EE2683 website

http://www.ece.unb.ca/Courses/Coursehp.htm

March 1, 2006 **Dr. A.M. Sharif**

EE 2683

Design Project 10% **DUE by March 24, 2006**

One report per student - Group Discussions and Open Discussions are encouraged.

Engineering Design Component 10%

Objectives

1. Model an industrial separately excited DC motor using matlab/simulink or other modeling CAD/CAE software. Select any motor parameter from papers located at
   `http://www.ece.unb.ca/Courses/EE2683/AS/EE2683_paper1.pdf`
   `http://www.ece.unb.ca/Courses/EE2683/AS/EE2683_paper2.pdf`
   or textbook.
2. Design a Robust fast acting speed control scheme.
   2.a. PID
   2.b. Bang - Bang

TIPS

- Use any DC Motor machine parameters from any source and parameter
- Justify any design selection.
- Refer to the sample two papers and designs done by formal U/G students
- Show the dynamic response of armature, field and shaft sections.
- Plot W_m -vs T_L for load
- Plot T_e $I_{<1}$, I_{1ss} versus time
- Plot $T_{acc} = J \dfrac{dw_m}{dt}$, $T = B.W_m$ damping torque versus time.
- Plot phase portraits V_m vs i_m and T_m vs i_m
- Assume a mechanical load $T_L = K_o + K_1 W_m + K_2 W_m^2$ of Torque - speed quadratic relationship - select parameters such that T rated occur at W_m - rated.
- Use either a (P + I + D) classical controller or a bang-bang speed regulator.
- A control scheme can vary the armature applied voltage V_t alone or in conjunction with field current control.
- Refer to Dynamic "Transient" DC motor full model discussed in the D.E. and A.E. class.
- Assume K_a ∅ - vs - i_f mag - curve to be linear.

GOOD LUCK **A best project report prize of a DMM Digital Multi Meter will be personally donated by Dr. Sharaf to Best Report.**

Nonlinear Speed Control of Large Industrial Dc Motor Drives with an Energy Efficiency Enhancement Loop

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Abstract

The paper presents a novel dynamic speed reference trajectory tracking controller using an error driven self-adjustable, self-regulating nonlinear control block. The speed controller has two time-decoupled control/regulation loops namely:

I. *The speed reference trajectory tracking loop*

II. *A supplementary minimum power input dynamic tracking-search loop to ensure higher utilization efficiency for inrush type, cyclical and dynamic loads.*

The paper presents Matlab digital simulation results of a DC motor drive system with the switching inherent delay and other drive/control nonlinearities taken into consideration. The self adjusting hyper error driven nonlinear control block ensures good speed reference tracking, minimum inrush current and excursions as well as online energy conservation and electrical power energy savings for large industrial DC motor drives in the range (100kW-1000kW).

1 Introduction

Large industrial DC motor drives are still used in a multitude of industrial and manufacturing processes such as pulp and paper, steel mills, conveyors, robotics, guided vehicles, mining and earth-moving equipment [1, 7, 8]. Several control techniques [2, 1] are currently utilized, including conventional proportional plus integral, tunable, model reference, adaptive, state space optimal control schemes as well as novel neural, fuzzy and [5, 6, 9–10] neuro fuzzy speed/position regulating loops

To ensure the design of high performance and efficient DC motor drives, all nonlinearities associated with the converter's switching, common discontinuous current mode and firing angle limitations as well as inrush current and starting conditions should be accounted for. Control objectives of fast response time, minimum overshoot/undershoot, short settling time should also be augmented with the additional requirement of energy/power utilization efficiency, especially for large industrial motor drives in the range of [100kW - 1000kW].

The use of a new concept of hyper-error driven (speed and power) regulation is introduced in this paper. Figure 3 depicts the basic structure of the dual bridge armature voltage control scheme driven by the combined slow and fast acting loops of speed reference tracking as well as dynamic "minimum" motor input power tracking. Figure 4 shows a block diagram of the two-loop speed/power tracking controller with the TANSIGMOID error driven nonlinear block.

2 Control Equations

The motor drive system was simulated on the Matlab/Simulink software environment using typical DC motor equations [9]. Figure 5 depicts the motor /controller/drive system model as represented by the Simulink block structure. The control scheme utilizes the (per-unit) hyper-error vector $(e_w, \dot{e_w}, e_p)$ governed by the following equations:

Define all per-unit errors with $T_{sampling}\ T_s = 20ms$

$$e_w(k) = \omega_{ref}(k) - \frac{\omega_m(k)}{\omega_{base}} \quad (1)$$

$$e_p(k) = P_a(k) - P_a(k-1) \quad (2)$$

$$\dot{e_w}(k) = \frac{e_w(k) - e_w(k)}{T_s} \quad (3)$$

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The total error $e_0(k)$ at a time instant:

$$e_0(k) = e_w(k) + \gamma \dot{e_w}(k) + k_p e_p(k) \tag{4}$$

$$\Delta v_c(k) = K_0 |R_e(k)| \frac{1 - e^{(-\beta e_0(k))}}{1 + e^{(-\beta e_0(k))}} \tag{5}$$

