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Flux Search Control of Field Oriented Control of Six-Phase Induction Motor supplied by SVPWM

***Abstract**. This paper deals with the efficiency optimization of Field Oriented Control (FOC) of a six–phase induction motor supplied by Space Vector PWM (SVPWM) using the flux Search Controller (SC) technique. The proposed technique is based on controlling flux to achieve maximum efficiency at light load or low speed. Flux search controller technique is not only cost effective and easy to implement but also robust against parameter variations. Flux control algorithm in six-phase induction machine speed controller reduces 6n±1 harmonic loss as well as other losses like that of copper and core. Simulation results are carried out and they verify the effectiveness of the proposed approach.*

***Streszczenie.** Przedstawiono metodę optymalizacji skuteczności sześciofazowego silnika indukcyjnego zasilanego za pośrednictwem SVPWM przy wykorzystaniu techniki SC. Metoda SC bazuje na kontroli strumienia w celu osiągnięcia maksimum wydajności przy małych obciążeniach i małej prędkości. Zaproponowana kontrola strumienia w silniku sześciofazowym redukuje straty. (**Kontrola strumienia jako metoda optymalizacji sześciofazowego silnika indukcyjnego zasilanego za pośrednictwem SVPWM**)*

Keywords: six phase induction motor- efficiency optimization- Field Oriented control- SVPWM- flux search control.
Słowa kluczowe: silnik indukcyjny, optymalizacja wydajności, kontrola strumienia

Introduction

Advantages of multi-phase machines have resulted in their possible attention in some applications. These machines have some advantages compared with three or one phase machines such as higher redundancy in fault conditions [1][2]. Other advantages of these machines are lower dc-link voltage requirement, lower power per phase [3][4], and lower rotor harmonic currents and stator copper loss [4]. Multiphase induction machines are used in some applications like high marine propulsion, aerospace applications [3][5][6].

Because six-phase induction machines are recently in attention and frequently in use, efficiency improvement of these machines can be important. There are some papers proceed to this important subject. Williamson *et al*. [4] worked on multi- phase machine pulsating and losses. Efficiency analysis of Voltage Source Inverter (VSI) fed three-phase and dual three-phase induction machines and comparing three-phase and six-phase induction machines efficiency is reported in [7].

If the six-phase induction motor works in a speed or torque under its nominal point, the motor efficiency becomes less than nominal. While the six-phase induction motor is controlled by rotor field oriented as mentioned in [3][6][8]. Generally, in FOC of the six-phase machine mentioned above, the flux component of motor is set to maintain the rated field flux in the whole range of loading to get the best transient response. Thus, the efficiency in the light load is decreased. There are many approaches for choosing a suitable control method implanted in other machines like SC [13][14][15] and Loss Model Control (LMC)[16-20].

VSI fed six-phase induction machine can be controlled by the conventional SVPWM, SPWM, and SVPWM techniques. In the conventional SVPWM, two separated three-phase SVPWM are used. In this method, each SVPWM has two none zero and one zero voltage vector. Controlling variables in d-q plan in the conventional SVPWM causes large harmonic currents on the $(z_1 - z_2)$ subspace [20].

In the SPWM technique with sine and triangular carrier waves, the voltage vector in $(z_1 - z_2)$ plane is not minimum, thus large harmonics in that subspace are produced [20]. These current harmonics circulate only in the stator and cause additional losses [21]. The amplitude of these harmonics can be reduced by adding active filter or a change in the driving technique. One of the suitable techniques for the six-phase induction machine driving that minimize these harmonics is SVPWM [21][22][23].

Space vector modulation in induction machine is used to generate harmonically optimum waves at the output. The PWM switching frequency is quantitatively limited, since the SVM technique is complex and computationally intensive [21][23]. Yazdani *et al*. [24] proceeds full control of the voltage gain up to the maximum achievable gain with negligible low-order harmonics and utilizes a simple classification algorithm for the implementation of the space vector modulation (SVM) in both linear and over modulation modes.

