ORIGINAL ARTICLE

Real time DSP-based adaptive controller implementation for 6/4 pole switched reluctance motor drive

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Abstract

Paramasivam, S. and Arumugam, R.
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Songklanakarin J. Sci. Technol., 2005, 27(3) : 523-534

This paper presents the design and implementation of an adaptive PID control system for a high performance Switched Reluctance Motor (SRM) drive. The concept behind the proposed control system is to use an adaptive PID controller in steady state as well as transient state, which implements the control excellently in most cases. The modality of the control for the adaptive PID controller is such that the coefficients of the controller are adaptable during the running conditions. Thus, the PID controller along with adaptable coefficients is implemented to take the advantage of its positive attributes. The adaptive PID controller for SRM drive is implemented through a TMS320F2812 DSP to evaluate the performance. The implementation is based on discrete time PID controller, whose coefficients are derived from practical experiments at different operating conditions with disturbances. Experimental results have shown excellent tracking performance of the proposed control system, and have convincingly demonstrated the usefulness of the adaptive PID controller in high performance SRM drives with uncertainties.

Key words : Switched Reluctance Motor (SRM), discrete time PID controller and Adaptive control

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Received, 17 May 2004 Accepted, 28 October 2004

In recent years, Switched Reluctance Motor (SRM) drives have gained widespread use in electric drives. These motors are ideal for use in clean environments such as aeronautics, robotics, electric vehicles and industries. Using these motors in high performance drives requires advance and robust control methods (Krishnan, 2001; Miller, 1989; Lindsay *et al*., 1986; Byrne and McMullion, 1982, Bruce, 1988; Rose, 1989; Ray *et al*., 1986; Caio *et al*., 1995; Chen and Xie, 1984; Krishnan and Bharadwaj, 1992). Conventional control techniques require accurate mathematical models describing the dynamics of the SRM under study. These techniques result in tracking error when the load varies fast and overshoot during transients. SRM cannot be run directly from the supply. It can be run only when the motor is integrated with power converter, controller and rotor position sensor. Many papers have been reported on the performance simulation of SRM with experimental validation for different control strategies such as feed back linearization control, variable structure control, fuzzy logic control and four-quadrant operation of SRM (Moreira and Lipo, 1989; Arkadan and Kielgas, 1994; Panda and Dash, 1996; Buju *et al*., 1993; Silveri and Mauro, 1996; Syed *et al*., 2003). None of these papers (Moreira and Lipo, 1989; Arkadan and Kielgas, 1994; Panda and Dash, 1996; Buju *et al*., 1993; Silveri and Mauro, 1996; Syed *et al*., 2003) has focused exclusively on fast tracking capability, low steady state error and robustness to load disturbance during steady state and transient conditions. If an adaptive control strategy is used instead of existing non-adaptive controllers, the system will perform more accurately or robustly. It is, therefore, desired to develop an adaptive PID controller that has the ability to adjust its own controller coefficients, when it is working in real time environments to obtain satisfactory control performance. This PID algorithm requires a simple mathematical model and it is obtained experimentally by conducting suitable tests on SRM. The real values obtained from the experiments are used to find the controller coefficients through MATLAB simulation. The coefficients obtained from the MATLAB are used to obtain the closed loop control of a SRM with coefficients gain adjusting mechanism to get enhanced operation in real time operating conditions. The results suggest that discrete time adaptive PID is highly suitable for high performance SRM drive applications. The proposed control system is designed and implemented through TMS320F2812 to check its effectiveness at various operating conditions. In this research, the PID controller is ready to respond during steady state and transient state with severe perturbations. The best attributes of the adaptive PID controller with adaptable coefficients results a controller, which is smooth and fast and very low NRMSE (Speed root mean square error). Results from real time implementation are presented. This paper is organized as follows. Section II reviews the SRM description. Section III reviews the hardware system description. Section IV discusses the discrete time PID controller implementation. Section V discusses the adaptive PID controller implementation. Section VI discusses the experimental results. The conclusion is given in the last section.