Where $R_e(k)$ defines the measure of the error excursion in the projected $(e_w - e_p)$ plane

$$R_e(k) = \sqrt{e_P^{-2} + e_w^{-2}} \tag{6}$$

$$V_c(k) = \int_0^t \Delta v_c(k) \tag{7}$$

The control signal $V_c(k)$ $(\pm 5V)$ is applied to the grid switching block (GS) to yield the control angle $\alpha(k)$

$$\alpha(k) = cos^{-1}(k_\alpha \cdot V_c(k)) \tag{8}$$

The motor armature voltage $V_a(k)$ is finally given by the following equation

$$V_a(k) = V_R(k) \frac{\frac{1}{L_P C_P}}{s^2 + \frac{R_P}{L_P} + \frac{1}{L_P C_P}} \tag{9}$$

$$V_R(k) \cong 1.35 V_{LL} cos(\bar{\alpha}(k)) e^{-T_0 s} \tag{10}$$

The inherent switching time delay T_0 is chosen to be $\frac{16.66}{6}$ milliseconds, which corresponds to the 6-pulse converter bridge with control(α) limited in the range $(5^o < \alpha < 175^o)$ for a dual rectifier bridge.

3 Simulation Results

The full motor drive and a novel controller model was implemented using the Simulink 5 model shown in Figure 5. The motor and drive system and control parameters are given in the Appendix

The controller effectiveness in tracking different speed reference trajectories were tested for step, sinusoidal and trapezoidal references. Figures 1 and 2 depict results for the sinusoidal reference. Per-unit error excursions are depicted in the projected error planes of the three-dimensional $(e_w, \dot{e_w}, e_p)$ vector. The need for better selection and tuning of the control parameters (K_0, γ, K_p) was very evident in the case of sinusoidal speed reference tracking. The offline trial and error selection process was formalized by defining the time-scaled objective functional J to be minimized as follows:

$$J = \sum_{k=1}^{N} (k \cdot T_s \cdot |R_e^2(k)| \tag{11}$$

where

$$N = Settlingcount = \frac{T_{largestmechanicaltimeconstant}}{T_s} \tag{12}$$

An online slow optimization algorithm based on (11) above can also be utilized to perform selective online snap-shot calculations of (K_0, γ, K_p) and control parameter tuning.

4 Conclusions

The paper presented a novel nonlinear error-driven self-adjusting speed regulator for large industrial DC motor drives. The nonlinear self-adjusting error-driven "Tansigmoid" block ensures an effective control signal as dictated by the per-unit three-dimensional hyper-error $(e_w, \dot{e_w}, e_p)$.

The addition of a slow-acting dynamic motor input power tracking loop ensures power energy efficiency, minimum inrush and associated supply line harmonics, minimum load excursions, and less electric energy consumption in case of a cyclical inrush type motorized load. The selection of optimal control parameters is essential for better robust tracking of complex speed reference trajectories. The novel controller is now being extended to position control of robotic manipulators and guided vehicles with the inclusion of a second speed derivative $(\ddot{e_w})$ and extending the error hyperplane to a fourth dimension, as well as the addition of an online tuning block.

Appendix

Supply : V_{LL} = 240 V (L - L)

Motor Values

Power = 93.25 kW ; Input Voltage = 230 V; Reference Speed = 120.4 rad/sec $R_f = 1.0\ \Omega$ $L_f = 20.0$ mH $C_f = 100\ \mu$ F $K_0 = 5$ $K_1 = 0$ $K_2 = 0.022$ $R_a = 0.0125\ \Omega$ $L_a = 10$ mH J = 3.5 $Nm \cdot s^2$ B = 0.6 $Nm \cdot s$ Ke = Km = 1.91 $K_\alpha = 0.20$

Controller Values

K_P=0.7 $\gamma = 0.15$ $K_O = 9$ $T_s = 20$ msec $\beta = 3.0$

References

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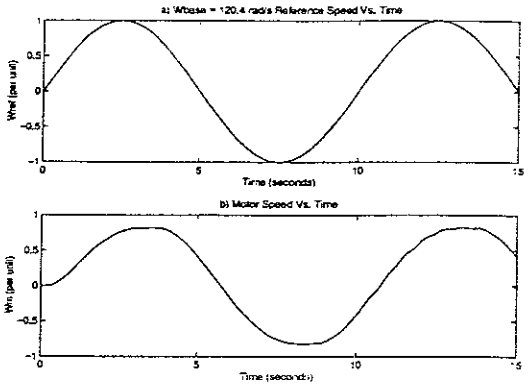

