International Journal of Science and Advanced Technology (ISSN 2221-8386) Volume 2 No 4 April 2012
http://www.ijsat.com

Sensorless Vector Control of Single Phase Line Start Permanent Magnet Motors (LSPMs)

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Abstract— **In this paper, sensorless vector control of single phase line-start permanent magnet (LSPM) motors is proposed. Providing two phase voltages for the motor, both start-up and run-up capacitors are eliminated. The provided voltage is such that, electrical angle between main and auxiliary windings voltages is 90 degrees and their amplitude ratio is related to the windings turn ratio. Accordingly, air gap magnetic flux will be similar to the circular form and then the torque pulsation is reduced as same as the three phase motor. Moreover a novel speed/position sensorless control for is developed for closed-loop control of LPMSM that yields a cost effective and reliable solution. In order to improve the efficiency of control, a Maximum Torque Per unit Current (MTPC) method is used, in which the stator current vector is controlled based on the load condition. This method provides maximum torque for a given current and minimizes copper losses for a given torque. Finally, the simulation results are provided to confirm the proposed control design.**

Keywords: sensorless control, single phase LSPM, MTPC control method, efficiency, PLL

I. INTRODUCTION

More than 50% of electrical energy is consumed by electrical motors [1], so a straightforward way to save energy is optimizing electric motors. Efficiency optimization of induction motors has been investigated for over 30 years [2]. An alternative solution is to replace the induction motors with high efficiency permanent magnet (PM) motors, which have gained more attention by reduction of permanent magnet cost [3].

PM motors are not self-starting; in order to solve this problem cage-equipped PM motors so-called line start permanent magnet (LSPMSM) motors are developed [3]. In the case of single phase, these motors need start-up capacitors to start as a single phase induction motor. In addition, to achieve a better performance some papers use a run-up capacitor [4]. The thorough analysis of start-up, synchronization and steady state operation of these motors is done in [5], [6]. In [7] the capacitor start/run and PWM inverter fed methods for starting and running of single phase LSPM motors are compared and the advantages and disadvantages of methods have been investigated.

In the literature, the operation of LSPM motors has been investigated just for fixed-speed and there isn’t any report about application of LPMSM for variable-speed frequency up to now. In this paper, sensorless vector control of single phase LSPM motors is proposed. Using a full bridge single phase IGBT inverter, a 2-phase voltage is provided for the motor and then both start-up and run-up capacitors are eliminated. Appling the position/speed estimation method eliminates the cost position sensors and leads to low-cost and high reliable system.

In the region lower than base speed operating, one performance criteria can be optimized while torque linearity is being maintained at the same time [8]. Using this degree of freedom, many control strategies are reported that can be categorized in these groups: 1) Zero d-axis Current (ZDAC) [9], 2) Maximum Torque per unit Current (MTPC) [10], 3) Maximum efficiency (ME) [11], 4) Unity Power Factor (UPF) [12] and 5) Constant Mutual Flux Linkages (CMFL) [12]. In order to improve the efficiency of the system, in this paper the MTPC method is applied, in which stator current vector is controlled based on the load condition that leads to maximum torque for a given current and minimizes the copper losses for a given torque.

The rest of this paper is organized as follows. In section II the mathematical model of the motor is developed and simulated. In section III, the speed estimation scheme as well as vector control method are presented and section IV contains simulation results.