The innovation of this paper is to reduce loss in six-induction motors with SC technique where it is operated below its nominal torque or speed. In addition, in this paper, we implement SVPWM in the FOC. The first part of this paper is machine modeling and analysis in VSD (Vector Space Decomposition) method. Then the field oriented control of six-phase induction motor is exposed. SVPWM control of six-phase induction motor and the influence of this technique in efficiency improvement is described in next section. Then proposed losses, input power, output power, and efficiency modeling in 6PIM are presented. In the next section, the flux search control in 6PIM is investigated. Simulations results are shown finally.

Six-phase Induction Motor Model

The mode of 6PIM described in [8][20] has been used in this paper. Six-phase induction machine has two sets of three phase windings shifted by 30 or 60 electrical degrees and single or double neutral point (isolated neutral points or double neutral point is popular). The Six-phase induction machine considered in this paper consists of a stator with two separate windings shifted by 30 electrical degrees and a double neutral point, having similar pole numbers and parameters.

The popular method in six-phase induction machine modeling is VSD (Vector Space Decomposition). In VSD method, the machine modeling is achieved in three two-dimensional orthogonal subspaces [20]. Fundamental harmonic of the machine, which produces electromechanical energy conversion and the harmonics of the order 12n±1 (n=1, 2, 3 …) are mapped to the $(d-q)$ subspace. Harmonics of the order 6n±1 (n=1, 3, 5 …) are mapped to $(z_1 - z_2)$ subspace and produces losses and then they must be reduced to improve efficiency. Third harmonics are mapped to $(o_1 - o_2)$ subspace. These harmonics become zero by isolating the neutral points of two three-phase windings. In modeling six-phase induction machine we assume that: flux path is linear, machine windings are sinusoidally distributed, and mutual inductance is negligible [5]. The voltage equations of the motor in the $(d-q)$ subspace in the rotary reference frame can be achieved by using the [T6] transformation of the motor voltage equations to this subspace. This model can be described by the following set of differential equations:

$$(1)\begin{cases}\overline{V}_s = R_s\overline{I}_s + \rho\overline{\Psi}_s + j\omega_e\overline{\Psi}_s \\ 0 = R_r\overline{I}_r + \rho\overline{\Psi}_r + j(\omega_e - \omega_r)\overline{\Psi}_s\end{cases}, \ \rho = \frac{d}{dt}$$

$$(2)\begin{bmatrix}\overline{\Psi}_s \\ \overline{\Psi}_r\end{bmatrix} = \begin{bmatrix}L_s & M \\ M & L_r\end{bmatrix}\begin{bmatrix}\overline{I}_s \\ \overline{I}_r\end{bmatrix} \Rightarrow \begin{bmatrix}\overline{I}_s \\ \overline{I}_r\end{bmatrix} = \begin{bmatrix}\sigma L_r & -\sigma M \\ -\sigma M & \sigma L_s\end{bmatrix}\begin{bmatrix}\overline{\Psi}_s \\ \overline{\Psi}_r\end{bmatrix}$$

Where: $\sigma = \dfrac{1}{L_s L_r - M^2}$

$$(3)\ \begin{cases}\overline{\Psi}_s = \psi_{sd} + j\psi_{sq}, \bar{I}_s = I_{sd} + jI_{sq}, \overline{V}_s = V_{sd} + jV_{sq} \\ \overline{\Psi}_r = \psi_{rd} + j\psi_{rq}, \bar{I}_r = I_{rd} + jI_{rq}, \overline{V}_r = V_{rd} + jV_{rq}\end{cases}$$

~~$L_s = L_{ls} + M$, $L_r = L_{lr} + M$, $M = 3L_{ms}$~~

Electromechanical energy conversion is as the following:

$$(4)\qquad T_e = \frac{3P}{2} I_m\left(\overline{\Psi}_r . \overline{I}_r^{\,*}\right)$$