Figure 1: Tracking Results for Sinusoidal Reference

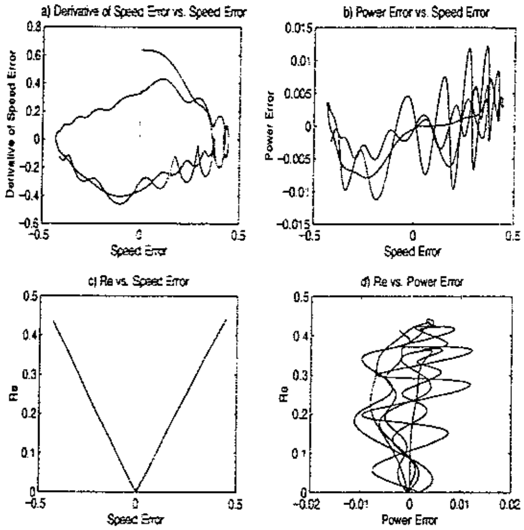

Figure 2: Error Results for Tracking of Sinusoidal Reference

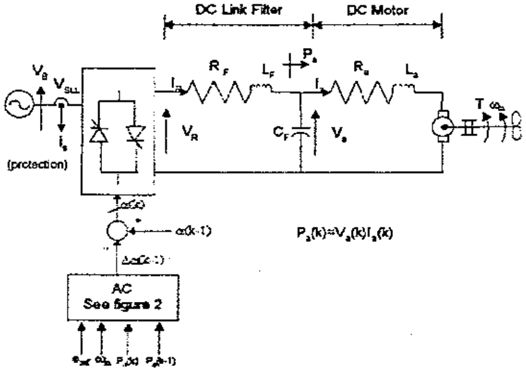

Figure 3: DC Motor Drive System with Dual Bridge Armature Control

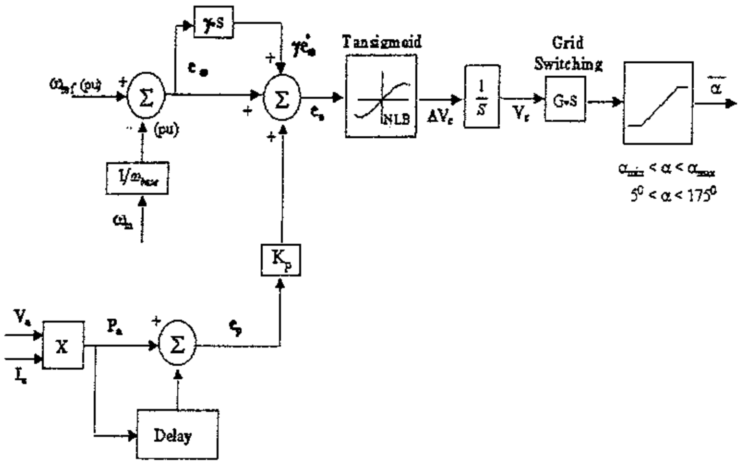

Figure 4: Controller Block Diagram

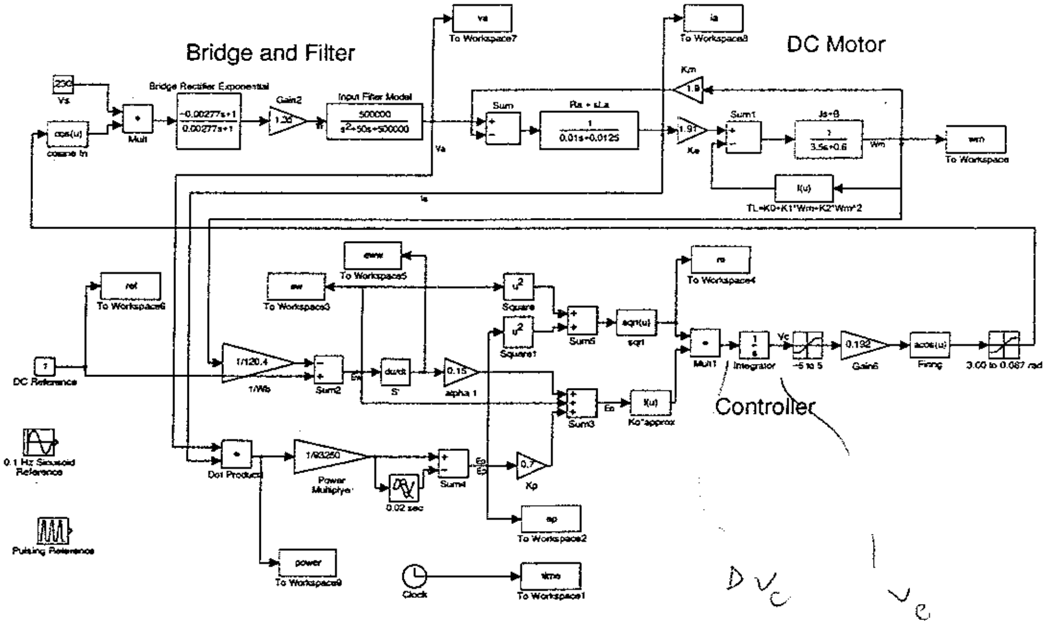

Figure 5: Motor/Controller/Filter System Block Diagram

Bridge inherent delay

$$\boxed{\frac{1 - T_0 s}{1 + T_0 s}}$$

$T_0 \sim \frac{16.66}{6}$

AN ENERGY EFFICIENT SELF-ADJUSTING SPEED CONTROLLER FOR INDUSTRIAL DC MOTOR DRIVES

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Abstract

The paper presents a novel self adjusting speed (SAC) controller comprising two dynamic error regulation loops (speed and power) to ensure effective speed reference tracking as well as power/energy conservation for common cyclical loads driven by industrial large DC motor drives.

