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A Reduced Order Observer based CSI Fed AC Drives Using WAN

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Abstract

In this paper a new control strategy for induction motor drives fed by CSI (Current Source Inverter) is proposed. A multivariable state feedback as well as FF (Feed Forward) control is applied for fast regulation and stability of the drive system. The design of the state feedback controller is based on the application of the pole assignment technique of industrial regulation control theory to a d-q axis state space linearised model of the drive and includes a reduced order observer to obtain faster dynamic response. The observer is designed to reconstruct the inaccessible states such as d-q axis rotor currents from the knowledge of the system inputs and outputs. The hardware and software implementation of the controller around an inexpensive microcontroller based kit, controlled by WAN/wLAN is discussed. The simulation results for step changes in references and load torque show the possible improvement in response with the addition of feed forward control.

Keywords: CSI, feed forward, microcontroller, observer, pole placement, WAN/wLAN.

Introduction

The Current Source Inverter fed Induction Motor drive (CSI-IM), the basic scheme of which is shown in Fig. 1, has several advantages but has the serious limitation of being open-loop unstable [1]-[2]. Stability improvement of this drive has been attempted over the years with different kinds of output feedback [2]-[7] that use conventional proportional integral (PI) controllers in individual loops and are designed using the classical transfer function approach based on a single-input single-output (SISO) system. These PI controllers have less freedom, their gain settings are rather too empirical, and their applications inherently assume noninteraction between different system states. However, one of these schemes, field-oriented or vector control [6], provides a decoupling method for ideal control of the induction motor that is a nonlinear multivariable system; but implementation of this scheme, as observed by Bose [7], is characterized by complex coordinate transformation, intricate vector signal sensing and processing, and parameter dependency. A detailed design procedure for an application of pole-placement technique [8]-[9] by a complete state feedback control strategy of multivariable system regulation theory [10] to a CSI-IM drive for fast regulation and stability of the drive in the face of disturbance have reported in [12].

The pole-placement technique is a method in modem control theory by which the poles or eigenvalues of a closed-loop system can be assigned at prescribed locations by means of state feedback with proper engineering judgment to improve the system performance and ensure stability. State feedback provides more room for design alternatives than does output feedback and can give complete control over the dynamics of the system. While previous attempts [9]-[10] for "state space compensation" of induction motor drive considered the system as having single input and single output and dealt with only stator current feedback, a control law has been derived in [8] that is a function of all the states, namely, the stator current, the d-axis, q-axis rotor currents and the speed, as well as the integral-of-errors (IOE) of output speed and stator current. Thus the structure of the feedback controller developed here resembles that of the classical PI controller but is more versatile as it can handle multiple inputs and multiple outputs (MIMO). The inputs in this case are the dc link voltage $\mathbf{V_d}$, the stator frequency $\boldsymbol{\omega_e}$, and load torque $\mathbf{T_L}$ (disturbance), while the outputs are rotor speed $\boldsymbol{\omega_r}$, and the dc link current $\mathbf{I_d}$.

The combination of the state feedback with the IOE feed-back makes the controller fairly robust against parameter variations. The steps in controller design, starting with a linearized d-q state space model of the CSI-IM drive in a synchronously rotating reference frame [2], are systematic and straightforward, as shown in [7]. The inaccessible states like the dq-axis rotor currents required for the determination of the control law have been obtained by designing a reduced-order observer [11] from the knowledge of inputs and outputs. The designed observer-controller performance is then tested for regulated current and speed with step changes in load torque and references using a digital computer simulation of the whole drive system.

In this modern world the internet (World Wide Web) is used to access and control the electrical systems world-wide by using WAN/wireless LAN (wLAN). This type of control can be done at anytime from anywhere to effectively use the energy especially in developing countries where energy management is a big problem [13]-[17]. The aim of the present paper is to review briefly the earlier development and report a practical implementation of the state feedback controller-observer for the CSI-IM drive using a simple and inexpensive microcontroller based kit controlled by

WAN/wLAN and a few peripheral chips. The microcontroller reads the states through hardware interfacing, estimates the dq-axis rotor currents through the observer, and calculates the controller outputs which control the firing angle of the converter and the output frequency of the inverter. The hardware supports and interfaces developed are conventional while the control software, involving the computation of the state feedback law, is novel and is shown to be surprisingly simple to implement, though the controller structure looks complex. The implemented controller is then tested on a laboratory model of CSI-IM drive, for its performance in regulating current and speed under step changes in load torque and references as in the case of the simulation model.