II. MATHEMATICAL MODEL

The employed motor is a single phase LSPM capacitor-start capacitor-run motor which its parameters are listed in table A.1 (see appendix A). Since the motor has an asymmetry on its stator electric circuit and rotor magnetic circuit, the process of mathematical modeling and analysis has two main steps [7]:

- Winding transformation: The stator windings are assumed to have the same copper weight and distribution i.e., $r_s = r_m = \beta^2 r_a$, $A_a = \beta A_m$ and $L_{lm} = \beta^2 L_{la}$ [5] in which $\beta = N_m / N_a$. Using these assumptions winding transformation refers parameters to auxiliary winding side. So the motor windings will be ideal 2-phase windings. Transformation of voltages and currents can be done as follows

$$\begin{bmatrix} v'_a \\ v'_m \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1/\beta \end{bmatrix} \begin{bmatrix} v_a \\ v_m \end{bmatrix} = T_v \begin{bmatrix} v_a \\ v_m \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} i'_a \\ i'_m \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & \beta \end{bmatrix} \begin{bmatrix} i_a \\ i_m \end{bmatrix} = T_i \begin{bmatrix} i_a \\ i_m \end{bmatrix} \qquad (2)$$

- dq transformation: It transforms the ideal 2-phase system from stationary frame into a fixed rotor reference frame to eliminate time varying parameters. The transformation matrix is given by:

$$T_{dq} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \qquad (3)$$

Using these transformations the KVL equations are as follows:

$$V_{sq} = r_s i_{sq} + \omega_r \lambda_{sd} + \frac{d\lambda_{sq}}{dt} \qquad (4)$$

$$V_{sd} = r_s i_{sd} - \omega_r \lambda_{sq} + \frac{d\lambda_{sd}}{dt} \qquad (5)$$

$$V_{rq} = r_{rq} i_{rq} + \frac{d\lambda_{rq}}{dt} = 0 \qquad (6)$$

$$V_{rd} = r_{rd} i_{rd} + \frac{d\lambda_{rd}}{dt} = 0 \qquad (7)$$

where V_{sq}, V_{sd}, V_{rq} and V_{rd} are the stator and rotor voltages, $\lambda_{sq}, \lambda_{sd,} \lambda_{rq}$ and λ_{rd} stator for linkage fluxes of stator and rotor and i_{sq}, i_{sd}, i_{rq} and i_{rd} represent stator and rotor currents, respectively$.\omega_r, r_s, i_{rd}$ and i_{rq} denote rotor speed, stator resistance and rotor resistances, respectively. Flux linkages can be written as follows [14]

$$\lambda_{sq} = L_{sq} i_{sq} + L_{mq} i_{rq} \qquad (8)$$

$$\lambda_{sd} = L_{sd} i_{sd} + L_{md} i_{rd} + \lambda_m \qquad (9)$$

$$\lambda_{rq} = L_{rq} i_{rq} + L_{mq} i_{sq} \qquad (10)$$

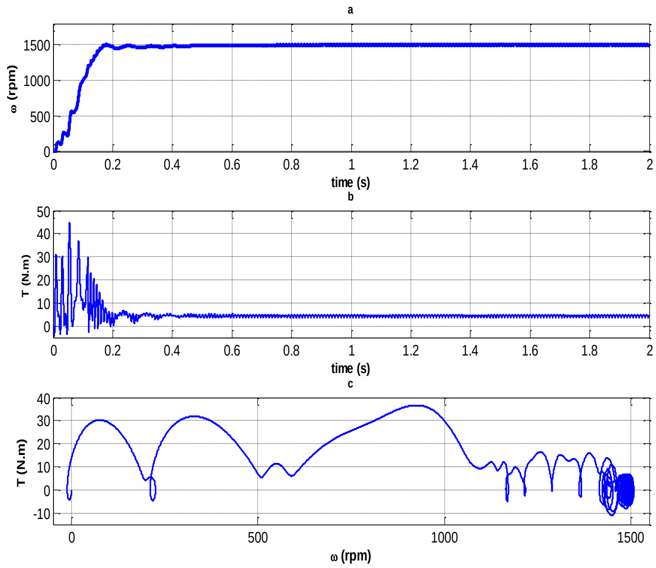
$$\lambda_{rd} = L_{rd} i_{rd} + L_{md} i_{sd} + \lambda_m \qquad (11)$$