SRM Description

A proto type SRM having 6 stator poles and 4 rotor poles is shown in Figure 1. The prototype motor parameters are given in Appendix 1

Figure 2 shows an idealized inductance profile of an SR motor. The phase inductance is maximum when the rotor pole is aligned with the stator pole and is minimum when the rotor pole is aligned with the inter polar axis of the stator (Krishnan, 2001; Miller, 1989).

$$L(\theta) = \begin{cases} L_{\min} & \theta_0 \le \theta_p \theta_1 \\ L_{\min} \quad + p\theta & \theta_1 \le \theta_p \theta_2 \\ L_{\max} & \theta_2 \le \theta_p \theta_3 \\ L_{\max} \quad - p(\theta - \beta_{r)} & \theta_3 \le \theta_p \theta_4 \\ L_{\max} & \theta_4 \le \theta_p \theta_5 \end{cases} \qquad (1)$$

Where

L(θ) - Inductance variation over one rotor pole pitch

$L_{\min}$ - Unaligned inductance (H)

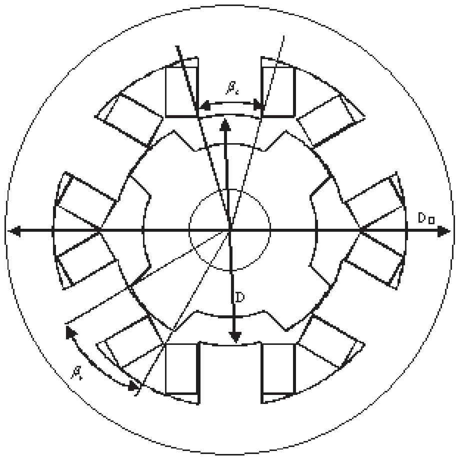


Figure 1. 6/4 Pole prototype SRM

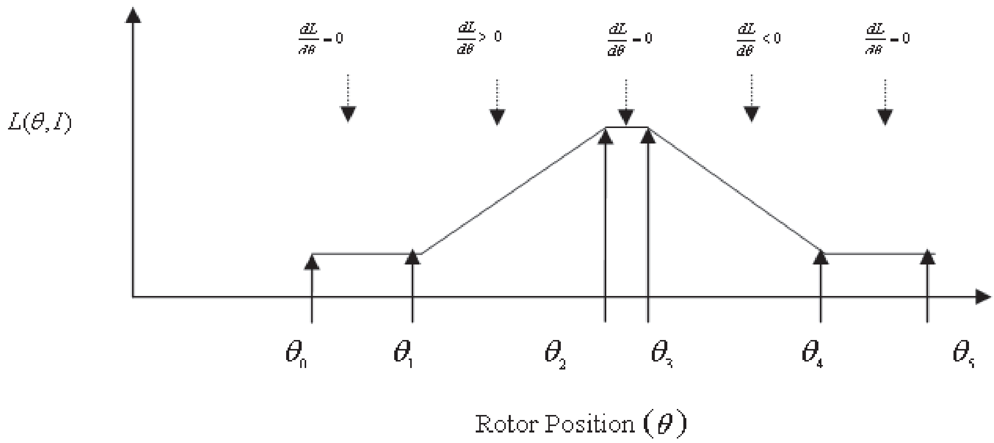


Figure 2. Inductance (L) variation over one rotor pole pitch with constant current magnitude.

L_{max} - Aligned Inductance (H)
β_s - Stator pole arc (rad)
β_r - Rotor pole arc (rad)

$\beta_r > \beta_s$ and $p = \dfrac{L_{max} - L_{min}}{\beta_s}$

The per phase equivalent circuit of the SRM can be drawn as shown in Figure 3.

$$V(t) = Ri(t) + L(\theta,i)\frac{di}{dt} + i\varpi\frac{dL(\theta,i)}{d\theta} \qquad (2)$$

where

V - is the voltage applied to the phase
r - is the phase resistance
$Ri(t)$ - is the resistive voltage drop
$L(\theta,i)\frac{di}{dt}$ - is the static voltage
$i\varpi\frac{dL(\theta,i)}{d\theta}$ - is the speed voltage

Equation (2) is applicable only when the mutual inductances are neglected. From the equation (2), it is understood that the speed voltage of each phase is proportional to the actual speed of the motor and rate of change of inductance with respect to rotor position (Krishnan, 2001; Miller, 1989). The instantaneous torque (T) produced in the SRM is given by the formula (Krishnan, 2001;

Miller, 1989)

$$T_d = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (3)$$

From the above non linear equation, it is understood that motoring torque can be obtained only when phase current is switched on during the rising period of phase inductance and braking torque can be obtained by switching phase current during the decreasing period of phase inductance. It is obvious from Figure 2. that in order to get optimum speed control, switching of phase currents must be done at appropriate rotor positions. This is why rotor position information is always important to operate an SRM drive. Rotor position information is fed back to the controller to determine the phase commutation sequence and speed of the SRM. The proper choice of the turn-on and turn-off angles, determine the ultimate performance of the SRM. In order to implement the control algorithm effectively, a high-speed digital controller has to be implemented. The basic block diagram of feedback speed control system of a SRM drive is shown in Figure 4.