The dynamic model of the machine after applying [T6] to machine voltage in $(z_1 - z_2)$ subspace is:

$$(5)\quad \begin{bmatrix}V_{sz1} \\ V_{sz2}\end{bmatrix} = \begin{bmatrix}R_s + \rho L_{ls} & 0 \\ 0 & R_s + \rho L_{ls}\end{bmatrix}\begin{bmatrix}i_{sz1} \\ i_{sz2}\end{bmatrix}$$

The control algorithm and supplying technology must minimize the current harmonics generated in the subspace. In figure (1), diagram of six-phase induction motor and inverter is depicted.

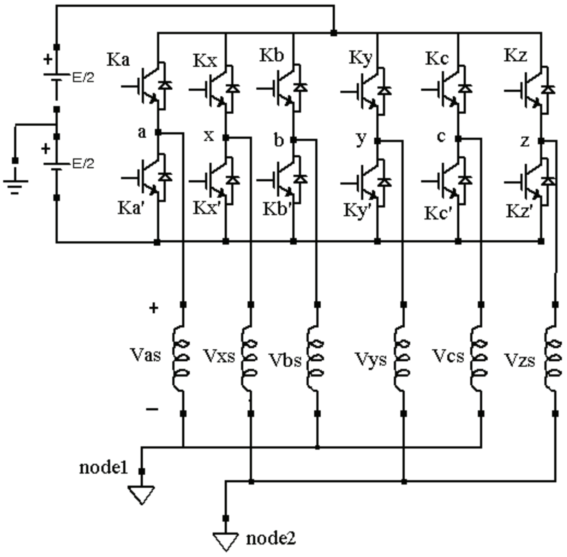

Fig. 1. Diagram of six-phase induction motor and inverter

Field Oriented Control of Six- phase Induction Motor

In FOC of 6PIM $\psi_{rq} = 0$, thus by (1) and (2) we can say:

$$(6)\qquad I_{rq} = -\frac{M}{L_r} I_{sq} \quad , \psi_{rd} = \frac{MI_{sd}}{1 + ST_R}$$

$$(7)\qquad \omega_s = -\frac{R_r I_{rq}}{\psi_{rd}} = \frac{M}{T_R}\frac{I_{sq}}{\psi_{rd}}$$

$T_R = \dfrac{L_r}{R_r}$ is rotor time constant. Thus from (4) and (6) the motor torque in FOC is defined as:

$$(8)\qquad T_e = \frac{3P}{2}(\psi_{rd} I_{sq})$$

$$(9)\qquad T_e - T_L - F * \omega = J\frac{d\omega}{dt}$$

From (6), in the steady state, the constant flux can be obtained by constant i_{ds}. As a result, the torque control can be easily obtained by controlling i_{qs} as seen in (8). The general block diagram of a field orientation control system for 6-phase induction motor is shown in Figure 3.

Space Vector PWM Control of Six- phase Induction Motor (6PIM) fed by VSI has very large stator harmonic currents causing extra losses. Low impedance seen by the voltage harmonic of inverter causes large circulating current harmonics with extra losses. Space vector PWM control method is proposed to reduce these harmonics and losses [21 and 23]. The PWM switching frequency is quantitatively limited, because the SVM technique is complex and computation intensive.

