***Abdolhossein EJLALI, **Davood Arab KHABURI, *Javad SOLEIMANI**

*Department of Engineering, Mehran Branch, Islamic Azad University, Mehran, ilam, Iran
** Department of Electrical Engineering, Iran University of Science & Technology (IUST), Tehran, Iran

Sensorless Field Oriented Control Strategy for Single Phase Line-Start PMSM Drive

***Abstract**. In this paper, sensorless field oriented control strategy has been presented for single phase LSPMSM drive. Single phase type of LSPMSM is the same as single phase induction motor which has embedded permanent magnet in caged rotor. This modified motor provides higher efficiency than induction motor and has a better power factor. Also, two-leg topology of inverter used in this scheme provides regenerative mode operation and power factor control. Field oriented control (FOC) strategy is a high performance method which has been used in this paper. For elimination of required sensor in FOC method, A Phase Locked Loop (PLL) observer has been used to extract rotor speed from stator voltages and currents.*

***Streszczenie.** Przedstawiono strategię bezczujnikowego sterowania napędem jednofazowym PSPMSM. Do tego celu wykorzystano zmodyfikowany silnik indukcyjny z wbudowanym wirnikiem zawierającym magnes stały. Zamiast czujników stosuje się obserwator typu PLL. (**Bezczujnikowe sterowanie silnikiem jednofazowym z napędem PMSM**)*

Keywords: Field Oriented Control (FOC), Single Phase Line-Start Permanent Magnet Synchronous Motor (LSPMSM), Speed Estimation;.
Słowa kluczowe: PMSM – permanent magnet synchronous motor – silnik synchroniczny z magnesem stałym.

Introduction

Recently, energy saving is an important concern for most of countries. Improving efficiency of electrical motors is a main task for this target. Some attempts have been made for efficiency increment of electrical motors which most of it belongs to induction motor because of its extensive application in industries and home appliance. However, the optimization of this type of motor is limited [1].

Permanent magnet (PM) motor has high efficiency and in recent years, has received increasing attention as a good alternative to induction motor. But PM motor need to peripheral inverter for starting stage which is not economical scheme for most of applications [2].

Advantages combination of PM motor and induction motor's starting ability has been presented in 1950 [3]. The new PM motor equipped by squirrel cage is generally known as Line-Start Permanent Magnet Synchronous Motor (LSPMSM).

Single phase type of LSPMSM is the same as single phase induction motor which has embedded permanent magnet in caged rotor. This modified motor provides higher efficiency than induction motor and has a better power factor. But due to higher cost of such motor, it had been used in lower applications compare to induction motor. Recently, single phase LSPMSM is becoming economic alternative to induction motor [4].

Most of researches on LSPMSM belong to 3-phase type and those researches which study on single phase type has been focused on its modeling and analysis because single phase motors applications didn't need any control method.

Improvement of efficiency by providing power factor control and cost reduction of power electronic devices provide conditions for implementation of single phase induction motor drive used in domestic and industrial applications [5].

There are different topologies of two phase inverter for single phase motor drive. The topology with two-leg shown in figure 1 has been used in this paper. This configuration provides regenerative mode operation and power factor control [6].

Studies on motion control of electrical motors have developed good methods. Field oriented control (FOC) strategy is a high performance method. However, FOC requires speed sensor which increases the cost of dive system [7]. Recently, researches on speed estimators has been developed which firstly had been developed for 3-phase induction motors.

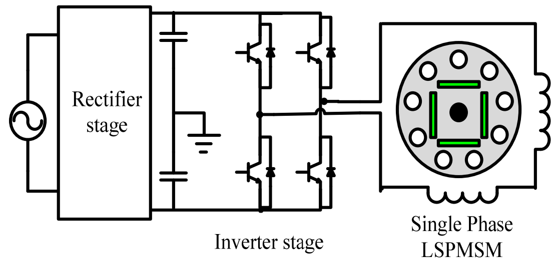

Fig 1. Single phase LSPMSM drive system

In this paper, sensorless field oriented control strategy has been presented for single phase LSPMSM drive. The FOC method has been carried out by current hysteresis controllers and speed regulator is a conventional PI controller. For elimination of speed sensor, a speed estimator using Phase Locked Loop (PLL) has been proposed. Also, the used power electronic converter can be consisted of a single phase rectifier and a two-leg inverter. This configuration provides power flow in two directions.

