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Loss Minimization in Surface Permanent-Magnet Synchronous Motor Drives

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ABSTRACT: The loss minimization in surface permanent magnet synchronous motor drives is investigated. In order to reduce motor losses based on theoretical analysis, a Loss model controller is introduced to specify the optimal air-gap flux that minimizes losses. This Loss model controller is simple and does not affect adversely the cost and complexity of the drive. The Loss model controller implementation does not require knowledge of the loss model. The suggested loss minimization method can be applied in V/f controlled schemes.

KETWORDS: Adjustable-speed drives, efficiency optimization loss minimization, permanent magnet, synchronous motor.

I.INTRODUCTION

Electric machines are employed in almost every industrial and manufacturing process. The need to save energy has drawn the industrial attention to the losses and efficiency of motors. The main efforts for higher efficiency are focused on improvement of materials and optimization of design strategies. However, efficiency can also be improved by intervening in the operational principle of motors. Such methods can be adjustable-speed drives fed through an inverter.

Several simple and effective control methods have been proposed in order to minimize the losses of dc, induction, and synchronous motor drives [1]–[6]. All these methods are based on the air-gap flux weakening and attempt to make the air-gap flux an increasing function of the load torque. This can be achieved by using mainly two control methods: one based on search controllers (SC's) and another based on loss model controllers (LMC's).

Adjustable-speed PM motor drives are rapidly introduced in the area of electric vehicles, computer applications, medical instruments, and motion control devices. These drives are often powered by a battery source. Due to restrictions in energy supply, the improvement of motor efficiency is a most important priority.

Attempts to minimize the loss on PM synchronous motor drives are made in [7]–[10]. An effort to specify the loss minimization condition for surface and interior PM synchronous motor drives is presented in [10]. However, the proposed condition is complicated and its implementation is based on the knowledge of the machine parameters. Consequently, the suggested method is implemented by using a lookup table where a number of costly and time-consuming measurements for each motor are required. Such measurements are practically impossible on motors already in operation and, therefore, the method is not widely applicable.

In this paper, the loss minimization problem in surface PM synchronous motor drives is investigated in detail. The proposed method is based on the air-gap flux weakening and its implementation does not require knowledge of the machine parameters. The proposed method is compared with the conventional "I_d = 0 control" method, where the direct axis component of the stator current is always kept at zero and demagnetization of the permanent magnet is prevented [11].

A block diagram of optimal PM synchronous motor drive is shown in Fig. 1. In this diagram, it is possible to embody one of the two controllers that minimize the losses on the drive. The SC measures the input power to the drive and adjusts the stator voltage, while it searches the minimum input power. The LMC measures the speed and armature current and, through the motor loss model, it specifies the optimal value of stator voltage. According to relevant literature [5] and [6], SC's have several disadvantages and, consequently, LMC's offer a superior performance. For example, SC's cannot successfully find the minimum of the input power function that is smooth and flat around the

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minimum. An SC in a real system does not reach a steady state and causes oscillations in the air-gap flux that results in undesirable torque disturbances.

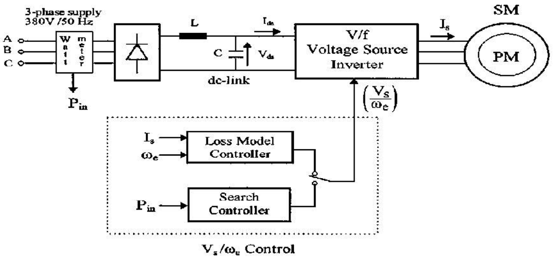

Fig.1.Optimal surface PM synchronous motor.

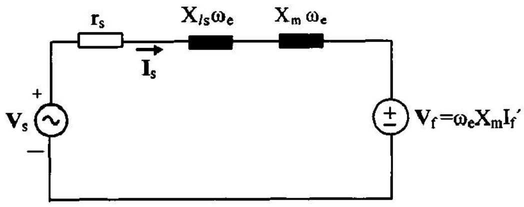

Fig.2.Per-unit equivalent circuit of surface PM synchronous motor.

