A Novel Efficiency Optimization Strategy of IPMSM for Pump Applications

Guangxu Zhou* and Jin-Woo Ahn†

Abstract – According to the operating characteristics of pump applications, they should exhibit high efficiency and energy saving capabilities throughout the whole operating process. A novel efficiency-optimization control strategy is presented here to meet the high efficiency demand of a variable speed Permanent Magnet Synchronous Motor (PMSM). The core of this strategy is the excellent integration of mended maximum torque to the current control algorithm, based on the losses model during the dynamic and the grade search method with changed step by fuzzy logic during the steady. The performance experiments for the control system of a variable speed high efficiency PMSM have been completed. The test results verified that the system can reliably operate with a different control strategy during dynamic and steady operation, and the system exhibits better performance when using the efficiency-optimization control.

Keywords: Permanent Magnet Synchronous Motor, efficiency-optimization control

1. Introduction

Thanks to their high performance, permanent-magnet synchronous motors (PMSM) are widely used in industrial drive applications [1]. Their main advantages, which are highly appreciated in comparison to those of other solutions such as dc and induction motors, are their high efficiency and high power factor

Loss minimization control strategies have been extensively investigated in literature, and can fundamentally be summarized in two main categories: "loss model control" strategies, and "search control" strategies [2-6]. The "loss model control" technique is based on the development of a mathematical model allowing for the estimation of the motor's energy losses [7]. By expressing the losses as a function of the control variables of the electrical drive, it is then possible to impose an operating condition in order to minimize the whole electrical loss. The "search control" algorithm is based on a searching procedure that can successfully find a maximum efficiency operating point. The latter's advantage is that it doesn't need to know the mathematical model of the motor and its parameters [8-9]. However, the major drawback of this technique is that additional devices (such as voltage and current transducers) are required on the DC-link in order to obtain a measurement of the power absorption of the electrical drive, which results in increasing the system's complexity and costs.

Due to the effect of permanent magnet material, the reactance parameters calculating method of a PMSM is different from other AC machines. For a PMSM, there are no open circuit and short circuit states such as the electrical excited motor. The excitation of permanent magnet material is effected at all times. At the same time, due to different magnetic motive forces and field saturation, the reactance parameters are different. The parameters calculating method must take into account the influence of PM material. The performance of the PM material changes with the running condition of the motor. Consequently, it is difficult to obtain the parameters that have changed with different conditions using the experimental method.

According to the operating characteristics of pump application, it should exhibit high efficiency and have energy saving capabilities during the whole operation. A novel efficiency optimization control strategy is presented in this paper. First, the torque equation is obtained through the precise analysis of the losses model of the interior PMSM, then the maximum torque to current control method is mended during the dynamic state. Second, the gradient search method with variable step by fuzzy logic is used to real time search the optimal running point during the steady operation. Lastly, a DSP-based digital control inverter for a variable speed high efficiency PMSM is developed. The performance experiments for the control system of a variable speed high efficiency PMSM have been completed. The system is verified to be reliable and as seen in the experiment offers perfect performance, and also has the obvious effect of saving on energy.

2. The Efficiency Optimizing Strategy During the Dynamic State

During the dynamic process, the parameter's equations can be achieved from the dynamic mathematical model, including the losses. The classical maximum torque to current is then improved in light of the load characteristics of

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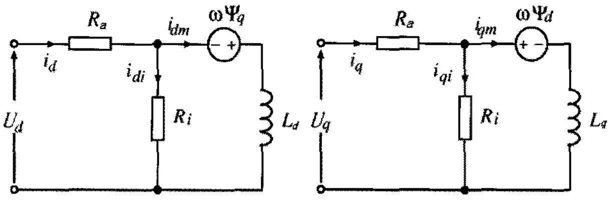
the pump applications.