Hardware system description

The SRM drive system is made up of several distinct subsystems and is illustrated in Figure 5. The subsystem consists of a 6/4 pole SRM, personal computer (PC), driving circuit, classic bridge converter (Sayeed, 2000), sensing circuitry and the eZdsp F2812 board from Texas Instruments as a development tool board (TMS320 F2812). The SRM is equipped with a rotor position sensor. The three sensors are mounted on the shaft of the SRM, wherein a combination of infrared LED (MLED930) and photo transistor (MRD5009) are used to sense the rotor position to indicate which of the three phases of the SRM is to be excited as the motor runs. One of the rotor position

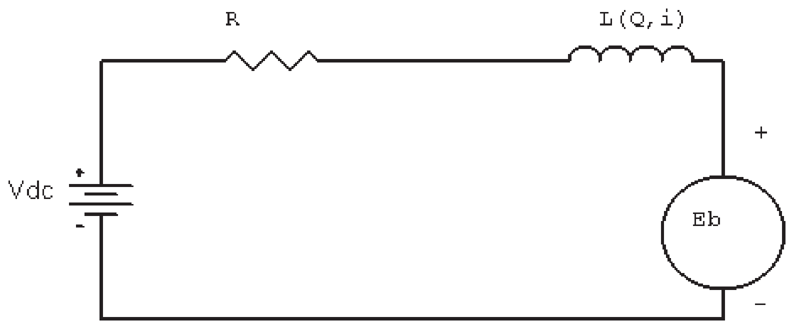


Figure 3. Per phase electrical equivalent circuit of SRM

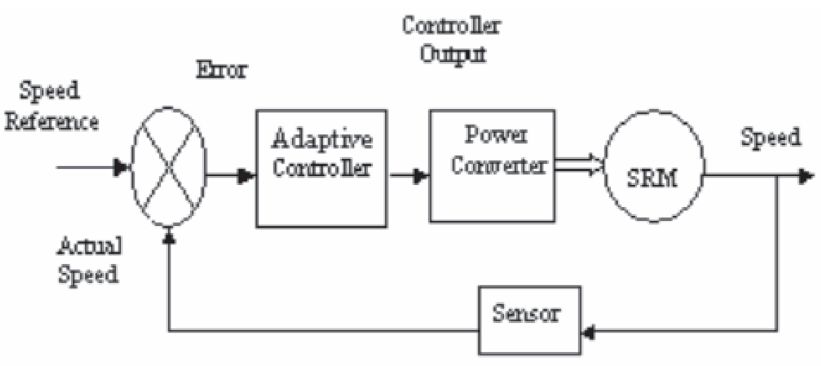


Figure 4. Basic speed feed back control system

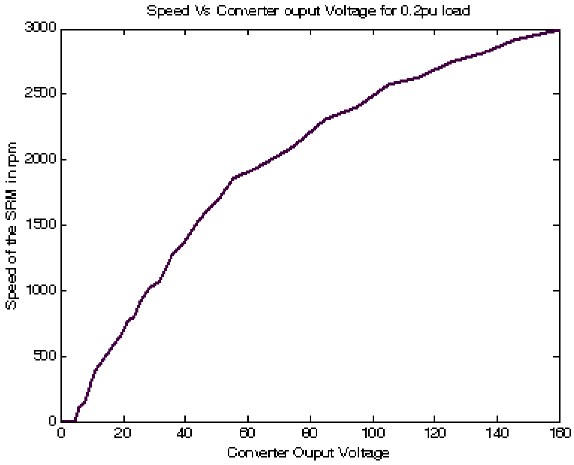


Figure 5. Converter output voltage Vs Speed of the SRM

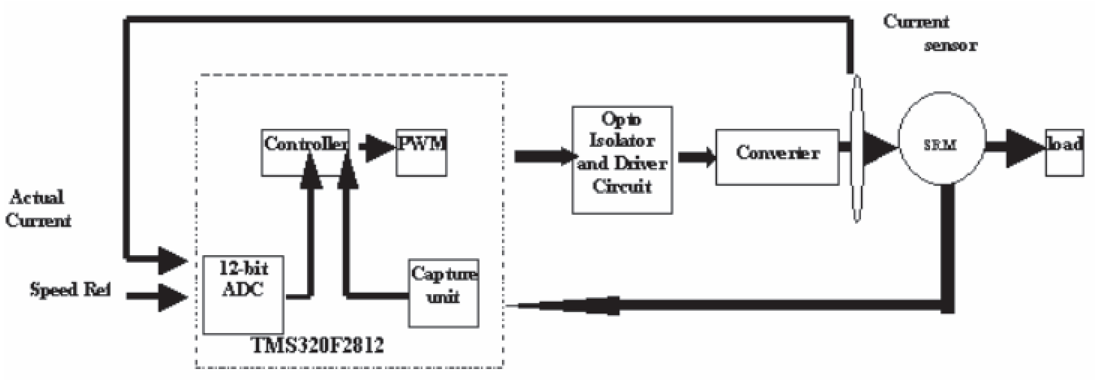
sensorís output is used to calculate the actual speed of the SRM. The controller is implemented by software and executed by an eZdsp F2812 board. The eZdsp kit provides a complete development environment, and includes the DSP board, power supply for the board, on-board JTAG compliant emulator, and an eZdsp specific version of the Code Composer Studio (CCS) integrated development environment (full featured, including debugger IDE, and ANSI C and C++ compliant compiler). The DSP board itself has nearly all-peripheral signals available on the board headers, making it easy to interface the board with other system hardware. The program is completely contained in the DSP and the computer is only required to load new programs into the DSP. Additionally, it has an internal ADC, which can accept up to sixteen analog inputs and