Abstract—Conventional Proportional/Proportional-Integral (P/PI) speed controller of today’s servo drives should be manually tuned the controller switching set-point by trial-and-errors, which may translate the drive system down-time and loss of productivity. The adjustable drive performance is heavily dependent on the quality of the expert knowledge and becomes inadequate in applications where the operating conditions change in a wide range. In this paper, the demands on simple controls/setup are discussed for industry servo drives. Analyzing the frequency content of motor torque command, P/PI control mode switching is automatically performed with some prior knowledge of the mechanical dynamics. The dynamic performance of the proposed scheme assures a desired tracking response curve with minimal oscillation and settling time over the whole operating conditions. For comprehensive comparison of traditional P/PI control scheme, extensive test is carried out on actual servo system.

Index Terms—Industrial servo drive, P/PI speed controller, simple control setup, frequency content of motor torque.

I. INTRODUCTION

Proportional-Integral (PI) type controller has been proven to be remarkably effective and economic in regulating a wide range of processes in industry. This is inherently more robust and simpler than typical modern controllers that require an exact model. However, PI controller generally suffers from the effect of integrator windup. This often leads to a large overshoot and a long settling time of the process output. To avoid this problem, many related methods have been reported under the names conditional integration, limited integration, tracing anti-windup, and others [1-3]. Some of anti-windup strategies only activate during saturation and so these provide a limited improvement in performance. Others need an extra feedback compensation with/or some tuning parameters and the problem is “tuning” the parameters by selecting the proper values. Yet a practical control engineer may still look for a simpler tutorial of anti-windup.

On the other hand, a commonly encountered control strategy is to switch from one control mode to the other one. Industrial experience has shown that P/PI control mode switching is more effective to cope with the motion control applications [4-5]. In this method, integral action switches off (P control) when the control is far from steady state and switches on (PI control) when output is close to command. The iterative tuning tests should be performed even in the factory. Often, when the iterative tuning tests may cause mechanical and electrical problems in the fields. Therefore, this process may appear to be an intimidating and time-consuming task. In addition, the resulting responses at some given motion profiles are not consistent with other motion profiles. The conventional P/PI control scheme with a fixed switching point depends on the operating conditions such as speed command, acceleration rate, and load conditions. Despite of its conceptual simplicity, the practical implementation of this approach requires considerable efforts to tune P/PI control switching point by trial-and-errors, which may translate the drive system down-time and loss of productivity.

The purpose of this paper is to develop an automatic P/PI controller switching scheme for simple controls/setup and consequently that improves motor dynamic characteristics. Analyzing the spectral content of motor torque command in the frequency domain, the P/PI control switching point is automatically determined in real time. This greatly reduces engineering effort for the machine builder, since all the code is built-in to the amplifier. The dynamic performance of the proposed scheme assures a desired tracking response curve with minimal oscillation and settling time over whole operating motion profiles. The proposed control scheme is applicable in conjunction with the existing cascaded control loop that is simple to implement in practice. For comprehensive comparison of conventional P/PI control scheme, some tests are carried out on a 400W servo drive system.

II. P/PI SPEED CONTROL MODE SWITCHING

Many processes in industry servo applications can be reasonably well controlled by means of PI speed controllers. This is due to the fact that these processes can be more or less accurately described by means of a first-order model with moment of inertia and viscous friction.

\[ \omega_m(s) = \frac{1}{J_m s^2 + B_m} T(s) \]

Fig. 1 shows general block diagram of speed control sys-
tem, where the speed command and speed feedback are represented by \( \omega_m^*(s) \) and \( \omega_m(s) \), respectively. The P/PI speed controller generates the motor torque \( T_m(s) \) that tracks the torque command \( T_m^*(s) \). The quantity \( J_m \) and \( B_m \) indicate the system moment of inertia and the viscous friction coefficient.

![Fig 2 Frequency response of mechanical system](image)

Fig. 2 shows the low and high frequency characteristics of a first-order mechanical system. Above a break frequency \( f_T \), the \( B_m \) term will vanish and it will be overwhelmed by the \( J_m s^2 \) term. Notice that well above \( f_T \), the plot looks like \( \frac{1}{J_m s^2} \); the magnitude falls with the frequency. For such high frequency range there are no benefits by PI controller that may cause overshoot and ringing near steady state due to integral term of the speed error [6]. To avoid steady state error, the speed controller had better be PI controller below \( f_T \) and switch to P controller above \( f_T \). Hence, an automatic P/PI control mode switching is possible if the spectrum of torque command can be examined in the frequency domain.

### III. On-Line Spectrum Analysis

In practice, \( T_m^* \) is an aperiodic discrete time (DT) signal as it is usually generated in every speed control period by speed error. The discrete Fourier transform (DFT) is an important and extremely powerful technique for analyzing DT signal. DFT is also applicable to finite-length sequences and it produces finite-length discrete spectra [7-8]. Consequently, this transformation is amenable to digital computations and it is suitable for use in digital hardware implementations.