Introduction

DC motor drives are extensively utilized in industries such as steel, pulp and paper, chemical, mining, earth moving and food processing due to their superior controllability and the low cost control effectiveness of either DC-DC (chopper) drives or industrial thyristor controlled dual rectifier converters [1]. Different control strategies were extensively utilized [2-6] including classical (PID), optimal control, adaptive control, self-tuning and variable-structure nonlinear control. New A.I. based control designs were introduced due to severe mechanical load nonlinearly also, unexpected load excursions, parameter uncertainties, drive converter inherent dead-time, triggering inherent delays, DC current possible discontinuous-mode-of operation and switching/firing circuit common maloperation problems. Artificial intelligence control strategies implemented for DC motor drives include fuzzy logic (FL) and neural network (NN) based speed/position controllers. Both fixed-structure and online "adjustable" neurofuzzy control techniques were implemented and utilized especially in large industrial type DC motor drives.

This paper presents a simple and novel nonlinear error driven, error scaled and self adjusting speed controller (SAC) for industrial DC motor drives equipped with large thyristor controlled six-pulse dual rectifier converter with their switching inherent circuit delay (T_o).

Control Design

Figure1 shows the full DC motor drive system comprising the AC supply interface transformer, 6-pulse dual controlled rectifier converter with the both forward and reverse thyristor bridges using α-control and the DC motor driving a mechanical load. The DC motor drive is usually a separately excited or a permanent magnet type DC motor.

Figure2 depicts the proposed self-adjusting speed controller comprising the two time decoupled regulation loops namely:

a. Fast speed regulation loop tracking a complex reference speed trajectory.
b. A supplementary power slow acting loop to ensure power/energy savings and electrical energy conservation any for any cyclical, inrush or on/off type mechanical load cycles.

The fast acting error-driven, error-scaled self adjusting speed loop utilizes the speed error (e_w) and its derivative ($\dot{e}_w$) while the slow acting decoupled power loop utilizes a dynamic error tracking/minimum motor input power (p_m) power loop. The building block of the novel control action is a nonlinear self-adjusting "Tansigmoid" nonlinear error-driven block (NLL) as shown in figure2. The effects of thyristor switching-inherent delay is also included in the Matlab/Simulink full drive-system model as shown in figure3.

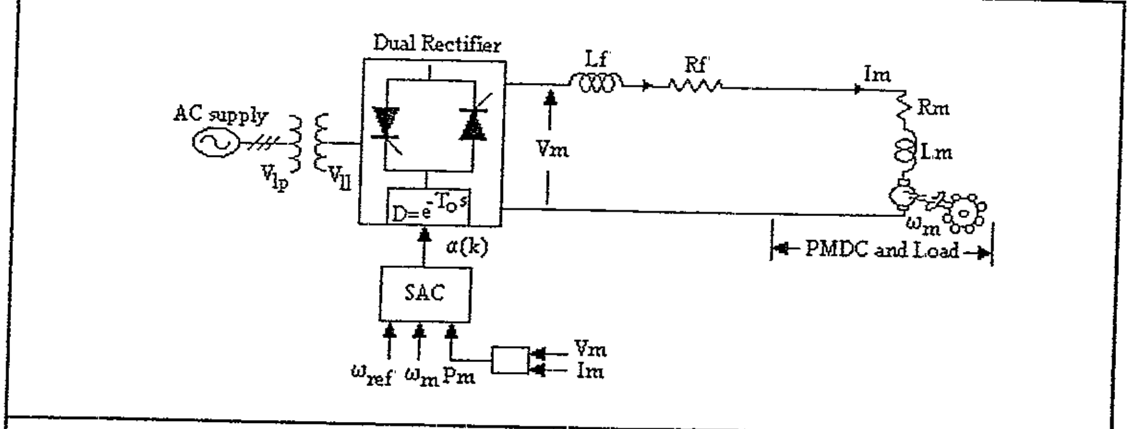

Figure 1: DC motor drive system with self adjusting speed controller (SAC).

