Speed Control of Permanent Magnet synchronous motor with smith Predictor and Performance Enhancement using temporal mismatch

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ABSTRACT

The main objectives of the speed controller of the PMSM drive are to ensure that the measured motor speed track the required values accurately and to shorten the transient interval as much as possible. However, in a full digital control system for a PMSM, there are inevitable delays in calculating the speeds and the currents and applying the inverter output voltages to the motor terminals. But the conventional PI controller doesn t have the ability to compensate these delays. Delay compensation in PMSM drive is one of the major problems.

The predictive controllers are necessary for the PMSM drive system. The Smith Predictor is the most quoted to solve time-delay problems. It has the capability of transforming a time-delay control design to a delay free problem. So we use the SP in the speed control loop to compensate the time-delay of the drive system. Sensitivity to plant parameter variations is dealt with optimal parameter mismatch. The parameter which is tuned is delay time in the model which is known as the temporal mismatch.

Keywords: *PMSM, time delay,smith predictor, PID tuning,relay feedback control, temporal mismatch*

I. INTRODUCTION

The advances in the area of power electronics together with the increase in speed of digital processing technique have resulted in the replacement of DC machines by AC machines for variable speed applications. The control and estimation of AC drives in general are quite complex. The advent of vector control in the beginning of 1970 s had initialized the use of AC motors for variable speed drives. Recent research has indicated that the permanent magnet motor drives, which include the permanent magnet synchronous motor (PMSM) and the brushless dc motor (BDCM) could become serious competitors to the induction motor for servo applications. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque. In recent years, PMSM AC servo system which uses PMSM as executing device and adopts high powered control strategy has caused the extensive concern all around the world. PMSM AC servo system has such characteristics as good low-speed operation performance, higher efficiency, and simple control.

PMSMs are used where in general high demands are made with regard to speed stability and the synchronous operation of several interconnected motors. They are suitable for applications where load independent or synchronous operations are required under strict observance of defined speed relations with in a large frequency range. Synchronous motors are generally preferred where as constant speed is desired under varying loads. Their speed can be adjusted by using inverters or adjustable 2 frequency source. Their size and inertia moment values are smaller compared to the DC motors. Their efficiency and power factors are larger

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compared to asynchronous motors. Recent research [1]-[3] has indicated that the permanent magnet motor drives, which include the permanent magnet synchronous motor (PMSM) and the brushless dc motor (BDCM) could become serious competitors to the induction motor for servo applications. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BDCM has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. Some confusion exists, both in the industry and in the university research environment, as to the correct models that should be used in each case. The PMSM is very similar to the standard wound rotor synchronous machine except that the PMSM has no damper windings and excitation is provided by a permanent magnet instead of a field winding. Hence the *d, q* model of the PMSM can be derived from the well-known [4] model of the synchronous machine with the equations of the damper windings and field current dynamics removed. The *d, q* model of the PMSM has been used to examine the transient behavior of a high-performance vector controlled PMSM servo drive [5].

The PMSM drives are widely used in robotics, machine tools, and other high performance industrial servo applications. PMSM is preferred over the traditional brush-type dc motors because of the absence of mechanical commutators, which reduces mechanical wear and tear of the brushes and increases the life span of the motor [6]. As compared to induction motor, PMSM is still favored for high-performance servo applications because of their high efficiency, power density and torque-to inertia ratio, which make them a suitable choice for variable speed direct-drive applications [7].

Owing to the existence of nonlinearities and uncertainties, the control of the PMSM servo system is not an easy task. Conventional proportional-integral (PI) control, which is often used to regulate the static and dynamic performance of control system, is a classical linear control scheme. However, a sufficiently high performance for PMSM servo system under such controller could not be ensured [8], [9]. In recent years, numerous methods have been reported to enhance the control performance of PMSM servo system, for example, linearization techniques [10], adaptive control [11], fuzzy control [12], sliding mode control [13], and so on. These approaches improve the control performance of the motor in different aspects. Predictive control techniques, as practical alternative approaches, have been receiving increasing attention for many decades [14]-[16]. The model based predictive control (MPC), as one of the most widely used predictive control schemes, is applied to recalculate the behavior of the plant and to choose an optimal value of the control variables [17]-[20].