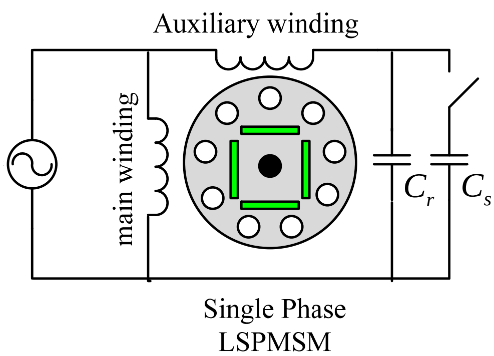

Fig. 2. Structure of single phase capacitor-start capacitor-run LSPMSM and winding connections.

Transformations

Figure 2 shows structure of single phase capacitor-start capacitor-run LSPMSM and its winding connections. The motor considered in this paper is electrically and magnetically asymmetrical. Therefore, mathematical model of single phase LSPMSM is established in dq reference frame.

The asymmetry of this motor can be compensated by applying a transformation to main and auxiliary parameters of windings. Equation (1) and (2) shows such transformation which model the actual motor as a symmetrical one with equal winding [8].

$$\begin{bmatrix} i_m' \\ i_a' \end{bmatrix} = \begin{bmatrix} \beta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_m \\ i_a \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_m' \\ v_a' \end{bmatrix} = \begin{bmatrix} \beta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_m \\ v_a \end{bmatrix} \tag{2}$$

where i and v is current and voltage respectively, m and a indicate main and auxiliary windings and quotation shows transformed parameters. β is the turn ratio calculated by:

$$\beta = \frac{N_m}{N_a} \tag{3}$$

where N_m and N_a are turn number of motor windings.

Transformation to dq reference frame can be done by a matrix as below [9]:

$$T = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{4}$$

where θ is the rotor angel. Both transformations for voltages and currents which have been shown in figure 3 can be written as equation (5) and (6). The former can be obtained by applying both transformations to voltages and considering that $V_s = v_m = v_a - jX_c I_a$.

$$\begin{bmatrix} i_m' \\ i_a' \end{bmatrix} = \begin{bmatrix} \sin\theta/\beta & \cos\theta/\beta \\ \cos\theta & -\sin\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \sin\theta/\beta + \cos\theta & -\cos\theta \\ \cos\theta/\beta + \sin\theta & \sin\theta \end{bmatrix} \begin{bmatrix} V_s \\ V_c \end{bmatrix} \tag{6}$$

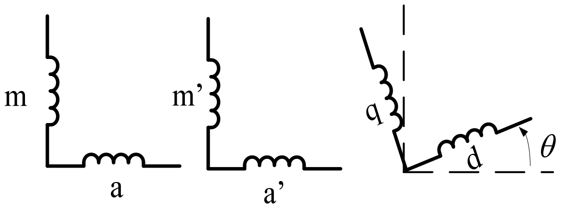

Fig. 3. Relationship between transformation models.

Mathematical Model of single phase LSPMSM

Motor dynamic equations, which are somewhat the same as induction motor equation, in rotating reference frame can be written as bellow [10]:

a) Stator voltage equations:

$$\begin{cases} V_{sd} = R_a i_{sd} + p\lambda_{sd} - \omega\lambda_{sq} \\ V_{sq} = R_a i_{sq} + p\lambda_{sq} + \omega\lambda_{sd} \end{cases} \tag{7}$$

b) Rotor voltage equations:

$$\begin{cases} V_{rd} = R_{rd} i_{rd} + p\lambda_{rd} = 0 \\ V_{rq} = R_{rq} i_{rq} + p\lambda_{rq} = 0 \end{cases} \tag{8}$$

where s and r indicate stator and rotor respectively, R_a is the stator windings resistance, ω is the rotor angular speed and p is differential operator. R_{rd} and R_{rq} are the rotor dq resistances, λ_{rd} and λ_{rq} are the rotor dq flux linkages.

c) Stator flux linkage:

$$\begin{cases} \lambda_{sd} = L_{sd} i_{sd} + L_{md} i_{rd} + \lambda_f \\ \lambda_{sq} = L_{sq} i_{sq} + L_{mq} i_{rd} \end{cases} \tag{9}$$

$$\begin{cases} \lambda_{rd} = L_{rd} i_{rd} + L_{md} i_{sd} + \lambda_f \\ \lambda_{rq} = L_{rq} i_{rq} + L_{mq} i_{sq} \end{cases} \tag{10}$$

where L_{sd} and L_{sq} are the stator dq inductances, L_{md} and L_{mq} are the dq mutual inductances, L_{rd} and L_{rq} are the rotor dq inductances and λ_f is the flux produced by permanent magnet in the rotor.

e) Mechanical equations:

$$\begin{cases} T_e = P(\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd}) \\ Jp\omega + B\omega = P(T_e - T_L) \\ \theta = \int \omega dt + \theta_0 \end{cases} \tag{11}$$

where T_e and T_L are the electromagnetic torque and the load torque, P is the pole pairs, J is the rotor inertia, B is the viscous friction coefficient.