2.1 PMSM dynamic mathematical model includes losses

As for the interior PMSM, the equivalent electric circuit in Fig.1 is used to analysis the losses and takes the copper and iron loses into accretion. Where R_a is the resistance of copper loss, iron losses including hysteresis loss, and eddy loss, R_i is the resistance of all iron losses. The *d-q* axes armature currents are disported and are distributed to the iron loss currents i_{di}, i_{qi} and torque currents i_{dm}, i_{qm}.



a) *d*- axis b) *q*- axis

Fig. 1. *d-q* axes equivalent circuit for IPMSM.

From a steady state, $L_d(\mathrm{d}i_{qm}/\mathrm{d}t)$ and $L_q(\mathrm{d}i_{dm}/\mathrm{d}t)$ are zero, and the voltage balance equation is expressed as:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = R_a \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix} \tag{1}$$

where the flux linkages Ψ_d and Ψ_q are given as:

$$\begin{cases} \psi_d = L_d i_{dm} + \psi_f \\ \psi_q = L_q i_{qm} \end{cases} \tag{2}$$

(1) is expressed as:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = R_a \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_f \end{bmatrix} \tag{3}$$

where, L_d and L_q are the d-q axes inductances, Ψ_f is the permanent magnet flux linkage, ω is the electrical angular velocity.

The iron loss is expressed in the same way as copper loss. (4) is the equation of copper loss. (5) is the equation of iron loss. (6) is the equality iron loss current.

$$P_{\mathrm{Cu}} = R_a(i_d^2 + i_q^2) \tag{4}$$

$$P_i = R_i(i_{di}^2 + i_{qi}^2) \tag{5}$$

$$\begin{cases} i_{di} = -\dfrac{\omega L_q i_{qm}}{R_i} \\ i_{qi} = \dfrac{\omega(\psi_f + L_d i_{dm})}{R_i} \\ i_{dm} = i_d - i_{di} \\ i_{qm} = i_q - i_{qi} \end{cases} \tag{6}$$

$$P_i = \frac{\omega^2(\psi_d^2 + \psi_q^2)}{R_i} \tag{7}$$

$$\begin{aligned} P_{in} &= (u_d i_d + u_q i_q) \\ &= \left(R_a(i_d^2 + i_q^2) + \frac{\omega^2(\psi_d^2 + \psi_q^2)}{R_i} + \omega\left[\psi_f i_{qm} + (L_d - L_q) i_{dm} i_{qm}\right] \right) \end{aligned} \tag{8}$$

where, P_{in} is the input power, the first item is the copper loss and the second item is the iron loss in the right side; the third item is the electromagnetic power. It is the sum of the mechanical loss, stray loss and mechanical output power. Consequently, the electromagnetic torque is expressed as:

$$T_{em} = p\left[\psi_f i_{qm} + (L_d - L_q) i_{dm} i_{qm}\right] = \frac{P_{ms} + P_s + P_2}{\Omega} \tag{9}$$

2.2 The mended maximum torque to current method

With the increasing of load, the current becomes greater and larger. The stray loss in (9) is an approximately proportional enhancement with the square of i_s, where, i_{sN} is the rated current and P_{sN} is the stray loss at the rated load. Obtaining the linear expression of mechanical loss by experimental method (K_{ms} is a constant) is achieved by:

$$\begin{cases} P_s = \dfrac{i_d^2 + i_q^2}{i_{sN}^2} P_{sN} \\ P_{ms} = K_{ms} \Omega \end{cases} \tag{10}$$

According to the above equations, the torque expression is arranged as (11).

$$T_m = p\left[\psi_f i_{qm} + (L_d - L_q) i_{dm} i_{qm}\right] - K_s(i_d^2 + i_q^2) - K_{ms} \tag{11}$$

where, T_m is the mechanical output torque.