To minimize $(z_1 - z_2)$ current harmonics and switching frequency, there are different choices to select space vectors in SVPWM. In the 12-sector SVPWM, each sector is 30^o that is discussed in [23]. In this method, four nearly vectors by maximum amplitude in $(\alpha - \beta)$ subspace resulting in minimum amplitude in $(z_1 - z_2)$ subspace are selected. As mentioned in [11], D6ϕSVPWM-B2 where zero vectors are in the center of selected voltages has better responses. Another technique is the 24-sector SVPWM method where 24 sectors by 15 degrees distance are selected. As mentioned in [22], this choice has less current harmonics in $(z_1 - z_2)$ subspace, but it is more complex than 12-sector and needs a large space in memory. Thus we here use the D6ϕSVPWM-B2 technique in FOC of six-phase induction motor supplying. As mentioned in figure 3, after calculating $\begin{bmatrix}v_{s\alpha}^* \\ v_{s\beta}^*\end{bmatrix}$, these voltages are applied to the motor. For this purpose like [22 and 23], we have six times applied to the vectors in all of sectors calculated as (11). Then, by table III in [23], four of them are selected to be applied to voltage vectors in the inverter. For example, when the reference voltage vector is located in sector 4, voltage vectors V2, 3, 4, and 5 are selected. Then, the voltage vectors applying times are obtained as:

$$t_1 = T_5,\ t_2 = T_6,\ t_3 = -T_3,\ and\ t_4 = T_4$$

For the remaining time, a zero state voltage vector including (0, 7, 56 or 63) is applied.

(10) $$\begin{bmatrix} T1 \\ T2 \\ T3 \\ T4 \\ T5 \\ T6 \end{bmatrix} = k_1 * \begin{bmatrix} -(\sqrt{3}-2) & -1 \\ (\sqrt{3}-1) & -(\sqrt{3}-1) \\ 1 & (\sqrt{3}-2) \\ 1 & -(\sqrt{3}-2) \\ (\sqrt{3}-1) & (\sqrt{3}-1) \\ -(\sqrt{3}-2) & 1 \end{bmatrix} \begin{bmatrix} v_{s\alpha}^{*} \\ v_{s\beta}^{*} \end{bmatrix}$$

$$k_1 = \frac{T_s}{2V_{DC}}$$

Table1 Number of Switching and Array Numbers

V0	V1	V2	V3	V4	V5	V6	V7	V8	V9	V 10	V11	V12
0,7,56, 63	48	56	60	28	12	14	15	7	3	35	51	49

Motor losses determination

Motor losses can be divided into the electrical and mechanical losses. Electrical losses consist of stator and rotor copper losses P_{cu} , copper loss in $(z_1 - z_2)$ subspace P_z and core loss P_{core} -.

The effect of torque ripple variation on mechanical loss is neglected, thus mechanical loss P_m is approximately constant. If the motor output torque and speed are constant, the output power is remained constant.

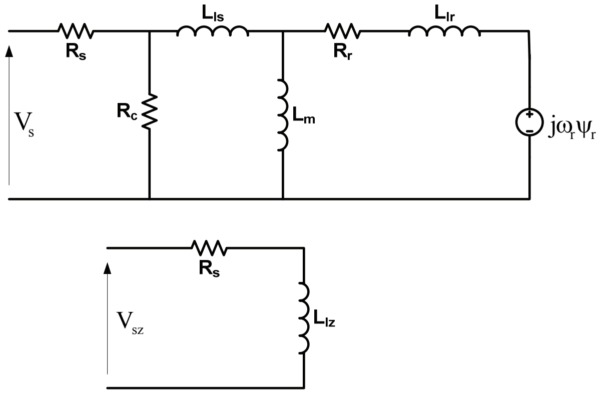

Fig. 2. Loss model of 6PIM.

General expression of the machine input electrical power is calculated as:

(11) $$P_{in} = P_{out} + P_{loss}$$

The total losses of six-phase induction machine is

(12) $$P_{loss} = P_{core} + P_z + P_{cu} + P_m$$

The core losses consist of hysteresis and eddy current loss. The approximate model of core loss is as

(13) $$P_{core} = k_h \left|\Psi\right|^2 + k_e \left|\Psi\right|^2 \approx K \left|\Psi\right|^2$$

Where k_h, k_e, K are the hysteresis, eddy current, and core loss coefficients. From (14) and (6) in the steady state conditions:

(14) $$P_{core} = KM^2 I_{sd}^2$$

The stator and rotor copper losses are essentially determined by the corresponding resistances and currents. In the steady state, there is no leakage inductance. Thus, a typical method for simple modeling of loss power is to ignore the leakage inductance [25]. Stator and rotor copper losses are given by:

(15) $$P_{cu} = P_{cu_s} + P_{cu_r} = \frac{1}{2} R_s \left(I_{sd}{}^2 + I_{sq}{}^2 \right) + \frac{1}{2} R_r \left(I_{rd}{}^2 + I_{rq}{}^2 \right)$$

Copper losses in $(z_1 - z_2)$ subspace are determined by the corresponding resistances and currents. Loss in $(z_1 - z_2)$ domain can be written as:

(16) $$P_z = \frac{1}{2} R_s \left(I_{sz1}{}^2 + I_{sz2}{}^2 \right) + \frac{1}{2} R_s \left(I_{rz1}{}^2 + I_{rz2}{}^2 \right)$$

The mechanical loss depends on rotor speed:

(17) $$P_m = k_m \omega_r{}^2$$

The mechanical loss is constant because motor speed is constant. Another loss is inverter loss, which should be added to the above equations. However, we ignore the inverter loss due to its negliable value. To simplify computing of P_{in} , we can use (18). As seen in this equation, we do not need to calculate P_{loss} . Input power can be calculated using only DC voltage and current.

(18) $$P_{in} = V_{dc} I_{dc}$$

From (12) to (17), we can get the expression for total motor losses:

(19) $$P_{loss} = \frac{1}{2}\left[R_S \left(i_{ds}^2 + i_{qs}^2 \right) + R_r \left(\frac{L_m}{L_r} i_{qs} \right)^2 \right] + P_{core} + k_m \omega_r^2$$

The motor torque can be expressed by:

(20) $$T_e = 3 \frac{P}{2} \frac{M^2}{L_R} i_{ds} i_{qs} = K_{Te} i_{ds} i_{qs}$$

Where $K_{Te} = 3 \frac{P}{2} \frac{M^2}{L_R}$

From (14) to (20) total loss is calculated as:

(21) $$P_{loss} = \left(A i_{ds}^2 + B \frac{1}{i_{ds}^2} \right) + \frac{1}{2} \left(R_s \left| i_{sz} \right|^2 + R_r \left| i_{rz} \right|^2 \right) + k_m \omega_r^2$$

where:

$$A = R_s + KM^2,$$

$$B = (R_s + R_r \frac{L_m^2}{L_r^2}) \frac{T_e^2}{K_{Te}{}^2},$$

By fixing the load in the simulation operating conditions, coefficient A is almost 30 to 100 times as much as B. Reduction of flux in search algorithm is resulted in reducing Id and increasing Iq because electromechanical motor torque is fixed in the search algorithm. In SVPWM supplying of the six-phase induction motor, the value of loss in z domain is very low and it can be ignored in (21). With (21) and above mentioned coefficient values, decreasing flux leads to reduction in Id and loss. In this study, the motor output power is kept constant because its output torque and speed is constant. Output power is expressed as:

(22) $$P_{out} = T_e * \omega_{rm}$$

After calculating the input power by (11) or (18), the efficiency can be written as:

(23) $$\eta = \frac{P_{out}}{P_{in}}$$

Flux SC of FOC Six-phase Induction Motor

At the light load, the required load torque can be reached by using flux value lower than rated one. For any load torque, there is a value of the flux minimizing the total losses. Two general strategy control were investigated, the first technique is based on loss model of motor to investigate algorithms for efficiency improvement, it is known as Loss Model Control (LMC). the second strategy is