For modelling single phase LSPMSM equation (7) and (8) has been used to calculate stator and rotor d and q axis flux as bellow:

$$\begin{cases} \lambda_{sd} = \int (V_{sd} - R_a i_{sd} + \omega\lambda_{sq}) dt \\ \lambda_{sq} = \int (V_{sq} - R_a i_{sq} + \omega\lambda_{sd}) dt \end{cases} \tag{12}$$

$$\begin{cases} \lambda_{rd} = \int (-R_{rd} i_{rd}) dt \\ \lambda_{rq} = \int (-R_{rq} i_{rq}) dt \end{cases} \tag{13}$$

Also stator and rotor d and q axis currents can be calculated from equations (9) and (10) as bellow:

$$\begin{cases} i_{sd} = \dfrac{1}{L_{sd} L_{rd} - L_{md}^2} [L_{rd}\lambda_{sd} - L_{md}\lambda_{rd} + (L_{md} - L_{rd})\lambda_f] \\ i_{sq} = \dfrac{1}{L_{sq} L_{rq} - L_{mq}^2} [L_{rq}\lambda_{sq} - L_{mq}\lambda_{rq}] \end{cases} \tag{14}$$

$$\begin{cases} i_{rd} = \dfrac{1}{L_{sd} L_{rd} - L_{md}^2} [-L_{md}\lambda_{sd} + L_{sd}\lambda_{sd} + (L_{md} - L_{sd})\lambda_f] \\ i_{sq} = \dfrac{1}{L_{sq} L_{rq} - L_{mq}^2} [-L_{mq}\lambda_{sq} + L_{sq}\lambda_{rq}] \end{cases} \tag{15}$$

Equation (11) has been used for calculation of electromagnetic torque, rotor angular speed and rotor position.

Field Oriented Control Strategy for single phase LSPMSM

Figure 4 shows the speed control strategy applied to single phase LSPMSM. The speed control loop uses a proportional-integral regulator to produce the quadrature-axis current reference i_q* which controls the motor torque. The motor flux is controlled by the direct-axis current reference i_d*.

Stator currents controller acts in synchronous reference frame and uses hysteresis controller for this task. The mentioned frame has become an industry standard for control of currents in ac machines. The transformation block is used to convert id* and i_q* into current references i_a*, and i_m* for the current regulator. Current and Voltage Measurement provide signals for visualization purpose.

Current controllers provide signals for inverter switches so that an unbalanced voltage values with 90 degree difference in their peak values are applied to main and auxiliary windings.

Field oriented control (FOC) strategy is a high performance method. However, FOC requires speed sensor which increases the cost of dive system [6]. In the next section a speed estimation method is proposed.

Speed Estimation

The purpose of observer is to estimate rotor speed using measured stator currents and voltages. The proposed observer has been shown in figure 5.

The stator flux observer which has been shown in figure 6, uses voltages and currents in stationary reference frame and estimates position of stator flux. A Phase Locked Loop (PLL) observer is a good solution to extract rotor speed and position from stator flux position.

As shown in figure 5, the observer receives estimated position of stator flux as an input, filter it and estimate speed and rotor position.

