by means of a sinusoidal signal proportional to the input voltage.

Such a system acts as a current shaper, forcing the input current reference to be sinusoidal and in-phase with the input voltage.

The later, called the "voltage follower approach", does not require a specific input control loop since the average input current naturally follows the input voltage. This happens in any DC-DC converter designed to work in Discontinuous Current Mode (DCM). Since DCM heavily limits the allowed load range, Continuous Current Mode (CCM), is normally required when the output power is over 100W.

In the present Paper, an improved PFC boost stage, based on a ZCS quasi-resonant topology, is used in CCM performing an automatic line current shaping. This allows one to achieve the benefit of DCM operated converters, such as simple and low-cost circuits, avoiding the over-sizing of power devices.

In order to achieve the Automatic Current Shaping (ACS) in a boost converter working in CCM, the conversion ratio M and the apparent load R_a must follow the relation expressed by equation (1) & (2) without a specific line current control loop:

$$M \quad t \quad \frac{V_{out}}{V_{in}} \quad \frac{V_{DC}}{\hat{V}_{AC}.\sin \quad t} \qquad (1)$$

$$R_a \quad t \quad \frac{v_{out}}{i_{out}} \quad \frac{V_{DC}}{2\hat{I}_{AC}\sin^2 \quad t} \qquad (2)$$

Where $\hat{V}_{AC}$ and $\hat{I}_{AC}$ are the peak values of the line voltage and line current, respective.

Since the ZCS boost converter shown in the figure is controlled by acting on the switching frequency, a suitable frequency variation law must be developed to force the actual value of the conversion ratio and the apparent load to follow the relation given by the equation (1) and (2). It can be analytically proved that in a half wave ZCS Quasi-resonant boost converter, such a condition can be achieved by forcing the ratio f between the switching and the resonant frequencies to follow the modulation law expressed by

$$f(\omega t) = \frac{2\pi\left(1 - \frac{\hat{V}_{AC}\left|\sin(\omega t)\right|}{V_{DC}}\right)}{\frac{\delta}{2} + \pi + \sin^{-}(\delta) + \frac{1+\sqrt{1-\delta^2}}{\delta}} \qquad (3)$$

Where

$$\delta = 2\sqrt{\frac{L_r}{C_r}}\frac{I_{DC}}{V_{AC}}\left|\sin(\omega t)\right| = \delta_{max}\left|\sin(\omega t)\right|$$

L_r, and C_r are the inductance and the capacitance of the resonant tank.

By reconstructing the frequency modulation law given by the equation (3) from the actual value of the line voltage and the DC current, the open loop shaping of the current can be performed, working as PFC like any DCM operating converter by means of only the output voltage control loop.

Unfortunately, the developed frequency modulation law is too complex to be practically reconstructed by low-cost analog circuits. Moreover, output current sensing is also required, compromising the simplicity of the approach. Consequently an approximate modulation expressed by the equation (4) is proposed that can be easily implemented by a simple analog circuit, as shown in the fig.4, and using the output of the dc controller instead of the DC bus current.

$$f'(\omega t)=F+\delta^*\left[H\left|\sin(\omega t)\right|-K\sin^2(\omega t)\right] \text{———}(4)$$

Where F, H and K are suitable gain and δ^* are the output of the voltage regulator.

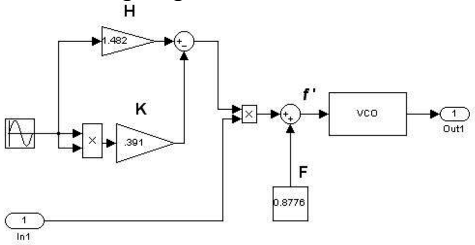

Fig 4, Analog Modulation Circuit

The parameters F, H and K can be selected for a given load condition by comprising the results of the equations (3) and (4) when ${}_{maz}$ is equal to δ^*. By the values given in the table.1 & .2, we get the values of gain, K=0.391, H=1.482, F= 0.8776.

As a consequence, it appears that in principle the PFC works correctly only around a load condition considered in the design, however, this is not a drawback of the addressed application. First, working conditions of the drives for home appliances are a well known priori and limited in numbers so that the parameters can be optimized for the specific task. Second, a perfect sinusoidal input current is never required, as it is sufficient to comply with the line current harmonic limitations. Finally, as it will be shown in the last section, the proposed automatic current shaping approach is able to work very well in a large range of loads around the design value. The main parameters of the ZCS quasi-resonant designed [2] to equip the PFC are presented in the Table.2.

IV. SENSORLESS CONTROL OF SRM

The most direct method of controlling the SRM is by using a shaft position sensor or encoder. The shaft position sensor is used to directly control the stator current ON and OFF angles referenced to the rotor position. However, in low cost applications, practically at low power levels, the shaft position sensor is too costly, and it also decreases the reliability of the system. Therefore, a high-performance sensorless system is preferred.