The Smith-predictor proposed by Smith [6] is the most quoted to solve long time-delay problems. The Smith predictor has classically employed a model of the plant characterized by a linear transfer function and a time delay. It uses a model to simulate both the delayed and un delayed states of the plant, which then uses the delayed state to cancel the real plant output and the un delayed state as the feedback signal for control calculation. Although the Smith-predictor has the capability of transforming a time-delay control design to a delay free problem, there is a controversial issue with regard to its sensitivity to plant parameter variations.

Marshall studied the possibilities for improving the system performance through the use of time delay elements, which opened an avenue for the study of performance improvement through the use of parameter mismatch. Walton has published a method for obtaining a closed form solution using an infinite time integral of a quadratic error function, which has made a significant contribution to the study of time-delay systems under a broader point of view. Huang and DeBra [21] summarized the previous results and proposed an automatic SP tuning procedure and firstly verified in on the temperature control system of Stanford s quiet hydraulic lathe. Until now, the automatic tuning SP with optimal parameter mismatch has not been applied in the PMSM control field. In this paper an automatic tuning SP speed controller with optimal parameter mismatch control scheme based on the mechanical model of the PMSM is firstly presented. In both transient and steady states, the proposed controller performs better than the conventional PI controller does. Finally, the experimental results are also presented to prove the feasibility and effectiveness of the proposed automatic tuning SP speed controller.

Permanent Magnet Synchronous Motor

The PMSM drives are most suitable for high performance adjustable speed ac drives. These drives have important role in realizing servo mechanisms for computer numerically controlled machine tools, industrial robots and aerospace actuators. In the machine tool industry the transfer of rotor losses of drives in the form of heat to the machine tools and work pieces, affects the machining operation. Thus, due to negligible rotor losses compared to other servo drives like dc motor, induction motor drives, these have wide scope in the machining operations. Advantages of PMSM drives over other drives are higher power factor operation, higher torque to inertia ratio and higher efficiency.

The model equations of the PMSM are:

$$V_d = RI_d + L_d\frac{dI_q}{dt} - P\omega L_q I_q \quad (1)$$

$$V_q = RI_q + L_q\frac{dI_q}{dt} + P\omega L_d I_d + P\omega\lambda_f \quad (2)$$

$$T_e = T_L + B\omega + J_m\frac{d\omega}{dt} \quad (3$$

$$T_e = K_t I_q + \frac{3}{2}P(L_d - L_q)I_d I_q \quad (4,$$

$$K_t = \frac{3}{2}P\lambda_f \quad (5,$$

The d,q variables are related with a,b,c variables through the Park s transformation defined as

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}\pi) & \cos(\theta + \frac{2\pi}{3}\pi) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}\pi) & \sin(\theta + \frac{2\pi}{3}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (6)$$

The inverse Park's transformation is defined below

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}\pi) & \sin(\theta - \frac{2\pi}{3}\pi) & 1 \\ \cos(\theta + \frac{2\pi}{3}\pi) & \sin(\theta + \frac{2\pi}{3}\pi) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \quad (7)$$

For a balanced system the power balance equation is

$$V_a I_a + V_b I_b + V_c I_c = \frac{3}{2}(V_d I_d + V_q I_q) \quad (8)$$

Vector Control of the PMSM Drive

In the PMSM drive the rotor flux rotates at speed É and its position angle can be obtained with respect to an arbitrary reference axis as;

$$\theta = \int \omega dt \quad (9)$$

Phase „a is aligned with the reference axis. If d-axis current Id is forced to zero, the stator current vector will be orthogonal to rotor flux. Thus, using equation (3) the developed torque will be given by;

$$Te = Kt\ Iq \quad (10)$$

Hence, from equation (10) it is evident that the vector control action forces the PMSM drive operation to that of an equivalent separately excited dc Motor.