two Event managers, which is used to produce necessary PWM. Additionally, necessary protection circuits are used to prevent damage to the DSP. The control algorithm is written and loaded into the DSP using the PC. The driver circuit is constructed using totem pole configuration, wherein NPN (3904) and PNP (2907) transistors are used. In order to maintain the current at its rated value, the DC bus current is measured through current sensor (LEM25-NP). The inputs to the DSP are the rotor position information and dc bus current. The output of the switching logic section is a sequence of gating signals that are pulse width modulated (PWM) gating signals used to drive the classic bridge converter. The power converter is a classic bridge converter utilizing six MOSFETs (IRFP360) and fast recovery diodes (MUR3060). The output of the power converter is a chopped to get the desired voltage. The converter output voltage Vs speed of the SRM for 0.2pu load is given in Figure 5. The complete Block diagram of the experimental setup and its photograph is shown in Figure 6.

Discrtete Pid Controller Implementation

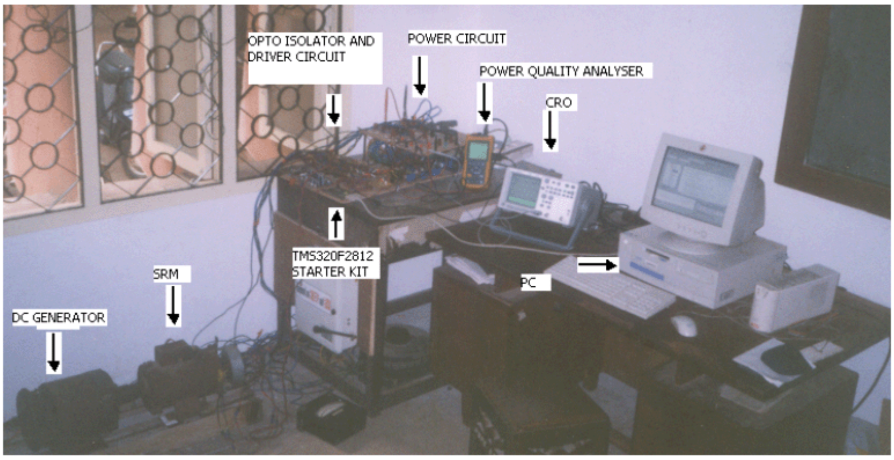
Many motor drive systems today employ conventional controllers such as a PID type controller. In general, these kinds of PID controllers are implemented as digital filters in the following form, where k is the current sample in time, for a given sample period T

$$y(k) = \sum_{i=0}^{n} a_i x(k-i) - \sum_{i=1}^{n} b_i y(k-i) \qquad (4)$$

In this form y (k) is the output, x (k) is the input, a_i and b_i are coefficients of the controller. These gains must be selected to produce the desired controller response for a given SRM to be controlled. The structure of this digital controller is illustrated in Figure 7. In Figure 7, the Z^{-1} blocks represent delays of one sample period. When n =