Sensorless control schemes can be divided into four classes:

1. Open–loop control with additional stabilization.
2. Passive waveform detection.
3. Active probing.
4. State observers.

For the proposed drive, the first scheme is taken with the reference of [3]. A sensorless key presented in [4] can be divided into open loop and current sensing controls. The current sensing controls sense the freewheeling current in one of the OFF phase of the drive converter to estimate the rotor position from the current wave shape. This estimated position is used to determine when one stage should be switched OFF and the other one switched ON. The open-loop system sends a series of stator current pulse without any indication of rotor position. The pulse switch is defined as the difference between the ON and OFF angles. The frequency of the stator current pulses determines the motor speed. In order to maintain synchronism even when the load increases or is disturbed, the sensorless controls drive the motor with a much larger pulse- width angle than necessary for the nominal load. Consequently, the efficiency of the system is quite low. For the motor used in this investigation, the efficiency at the rated load is no better than 14% using this sensorless control method.

A sensorless control using pulse-width was introduced in [4]. This scheme senses the DC link current to determine the pulse-width. This permits the motor to operate efficiently with a narrow pulse-width under normal conditions. Any change in the load is sensed by the controller through the DC link current, and the pulse-width is adjusted appropriately. In this paper, the electronic implementation of the control has been dealt with.

The proposed drive filters the DC link current, to obtain the DC value, I_d. The function generated in a non-linear amplifier that uses I_d to produce a voltage representing the desired pulse-width. The gate signal generator produces a three-gate pulse with a pulse-width proportional to the function generator output.

Since position encoder has not been used the control system cannot fix the torque angle directly. The torque angle is defined as a mechanical angle between the rotor and the stator poles at the instant when a stator winding is deenergized. Instead, the DC link current is sense and the pulse-width or dwell angle is set according to a predefined function of the DC link current.

V. INVERTER STRUCTURE SELECTION

Converter cost reduction can be obtained according to different issues, such as number of motor phases, power device number, power device rating, and so on. It is very difficult, in general, to determine an optimal motor converter system configuration, always depending on the specific application. Single and two-phase small SRM have recently been developed allowing one to use simple power converters. Unfortunately, the current rating of the power device must be increased if compared with three or four-phases converters of the same power. Also, the efficiency of the electromagnetic structures increases with the number of phases.

Moreover, motor starting is possible only if the rotor is correctly positioned. Suitable magnets inserted in the rotor structure are used to force the rotor to stop in the right position. However, in several applications, where the fractional torque is high, such as in home appliances, starting is critical. Three and four-phase machines are thus preferred, since they allow one to obtain better efficiencies and a much higher degree of flexibility despite the cost of a slight increase of the power converters in terms of size and cost.

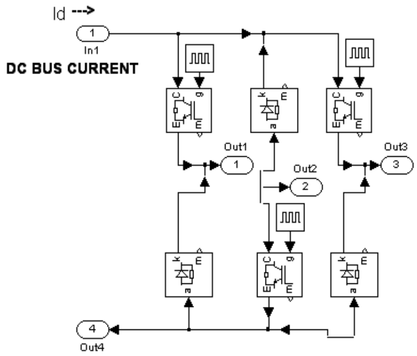

Fig 5, Proposed Inverter Topology

Several inverter topologies for SRM drives have been proposed in the literature. The best two-transistor-per-phase structure, shown in the fig 5, allow one to obtain the maximum level of flexibility with the minimum number of passive components, but it requires six power switches and six diodes to supply a three-phase SRM. This can be hardly accepted in low cost system. On the other hand the topology can be considered with less than two switches per phase. The split DC supply configuration is very attractive for low cost systems and has been selected to build the proposed drive. It requires only a diode and a switch per-phase and does not need motors with bifilar windings [6].

The power stage is based on three IGBT devices operating at 5KHz switching frequency. Such low switching frequency allows one to reduce the switching losses and to increase the efficiency of the drive without influencing the drive performance. The phase voltage duty cycle is started by the speed regulator in order to control the motor torque.

VI. SRM CONTROL AND SIMULATION

Fast and precise torque control is not required by the addressed applications, while the simplicity and low cost are of major concern. This leads one to simplify the inverter control circuit as much as possible, even at the cost of poor dynamic performance and reduced efficiency.

In such an approach, each phase is switched on at fixed phase angle and maintained active for 15 degrees. A simple but effective torque control strategy is then obtained chopping the phase voltage. In order to improve the efficiency of the drive switching-on, optimal angle can be computed case by case, using the machine model. The average torque produced at 1500 rpm by the actual SRM, normalized to the torque produced at 300V with a zero turn-on angle, versus the turn-on angle at the average phase voltage.

It is worth pointing out that the main function of the proposed drive can be implemented on a single analog chip which has the AC voltage, the DC bus voltage, the reference speed, and the encoder signals as inputs while the IGBT driving signals are its outputs. Finally, the over current protection, needed to ensure safety of the system in any working condition, is implemented at the IGBT drive circuit level.

