CHAPTER 3

ROBUST TUNING FOR THE SPEED CONTROLLER OF PMBLDC MOTOR

3.1 INTRODUCTION

Nowadays, motion control systems in industry are designed with fixed PI/PID cascade control loops. These control loops do not take into account the dynamic load variations that occur in many systems. Therefore, as the dynamics of the process inevitably varies, they fall out of tune, which causes the performance and stability to degrade. Also, time delays often arise in motor control systems, both from delays in the process itself and from the delays in the processing of sensed signals. In motion control applications, time delays have a significant impact which leads to unstable or oscillatory responses [63].

To control the motor drives with small lag, the modern control concepts like state observer, optimal controllers and smith predictors are normally used, which will reduce the speed error. Since the motor drives are non-linear, uncertain and time varying, the tuning of controller is very difficult. To avoid this problem, explicit gain scheduling controllers are generally employed to motors with predictable non-linearity. Also, the conventional self tuning speed control of PMBLDC motor is subjected to stringent problems because the usual controllers are not robust against the inertial and load variations. To overcome this problem, an auto-tuning technique for the robust operation of PMBLDC motor system under the dynamic condition is required. Thus a new auto tuning robust control is proposed in this chapter which really opens the way to the application of speed control of PMBLDC motor drive. Appropriate tuning is generally more crucial than selection of a controller and control scheme.
3.2 SELF TUNING CONTROLLERS

Conventional cascade PI controllers are tuned in a sequential manner. Initially, the outer speed loop controller is operated on manual mode and the inner current loop controller is tuned. Subsequently, the inner loop controller is commissioned and the outer loop controller is tuned to complete the tuning process. If the control performance achieved is unsatisfactory, the entire sequence must be repeated. Thus it is a fairly cumbersome and time consuming task to tune a cascade control system, especially for systems with large time constant and time delay. PI/PID self-tuning control relieves the pain of manually tuning a controller and has been successfully applied in many industries.

Many investigations reported on self-tuning for PI/PID controllers in single-input single-output (SISO) systems. However, only a few investigations are carried out on self-tuning PID controllers in cascade PI speed control systems. The most employed PI design technique used in the industry when dealing with time-delay systems is the Ziegler–Nichols method [64], which avoids the need for a model of the plant to be controlled and relies solely on the step response of the plant. In general the results of using the Ziegler–Nichols tuning method yields a high percent overshoot. When the control signal is high, it may lead the electronic drive to saturation. In several processes like chemical processes, high-percent overshoot is not a problem, providing that the system returns rapidly to the neighbourhood of the steady-state value. However, in motor control processes, it is desirable to have no overshoot at all. Therefore, the Ziegler–Nichols method cannot be used to tune PI controllers for such systems. Similarly, C.C. Hang et al [65] applied a renewed relay automatic tuning method to tune a cascade control system where the relay feedback test is carried out twice, first to the inner loop and then to the outer loop. While the individual controller tuning has been automated, the sequential nature of the tuning process remains unchanged. N. Tan et al [66] proposed a method to carry out the entire tuning process in one experiment, but the experiment requires prior information of the process.
Even though many techniques are available for conventional cascade structure, the existing self-tuning control techniques cannot be applied to the modified robust structure of PMBLDC motor system, because of the unstable pole-zero cancellation of signals in the self-tuning control systems. To avoid unstable pole-zero cancellation, pole-assignment schemes have been proposed [67, 68]. However, as these methods assign only the poles in the closed-loop system, they cannot give better response characteristic as that obtained from a reference model. Also, self-tuning controllers based on the pole-zero placements were proposed by K.J. Astrom and T. Hugglind [69]. However, in this method, the specifications must be such that unstable zeros are the desired zeros of the closed-loop transfer function. This implies that unstable zeros of a motor system cannot be assigned arbitrarily. Further, this controller cannot be used when the motor parameters vary during operation, which is inconvenient in practical applications.

To overcome the above drawbacks, a novel auto-tuning method for the robust cascade control system is proposed using the time delay identification technique. This technique is applied to identify simultaneously both inner and outer loop process model parameters. The performance of the proposed method is compared with conventional PI controller tuning using Ziegler–Nichols method and the relay feedback method.

3.3 ROBUST SPEED CONTROL SCHEME

Since the speed set-point is constant under normal operating conditions, generally there is not sufficient excitation for the closed loop identification of the PMBLDC motor drive. Then, the self tuning mode is superimposed with artificial excitation on speed set-points, when tuning or retuning is required. However, a very severe obstacle to self tuning speed control is that saturation of the control variable is quite common during controlled transients, because converter voltage is essentially altered for the load variations. The emblematic control scheme of PMBLDC motor with speed and current loop is shown in Fig.3.1.
Fig. 3.1 Conventional control scheme of PMBLDC motor drive

In this figure, the external controller operating in self tuning mode is defenseless to the controller saturation, because, the output variable of the speed controller is not in saturation with motor current. Such a condition develops to the motor parameter estimation, deviate from their correct values, causing an unacceptable controller tuning. Thus, an alternative control structure is considered in Fig 3.2 which is capable of making the outer speed loop behaviour fully robust against any change in the behaviour of the inner current loop \( G_{ic}(s) \).