When the traditional maximum torque to current is adopted, the current should be satisfied:

$$\begin{cases} \dfrac{\partial(T_m / i_s)}{\partial i_d} = 0 \\ \dfrac{\partial(T_m / i_s)}{\partial i_q} = 0 \end{cases} \tag{12}$$

Integrating (11) and (12), the solutions of i_d and i_q can't be obtained by the traditional maximum torque to current expression. Then the assistant function (13) is established.

$$F = i_d^2 + i_q^2 + \lambda\Big\{p\left[\psi_f i_{qm} + (L_d - L_q) i_{dm} i_{qm}\right] \\ - K_s(i_d^2 + i_q^2) - K_{ms} - T_m\Big\} \tag{13}$$

where, λ is the Lagrange operator.

$$\begin{cases} \dfrac{\partial F}{\partial i_d} = 2i_d + \lambda(p\begin{bmatrix} -\psi_f K_4 + (L_d - L_q)(-2K_1K_4 i_d + \\ (K_1^2 - K_2K_4)i_q + (K_3K_4 - K_1K_5) \end{bmatrix} \\ \qquad\qquad - 2K_s i_d) = 0 \\ \dfrac{\partial F}{\partial i_q} = 2i_q + \lambda(p\begin{bmatrix} \psi_f K_1 + (L_d - L_q)((K_1^2 - K_2K_4)i_d + \\ 2K_1K_2 i_q - (K_1K_3 + K_2K_5) \end{bmatrix} \\ \qquad\qquad - 2K_s i_q) = 0 \\ \dfrac{\partial F}{\partial \lambda} = p\begin{bmatrix} \psi_f(-K_4 i_d + K_1 i_q - K_5) + \\ (L_d - L_q)(-K_1K_4 i_d^2 + (K_1^2 - K_2K_4)i_d i_q + K_1K_2 i_q^2 + \\ (K_3K_4 - K_1K_5)i_d - (K_1K_3 + K_2K_5)i_q + K_3K_5) \end{bmatrix} \\ \qquad\qquad - K_s(i_d^2 + i_q^2) - K_{ms} - T_m = 0 \end{cases} \tag{14}$$

The non-linear equations are then obtained by the partial derivatives of i_d and i_q and λ from (14). The solutions of this equation are obtained using the Newton method. In the actual application, according to the load characteristic of the pump application, the i_d and i_q current at different torque and speeds are calculated by the proposed method. The mended maximum torque to current control strategy is realized by referring to the table in the DSP program.

3. The Efficiency Optimized Strategy During the Steady State

During steady operation, the gradient searching method is used to find the loss minimization point. The initial point is one dynamic value. To enhance the convergence speed, the step is altered using the fuzzy logic method.

3.1 The gradient searching method with fuzzy logic

The implementation steps of the gradient searching method are as follow:

First, during the search process, the slope is determined as i_d and decreases until the sign of the two slopes is reversed as shown in Fig. 2.

$$S_{21} = (P_2 - P_1)/(i_{d2} - i_{d1}) \tag{15}$$

$$S_{32} = (P_3 - P_2)/(i_{d3} - i_{d2}) \tag{16}$$

Second, a new i_{d4} can be desired from (17),

$$i_{d4} = i_{d3} + 0.5(i_{d2} - i_{d3}) \tag{17}$$

Third, the slope S_{42} can be calculated using (18), followed by a comparison of the sign of S_{32} and S_{42}. If the sign is different, then execute the fourth step, or execute the fifth step.

$$S_{42} = (P_4 - P_2)/(i_{d4} - i_{d2}) \tag{18}$$

Fourth, substitute the marker {2,4,3} by {1,2,3} in Fig. 2. Then execute the second step.

Fifth, substitute the marker {1,2,4} by {1,2,3}, and then execute the second step.

Repeat the above steps, until the convergence point is found.