The speed drive system of the PMSM

In the drive system the motor current is being supplied through a three phase inverter. The six switching devices of the inverter are turned on or off by switching pulses through gate drive circuit. The PMSM drive has two control loops, (i) inner current control loop, and (ii) outer speed control loop. Only two phase motor currents are sensed and the third phase current is obtained by summing and inverting the two-phase currents because there is no neutral connection. The three phase reference currents are generated by outer speed control loop. The outer speed control loop requires actual rotor position and its speed. The signals from the resolver are processed to obtain actual rotor speed and the rotor angle , with respect to some arbitrary reference axis. The main objective of the drive is to track speed command. The speed error is processed by the speed controller to obtain torque command.

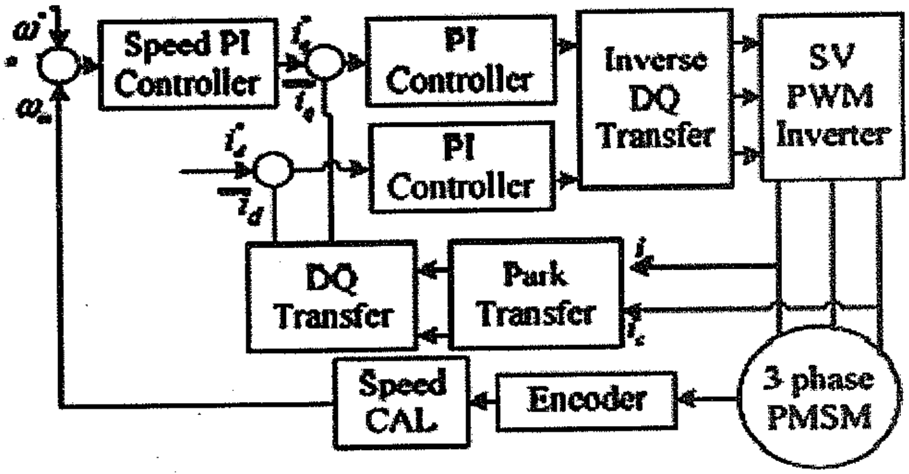

Figure 1 Conventional speed control diagram of PMSM drive system

Figure 1 shows the conventional PMSM speed drive system vector control block diagram. There are two control loops in this system. The outer loop is speed control loop which consists of a PI speed controller and a speed feedback and calculation module. The input of this loop is the reference speed and the output of the speed loop is the q axis reference current which is proportional to the reference torque. The inner loop is the PMSM current control loop which consists of two PI controllers (d axis current controller and q axis current controller), the vector control module and the current measurement module. However, an inherent system dead time might exist in a practical drive system. This dead time is distributed in nature and arises from the dead time of the inverter, the finite response time of the inner current loop and sensors, the computational delay, and other significant delays dependent on the mechanical coupling and the transmission characteristics. However these distributed delays can be lumped together to form an equivalent dead time element. A model of a PMSM vector drive with dead time is shown in Figure 2

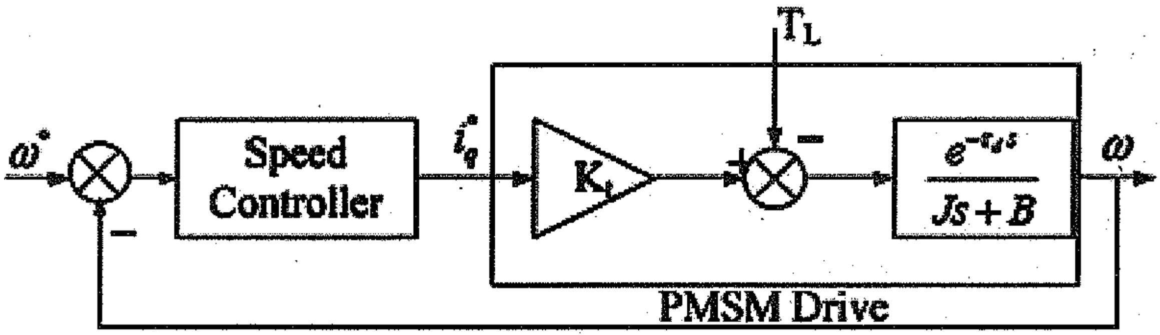

Figure 2. Model of a PMSM vector drive with dead time

Assuming perfect current tracking, the actual torque producing current component can be replaced with the reference one. Accordingly, the mechanical dynamics can be reasonably given in Laplace domain as a first order system