Using equation (7) in stationary reference frame, stator flux can be calculated as bellow:

$$\begin{cases} \lambda_{sd}^{s} = \int (V_{sd}^{s} - R_a i_{sd}^{s})dt \\ \lambda_{sq}^{s} = \int (V_{sq}^{s} - R_a i_{sq}^{s})dt \end{cases} \tag{16}$$

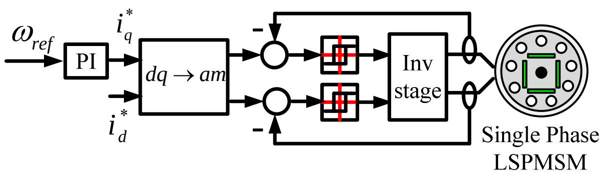

Fig. 4. Field oriented control strategy scheme applied to the motor

$$\tan^{-1}\left(\frac{\lambda_{sq}^{s}}{\lambda_{sd}^{s}}\right) \tag{17}$$

where V_{sd}^{s}, V_{sq}^{s}, i_{sd}^{s}, i_{sq}^{s}, λ_{sd}^{s}, λ_{sq}^{s} are stator d-q axis voltages, currents and fluxes in stationary reference frame. And flux position is:

Generally, speed estimation by differentiating from rotor position produced significant noise. Here, a PLL estimator is used to estimate rotor speed which has been widely used for speed calculation from encoder and resolver signals.

Simulation Results and Discussion

The sensorless control strategy was simulated using MATLAB/SIMULINK for a single phase LSPMSM which its parameter has been given in table 1.

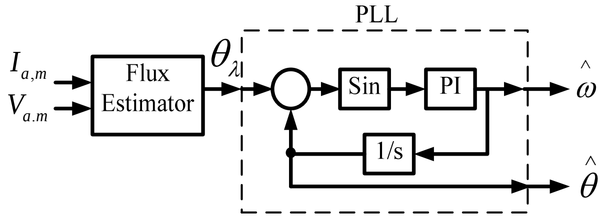

Fig. 5. Speed estimator.

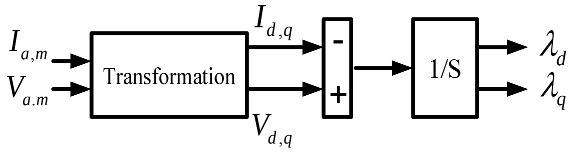

Fig. 6. Flux estimator.

Table 1. Motor parameter

Rated voltage	220v
Rated frequency	50Hz
Rated power	1100w
Stator resistance	7.06Ω
D axis stator inductance	0.2432H
Q axis stator inductance	0.4552H
D axis rotor inductance	0.2424H
Q axis rotor inductance	0.4532H
D axis Mutual inductance	0.2321H
Q axis Mutual inductance	0.4339H
Permanent magnet flux	0.51wb
Inertia	0.0085
Pole pairs	2
Turn ratio	0.78

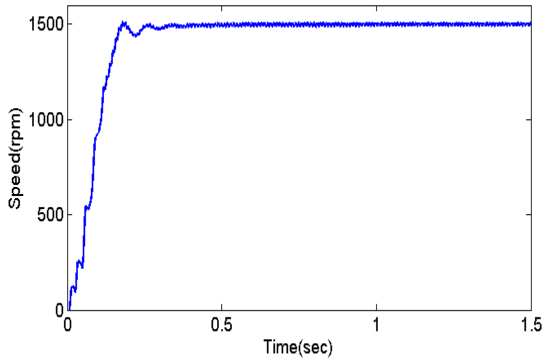

Fig. 7. Rotor speed characteristic.

Initially, the machine model constructed form equations (11)-(15) has been simulated with capacitor-start capacitor-run structure. Starting capacitor is 140μF and at 75% of rated speed capacitor value change to 6μF by a switch. Figure 7 and 8 show speed characteristic and torque-speed curve for the motor respectively.

Simulation results for sensorless field oriented control strategy have been shown in figure 9-13. Figure 9 shows real and reference motor speed which approve good performance of control strategy. At time t=0.8sec mechanical load TL=6N.m has been applied to motor. As it can be seen, speed tracking has been done appropriately. Also, comparing estimated speed and real speed of motor shows the precision of proposed estimator. To implement control method for single phase motors, voltages must be unbalances which figure 10 shows fundamental component of main and auxiliary winding voltages. Stator and rotor d-q axis currents have been shown in figure 11 and 12.

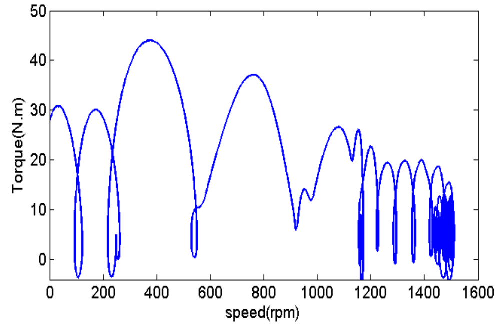

Fig. 8. Electromagnetic torque versus rotor speed.