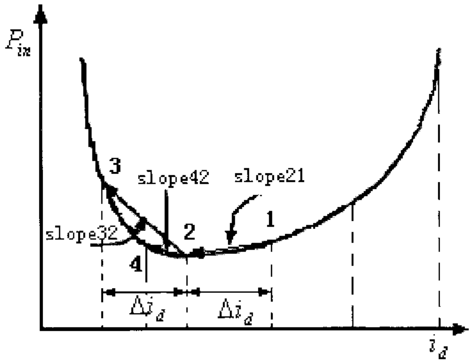
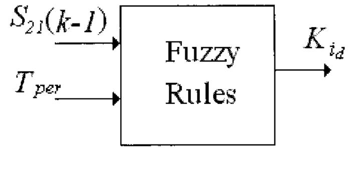


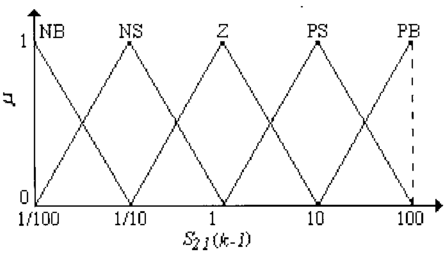
Fig. 2. Different slops of the gradient method

3.2 The step size changing rule by fuzzy logic

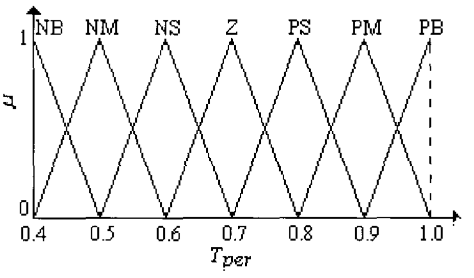
In order to increase the convergence speed, the fuzzy logic method is used to change the steps of the gradient search method on time. According to the load condition and the last slop variation ratio, the new d axis current increment is obtained automatically. Fig. 3 shows the membership functions for variables fuzzy sets.



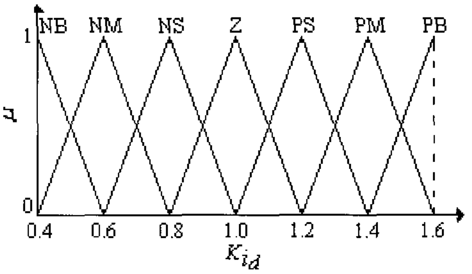
a) Control strategy of fuzzy logical controller



b) Membership function for slope



c) Membership function for torque



d) Membership function for step

Fig. 3. Membership functions for variables fuzzy sets

Table 1. The fuzzy logical rules of different variables fuzzy sets

TABLE 1 Fuzzy rules based matrix

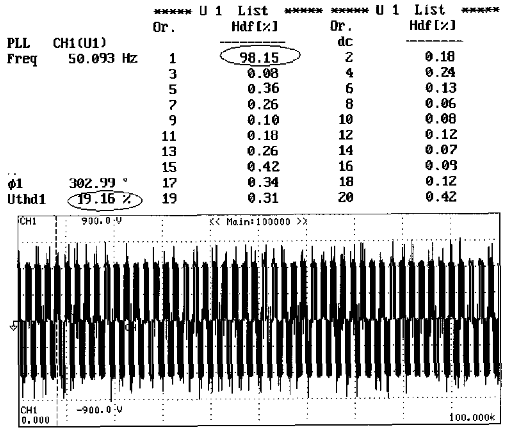
K_{id}		T_{per}						
		PB	PM	PS	Z	NS	NM	NB
S_{21} (K-1)	PB	PB	PB	PB	PM	PS	Z	NS
	PS	PB	PB	PM	PS	Z	NS	NM
	Z	PB	PM	PS	Z	NS	NM	NB
	NS	PM	PS	Z	NS	NM	NB	NB
	PB	PS	Z	NS	NM	NB	NB	NB

3.3 The estimation of running states

In the proposed efficiency optimized control strategy, different methods are adopted during different states, including dynamic and steady states. To obtain the exact operating conditions of the whole system, first check the speed error in the main program. Second, for the stability during the condition switching, the error hysteresis comparison is used. By distinguishing the above two terms, the operating state is captured for self-adaptive adjust i_d.