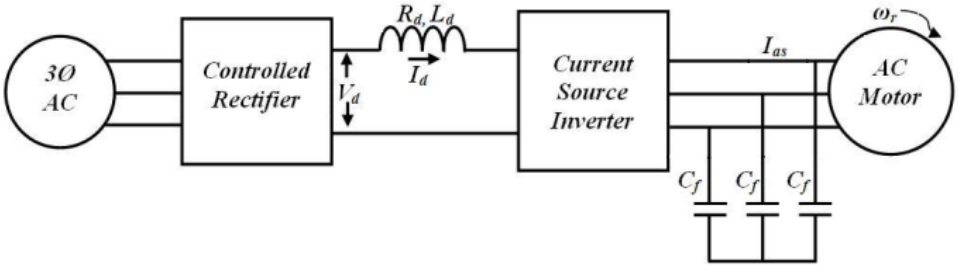

Figure 1: Current Source Inverter Induction Motor (CSI-IM) drive.

State Feedback Controller

Main Drive System Model

A dynamic model of the system as shown in Fig. 1 is obtained in synchronously rotating reference frame applying small signal linearization to the per-unit system equations around a steady state operating point in the following state variable form.

$$\underline{\dot{\mathbf{x}}} = \mathbf{A}\underline{\mathbf{x}} + \mathbf{B}\underline{\mathbf{u}} \tag{1}$$

$$\underline{\mathbf{y}} = \mathbf{C}\underline{\mathbf{x}} \tag{2}$$

Where the matrix quantities in equations (1)-(2), the investigated drive system's parameters are given in the appendix, elements of A and B are computed for steady state operating points of the slip-torque characteristics and the eigenvalues of the linearised A matrix for a sample operating point when the system is open loop unstable are obtained as given in the appendix. Stable closed loop operation at this point is achieved by pole placement with state feedback after deriving a control law with the help of the industrial regulator theory.

Industrial Regulator Theory

A generalised industrial regulator model is represented in state space form as

$$\underline{\dot{\mathbf{x}}} = \mathbf{A}\underline{\mathbf{x}} + \mathbf{B}\underline{\mathbf{u}} + \mathbf{E}\underline{\mathbf{d}} \tag{3}$$

$$\underline{\tilde{\mathbf{y}}} = \underline{\mathbf{y}} - \underline{\mathbf{y}}_{\mathbf{r}} = \mathbf{C}\underline{\mathbf{x}} - \underline{\mathbf{y}}_{\mathbf{r}} \tag{4}$$

Where $\underline{\mathbf{x}}$, $\underline{\mathbf{u}}$, $\underline{\mathbf{d}}$, $\underline{\mathbf{y}}$, $\underline{\mathbf{y}_r}$ are the state, control (input), disturbance (input), output and reference (set point) vectors of dimension n, m, q, p and p respectively and A, B, C and E are matrices of dimension (nxn), (nxm), (pxn) and (nxq) respectively. $\underline{\tilde{\mathbf{y}}}$ is the error between the reference $\underline{\mathbf{y}_r}$, and the output $\underline{\mathbf{y}}$.

For multivariable systems, the regulation problem with internal stability (RPIS) can be defined by $\underline{\dot{\mathbf{x}}} \rightarrow \mathbf{0}$ as $\mathbf{t} \rightarrow \infty$ (asymptotic stability) and $\underline{\tilde{\mathbf{y}}} \rightarrow \mathbf{0}$ as $\mathbf{t} \rightarrow \infty$ (output regulation). Assuming $\underline{\mathbf{y}_r}$ and $\underline{\mathbf{d}}$ as vectors of constants, differentiating (3) and rearranging, a standard form of state space equation is obtained as

$$\underline{\dot{\mathbf{z}}} = \widehat{\mathbf{A}}\,\underline{\mathbf{z}} + \widehat{\mathbf{B}}\,\underline{\mathbf{v}} \tag{5}$$