where $L_{sq}, L_{sd}, L_{rq}, L_{rd}$ are stator and rotor self inductances, respectively and L_{mq} and L_{md} are manual inductances and the permanent magnet flux is represented by λ_m. Electromagnetic torque of the motor is given by [14]:

$$T_{em} = p\left(L_{sd} - L_{sq}\right) i_{sd} i_{sq} + p\left(L_{md} i_{rd} i_{sq} - L_{mq} i_{rq} i_{sd}\right) + p\lambda_m i_{sq} \qquad (12)$$

where p is the motor pole pairs. In Eq. 12 the first term is reluctance torque and is produced due to the saliency of rotor. The second term is cage torque, which is the main component of the starting torque. This term disappears in synchronous speed. The third term is produced by the magnet and as investigated in, it has a braking effect during start-up process, called magnet braking torque [5].

The mathematical model of the motor is simulated in MATLAB/SIMULINK. Fig. 1 shows some characteristics of the motor.



FFig.1. Some characteristics of the study motor, a) synchronization process at T_{load} = 4 N.m, b) electromagnetic torque at T_{load} = 4 N.m and c) torque versus speed characteristic

III. Sensorless Vector Control

The power stage and control structure of the study system is depicted in Fig.2. The power stage is a full bridge single phase IGBT inverter with split DC-Link structure. While one end of each motor winding is grounded, the other end is connected to the inverter terminal.

Although this configuration is very simple to provide 2-phase voltages, it suffers from unbalance DC capacitor voltages and needs a balancing control circuit in application.

Control system has a multi-loop structure. Inner loop is a fast loop that guarantees tracking of dq reference currents. Since based on a rule of thumb in classic control the outer loops should be slower than inner ones, the speed control loop is slower than inner loop and it dictates dynamics of the system. The details of other control blocks are in the following subsections.

In order to achieve an ideal two phase motor the control system should provide two voltages that the electrical angle between them is 90 degree and their amplitude satisfy the following equation (12)

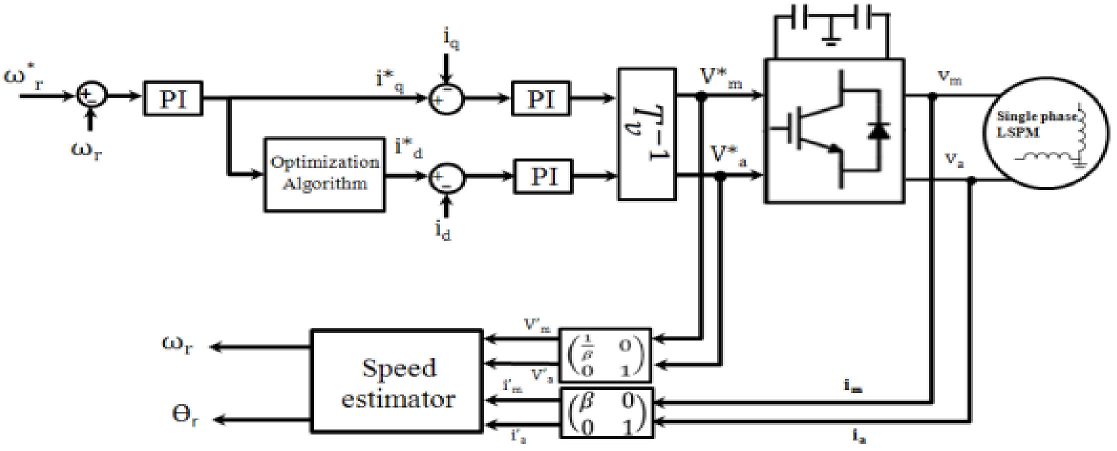


Fig.2. The power stage and control structure

$$V_m = \beta V_a \qquad (13)$$

Since

$$Z_m = \beta^2 Z_a \qquad (14)$$

It results:

$$i_a = \beta i_m \qquad (15)$$

Eq. (15) means that the motor works as an ideal two-phase motor [15].