$$w(s) = \frac{K_T i_q^*(s) - T_l(s)}{Js+B} e^{-T_d(s)} \qquad (11)$$

*K*T =Torque coefficient
=Q axis command current component
=Friction coefficient of the mechanical system
=The total rotator inertia of the drive system
=The equivalent dead time of the drive system

SMITH PREDICTOR

If a time delay is introduced into a well tuned system, the gain must be reduced to maintain stability. The Smith predictor control scheme can help overcome this limitation and allow larger gain.

The Smith-predictor proposed by Smith is the most quoted to solve long time-delay problems. The Smith predictor has classically employed a model of the plant characterized by a linear transfer function and a time delay. It uses a model to simulate both the delayed and un delayed states of the plant, which then uses the delayed state to cancel the real plant output and the un delayed state as the feedback signal for control calculation. Fig.3 shows the control scheme of the Smith-predictor and its transfer function can be written as

$$\frac{Y(s)}{X(s)} = \frac{C(s)G_p(s)e^{-sT_p}}{1+C(s)G_q(s)+C(s)[G_p(s)e^{-sT_p}-G_q(s)e^{-sT_q}]} \qquad (12)$$

(12) If the model parameter match the real plant, ie., 6 the above transfer function can be simplified to

$$\frac{Y(s)}{X(s)} = \frac{C(s)G_p(s)e^{-sT_p}}{1+C(s)G_p(s)} \qquad (13)$$

This simplification excludes the time-delay effect from the control loop and converts the corresponding control design to a delay free problem. Due to this attractive delay-free feature, the smith predictor is famous for compensating system with time delay.

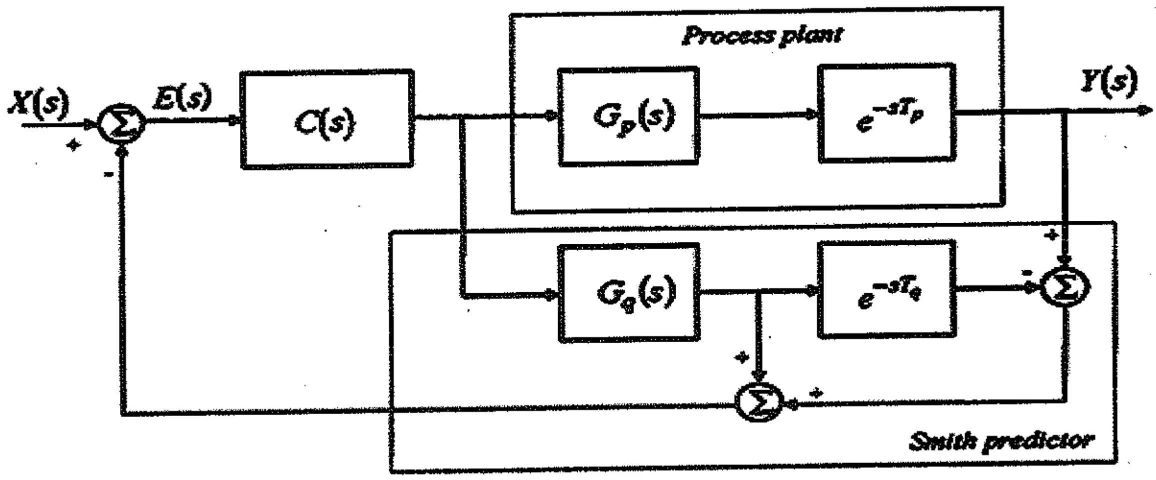

Figure 3 Control scheme of the smith predictor

DESIGN OF THE PREDICTIVE SPEED CONTROLLER

The structure of the PMSM drive system with Smith predictor the mechanical model of the drive system can be described as a first-order system in (6) and the speed controller is a PI controller. So we investigate the control strategy with a first order system plus a PI controller. Fig.4 shows the diagram of the proposed control strategy of a PMSM speed drive system with Smith-Predictor.