(a) DSP based SRM Drive system



(b)

Figure 6. (a) DSP based SRM drive system. (b) Photograph of an experimental system

2, a second order filter is obtained which can be used to implement PID controllers. This representation for a 2^{nd} order discrete time controller in the sampled time domain is shown below

$$y(k) = a_0 x(k) + a_1 x(k-1) + a_2 x(k-2) - b_1 y(k-1) - b_2 x(k-2) \quad (5)$$

The z-transform of this gives the following transfer function

$$D(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}} \quad (6)$$

These kinds of 2^{nd} order controller are generally implemented through high-speed digital signal processors. In this paper, speed control of SRM utilizes the PID algorithm (Astrom and Hagglund, 1995; Huang *et al.*, 2002; Ketata *et al.*, 1995. The proportional control mode gives rapid closed loop transient response to step changes in the speed reference and fast rejection of speed disturbances. The integral control mode assures that the final SRM speed will match the speed reference. Finally, the derivative control mode reduces transient overshoot and oscillation in the speed when the reference is changed from one value to another. The PID algorithm can be expressed in the discrete time domain as

(i) Proportional, Integral Controller and Derivative Controller (PID)

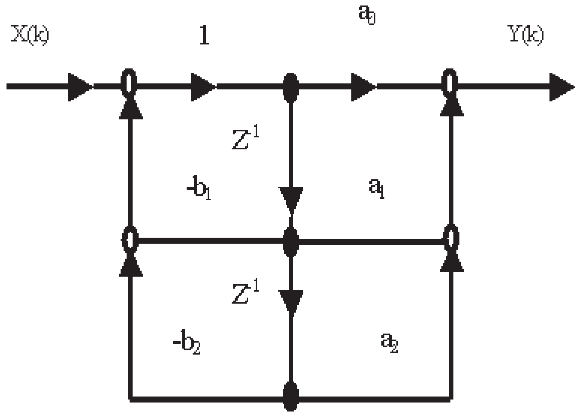


Figure 7. Second order discrete time PID controller

$$u(k) = k_P e(k) + K_1 T s(k) + K_D \left(\frac{e(k) - e(k-1)}{T}\right) \quad (7)$$

To eliminate the need to calculate the full summation in each time step the summation is expressed as a running sum

$$S(k) = S(k-1) + \frac{T}{2}[e(k) + e(k-1)] \quad (8)$$

Where:

u(k) is the control signal
e(k) is the error signal
T is the sample period
K_P is the proportional mode control gain
K_I is the integral mode control gain
K_D is the derivative mode control gain

The z-transform of discrete time PID controller gives the transfer function

$$D(z) = K_P + \frac{K_I T}{2}\left(\frac{z+1}{z-1}\right) + \frac{K_D}{T}\left(\frac{z-1}{z}\right) \quad (9)$$

$$D(z) = \frac{(K_P + K_I T/2 + K_D/T) + (-K_P + K_I T/2 - 2K_D/T)z^{-1} + K_D/T)z^{-2}}{(1 - z^{-1})} \quad (10)$$

$$D(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}} \quad (11)$$

where

$$a_0 = K_P + \frac{K_I T}{2} + \frac{K_D}{T}, a_1 = -K_P + \frac{K_I T}{2} - \frac{2K_D}{T}$$

$$a_2 = \frac{K_D}{T}, b_1 = -1 \; and \; b_2 = 0$$

a_o, a_1, a_2, b_1 and b_2 are the gains of the digital controller

The real values (phase voltage Vs speed at various loads) obtained from the experiments are used to obtain the mathematical model of SRM through MATLAB simulation. The non linear equation derived from the MATLAB simulation is linearised through Taylor series expansion. The continuous time equation is discretised and algorithm developed in the discrete time domain has been implemented through a high speed Digital Signal Processor (TMS320F2812).