Search Control (SC). Various papers were presented depending on these two strategies and were merged with new algorithms to perform a fast and a good response in motor drive and improve the performance of control algorithm. LMC depends on deducing loss model of IM then proposing an algorithm to minimize losses and improve efficiency. This done through computing the iron loss, copper losses (rotor and stator) by function of stator currents in d-q frame. For a given speed and torque, the solution of the loss model yields the flux current for which the total loss is minimal. The accuracy of LMC depends on the correct modeling and estimation of the motor parameters and the losses considerabl [7]. The SC technique depends on stator or rotor flux increases or decreases step by step until the measured input power is at a minimum. The merits are that this way is insensitive to motor parameters and operating condition, and can include all kinds of losses; including the converter losses since the power entering to the system is measured and used in the optimization algorithm. And the defects are the requirement for extra hardware to measure DC bus current, this way doesn't used in the classical. Also it is difficult to precisely measure the input power in some practical cases. In SC method, input power is selected as objective function and is minimized by adjusting the flux value. The motor flux in each step can be calculated by considering the flux of the previous step as following:

$$|\Psi_s(\ell+1)| = |\Psi_s(\ell)| - \Delta_\psi t \tag{24}$$

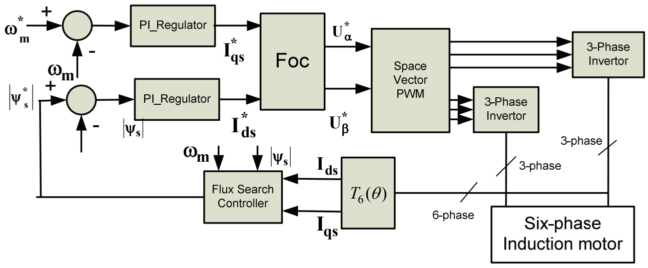

Fig.3 Diagram of flux search controller of FOC of six-phase induction motor supplying by SVPWM.

Results

In order to validate the efficiency of the proposed method, a computer simulation model is implemented using Matlab. Fig. 3 show the block diagram of the method. The specification of the six-phase induction motor used for simulations is shown in Table 4. The proposed algorithm is applied to the motor to show the preference of the algorithm in simulation. The electromagnetic torque is calculated based on the currents in the stator rotary *d-q* axis and fed to the mechanical equation. In the SC technique output power is remained fixed to find optimal input power. Because the load torque and rotor speed are constant the output power is remained fixed. Therefore, machine efficiency increases by reducing of input power. If the motor load is lower than nominal point and motor flux is in nominal amount, the core loss in motor is large and efficiency is low. If the motor flux decreases, the input power reduces. By decreasing the flux, the core loss is reduce, but first the copper loss reduces, and then will increase. When the increasing of copper loss is greater than core loss, the input power increasesinstead of reducing. By variation of the flux, the input power is as figure (5-b). When the input power is in minimum point, the efficiency of motor is in maximum point. Results of efficiency optimization simulation of FOC 6PIM supplied by SVPWM is shown in fig. 4-6. In these simulations, motor speed reference is 60 rad/s. The SC algorithm is run at 10th second. After running algorithm, stator flux amplitude is changed with (24). According to fig 6-a, Id current is changed to a value that is less than the nominal value. In as much as load torque is fixed in simulation, reducing Id causes to increase Iq. The flux, mean of input power, and efficiency change in the SC of FOC of six-phase induction motor supplied by SVPWM are shown in fig 5(a) to 5(c).

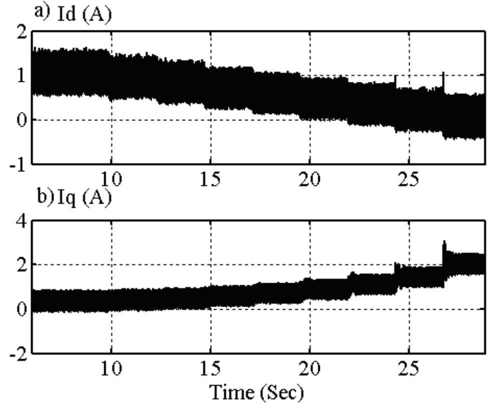

Fig. 4. Simulation results of change Id, Iq in SC of SVPWM FOC of 6PIM in all range.