Normalizing the parameters with respect to plant delay time obtains the corresponding time-scaled controller and plant transfer function as the Fig.4 shows. *Kc*

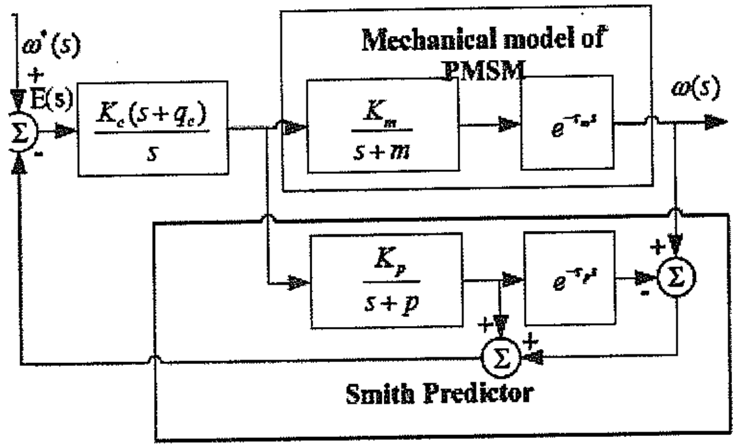

Figure 4 PMSM speed drive system with smith predictor

is the proportional gain of the speed controller; q_c = ⊗d / *Ti* ,where Äd is the time-delay of the PMSM mechanical model and *Ti* is the integration time constant of the speed controller; m = Äd /T_m ,where *Tm* is the model time constant of the PMSM (T_m = *J*/ *B*); *Km* = (K_T /*B*).(Äd / *Tm)* which is the normalized static gain of the PMSM model; *K* = *Km Kc* ; ⊃* (*S*) is the speed reference and É(*S*) is the speed output; *E*(*s*) is the error between the speed reference and the speed output. What s more we use the infinite time integration of a quadratic error function as the system performance index and to use Parseval s theorem to carry out the integration in the complex variable domain.

$$J_j = \frac{1}{2\pi j}\int_{-j\infty}^{+j\infty} E(s)E(-s)ds \qquad (14)$$

Where Jj is the system performance index. The calculation strategy of the performance index can be obtained:

$$\mathrm{J_j} = -\sum_{r}^{\substack{Residue \\ s=s_r}} \frac{1}{\Delta(s)} \times \frac{1}{P(s)+R(s)e^{-\tau_p s}} \times P(s) \quad (15)$$

As shown in Fig 4, if $q_c = p$ then

$$P(s) = (k_c k_q + s)/s\,;\; R(s) = [k_c k_m(s+q_c) - k_c k_q(s+m)]/s(s+m) \text{ and } \Delta(s) = P(s)P(-s) - R(s)R(-s); \quad (16)$$

S=Sr represents the root location of the delta functionΔ(s). Another parameter normalization procedure is to readjust the value of performance index to exclude the time-delay period and gain effect. As the system output always starts after the time delay, the quiet period can be excluded from the infinite time integration and the performance index becomes, *Jn* = *Jj* – Äm . In order to further exclude the gain factor from the performance index integration, multiply the performance index by the normalized gain *K*, KJ*n*=*KJj* -*K*Äm . As mentioned in [21], if the plant is modeled perfectly and the zero of a PI controller is chosen to cancel the pole of model, the equivalent delay free part of the Smith-predictor control system becomes a pure integral plant. In this case, the time integration of the normalized performance index is found as 0.5 [22]. The value of 0.5 for a parameter matched Smith predictor is therefore the important reference to compare the system performance with either temporal or parametric mismatches.