Where a new augmented state vector and a new control vector are defined as

$$\underline{\mathbf{z}} \triangleq \begin{bmatrix} \underline{\dot{\mathbf{x}}} \\ \underline{\tilde{\mathbf{y}}} \end{bmatrix} \tag{6}$$

$$\underline{\mathbf{v}} \triangleq \underline{\dot{\mathbf{u}}} \tag{7}$$

and

$$\widehat{\mathbf{A}} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{C} & \mathbf{0} \end{bmatrix} \widehat{\mathbf{B}} = \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix}$$

The augmented system matrix $\widehat{\mathbf{A}}$ consists of actual system dynamics along with the regulated output matrix of order (n+p), where n = number of system eigenvalues and p = number of regulation eigenvalues. The solution for RPIS now requires that $\underline{\dot{\mathbf{x}}} \rightarrow \mathbf{0}$ as $\mathbf{t} \rightarrow \infty$

A linear state feedback control law of the form

$$\underline{\mathbf{v}} = \mathbf{K}\underline{\mathbf{z}} \tag{8}$$

can now be designed for the augmented system of (5) by pole-placement technique, where K is suitably obtained gain matrix.

Pole-placement by State Feedback

For a linear time-invariant system

$$\underline{\dot{\mathbf{x}}} = \widehat{\mathbf{A}}\,\underline{\mathbf{x}} + \widehat{\mathbf{B}}\,\underline{\mathbf{u}} \tag{9}$$

With state feedback

$$\underline{\mathbf{u}} = \mathbf{K}\underline{\mathbf{x}} \tag{10}$$

The closed loop system becomes

$$\underline{\dot{\mathbf{x}}} = (\mathbf{A} + \mathbf{B}\mathbf{K})\underline{\mathbf{x}} \tag{11}$$

Which can have prescribed eigenvalues, if and only if, the pair (A, B) is controllable.

For the augmented system of (5) with control law of (8), the controllability conditions are

i. The pair (A, B) is controllable
ii. The matrix A has full rank (n+p), which imposes the condition that m > p.

Once the controllability conditions are satisfied, the pole placement control law can be derived from (8), which by partitioning K into K_1 and K_2 and integrating (6) and (7) yields;

$$\underline{\mathbf{u}} = \mathbf{K_1}\underline{\mathbf{x}} + \mathbf{K_2}\int_0^t(\underline{\mathbf{y}} - \underline{\mathbf{y}}_\mathbf{r})\mathbf{dt} \tag{12}$$

Note that it is a combined state feedback and IOE control and does not require the knowledge of the disturbance vector. The law (12) resembles the classical two-term P-I controller with K_1 and K_2 now being the gain matrices.

The steps in pole placement are detailed in [1, 8] and are not repeated here. The choice regarding the number of poles and the input vector used in each case is a matter of engineering judgment as these affect the gains of the feedback controller which should not be too high in a physical system.

Reduced Order Observer for Estimating Rotor Currents

The state feedback control law as derived in (12) is based on the assumption that all the states are accessible for feedback. However, for the CSI-IM drive, some of the states like q and d-axis rotor currents are not measurable. A reduced order observer is then necessary to estimate these states from system inputs and outputs. A fast observer has been designed for the drive, again using the pole placement technique, to reconstruct these states.

The system equations (3) can be rewritten as

$$\dot{\underline{\mathbf{x}}} = \mathbf{A}\underline{\mathbf{x}} + [\mathbf{B} \quad \mathbf{E}]\begin{bmatrix}\underline{\mathbf{u}} \\ \underline{\mathbf{d}}\end{bmatrix} = \mathbf{A}\underline{\mathbf{x}} + \mathbf{B}'\underline{\mathbf{u}}' \tag{13}$$

$$\underline{\mathbf{y}} = \mathbf{C}\underline{\mathbf{x}} \tag{14}$$

A reduced order observer is a dynamical system represented by

$$\hat{\underline{\zeta}} = \mathbf{D}\hat{\underline{\zeta}} + \mathbf{G}\underline{\mathbf{u}}' + \mathbf{F}\underline{\mathbf{y}}' \tag{15}$$

$$\underline{\zeta} = \mathbf{L}\underline{\mathbf{x}} \tag{16}$$

and

$$\hat{\mathbf{x}} = \begin{bmatrix}\mathbf{C}' \\ \mathbf{L}\end{bmatrix}^{-1} \begin{bmatrix}\underline{\mathbf{y}}' \\ \hat{\underline{\boldsymbol{\zeta}}}\end{bmatrix} \tag{17}$$