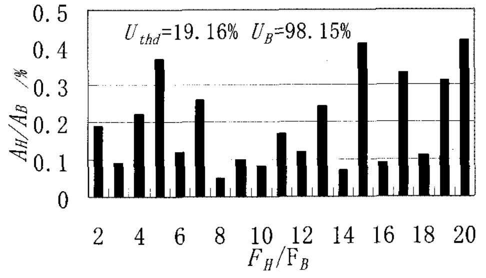
4. Experiment Test Bench and Results

A test bench for the validation of the loss minimization algorithm (LMA) has been set up for implementing the proposed control system. Fig. 4 is the Frequency spectra of the line voltage. Fig. 5 is the Frequency spectra of the current. A simplified block diagram of the test bench is shown in Fig. 6. Extensive laboratory tests, obtained by using the above mentioned control method, were carried out with the aim of verifying the optimized efficiency in a 7.5 kW prototype PMSM drive. Fig. 7 is the efficiency curve of the prototype PMSM before optimization. Fig. 8 is the efficiency curve of the prototype PMSM with optimization.



```
                    ***** U 1  List  ***** ***** U 1  List  *****
                    Or.       Hdf[%]       Or.       Hdf[%]
PLL   CH1(U1)                 ------       dc        ------
Freq    50.093 Hz    1        98.15         2         0.18
                     3         0.08         4         0.24
                     5         0.36         6         0.13
                     7         0.26         8         0.06
                     9         0.10        10         0.08
                    11         0.18        12         0.12
                    13         0.26        14         0.07
                    15         0.42        16         0.09
ϕ1      302.99 °    17         0.34        18         0.12
Uthd1    19.16 %    19         0.31        20         0.42
```

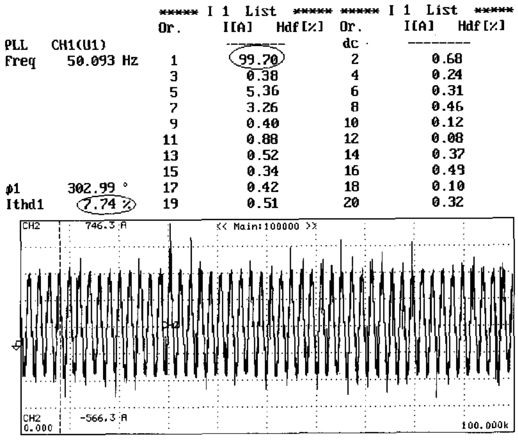
a) Waveform



b) Frequency spectra

Fig. 4. Frequency spectra of the line voltage

Fig. 7 shows the convergence speed of different methods. The fuzzy logical method needs little time compared to the general search method.