PERFORMANCE ENHANCEMENT USING PARAMETER MISMATCH

Assume a PI control is chosen as the regulator and the plant dynamics are described by a first order transfer function plus a time delay. Due to the time varying and distributed parameter characteristics of a real system, there are inevitable parametric or temporal mismatches between the motor and the model. Therefore, the time-normalized parameters in the Smith-predictor: the model gain,Kp , the pole location,-p and the delay time,Äp should also be regarded as part of the overall controller and tunable due to the inevitable parameter mismatches. In order to simplify the derivation of the performance index integration, the input command is chosen as a unit step function and the zero of the PI controller is chosen equal to the model pole p, viz .qc = p. The performance evaluations with intentional or inevitable parameter mismatches are discussed in the following sections.

Temporal mismatch

When there exists only a temporal mismatch in the Smith-predictor, the system parameters can be simplified as p = m and

$K = K_c K_m = K_c K_p$ Let $r = \tau_p / \tau_m$, $z = K_T$, $\tau_m = \tau$ (17) and substitute the model delay by the first-order Padé approximation (17)

Where r is the time delay ratio between the plant and model. The time integration of the performance index can be derived as where we have

$$KJ_\alpha = \frac{r^2\tau^2\alpha^2-(2+2rK_\tau)^2}{2r^2\tau^2\alpha(\alpha^2+\beta^2)} \cdot \frac{r\tau\alpha^2-2k\cosh[\alpha\tau]+r\alpha K\tau\sinh[\alpha\tau]}{2\frac{\alpha}{K}+2r\alpha\tau+r\alpha\tau\cosh[\alpha\tau]-2\sinh[\alpha\tau]} \quad (18)$$

$$KJ_\beta = \frac{r^2\tau^2\beta^2+(2+2rK_\tau)^2}{2r^2\tau^2\beta(\alpha^2+\beta^2)} \cdot \frac{r\tau\beta^2+2k\cos[\beta\tau]+r\beta K\tau\sin[\beta\tau]}{2\frac{\beta}{K}+2r\beta\tau+r\beta\tau\cos[\beta\tau]-2\sin[\beta\tau]} \quad (19)$$

$$\alpha = [\frac{-s_a+\sqrt{s_a^2+16r^2(K\tau)^2}}{2r^2\tau^2}]^{1/2} \quad (20)$$

$$\beta = [\frac{s_a+\sqrt{s_a^2+16r^2(K\tau)^2}}{2r^2\tau^2}]^{1/2} \quad (21)$$

$$s_a = -[3r^2(K\tau)^2 + 8r(K\tau) + 4] \quad (22)$$

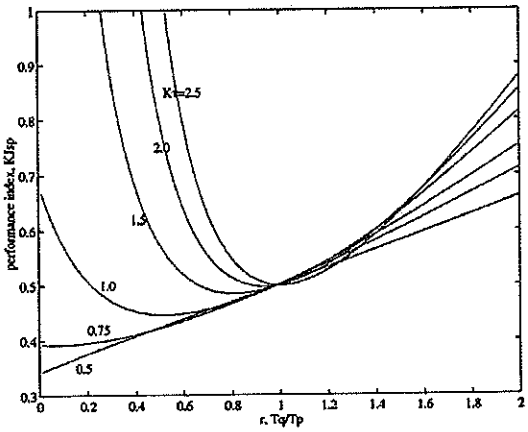

Figure 5 Mentioned preferences index plot for temporal mismatch case

The comparison of the performance index curves at different values is shown in Fig.5 When the value is small, the system performance can be improved by decreasing the value of model delay time. The use of temporal mismatch improves system performance, but the price is the reduction of the stability gain margin. An extreme case is to set the model delay equal to zero. Due to the quadratic form of the performance index, the theoretical optimal temporal mismatch might occur at negative values, but this would violate the causality property in the real world, therefore negative temporal mismatch does not exist. Refer to the block diagram shown in Fig.4 when the model delay is set to zero, the Smith-predictor loses its effect on the feedback loop and the resulting controller becomes a pure PI control. On the other hand, for those cases when values are large, the characteristic curves suggest that the temporal matched Smith-predictor offers better performance; however, the drawback is a system sensitive to parameter variations. The use of a Padé approximation to the plant model is a technique sometimes advocated as a practical method of the time-delay system analysis, which reduces the system to a single delay where closed form integration is possible to be carried out.. Following the approach in previous sections, the optimal temporal ratios can be found numerically based on above equations and the optimal values are curve fitted by the following empirical equation, from fig (6):