II.RELATIONSHIPS BETWEEN PM SYNCHRONOUS MOTOR VARIABLES

In Fig. 2, the per-phase equivalent circuit of the PM synchronous motor is given in the p.u. system. In this circuit, the effects of iron and stray losses are ignored. The phasor diagram in synchronously rotating - reference frame is illustrated in Fig. 3. Since the resistance of the stator winding is very small, the respective voltage drop could be neglected. The stator current I_s is resolved into the respective d and q-axis components. The excitation current I'_f is aligned with the axis. The d and q-axis components of stator voltage V_s are given, respectively, by

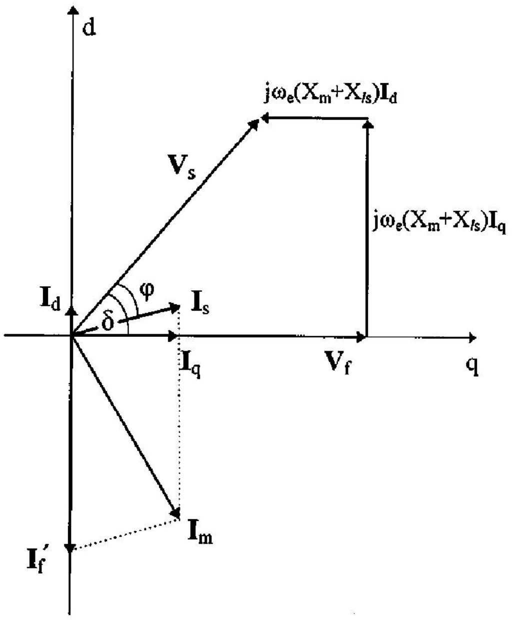

Fig.3. Approximate phase diagram of surface PM synchronous motor.

$$V_{sd} = j\omega_e X_m I'_f - j\omega_e (X_m + X_{ls}) I_d \quad (1)$$

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$$V_{sq} = j\omega_e (X_m + X_{ls}) I_q \quad (2)$$

and

$$V^2_s = V^2_{sd} + V^2_{sq} \quad (3)$$

Furthermore, the d- and q-axis components of magnetizing current I_m are given, respectively, by

$$I_{md} = I'_f - I_d \quad (4)$$

$$I_{mq} = I'_q \quad (5)$$

Finally, the electromagnetic torque of the motor is given by

$$T_e = X_m I'_f I_q \quad (6)$$

III. LOSS MODEL

The main losses on the PM synchronous motor are the following.

1) Copper Losses: These are due to the flow of load current through the stator windings and are given by

$$P_{cu} = r_s I_s^2 \quad (7)$$

2) Iron Losses: These are due to hysteresis and eddy currents and are given by the following empirical formula :

$$P_{Fe} = c_{Fe}\omega_e^{\beta}\phi_m^2 = c_{Fe}\omega_e^{\beta} X_m^2 I_m^2 \quad (8)$$

where ß = 1.5~1.6

3) Stray Losses: These arise on the copper and iron of the motor and are given by

$$P_{str} = c_{str}\omega_e^2 I_s^2 \quad (9)$$

4) Mechanical Losses: These are due to friction and windage losses and are proportional to the square of rotating speed

$$P_m = c_m \omega_e^2 \quad (10)$$

5) Harmonic Losses: These are additional losses due to nonsinusoidal stator voltage that supplies the synchronous motor. The presence of harmonic currents increases the stator copper losses. The presence of harmonic voltages increases the iron losses.

Since mechanical losses are independent from the electrical variables, they are not controlled by flux weakening. Additionally, harmonic losses are not directly controlled by flux weakening. However, these losses are indirectly controlled by the decreasing of the harmonic voltages, because of flux weakening. The losses that can be minimized by flux weakening are

$$P_l = P_{cu} + P_{Fe} + P_{str} = aI^2_s + bI^2_m \quad (11)$$

where

$$a = r_s + cstr\omega^2_e \quad (12)$$

and

$$b = c_{Fe}\omega^{\beta}_e X^2_m \quad (13)$$

Finally, (10) can be expressed in – axes components as follows:

$$P_l = P_{cu}+P_{Fe}+P_{str} = a(I^2_d + I^2_q)+b(I^2_{md}+I^2_{mq}) \quad (14)$$