To avoid these restrictions, a new self tuning approach to robust speed control schemes that are applicable to the non-minimum phase systems is proposed. In the proposed method, unstable pole-zero cancellation can be avoided, and the desired poles and zeros of the closed-loop transfer function can be assigned arbitrarily. Furthermore, the method makes it possible to adjust the parameters of the controller automatically according to motor parameter variations. The new transfer functions for the robust structure are

\[
G_{s,new}(s) = \frac{G_{scl,ideal}(s)}{G_p(s)} \quad (3.1)
\]

\[
G_{robust}(s) = G_{scl,ideal}(s) \quad (3.2)
\]

where \( G_{scl}(s) \) is the designed closed loop transfer function from \( \omega_m^* \) to \( \omega_m \) with the inner loop transfer function \( G_{ic}(s) = 1 \). The inner closed loop transfer function from motor input voltage \( V_i \) to the current set-point \( i_i^* \) is obtained as
The robust cascade speed control scheme determines the following input output relationship for the speed loop

\[ \omega_m = G_{sc}(s)G_{ci}(s)\omega_m^* + (1 - G_{sc}(s)G_{ci}(s)) \]  

(3.4)

It is noted that the only consequence of \( G_{ci}(s) \) being not equal to one \( (G_{ci}(s) \neq 1) \) is that the closed loop transfer function of the speed loop is simply multiplied by \( G_{ci}(s) \). The self tuning technique for the robust control scheme is analysed in the next section.

### 3.4 PROPOSED SELF TUNING SPEED CONTROLLERS

The robust cascade speed scheme can also be extended with the relevant transfer functions of transducers in current and speed feedback paths as shown in Fig. 3.3. The standardisation requirements for tuning, speed controllers are designed based on the fixed-structure process models. PI controllers can satisfactorily be tuned based on the model given in equation (3.5).

\[ G_m(s) = \frac{1}{m_0s^2 + m_1s + m_2} \]  

(3.5)

where \( G_m(s) \) denotes the model of the PMBLDC motor
$m_0$, $m_1$, $m_2$ are the model parameters to be estimated from the input output data.

![Fig. 3.3 Extended robust cascade speed control scheme](image)

Fig. 3.3 Extended robust cascade speed control scheme

These parameters are effectively utilised for the proposed self tuning strategy. The proposed tuning strategy for PI controller has been developed using time delay identification technique. The synthesis criterion is mainly based on the cancellation of the poles of the standard model with reference to the speed control scheme as shown in Fig. 3.4.

![Fig. 3.4 Self tuning robust speed control scheme](image)

Fig. 3.4 Self tuning robust speed control scheme
To enhance standardisation, the self-tuning strategy based on $G_m(s)$ is associated to any individual PI algorithm, independent of the role played by the controller itself. The only data required for the synthesis are the phase margin and the maximum control bandwidth. The self-tuning PI controller has been designed for different inertial load variations, showing very good performances, even for processes with a dynamic behaviour significantly vary. In the configuration of Fig.3.4 the parameter estimator TDIT of the external PI controller considers $\Delta \omega_m/\Delta I$, to identify the speed response. It works properly when the internal loop control variable is not in saturation and set point to the current controller has to vary continuously. However its variations cannot determine any response of the process variable $\omega_m$ so that the estimator TDIT receives contradictory information and produces totally wrong parameters estimation. To avoid this kind of parameter divergence, a logical signal can be used that stops parameters estimation, when $V_i$ is in saturation. Also it requires reliable detection of saturation and cause relevant information loss in transient conditions. On contrary, the cascade control scheme is equipped with self-tuning capacity, without any particular problem regarding to saturation and without any additional logical function.

3.4.1 Time Delay Identification Technique

The TDIT is applied to system with delay and to the system which are time varying and uncertain. Thus it is used in this work to tune the PMBLDC motor for speed control in both offline and online. The tuning based on this technique is fully robust against any irregularity affecting the inner loop, in particular can properly work in self-tuning mode while the final control variable undergoes saturation. Considering the measurement signals $x_m(t)$ and $x_c(t)$ received from the speed and current sensors respectively. The signals are represented as

$$x_r(t) = s_r(t) + n_r(t)$$
$$x_m(t) = s_m(t - d) + n_m(t)$$  (3.6)
where \( x_i(t) \) and \( x_n(t) \) are the sensor signals
\( s_i(t) \) and \( s_n(t) \) are the source signal values
\( t \) is the time period.
\( d \) is the time delay between loops
\( n_i(t) \) and \( n_n(t) \) are noises in the sensor signals, which are normally negligible.