$$\frac{T_q}{T_{p_{opt}}} = r_{opt} = \frac{1.387K\tau - 1}{1.135K\tau - 0.358}, \quad for\ K\tau > 0.74 \quad (23)$$

$$\frac{T_q}{T_{p_{opt}}} = r_{opt} = 0, \quad for\ K\tau \leq 0.74 \quad (24)$$

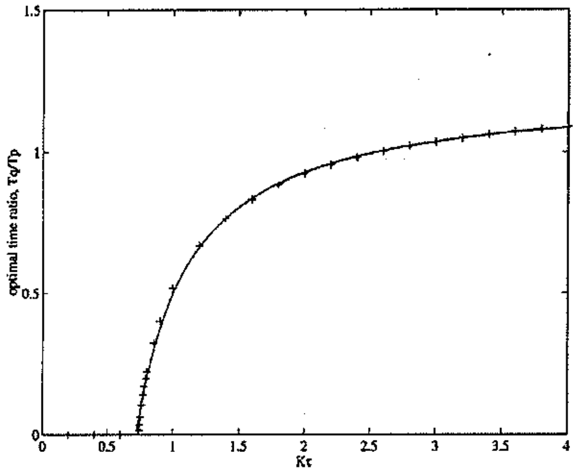

Figure 6 Optional gain ratios and curve fitting result for temporal mismatched case.

PLANT PARAMETER ESTIMATION

Plant parameters must be estimated before designing the smith predictor. The combination of open-loop step response and relay excitation feedback methods are chosen for plant parameter estimation. The step response is used to determine the static gain of the plant, while the relay excitation method is used to determine the plant parameters. The ultimate gain of the process is approximated as where d is the relay output and e is the following error. By finding the static gain of the PMSM ( ) and the ultimate oscillation period Tu from the registered oscillation data, the process parameters can be derived as

$$time\ constant, a = \frac{J}{B} = \frac{T_u}{2\pi}\sqrt{(K_T K_u/B)^2 - 1} \quad (25)$$

$$dead\ time\ \tau_d = \frac{T_u}{2\pi}(\pi - \tan^{-1}(\frac{2\pi a}{T_u})) \quad (26)$$

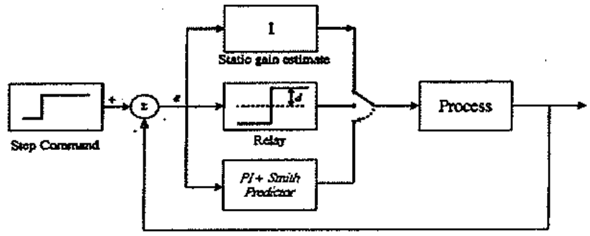

Figure 7 The block diagram representation of the automatic tuning procedure

AUTOMATIC SMITH-PREDICTOR DESIGN PROCEDURE

Summarizing the above results, an automatic Smith-predictor design procedure that uses the numerically searched optimal mismatch values is proposed as follows.

1) **Process model identification:**

   1.1. Change the set point level as a step input and register the steady state open-loop output response of the speed control process. Find the static gain ( ) of the PMSM.

   1.2. Switch to relay control, register the oscillation data and determine the resulting ultimate gain and ultimate oscillation period ( ).

   1.3. Based on the registered oscillation data, find the estimated process time constant and delay-time by use of 25 and 26.