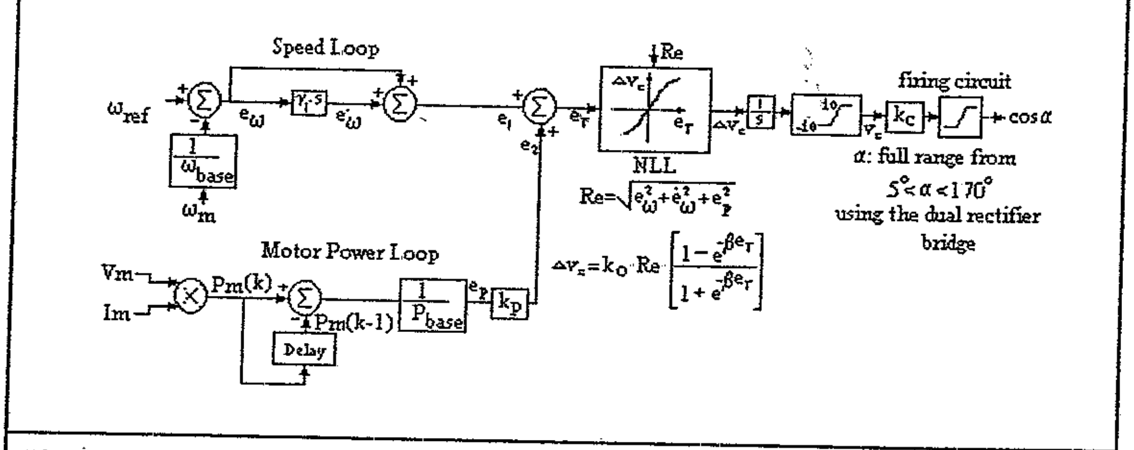

Figure 2: Novel self-adjusting speed controller with supplementary minimum motor input power

The SAC controller dynamic equations are based on speed and power error at every instant in time *k*

$$e_w(k)=\omega_m(k)-\omega_m(k-1) \quad \text{.........} (1)$$

$$e_p(k)=P_m(k)-P_m(k-1) \quad \text{.........} (2)$$

$$P_m(k)=V_m(k).I_m(k) \quad \text{.........} (3)$$

$$e_T(k)=e_w(k)+\gamma_1 e_w(k)+k_p e_p(k) \quad (4)$$

The control modulation Δv_c is:

$$\Delta v_c(k)=k_o\, R_e(k)\left[\frac{1-e^{-\beta e_T(k)}}{1+e^{-\beta e_T(k)}}\right] \quad \text{....} \quad (5)$$

Where k_o and β are the main control gains, selected by off-line simulation to minimize a performance index $[J_o]$ with preselected scaling parameters (γ_1, k_p), to allow flexibility and control action scaling if needed.

$$R_e(k)=\sqrt{e_\omega^2+(\dot{\gamma}_1 e_w)^2+(k_p e_p)^2} \quad \text{.....}(6)$$

$$v_c(k)= v_c(k-1)+\Delta v_c(k) \quad \text{.......}(7)$$

Inverse cosine control or voltage controlled oscillator α-triggering circuit can be used.

$$\cos\alpha(k)=k_\alpha . v_c(k) \quad \text{.........}(8)$$

and $\alpha(k)$ is typically limited between (5°, 170°) (safe operating zone for industrial thyristor rectifier).

The selection of the nonlinear tansigmoid control activation block parameters (k_o, β) is very crucial for satisfactory dynamic operation and is also is reference-speed trajectory dependent. Different off-line or a slow on-line minimization algorithm can be a utilized for performance index J-minimization as follows: define J as the error-index time scaled function:

a. $J_o=\sum_{k=1}^{Ns}\left|R_e(k)\right|^2$ (J_o is utilized in this paper)

b. $J=\sum_{k=1}^{Ns}\left|kT_sR_e(k)\right|^2$

c. $J=\sum_{k=1}^{Ns}(e_\omega^2(k)+e_\omega^2(k))$

d. $J=\sum_{k=1}^{Ns}\left[kT_se_w(k)\right]^2$

e. $J=\sum_{k=1}^{Ns}[kT_s(e_\omega^2(k)+e_p^2(k))]$

The settling count Ns is defined by eqn. (9):

$$Ns=\frac{T_{l\arg est}}{T_s} \quad \ldots\ldots (9)$$

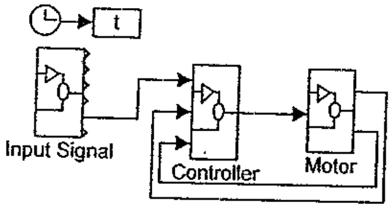

Figure 3a: Matlab-Simulink System model.