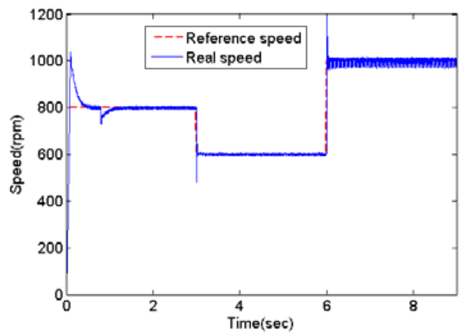

Fig. 9. Real and reference speed.

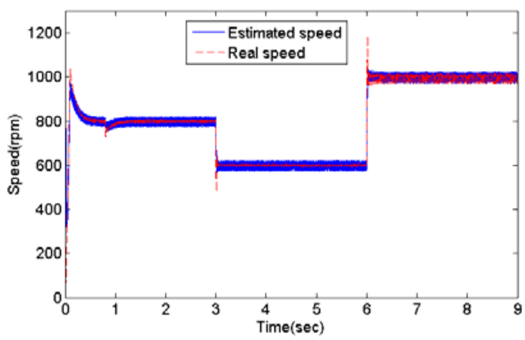

Fig. 10. Real and estimated speed.

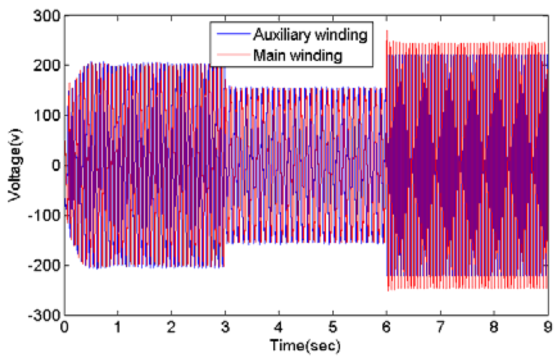

Fig. 11. Fundamental component of voltages.

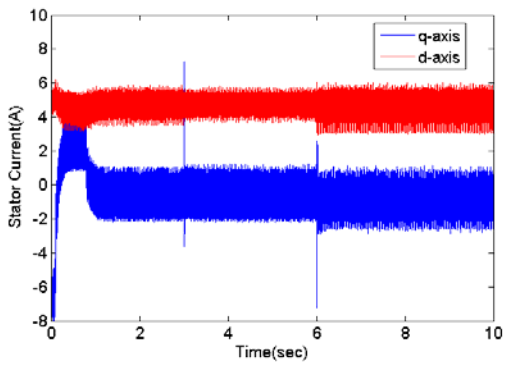

Fig. 12. Stator d-q axis currents.

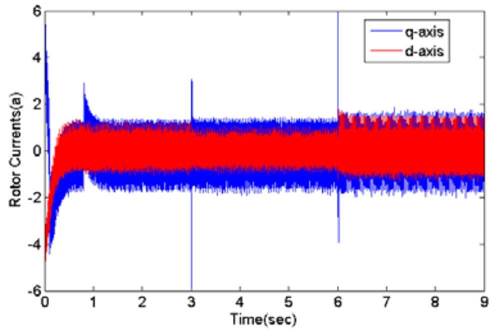

Fig. 13. Rotor d-q axis current.

Conclusions

The single phase type of LSPMSM provides higher efficiency than induction motor and has a better power factor. Due to reduction in power electronic devices and permanent magnet materials, this motor is becoming economic alternative to induction motor

In this paper, the motor was modelled and its performance was investigated with capacitor-start capacitor run system.

Also, sensorless field oriented control strategy was presented for single phase LSPMSM drive. The FOC method was carried out by current hysteresis controllers and its speed regulator is a conventional PI controller. For elimination of speed sensor, a speed estimator using Phase Locked Loop was proposed which used stator voltages and currents.

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Authors: **Abdolhossein Ejlali, Department of Engineering, Mehran Branch, Islamic Azad University, Mehran ilam, Iran.*
***Davood Arab Khaburi, Department of Electrical Engineering, Iran University of Science & Technology (IUST), Tehran, Iran.*
****Javad Soleimani, Department of Engineering, Mehran Branch, Islamic Azad University, Mehran ilam, Iran.*
*E-mails:*ejlali@elec.iust.ac.ir, **khaburi@iust.ac.ir, ***Jsoleimani@elec.iust.ac.ir*