A) Speed estimation

In order to decrease the prime cost of speed control and increase the system reliability, the sensorless method is used. The speed estimation method is based on stator flux estimation. Stator flux vector can be obtain by the following equations [8]

$$\lambda_m = \int (V'_m - r_s i'_m) dt \qquad (16)$$

$$\lambda_a = \int (V'_a - r_s i'_a) dt \qquad (17)$$

where V'_m, V'_a, i'_m and i'_a are voltages and currents in the ideal 2-phase reference frame, respectively. Assuming that the inverter is approximately ideal, and the voltage drop on its switches is very low, voltage measurement sensors can be eliminated

and the output of PI current controllers which are transformed into ideal 2-phase (by winding transformation) can be used. After making orthogonal fluxes from Eq. (16) and (17) tan^{-1} block is used to determine the position of flux vector. As shown in Fig. 3, to get rid of noise effect, a PLL is used to extract the rotor speed from the estimated position [16].

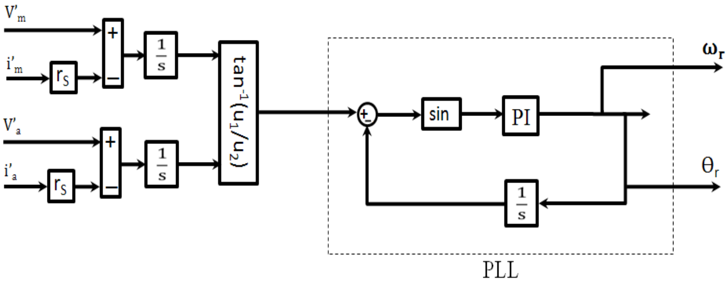


Fig.3. Speed and position estimation

B) Optimization Method

Since in this study motor reluctant torque component is considerable, ZDAC method is not effective. Simulation results show that the stator copper loss is the main portion of the motor losses (copper loss≈ 61%, mechanical loss ≈ 30% and iron loss ≈ 9%). Taking these results into account, MPTC method seems appropriate to optimize drive performance. This method provides maximum torque for a given current. This, in turn, minimizes copper losses for a given torque.
The stator copper losses can be written as follows [11]

$$W_{cu} = r_s I_s^2 = r_s\left(i_d^2 + i_q^2\right) \qquad (11)$$

Where $I_s$is stator current.By substituting i_q from Eq. 10 and setting the derivative of W_{cu} with respect to i_d, equal to zero and solving the equation for the independent variable i_d, the optimization constraint on i_d can be obtained as follows

$$i_q^2 = i_d^2 + \left(\frac{\lambda_m}{L_d - L_q}\right) i_d \qquad (12)$$

By solving this equation for different values of i_q, it is possible to provide a look-up table and use it in optimization loop. Fig. 4 shows i_d vaues as a function of i_q.

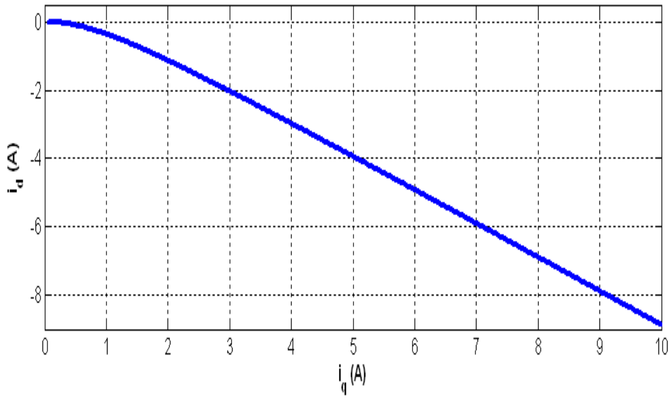


Fig.4. I_d versus i_q

IV. SIMULATION RESULTS

In this section for verification of the presented control system, the model of control system is implemented in MATLAB/SIMULINK and simulated.