2) **KÄ value determination:**

   2.1. Use the proportional control only and tune the gain to 0.5 as suggested by Ziegler-Nichols

   2.2. Normalize process parameters and determine the corresponding KÄ value.

3) **Optimal Smith-predictor tuning design:**

   3.1. Based on the resulting KÄ value, determine the appropriate control construction and tune up system performance by introducing the optimal parameter mismatch of the Smith-predictor referring to optimal equations (23 and 24)

3.2. Test step response of the process, wait for the output to reach steady state and evaluate the performance index.

3.3. Repeat Step 3.2 and change the mismatched parameter in turn until the optimal Smith-predictor tuning is found.

A block diagram that shows the tuning procedure is given in Fig. During the test, due to the slow dynamics of the process, a waiting time has to be added between each step to make sure that the process has smoothly migrated from one state to another steady state.

RESULT AND CONCLUSION

An optimal control strategy is the basic idea behind the smith predictor scheme. The performance of the PI controller is severely limited by the long dead time. This is because the PI controller has no knowledge of the dead time and reacts too impatiently when the actual output does not match the step point. Smith predictor uses an internal model to predict the delay free response of the process. It then compares this prediction with desired step point to decide what adjustments are needed. Designed a smith prediction model for the PMSM and tested using matlab simulation and verified the step response. The smith predictor provides much faster response with no over shoot.

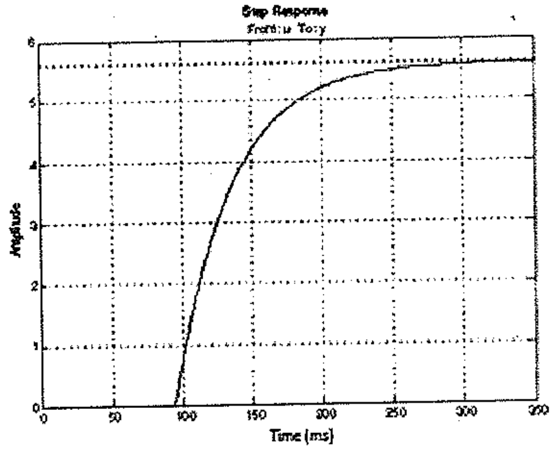

Figure 8

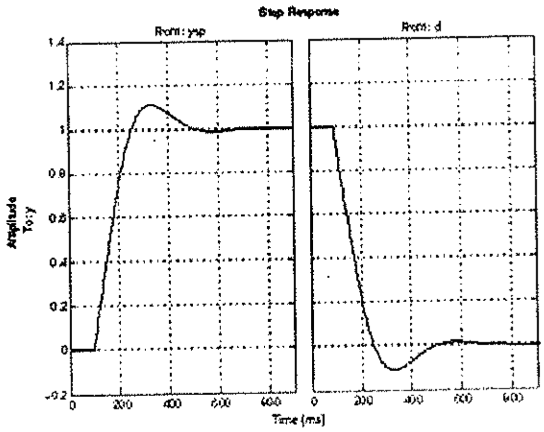

Figure 9

Fig

9 Response of the PMSM with PI controller

Figures 8 to11 are the step response in different stages. These results shows that the optimal SP tuning speed controller has better dynamic response and parameter robustness than the conventional PI control. Optimal control for temporal mismatch is dealt within this paper.

There is further research is needed in optimal control for model gain Fig 10 Loss of stability when increassing gain Fig 11 Step response of the PMSM with PI controller alone and the same with PI controller and smith predictor

Figure 10

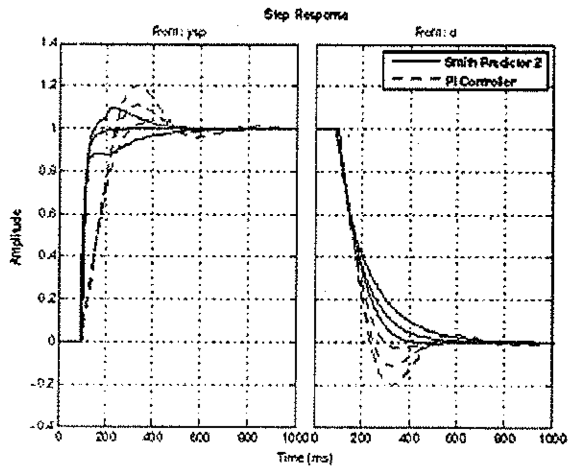

Figure 11

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