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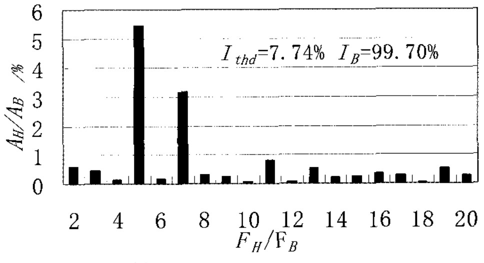
                    ***** I 1  List  ***** ***** I 1  List  *****
                    Or.     I[A]  Hdf[%]   Or.     I[A]   Hdf[%]
PLL   CH1(U1)               ------         dc      ------
Freq    50.093 Hz    1        99.70         2         0.68
                     3         0.38         4         0.24
                     5         5.36         6         0.31
                     7         3.26         8         0.46
                     9         0.40        10         0.12
                    11         0.88        12         0.08
                    13         0.52        14         0.37
                    15         0.34        16         0.49
ϕ1      302.99 °    17         0.42        18         0.10
Ithd1     7.74 %    19         0.51        20         0.32
```

a) Waveform



b) Frequency spectra

Fig. 5. Frequency spectra of the current

From Figs. 8 and 9, we can see that after efficiency optimization, the characteristic of efficiency is improved. The efficiency increase is about 3.9 % in the whole system, about 2.1 % in average. It is obvious that the efficiency increases with the proposed optimizing strategy.

From Fig. 9, we can see the efficiency of the system is over 60% during the whole operation scope, and the efficiency of the motor is up to 92.1%, while that of the induction motor is about 86.2% at the same power level.

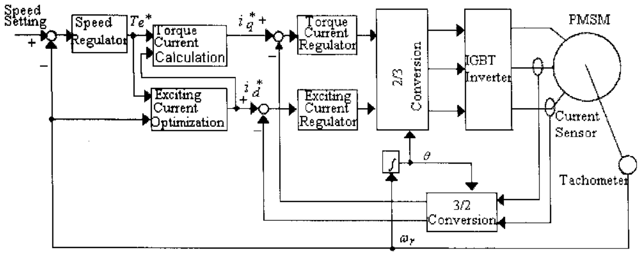


Fig. 6. Simplified block diagram of the PMSM efficiency optimization drive system

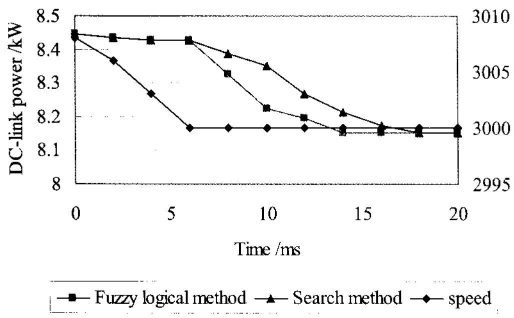


Fig.7. Different convergence speed of different method

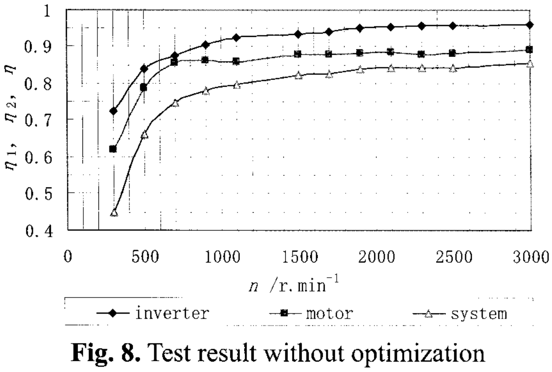


Fig. 8. Test result without optimization

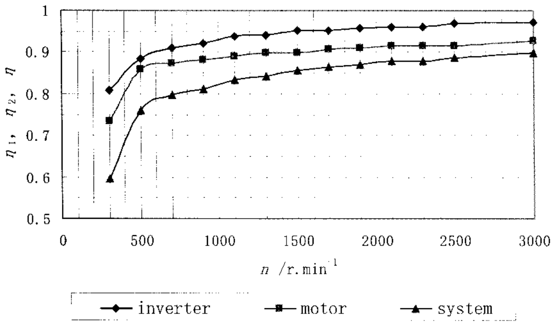


Fig. 9. Test result with optimization

5. Conclusion

In this paper, a novel efficiency optimization control strategy is proposed to meet the high running efficiency demand of a variable speed high efficiency PMSM. The key of this strategy is the excellent integration of mended maximum torque to the current control algorithm based on the losses model during dynamic operation, and the grade search method with varied step by fuzzy logic during steady operation. The performance experiments for a control system of a variable speed high efficiency PMSM have been completed. The test results verified that the system can reliably run with the different control strategy during dynamic and steady operation, and the system has better performances with the efficiency optimization control.

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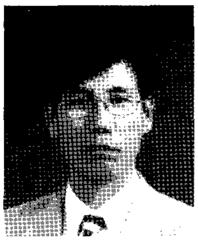

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