Adaptive Pid Controller Implementation

In the previous section, the discrete time non-adaptive PID controller implementation is explained. But it is found that the implementation of the equation (11) does not provide complete control solution at various operating conditions. Hence an adaptive controller with on line gain adjusting mechanism is required to get enhanced operation in real time operating conditions. The adaptive PID control scheme is shown in Figure 8, wherein a gain tuning mechanism is incorporated. From the experimental results, it is found that adaptive controller gives better performance at various operating conditions. If the controller coefficients (a_o, a_1 and a_2) are constant during real

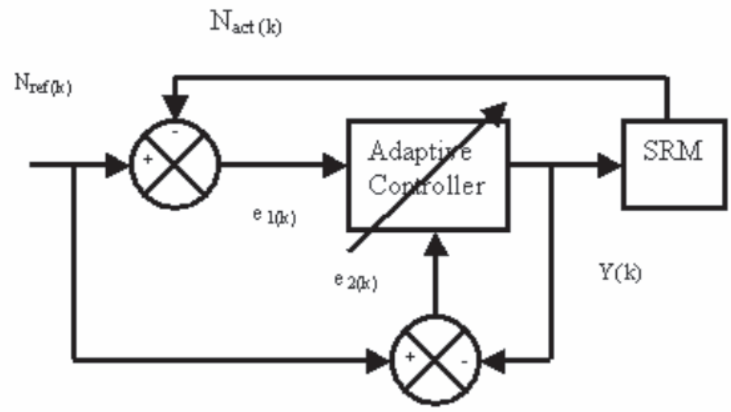


Figure 8. Adaptive PID control scheme

time operating conditions, then it is said to be a non-adaptive controller and if the coefficients are adjusted during real time operating conditions, then is said to be an adaptive controller. The major advantage of tuning the controller coefficients is to provide oscillation free, efficient and smooth operation. The inputs to the adaptive controller are e_1(k), e_2(k) and output is y(k). The output of the adaptive controller depends on e_1(k) and e_2(k), whereas in the non-adaptive controller y(k) depends only on e_1(k). The e_2(k) can be found as follows.

$$^{e}2^{(k)} = N_{ref}(k) - y(k) \quad (12)$$

Taking Z transform of the equation (12)

$$E_2(z) = N_{ref}(z) - y(z) \quad (13)$$

$$E_2(z) = N_{ref}(z) - \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 - z^{-1}} \times E_1(z) \quad (14)$$

A quadratic objective function is developed based on minimizing E_2 with respect to the controller parameters

$$J(a_0, a_1, a_2) = \frac{1}{2} E_2^2 \quad (15)$$

$$J(a_0, a_1, a_2) = \frac{1}{2}(N_{ref} - \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 - z^{-1}} \times E_1)^2 \quad (16)$$

Taking the first order partial derivative with respect to the controller parameter a's

$$\frac{\partial J}{\partial a_0} = -2N_{ref}\left(\frac{1}{1-z^{-1}}\right)E_1 + (2\left(\frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1-z^{-1}}\right)\left(\frac{1}{1-z^{-1}}\right)E_1)^2 \quad (17)$$

$$\frac{\partial J}{\partial a_1} = -2N_{ref}\left(\frac{z^{-1}}{1-z^{-1}}\right)E_1 + (2\left(\frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1-z^{-1}}\right)\left(\frac{z^{-1}}{1-z^{-1}}\right)E_1)^2 \quad (18)$$

$$\frac{\partial J}{\partial a_2} = -2N_{ref}\left(\frac{z^{-2}}{1-z^{-1}}\right)E_1 + (2\left(\frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1-z^{-1}}\right)\left(\frac{z^{-2}}{1-z^{-1}}\right)E_1)^2 \quad (19)$$

Table 1.

Type of control	**RMSE**			
	1750 rpm	**1210 rpm**	**790 rpm**	**190 rpm**
PI Control	8.25	5.82	4.72	5.45
PID type	17.25	12.12	11.93	14.91
Adaptive Control	2.95	2.32	1.95	2.32

Using the first order approximation, the negative gradient is the multiplication of speed reference (N_{ref}) and speed error (E_1). But normally using E_1 and E_2 gives better convergence, which is equivalent to an adaptive mechanism mentioned in (Dote, 1990)

$$a_n(k+1) = a_n(k) + \beta e_2(k) e_1(k-n) \qquad (20)$$

Where n = 0, 1 and 2

β - Step size

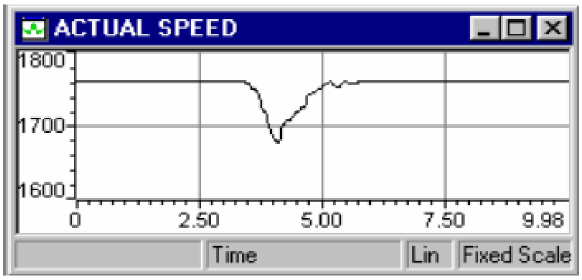
$a_n(k+1)$ - Controller coefficients at $(k+1)^{th}$ instant