The DFT is a mapping of an \( N \) sample sequence, \( T_m^*[n] \), into another \( N \) sequence \( X[k] \) in the frequency domain, that is,

\[
X[k] = \sum_{n=0}^{N-1} T_m^*[n] e^{-j(2\pi k/n)n} \quad k = 0, 1, 2, ..., N - 1
\]

where \( X[k] \) is called the \( k \)-th harmonics and this exists provided all the samples of \( T_m^*[n] \) are bounded. From (1), it is noted that to compute the DFT coefficients would require \( N^2 \) complex multiplications and \( N(N-1) \) complex additions. Fast Fourier Transform (FFT) is introduced to speed up the computation of the DFT coefficients. The use of FFT imposes some constraints on the value of \( N \), for example \( N \) has to be a power of 2 for radix-2 FFT algorithm. For online computation of FFT, the zero-padding technique is used to augment the sequence length [8-9].

It has been stated in Section II that the PI controller is more favorable for \( 0 < f < f_T \) and P controller for \( f_T < f < f_C \). \( f_C \) is the crossover frequency that is uniquely determined by

\[
\frac{1}{J_m s^2} \bigg|_{s=1/2 \pi f_C} = 1
\]

The controller switching method in the frequency domain is illustrated in Fig. 3.

![Fig 3 Illustration of P/PI controller switching in the frequency domain](image)

From DFT analysis, online spectral energy ratio \( R \) can be defined as

\[
R = \frac{\sum_{k=0}^{N-1} |X[k]|^2}{\sum_{k=0}^{N-1} |X[k]|^2} \times 100[\%]
\]

In (3), the spectrum index is computed from

\[
N_f = \text{int} \left( \frac{f_T}{f_s} \right) N
\]

\[
N_c = \text{int} \left( \frac{f_C}{f_s} \right) N
\]

where \( f_s \) is a sampling frequency of the torque command. Generally, the discrete torque command signal exhibits a broad range of spectrum over time. In this situation, it is reasonable that P controller changes to PI controller when the frequency content in \( 0 < f < f_T \) is larger than that in
$f_T < f < f_C$ and vice versa. Therefore, P controller automatically switches to PI controller when the calculated spectral energy ratio is the condition of (6).

$$R \leq 50 \, [%] \quad (6)$$

IV. IMPLEMENTATION CONSIDERATIONS

A. Operation in Saturation Region

Fig. 4 shows a typical torque command trajectory for step speed command. The torque command increases initially because the error is positive. At this point, the controller enters the saturation region as shown in Fig. 4 due to the large value of the speed error. When this happens the actual motor torque will remain at its limit independently of the actual controller output. It seems that the motor torque contains the low frequency content in this region, but actually the output signal has the high frequency content. Hence, the integration should be suspended during saturation.

B. Selection of Break Frequency

All commercial servo drives typically identify mechanical inertia by on-line and/or off-line manner [4-5], but does not mechanical friction. Therefore, it is important that during an early stage of the controller design a proper choice of $f_T$ can be made with respect to a servo system with unknown mechanical friction.

When selecting $f_T$, in a practical point of view, the following two conditions are considered.

1) Minimum load inertia is same as motor inertia.

2) Maximum friction torque is less than 50% of rated motor torque at rated speed.

Based on above conditions, it is possible to obtain the break frequency for general servo motors on the market. Consequently, the maximum break frequency is not more than 55Hz. By the simulation and experimental tests, it is observed that the spectrum index in (4) should have the value of more than 2 to maintain the enough resolution of spectral energy ratio. In this study, the break frequency is set to 120 Hz and that corresponds to $N_T = 3$. Hence, the break frequency can be determined independent of friction uncertainties and the resulting performance is practically acceptable.

V. SIMULATION RESULTS

Several simulations have been carried out to examine the feasibility of the proposed algorithm. Table I shows the rated values and the nominal parameters of a tested 220V servo motor. The sampling period of current and speed control loop is 50 $\mu$s and 200 $\mu$s, respectively. The load inertia is coupled to the motor and an inertia ratio is 4:1. The on-line 128 points FFT algorithm is performed every speed control and the break frequency is set to 120 Hz.