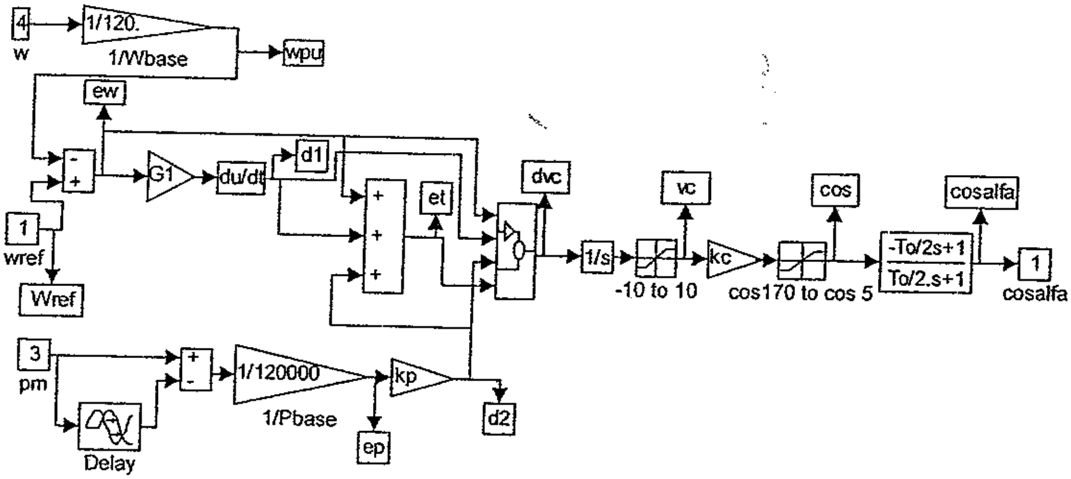

Figure 3b: Novel Self Adjusting Speed Controller (SAC)

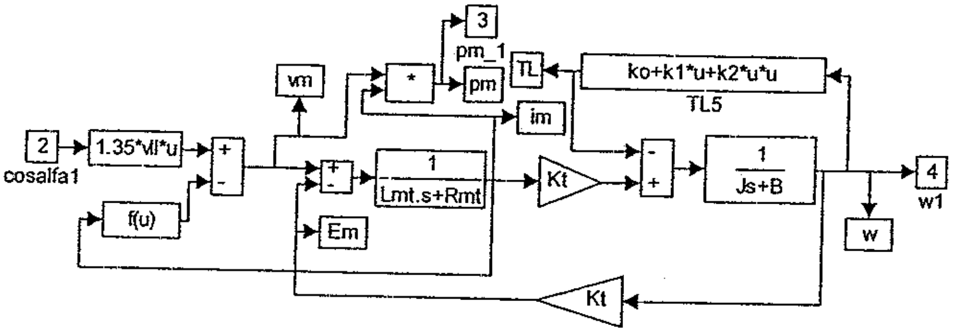

Figure 3c: DC motor block diagram.

Figure3:Full Matlab-Simulink motor drive mode.

Where $T_{largest}$ is the largest mechanical motor drive plus load time constant and T_s is the control selected sampling period.

Simulation Results

The Matlab/Simulink software was utilized to design, test and validate the effectiveness of the proposed self-adjusting (SAC) speed controller. DC motor drive and control parameters are given in the Appendix.

Figure4 depicts the dynamic response of the motor drive and controller states to a complex sinusoidal speed reference trajectory for a quadratic (T_m-vs-ω_m) mechanical load. Figure5 depicts the same dynamic response for a cyclical speed reference trapezoidal trajectory.

The phase portraits and error states (e_w, e_p) indicate the effectiveness of the proposed (SAC) controller with fixed off-line selected control parameters (k_o, β). However, for a complex speed trajectory and mechanical load an 0n-line controller parameter selection method of (k_o, β) maybe necessary using available optimization tools, direct search methods, neural network and/or genetic algorithms (GA).

Conclusions

The paper presents a novel self-adjusting speed controller for industrial DC motor drives using a dual industrial controlled rectifier converter. The error-driven, error-scaled two-loop scheme comprises a speed error-driven loop and a supplementary slow dynamic minimum motor input power loop. The error hyper-plane excursion vector magnitude $|R_e|$ was also utilized in the scaling control gain action at every time step as well as for an off-line optimal control parameter (k_o, β) search. This is achieved by error-index (J_o) minimization. The proposed self-adjusting control (SAC) scheme ensures good speed reference-speed trajectory tracking and power/energy efficient operation for large cyclical mechanical load cycles.

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Appendix

(a) motor

The following time domain dynamic equations were used to simulate the PMDC motor to be controlled.

$$\begin{bmatrix} \frac{di_m}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_m}{L_m} & -\frac{K_i}{L_m} \\ \frac{K_t}{J_m} & -\frac{B_m}{J_m} \end{bmatrix} \begin{bmatrix} i_m \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{V_m}{L_m} \\ \frac{T_L}{J_m} \end{bmatrix}$$

Motor is rated 120KW, 600V , 200A DC.

Where;

$B_m \equiv$ Damping coefficient (0.6 Nms).

ω $\equiv$ Angular motor speed (rad/s).

$J_m \equiv$ Inertia of rotor (4 kg m^2).

$K_V \equiv$ EMF constant (5.12) determined by the strength of excitation field and the number of turns of armature winding.

$K_t \equiv$ Torque constant, it is equal to K_V if the proper units are used.

$L_m \equiv$ Armature inductance (250 mH).

$R_m \equiv$ Armature resistance (.25 ohm).

(b) DC Filter:

$L_f \equiv$ .05 H.

$R_f \equiv$ .25 ohm.