$a_n(k)$ - Controller coefficients at k^{th} instant

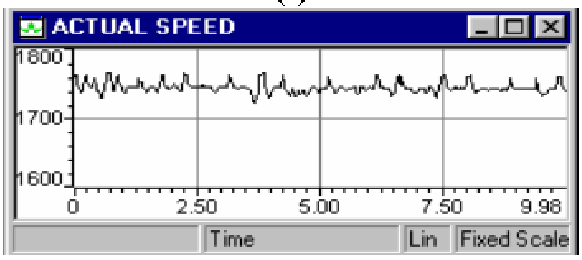
$e_2(k)$ - Function input at k^{th} instant $(N_{ref}(k) - y(k))$

$e_1(k-n)$ - Function error at k^{th} instant

For initial conditions, the controller coefficients a_1, a_2, a_2, b_1 and b_2 are fixed as 1,0,0,1 and 0 respectively. The mathematical model derived from the MATLAB simulation, is used to calculate the final PID parameters as a_0 = 0.5116111, a_1 = -0.2549778 and a_2 = -0.2562406



(a)



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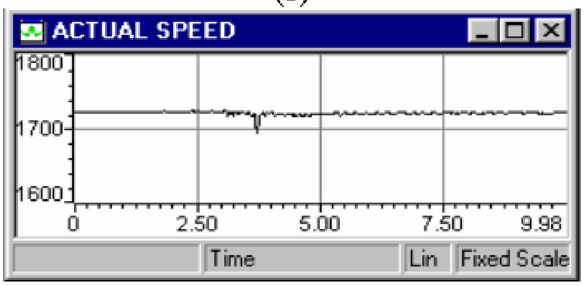
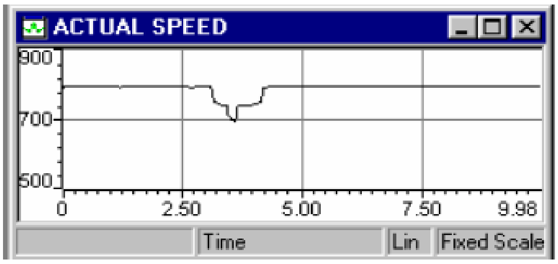


(c)

Figure 9. Experimental results for actual speed of 1760 rpm for a load of 1.1 N-m at the time duration between 2 secs to 4 secs (a) PI control. (b) PID control. (c) Adaptive PID control.



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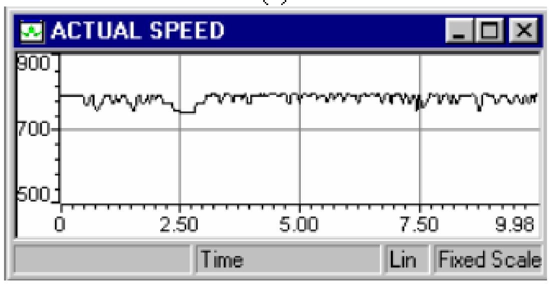

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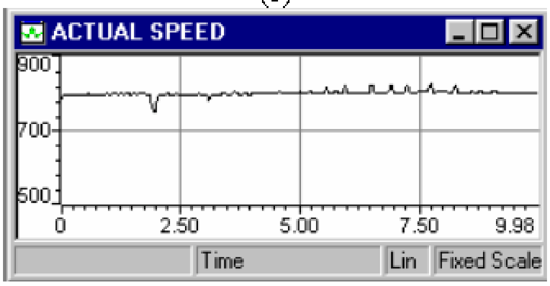

(c)

Figure 10. Experimental results for actual speed of 810 rpm for a load of 1.1 N-m at the time duration between 2 secs to 4 secs (a) PI control. (b) PID control. (c) Adaptive PID control.