Assume that the process part \( G_p(s) \) be modeled by (3.4). Then the closed loop response \( G_{ucf}(s) \) is naturally assumed as the time delay second order system:

\[
\frac{\omega_m(s)}{\omega_m(s)} = \frac{e^{-ds}}{b_0s^2 + b_is + b_2} \quad (3.7)
\]

where \( b_2 \) is the inverse of the gain of the speed measurement system.

Since \( G_m(s) \) is a model of \( G_p(s) \), its identification is performed by considering the signals \( x_i(t) \) and \( x_n(t) \). The identification model transfer function is

\[
\frac{\hat{\omega}_m(s)}{\omega_m(s)} = \frac{e^{-ds}}{b_0s^2 + b_is + b_2} \quad (3.8)
\]

where \( \hat{\omega}_m(s) \) is estimation of \( \omega_m(s) \)

The parameters \( b_0/b_2 \) and \( b_1/b_2 \) of \( G_{ucf}(s) \) are chosen with the following criteria:

- The damping \( \xi_m \) of \( G_{ucf}(s) \) should be the optimum between the lower bound \( \xi \) and the estimated ratio \( \xi_m \) of \( G_m(s) \). This criteria is determined from the frequency response plot.
- The natural frequency of \( G_{ucf}(s) \) will be proportional to the one of \( G_m(s) \) through a user defined speed-up factor \( \gamma_s > 1 \).
With reference to the equation (3.5), the TDIT algorithm is formalised. The original system is given in the form of its true time delay plus all poles rational transfer function model. When the time delay uncertainty is larger than the adopted sampling period, the sampling period can be extended itself to cope up the time delay uncertainty. This measure could be impractical if the time delay uncertainty is large, especially when the estimated model is used for adaptive control purposes. The algorithm has been derived by measuring the time delay in loop, which is dealt using high frequency zeros. By inspecting the phase shift due to these zeros, the current estimate of the delay is recursively updated.

### 3.4.2 Self Tuning Robust Speed Controller

The model to be estimated corresponds to the PMBLDC motor response from the actual input current $i_n$ to the corresponding speed $\omega_m$ of the outer loop. Thus the saturation of inner loop control variable does not affect the estimate $G_m(s)$. The only effect of the saturation could eventually be that of blocking input excitation of the process under estimation. It is observed that the control concept expressed is quite general and is applicable for all asymptotically stable motor model $G_m(s)$.

### 3.5 SIMULATION RESULTS AND DISCUSSION

The PMBLDC motor drive system with the conventional and the proposed robust control schemes have been simulated using MATLAB. Speed response to the step change of reference value of 2000 rpm for various inertial loads $J=J_n$, $J=0.5J_n$ and $J=2J_n$ are shown in Fig.3.5 and Fig.3.6. To make the comparison more objective the PI/PI control and the robust cascade control were tuned so as to have the same performance in nominal conditions. In both cases excitation of the self tuning control was provided by applying a step change in input to the speed. The superiority of the proposed method is improved robustness against inertial load variations, which is evident from the Fig.3.5 and Fig.3.6. This is attained imposing that the Bode diagram magnitude of the closed loop transfer functions take the
identical value at an appropriate frequency. If there is any resonance condition, then the appropriate frequency is resonance frequency, otherwise, cut-off frequency.

Fig. 3.5 Simulated speed responses for a step change in input and MI change in the drive for conventional scheme

Fig. 3.6 Simulated speed response for a step change in input and MI change in drive under no load for the proposed robust tuning controller
The performance of the robust auto tuning controller is depicted in Fig.3.7 and Fig.3.8, where the estimated process models in frequency domain are obtained for conventional PI controller and robust auto tuning controller respectively.

**Fig. 3.7** PMBLDC motor model estimates with and without saturation using conventional PI control

**Fig. 3.8** PMBLDC motor model estimates with and without saturation using auto tuning robust PI control
A load torque is applied to the motor at 0.25s and the responses for the conventional PI controller, relay feedback auto-tuning and for the proposed tuning methods are depicted as shown in Figs. 3.9 to 3.11. It is noted that the overshoot and settling time are less for the robust auto-tuning scheme when compared to the conventional PI and relay feedback method.

Fig. 3.9. Measured speed response for a step input and MI change in drive for a step change of load torque at 0.25s for conventional PI tuning

Fig. 3.10. Measured speed response for a step input and change of MI with step change of load torque at 0.25s with relay feedback auto tuning control
Fig. 3.11. Measured speed response for a step input and change of MI with step change of load torque at 0.25 s with proposed robust tuning controller

From the Fig. 3.9, it is clear that the overshoot and undershoot for the various inertial loads are almost 38% for the conventional PI controller. Particularly, the ISE and IAE values for the conventional PI controller are given in the Table 3.1.