At first, a step change of the speed is applied to control system while the load torque is held constant in T_{load} = 4 N.m. Start-up performance and accuracy of the speed reference tracking can be seen in Fig. 5. Moreover, the main and auxiliary winding currents are also shown. It can be seen that the ratio of auxiliary winding current to main winding current is equal to β which is the ideal operation requirement for the single phase motor, as stated in Eq. 15.

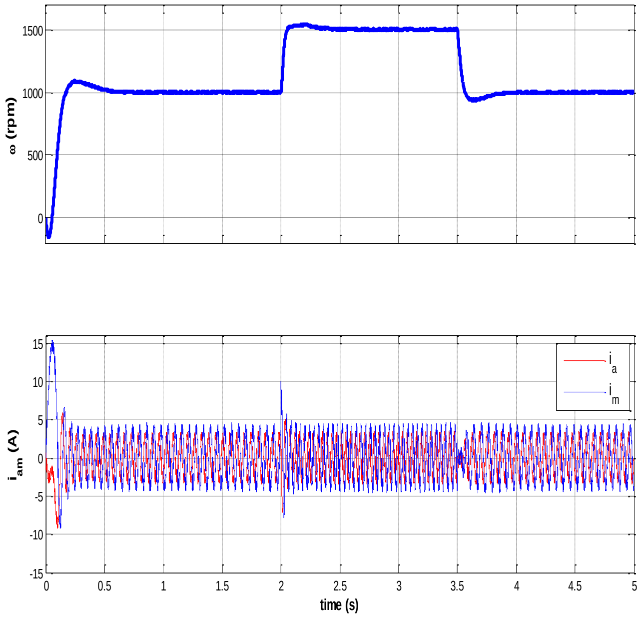


Fig.5. Motor speed and currents

In the second step of simulation, the load torque is changed whereas the reference speed is held constant. In this case the electromagnetic torque, the main and auxiliary winding currents and the reference values of q and d axis currents are shown in Fig. 6. The reference value of q axis current is determined by the speed loop, while optimization requirements determine the reference value of d axis current (Eq. 12).

A comparison between stator vector current in ZDAC and MTPC control methods is done in Fig. 7. For non-saliency types of LSPM motors, the MTPC and ZDAC control strategies lead to the same results. Since, the employed motor of this study has saliency, it can be seen that the MTPC control method is superior in torque per unit current and has higher efficiency comparing to the ZDAC method.

In slight load, the two control strategies yield the same stator currents. But while increasing the load torque, the stator current of ZDAC controlled motor increases with an excessive rate. It should be noted that ZDAC control strategy can not deliver more than 4.6 N.m at *ω* =1000 rpm. It is because of elimination of the motor reluctance torque.