$L_{mt} \equiv L_m + L_f$

$R_{mt} \equiv R_m + R_f$

(c) SAC Controller for sinusoidal w_{ref} case

This controller includes two loops:

- Speed loop: its parameters are: $W_{base}=120$ r.p.m, $\gamma_1=1$
- Motor power loop: its parameters are: $P_{base}=120000$, Delay = 300 ms, $K_p = 0.9$

Tansigmoid: $K_o = 20$, $\beta=3$

$-10 < v_c < 10$

$5^\circ < \alpha < 170^\circ$

$\cos\alpha = k_c . v_c$

$K_c = 0.1$, $T_o = 3.33$ ms

(d) SAC Controller for trapezoidal w_{ref} case

This controller includes two loops:

- Speed loop: its parameters are: $W_{base}=120$ r.p.m, $\gamma_1=0.7$
- Motor power loop: its parameters are: $P_{base}=120000$, Delay = 300 ms, $K_p = 1$

Tansigmoid: $K_o = 10$, $\beta=10$

$-10 < v_c < 10$

$5^\circ < \alpha < 170^\circ$

$\cos\alpha = k_c . v_c$

$K_c = 0.1$, $T_o = 3.33$ ms.

(e) Mechanical load: (T-vs-w quadratic)

$T_L = k_o + k_1\omega_m + k_2\omega^2_m$

$k_0=200$, $k_1=1.45$, $k_2=.05$

(f) Dual Bridge

vll=600 volt, Delay T_o = 20/6 ms, xc=0.2 ohm.

$5^\circ < \alpha < 170^\circ$

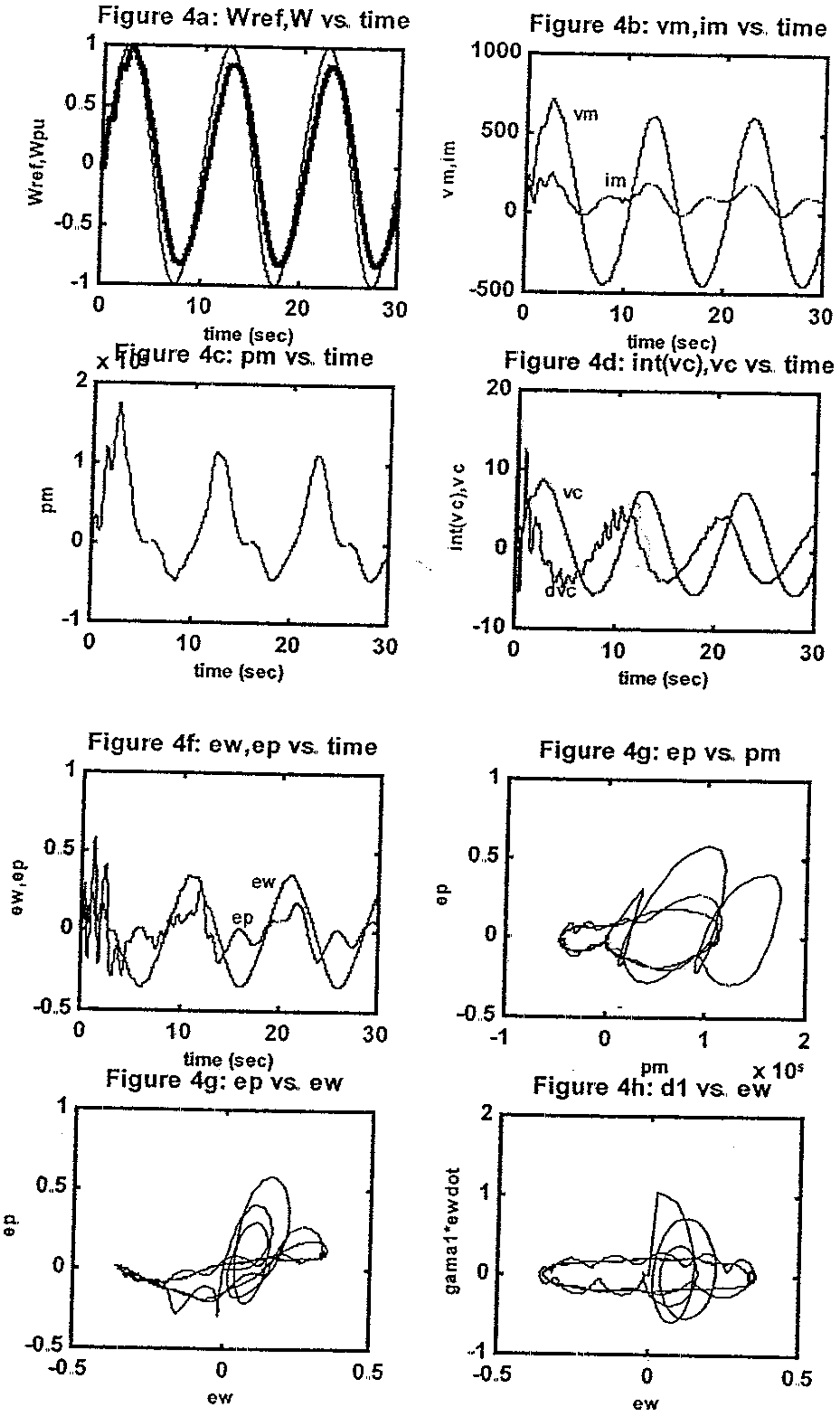

Figure 4a: Wref,W vs. time

Figure 4b: vm,im vs. time

Figure 4c: pm vs. time

Figure 4d: int(vc),vc vs. time

Figure 4f: ew,ep vs. time

Figure 4g: ep vs. pm

Figure 4g: ep vs. ew

Figure 4h: d1 vs. ew

Figure 4: Dynamic response of the motor drive for a cyclical speed reference sinusoidal variation.