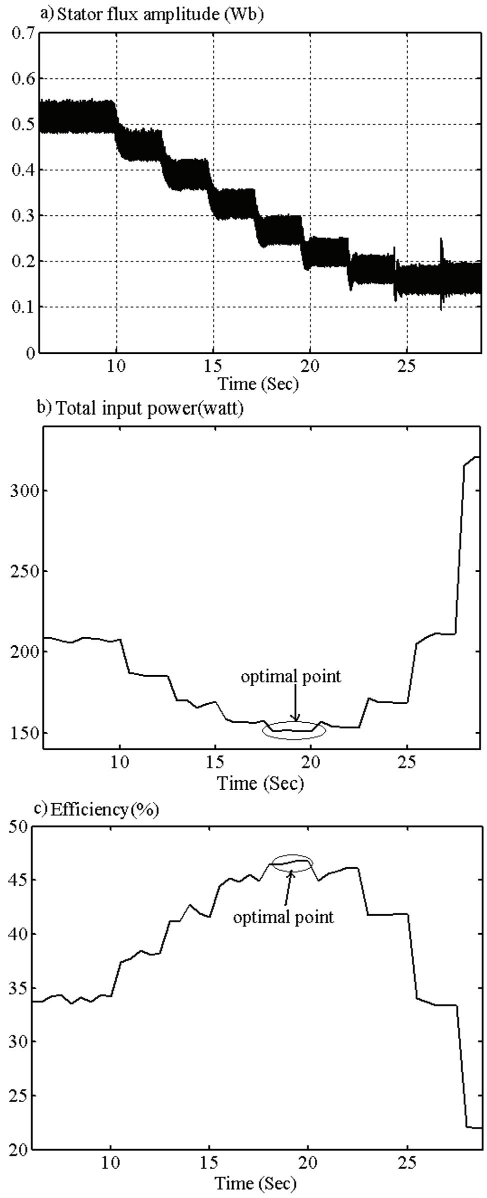

Fig. 5. SC of SVPWM FOC 6PIM a) stator flux, b) mean of input power, c) mean of efficiency.

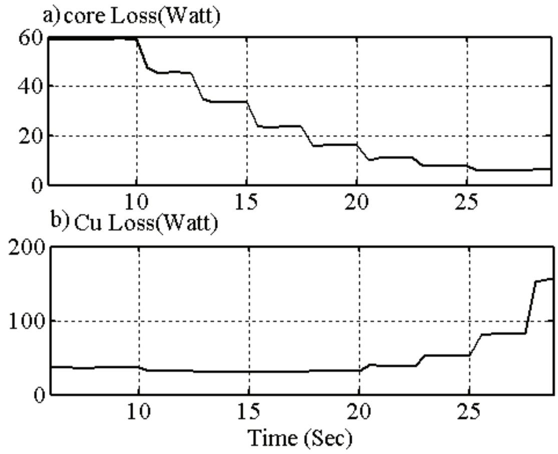

Fig. 6. Simulation results in SC of SVPWM FOC 6PIM a) averaging of core losses, b) averaging of cu loss.

Conclusion

An efficiency optimization method for a six phase induction motor control which is robust against motor parameter variations and does not require any extra hardware is presented in this paper. This method is based on the flux search controller. It is pointed that the FOC of 6PIM loss minimization can be achieved by the flux search controller. SVPMW technique is used in supplying of FOC of six-phase induction motor to minimize zero sequence harmonic currents of order 6k±1. Simulation results given in the paper verify the effectiveness of the proposed method.

Table 2. Motor Parameters

Parameter	Value
Number of poles	4
Mutual inductance	196 mH
Stator resistance	15Ω
Stator leakage inductance	15.1 mH
Rotor resistance	7.91Ω
Rotor leakage inductance	16.3mH

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