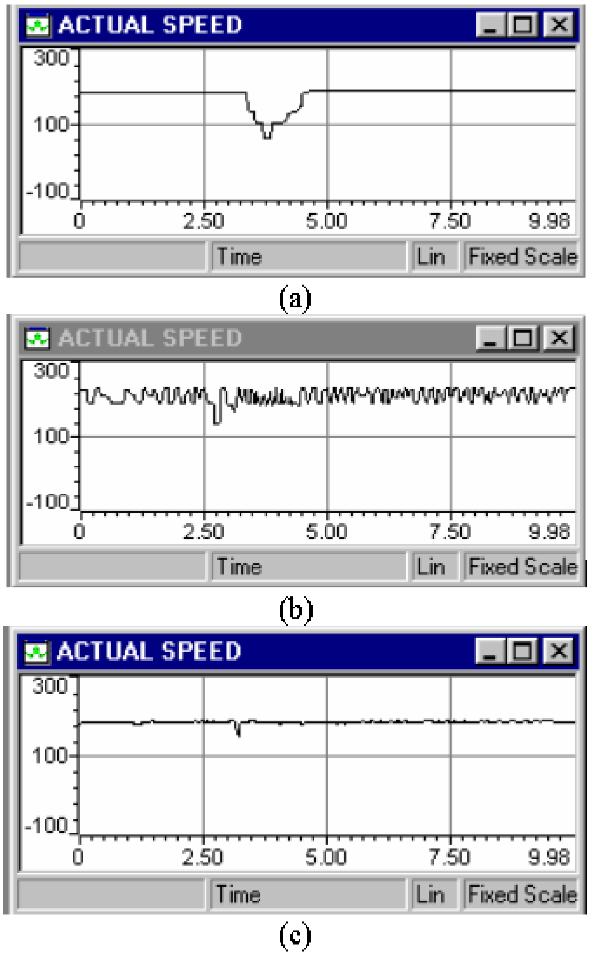

Figure 11. Experimental results for actual speed of 185 rpm for a load of 1.1 N-m at the time duration between 2 secs to 4 secs (a) PI control. (b) PID control. (c) Adaptive PID control.

Experimental Results

In order to highlight the importance of an adaptive controller during steady state and transient state, a controller of non-adaptive PI and PID controllers are also implemented. The following formula is used to find the NRMSE, wherein 100 samples are taken into consideration to find the NRMSE.

$$N_{RMSE} = \sqrt{\frac{\sum_{k=1}^{N}(N_{ref} - N_{act}(k))^2}{N}} \qquad (21)$$

Where

N_{RMSE} - Speed Root Mean square error

N_{ref} - Reference speed in rpm

N_{act} - Actual speed in rpm

N - No of samples

For the system presented in this paper, the maximum value of RMSE for PI controller is 8.25 rpm and PID controller is 17.25 rpm, which is given Table 1. Figure 9 through Figure 11 show the experimental results for the SRM drive using the adaptive PID controller and other non-adaptive

PI and PID controllers. As shown in Figures 9 to 11, for the case of steady state, the non-adaptive PI-controller dominates the control output to significantly reduce steady state error of the system and the non adaptive PID contributes to the output to provide fast response and low overshoot. Table 1, it is understood that for different operating conditions, the adaptive PID controller provides NRMSE much lower than non-adaptive controllers.

Conclusions

This paper has presented a simple, an effective and adaptive PID control for application of a 6/4 pole SRM drive. The proposed control system was designed and implemented through TMS320F2812 DSP and its effectiveness in error reduction was verified. The complete experimental system was built and implemented for 6/4-pole prototype SRM. Experimental results prove the suitability of the proposed methodology as a high-performance adaptive control system for SRM drives. The main advantage of designing and implementing the proposed adaptive PID controller is the ease of the design and flexibility. In addition, the controller design and implementation requires only complete knowledge of the SRM and its dynamics, high speed DSP, few logic IC's and single current sensor. Experimental results show that the proposed adaptive PID control scheme is very robust to motor parameter variations and load disturbances.

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APPENDIX-1

Motor Parameters

Power : 1.2KW
Voltage :160 V
Current :16 A
Stator outer diameter : 162 mm
Stator core length : 90 mm
Stator inner diameter : 80 mm
Shaft diameter : 25 mm
No of poles in the stator : 6
No of turns/pole : 75
Cross section of the conductor : 1.7 sq-mm
Stator pole arc : 29 deg
Stator pole height : 20 mm
No of poles in the rotor : 4
Rotor pole arc : 32 deg
Rotor Pole height : 15 mm