Table 3.1 Performance index of conventional PI controller for different inertial loads

<table>
<thead>
<tr>
<th>Method</th>
<th>Error</th>
<th>0.5 ( J_\alpha )</th>
<th>( J_\alpha )</th>
<th>2 ( J_\alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional PI tuning method</td>
<td>ISE</td>
<td>3.419</td>
<td>3.49</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>IAE</td>
<td>0.4099</td>
<td>0.415</td>
<td>0.3991</td>
</tr>
</tbody>
</table>

From the Fig. 3.10, it is observed that the overshoot and undershoot for the various inertial loads are almost 10% for the relay feedback technique. They are lesser when compared with conventional controller, however when the load torque disturbance occurs, the relay feedback technique fails to operate in an efficient way. Particularly, the ISE and IAE values for the relay feedback controller are more, whose values are given in the Table 3.2.
Table 3.2 Performance index of relay feedback auto tuning method for different inertial loads

<table>
<thead>
<tr>
<th>Method</th>
<th>Error</th>
<th>0.5 J&lt;sub&gt;n&lt;/sub&gt;</th>
<th>J&lt;sub&gt;n&lt;/sub&gt;</th>
<th>2 J&lt;sub&gt;n&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay feedback auto tuning</td>
<td>ISE</td>
<td>2.23</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>IAE</td>
<td>0.099</td>
<td>0.207</td>
<td>0.0591</td>
</tr>
</tbody>
</table>

For the robust self tuning controller, the obtained behaviour is faster and the speed error is smaller. The motor is subjected to various inertial loads and load torque disturbances and the responses obtained for robust self-tuning method through simulation is depicted in Fig.3.11. From the figure, it is noted that the oscillation for the different inertial loads are almost suppressed. The motor also recover its steady value, even when the load torque disturbance occurs at 0.25s. The maximum overshoot is around 10%, which is almost same as that of relay feedback method. But, the proposed method is insensitive to load and load torque disturbances. The ISE and IAE values calculated from the error response plots are presented in Table 3.3 for different inertial loads.

Table 3.3 Performance index of robust auto tuning method for different inertial loads

<table>
<thead>
<tr>
<th>Method</th>
<th>Error</th>
<th>0.5 J&lt;sub&gt;n&lt;/sub&gt;</th>
<th>J&lt;sub&gt;n&lt;/sub&gt;</th>
<th>2 J&lt;sub&gt;n&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust auto-tuning</td>
<td>ISE</td>
<td>0.2565</td>
<td>0.07388</td>
<td>0.07662</td>
</tr>
<tr>
<td></td>
<td>IAE</td>
<td>0.01573</td>
<td>0.01079</td>
<td>0.02258</td>
</tr>
</tbody>
</table>

Also, the proposed method gives consistent output irrespective of inertial load and torque load disturbances. The speed recovery for the external disturbance is very fast in case of proposed method with less oscillation. The Figs.3.12 and 3.13 present the error comparison of the conventional PI, in both relay auto-tuning method and the proposed robust self-tuning method. From the Figs.3.12 and 3.13, it is concluded that the proposed robust tuning controller make the system satisfactory for inertia and load changes in PMBLDC Motor drive.
Fig. 3.12. Comparison of measured speed error with different control strategies for change of MI in drive under no load.
Fig. 3.13. Comparison of measured speed error for different controller strategies for change of M1 in drive with step change of load torque at 0.25 s
3.6 SUMMARY

A new self tuning method using TDIT for the robust speed controller scheme is proposed in this chapter. Departing from the traditional approach towards tuning of speed control of PMBLDC motor drive systems where the outer speed and inner current loops are tuned in strict sequence, the proposed approach is to carry out the entire tuning process in one experiment. The proposed robust self-tuning method really opens the way to the application of speed control of PMBLDC motor drive, very important from economical point of view. The spontaneous excitation is generally not sufficient to allow identification of the converter process. The self tuning algorithm is activated only on the purpose of simultaneous perturbation of the speed set-point. In this way, the initial tuning or subsequent retuning is performed to follow variations of the motor dynamics. The features of the new control concept have been demonstrated on nonlinear modeling and simulation using MATLAB. The applicability and effectiveness of the auto tuning approach to the new robust speed controller design is realised through simulations. Thus, the proposed controller proves to be highly adaptable for PMBLDC motors irrespective of the load variations and disturbances. Compared with the existing methods, the proposed method is simple and effective for motor control systems with loop delay. For ease of practical applications, the entire procedure of controller design is automated and carried out online.