The control block diagram shown in the fig.6 is the speed control loop. Speed is regulated in an open-loop manner, by comparing the desired speed to the estimated speed from the current feed back signal, and then the speed error is estimated. Speed error is compensated by the Proportional and Integral (PI) controller. The compensated error signal is given as a current reference to the current loop, which in turn is compared with the actual current from the current feed back signal that estimates the current error. The current error, is then multiplied with the current gain and the PWM inverter gain which produces the required voltage signal that is fed to the SRM.

The transfer functions [5] of the SRM is given the equation (5)

$$G(s) = \frac{\left(1/R_m\right)}{\left(L/R_m\right)s + 1} \qquad (5)$$

Where

R_m ->is the phase resistance.

L ->is the effective inductance

By the value given in the table.1, we can calculate the mathematical module of the proposed SRM machine.

$$G(s) = \frac{0.1234}{0.0296\,s + 1}$$

PWM gain=V_{DC}/P=$\frac{300}{999}$=0.3003

DC bus voltage V_{DC}=300 volts

Current feedback gain K_{fb}=.85

Speed loop gain K_v=17.5

$$\text{PI control} = \frac{s + 0.73}{s}$$

A critical problem related to the simulation of the proposed drive is to find a suitable model. In fact a detailed model of the drive requires small integration steps (100 ns) in order to correctly simulate the dynamic of the quasi-resonant stage. An approximate time average model of the quasi-resonant ZCS boost stage as been developed that allows one to greatly increase integration steps (500 µs) while correctly describing the low frequency inverter the drive model useful to simulate speed and load transients is obtained and use to evaluate the performance of the drive. The averaged model applies the averaged pulse voltage to the SRM during the condition interval. The converter is always in square wave mode with its DC link voltage equal to the averaged chopped value. The fig 7 shows, MATLAB Simulink block diagram of SRM speed controller. Fig .8 shows, the speed response of SRM speed controller by MATLAB Simulink at 1500 RPM.

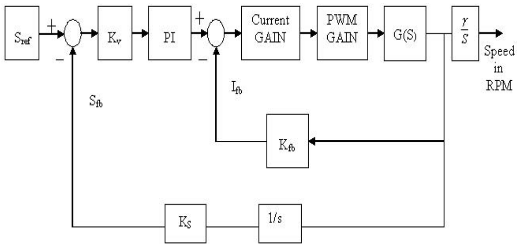

Fig 6, Block Diagram of SRM Speed Control Loop

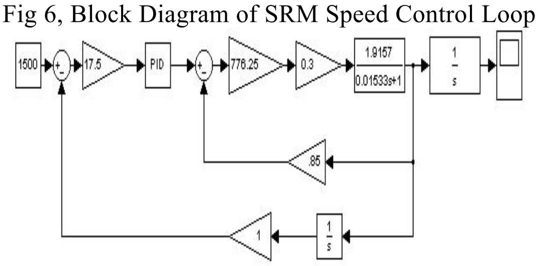

Fig 7, MATLAB Block Diagram of SRM Speed Controller

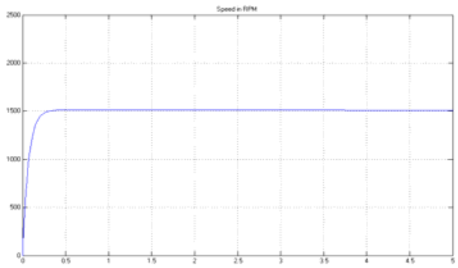

Fig 8, Response of SRM Speed Controller at 1500 RPM

VII. CONCLUSION

A low power Switched Reluctance Motor drive aimed to equip home appliances and featuring close to unity power factor and low cost has been presented. Key features of the presented SRM drive are simple speed control, minimum switch count inverter topology, open-loop sensorless operation and compact power factor controller input stage, based on a quasi-resonant boost topology. Such features allow one to develop an inexpensive and compact drive for the proposed application. Simulation results obtained by using MATLAB Simulink software will evident, the performance of the proposed drive in terms of speed response.

VIII. NOMENCLATURE

C_r	Capacitance of resonant tank
C_{out}	Filter Capacitance
f_r	Resonant frequency
$f_{s\,max}$	Maximum switching frequency
f'(ùt)	Function of modulation law
G(s)	SRM transfer function
$\hat{I}_{AC}$	Peak line current
i_{out}	DC out put current
K_{fb}	Current feedback gain
K_s	Speed feedback gain
K_v	Speed loop gain
L	Effective inductance
L_r	Inductance of resonant tank
L_{in}	Filter inductance
M(ùt)	Boost converter conversion ratio
P_{max}	Maximum power
R_a(ùt)	Apparent load
R_m	Phase resistance
V_{DC}	DC bus voltage
V_{in}	Input put of resonant converter
V_{out}	Out put of resonant converter
$\hat{V}_{AC}$	Peak line voltage
ä	Analog Modulation index

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