IV. LOSS MINIMIZATION CONDITION

Generally, the synchronous motor is a double-fed machine and its inputs are the stator voltage V_s and excitation current I'_f. In the PM motor, the field excitation is provided from the PM's, thus, the excitation current I'_f is constant. From (14), the loss minimization condition at steady state (T_e and ω_e constant) with respect to I_d is given by

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$$\frac{\partial P_l}{\partial I_d} \,\Big|_{T_e,\omega_e} = 0 \qquad (15)$$

Because of (4) and (5), condition (15) is satisfied when

$$I_d(a+b) - bI'_f + (a+b)I_q \frac{\partial I_q}{\partial I_d} = 0 \qquad (16)$$

Since the electromagnetic torque is constant, it is deduced that

$$\frac{\partial T_e}{\partial I_d} \,\Big|_{\omega_e} = 0 \qquad (17)$$

From (6), we conclude that (17) is satisfied when

$$\frac{\partial I_q}{\partial I_d} = 0 \qquad (18)$$

From (16) and (18) the following loss minimization condition is deduced:

$$I_{d_{opt}} = \frac{b}{a+b} I'_f \qquad (19)$$

Equation (19) gives the optimal -axis component of stator current. This equation can be applied in current-controlled schemes. It should be noted that I_{dopt} is independent of load conditions; however, it depends on the frequency and loss model parameters. A similar condition is presented in [10]. However, stray losses are not included and the condition is implemented using a lookup table.

Loss minimization condition for V/f-controlled schemes is obtained by substituting (19) in (1). Combining (1), (2) and (3), the optimal ratio V_s/ω_e is given by

$$\left(\frac{V_s}{\omega_e}\right)^2 = I_s^2 (X_m + X_{ls})^2 + I_f'^2 X_m^2 \frac{a - b\left(1 + 2\frac{X_{ls}}{X_m}\right)}{a+b} \qquad (20)$$

V. IMPLEMENTATION OF THE LOSS MINIMIZATION CONDITION WITH V/f -CONTROLLED SCHEME

The use of the SC is the obvious method for implementing the loss minimization condition (20). As shown in Fig. 1, the SC measures the input power to the drive and adjusts the stator voltage V_s so that the input power is minimized. However, experiments prove that the performance of the optimal PM synchronous motor drive with the SC is not satisfactory. Generally, the SC approach has several disadvantages and such performance is expected from the relevant literature [5], [6].

Substituting (12) and (13) in (20), the optimal ratio V_s/ω_e which is a practical measure of the air-gap flux, is given by

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$$\left(\frac{V_s}{\omega_e}\right)^2_{opt} = I_s^2\left(X_m + X_{ls}\right)^2 + \left(I'_f X_m\right)^2 \bullet \frac{r_s + \omega_e^2\left[c_{str} - c_{Fe}\omega_e^{\beta-2}X_m^2\left(\alpha + 2\frac{X_{ls}}{X_m}\right)\right]}{r_s + \omega_e^2\left[c_{str} + c_{Fe}\omega_e^{\beta-2}X_m^2\right]} \quad (21)$$

From (21), we have the equation of LMC

$$\left(\frac{V_s}{\omega_e}\right)_{opt} = \sqrt{K_s^2 I_s^2 + K_f^2\frac{1+\omega_e^2T_1^2}{1+\omega_e^2T_2^2}} \quad (22)$$

Where

$$K_s = X_m + X_{ls} \quad (23)$$

$$K_f = X_m I'_f \quad (24)$$

$$T_1^2 = \frac{c_{str} - c_{Fe}\omega_e^{\beta-2}X_m^2\left(1 + 2\frac{X_{ls}}{X_m}\right)}{r_s} \quad (25)$$

$$T_2^2 = \frac{c_{str} + c_{Fe}\omega_e^{\beta-2}X_m^2}{r_s} \quad (26)$$

The excitation current I'_f in the PM machine is constant, hence, the gain K_f in (24) is constant. K_f is easily derived from the open-circuit test when the machine is operated as a generator. The measured value of the open-circuit stator voltage provides the value of K_f. From (22), it is implied that the V_s/ω_e is composed of two terms