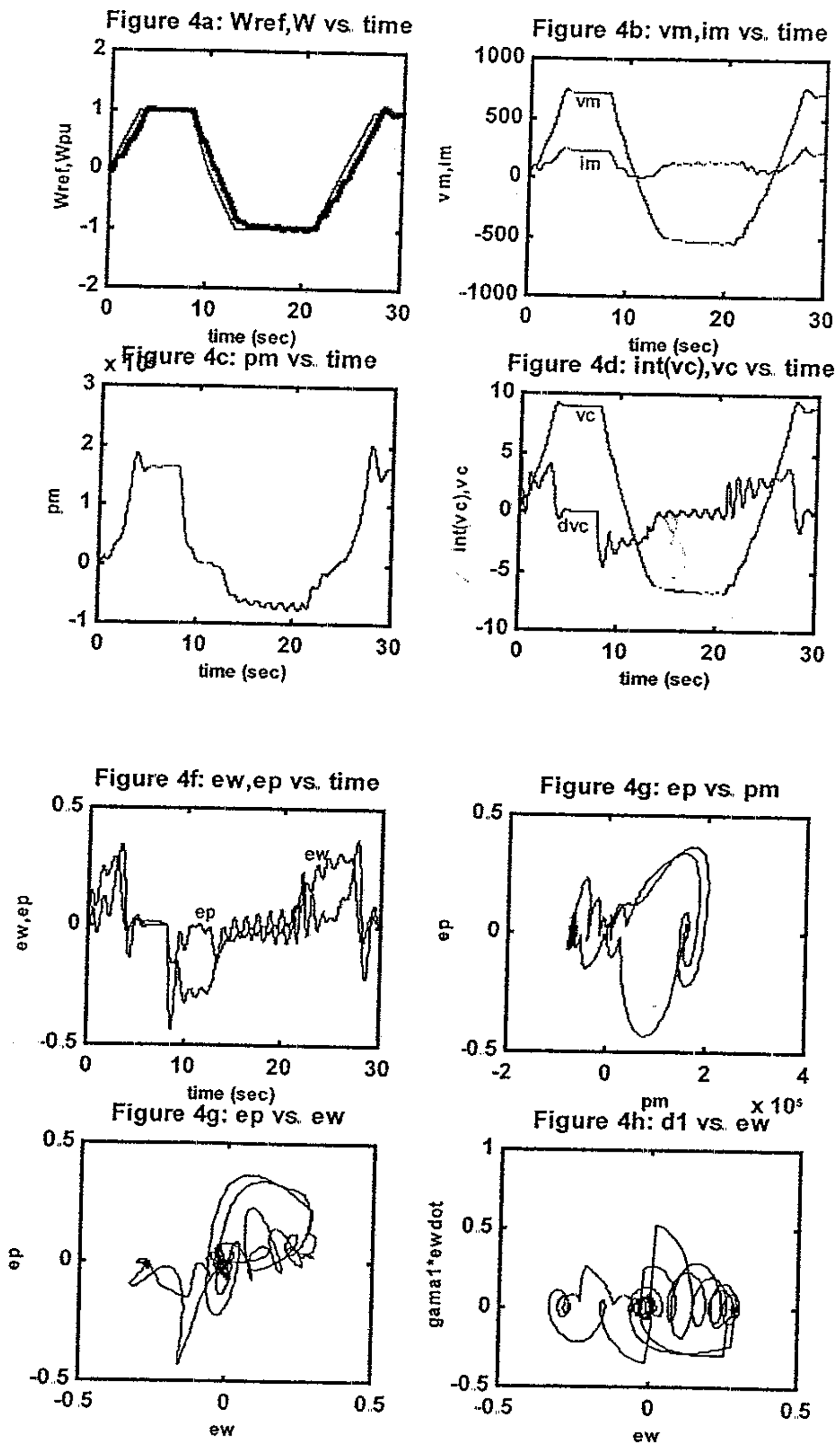

Figure 4a: Wref,W vs. time

Figure 4b: vm,im vs. time

Figure 4c: pm vs. time

Figure 4d: int(vc),vc vs. time

Figure 4f: ew,ep vs. time

Figure 4g: ep vs. pm

Figure 4g: ep vs. ew

Figure 4h: d1 vs. ew

Figure 5: Dynamic response of the motor drive for a cyclical trapezoidal speed reference variation.