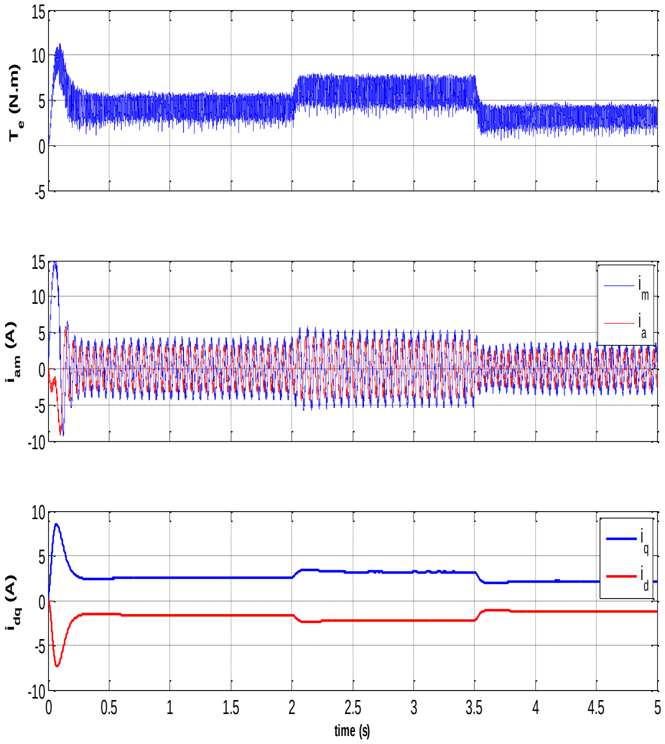


Fig.6. Electromagnetic torque, main and auxiliary currents and reference i_d and i_q currents

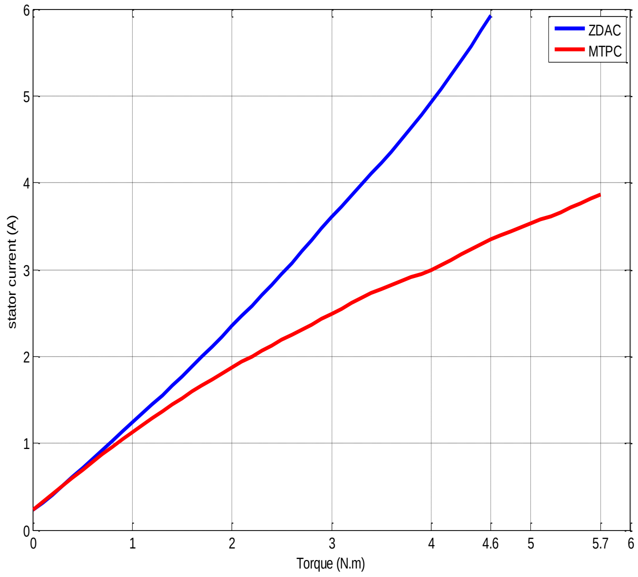


Fig.7. stator current ($I_s = \sqrt{i_{sd}^2 + i_{sq}^2}$) versus load torque for ZDAC and MTPC control strategies

V. CONCLUSION

In this paper a single-phase line-start PM motor has been controlled via well-known vector control scheme. To reduce the drive cost and get more reliability, a position/speed estimation method based on linkage-flux has been developed. Using the presented sensorless vector control provides the voltage in which the air gap magnetic flux is close to a circular form. So, the torque pulsation has been eliminated and the motor behaves as a three-phase induction motor. Moreover, a Maximum Torque per unit Current (MTPC) method has been used to enhance the efficiency and maximizes the torque. On this way, the stator current vector is controlled based on load condition. Simulation results show that MTPC control method is more accurate in torque per unit current and therefore efficiency, as compared to the ZDAC method.

Appendix A

Table A. Parameters of the study motor

parameter	symbol	value	unit	parameter	symbol	value	unit
Nominal voltage	$V_n\ (rms)$	220	V	Rotor d-axis inductance	L_{rd}	0.242	H
Nominal power	P_n	1100	W	Rotor q-axis inductance	L_{rq}	0.453	H
Nominal power	f_n	50	Hz	Start-up capacitor	C_s	110	μF
Stator resistance	r_s	7	Ω	Run-up capacitor	C_r	15	μF
Stator d-axis inductance	L_{sd}	0.243	H	Permanent magnet flux	λ_m	0.5	Wb
Stator q-axis inductance	L_{sq}	0.455	H	Pole pairs	p	2	-
Magnetization d-axis inductance	L_{md}	0.232	H	Rotor inertia constant	J	0.0085	Kg.m^2
Magnetization q-axis inductance	L_{mq}	0.434	H	Windings turn ratio	β	0.78	-
Rotor d-axis resistance	r_{rd}	4.15	Ω	Friction factor	F	0.002	N.m.s
Rotor q-axis resistance	r_{rq}	3.15	Ω				

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