<table>
<thead>
<tr>
<th>TABLE I. Ratings and known parameters of servo motor under test</th>
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<tbody>
<tr>
<td>Rated power output</td>
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<td>Rated speed</td>
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<tr>
<td>Torque constant</td>
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<tr>
<td>Moment of inertia</td>
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<td>Viscous friction coefficient</td>
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Fig. 5 shows the responses of conventional P/PI control mode switching for 500 r/min step speed command at 0.005 sec. The standard tracking anti-windup structure has been implemented to minimize integral windup [1]. From the top, speed command / feedback, torque command, and switching flag are depicted. The torque command increases rapidly due to the speed error. The switching flag shows the present P/PI control mode state, which indicates that PI control mode is performed when "FlagKi" equals 1. In this test, the torque command is selected as the switching variable and the switching point is tuned by the iterative tests at a given operating condition. The transient response is satisfactory but this spends a lot of time to adjust switching points.

Fig. 6 shows the responses of conventional P/PI control mode switching for 500 r/min ramp speed command. The switching variable and point are same as those in Fig. 5. Since the switching point is tuned for the case of Fig. 5, the response has a large overshoot and a long settling time. Depending on PI controller gains, speed command profile, and mechanical system structure, this kind of speed response
often leads to a vibration and may cause an instability problem.

From "FlagKi", it is observed that the switching of P control mode does not occur. Therefore, it is seen that the conventional P/PI control mode switching is heavily affected by the operating conditions.

never achieved in conventional P/PI control mode switching scheme.

Fig. 6 Conventional P/PI switching scheme for 500 r/min ramp speed command

Fig. 7 shows the responses of automatic P/PI control mode switching for 500 r/min step speed command at 0.005 sec. From the top, speed command / feedback, torque command, switching flag, and spectral energy ratio are depicted. The onset spectral energy ratio is set to 50% and this scheme does not require any tests for tuning. The speed command changes to 500 r/min and the speed response is almost same as tuned one in Fig. 5.

Fig. 7 Automatic P/PI switching scheme for 500 r/min step speed command

Fig. 8 shows the responses of automatic P/PI control mode switching for 500 r/min ramp speed command. Although the operating condition is changed, the response has a desired tracking response curve with consistent oscillation and settling time.

The torque command abruptly changes between 0.01 sec and 0.015sec and this means that the high frequency content increases in the torque signal. Thus, the spectral energy ratio also increases at this instant and "FlagKi" shows that the control mode has changed to P → PI → P mode. This can't be

VI. EXPERIMENTAL RESULTS

Extensive test are performed to verify the presented study. The algorithm is programmed and installed to 400 W servo drive and motor in Table I. The switching devices in the drive are IGBT's with 10kHz switching frequency and TMS320VC33 DSP is used as a main control processor which operates at 120 MHz clock speed. The dc link voltage is 300 V and the sampling period of current and speed control is performed at every 50 µs and 200 µs, respectively. The on-line FFT algorithm coded in assembly language is performed every speed control period 200 µs and the execution time is about 31 µs for N=128. The load inertia is coupled to the motor and an inertia ratio is 5:1, and the break frequency is set to 120 Hz.

Fig. 9 shows the actual waveforms of 500 r/min speed command for conventional P/PI control switching scheme with the standard tracking anti-windup controller. From the top, speed command / feedback, torque command, and switching flag . The switching point is tuned by the iterative tests at a given operating condition and this spends a lot of time to adjust switching points.

Fig. 9 Conventional P/PI switching scheme for 500 r/min speed Command

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Fig. 10 shows a typical problem when conventional P/PI control mode switching is adopted. The switching variable and point are same as those in Fig. 9. Depending on PI controller gains, speed command profile, and mechanical system structure, the speed response may cause a severe instability problem in motion control systems.

From "FlagKi", it is observed that the switching of P control mode does not occur. Therefore, it is seen that the conventional P/PI control mode switching is heavily affected by the operating conditions such as speed command, acceleration/deceleration rate, and load disturbances.

Fig. 10. Conventional P/PI switching scheme for 500 r/min ramp speed command

Fig. 11. Automatic P/PI switching scheme for 500 r/min speed command with different acceleration/deceleration time

Fig. 12. Speed control performance with automatic P/PI switching scheme for 1000 r/min speed command

Fig. 13 shows the 1000 r/min speed response with longer acceleration time than those of Fig. 12. According the frequency content of torque command signal, the control mode has automatically changed to P → PI → P mode. The dynamic response agrees quite well that of simulation. It is clear that the proposed scheme doesn’t require the iterative tunings in the fields and is also helpful to the inexperienced user.

VII. CONCLUSIONS

Analyzing the spectral content of motor torque command, the controller switching point is automatically determined and time-consuming experiments can be replaced by simple
software calculations in the controller. After the proposed algorithm is installed, on the line during a scheduled downtime, thereby minimizing impact on product scheduling and production. The dynamic performance of the proposed scheme assures a desired tracking response curve with minimal oscillation and settling time over the complete operating conditions. For comprehensive comparison of conventional P/Pi control scheme, extensive test is carried out on a 400W servo drive system.

VIII. REFERENCES