$$K_1 = I_s K_s \quad (27)$$

And

$$K_2 = K_f\sqrt{\frac{1+\omega_e^2T_1^2}{1+\omega_e^2T_2^2}} \quad (28)$$

The former depends on the load condition. The latter is proportional to the excitation electromotive force and depends on the speed. The square-root term at the right side of (28) is the amplitude of the frequency response of a first-order low-pass filter ($T_1<T_2$) with transfer function

$$G(jw) = \frac{1+jwT_1}{1+jwT_2} \quad (29)$$

The filter pole depends on the motor speed. However, as proved in [3] and [8], the filter can be approximated by a first-order low-pass filter with a constant pole provided that the cutoff frequency is the same.

In order to calculate the optimal ratio V_s/ω_e from (22), the values of the measurement of the stator current and motor speed are required. Since the loss minimization occurs at steady state, the reference speed can be used instead of the actual speed.

The conclusion is that, in practice, knowledge of the loss model is not required. The LMC minimizes not only the PM synchronous motor losses, but the whole drive losses as well. Due to the experimental measurement of the LMC parameters, the losses in all drive stages are implicitly included.

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VI.EXPERIMENTAL RESULTS

The control unit of the drive performs either as a loss model controller or as a search controller. The strategy is based on the fact that an abrupt decrease in the air-gap flux causes strong current in stator, loss increment, demagnetization, and electromagnetic torque disturbances. PM synchronous motor with the LMC performs better than the optimal PM synchronous motor with SC.

LMC response to an abrupt torque demand. It can be seen that the LMC compensates the torque demand almost immediately.

The LMC parameters can be easily adjusted, by performing two measurements of the current I_d for two different speed values. The current I_d is adjusted so that minimum power input is accomplished. This two measurements give an equation system with unknowns the parameters K_d and T_2. The solution of the equation system gives the values of K_d and T_2 The measurements are repeated for various couple of speeds, until the desired accuracy is reached.

VII. SIMULATION RESULTS

The simulation is done using MATLAB and the details are as follows, The output waveform for the PMSM is shown in the Fig 4. It contains losses because the input voltage is not in the proper pulse input form and also the stator voltage are not in the proper three phase waveform. The ouput waveform for the PMSM using LMCs is shown in the Fig 5. It does not contain losses. Because the input voltage and stator voltage are in the proper waveform. So it does not contain losses.

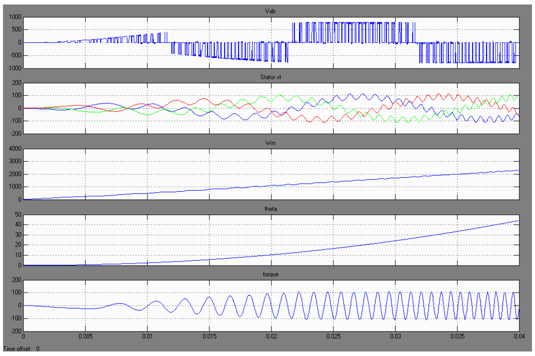

Fig 4.Output Waveform For PMSM

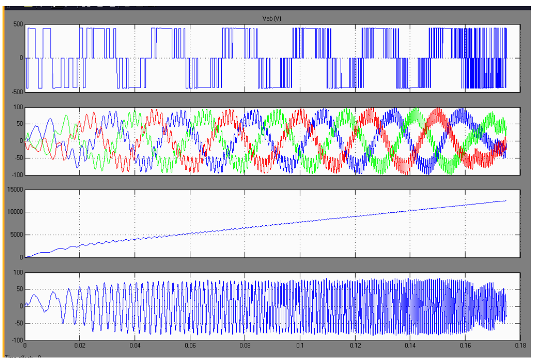

Fig 5.Output Waveform For PMSM Using LMC

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VIII.CONCLUSION

In this paper, the loss minimization problem in surface PM synchronous motor drives at steady state has been investigated. LMC's for determining the optimal ratio V_s/ω_e in V/f controlled schemes have been presented. Although the conception of the suggested method is based on the motor loss model, its implementation does not require knowledge of the loss model. The proposed LMC's do not affect significantly the dynamics of the drive. The suggested loss minimization method can be used in both open and closed speed loop drives.

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