Where $\hat{\underline{\boldsymbol{\zeta}}}$ is an estimate of $\underline{\boldsymbol{\zeta}}$. $\hat{\mathbf{x}}$ is an estimate of $\mathbf{x}$, $\mathbf{L}$ is a transformation matrix such that $[\mathbf{C}'\ \mathbf{L}]^T$has an inverse and $\mathbf{C}'$ consist of linearly dependent rows of $\mathbf{C}$. The order of the observer is given by (n-r), where r is the rank of $\mathbf{C}$, r < p. For the purpose of the observer, no difference is made between the control and the disturbance inputs as $\mathbf{B}$ is extended to $\mathbf{B}'$ as given in (13).

For the error in the estimate to decay

i. $\mathbf{LA} - \mathbf{DL} - \mathbf{FC} = \mathbf{0}$

ii. $\mathbf{D}$ should be a stable matrix with the restriction that $\{\lambda_i\}_D \neq \{\lambda_i\}_A$

F is obtained by choice. **G** is found as

$$\mathbf{G} = \mathbf{LB}' \tag{18}$$

Fig. 2 shows the block diagram of the combined observer-feedback controller for the CSI-IM drive.

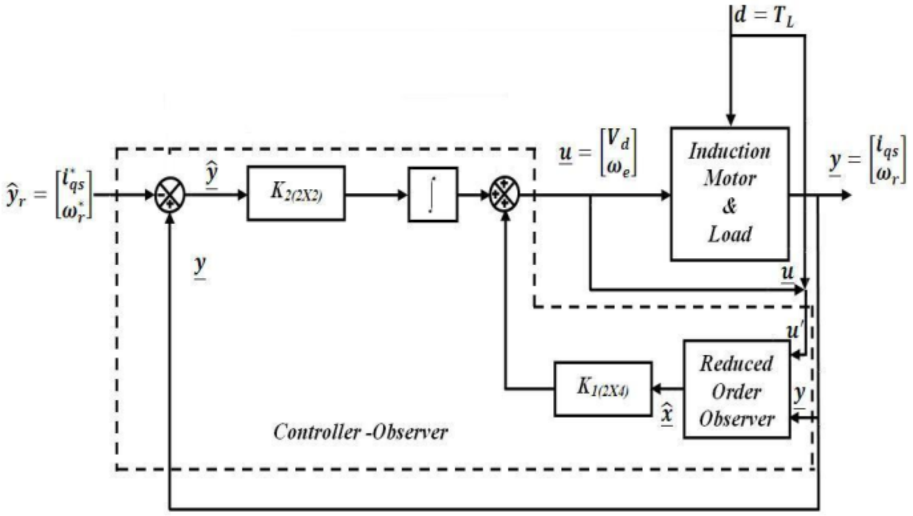

Figure 2: Combined Observer-Controller block diagram.

Theory

The system equations are the same as given in (3). In the steady state, as $\mathbf{t} \to \infty$, $\dot{\underline{\mathbf{x}}} \to \mathbf{0}$, and $\tilde{\underline{\mathbf{y}}} \to \mathbf{0}$, the equations become algebraic:

$$\begin{bmatrix}\mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{0}\end{bmatrix} \begin{bmatrix}\underline{\mathbf{x}}_\mathrm{f} \\ \underline{\mathbf{u}}_\mathrm{f}\end{bmatrix} + \begin{bmatrix}\mathbf{E} & \mathbf{0} \\ \mathbf{0} & -\mathbf{1}\end{bmatrix} \begin{bmatrix}\underline{\mathbf{d}} \\ \underline{\mathbf{y}}_\mathrm{r}\end{bmatrix} = \begin{bmatrix}\mathbf{0} \\ \mathbf{0}\end{bmatrix} \tag{19}$$

Where $\underline{\mathbf{x}}_\mathbf{f}$ and $\underline{\mathbf{u}}_\mathbf{f}$ are steady state values.

The feed forward control law is in the form (21). Note that the control law is a function of all the states as well as the reference and disturbance inputs. Also it requires exact knowledge of the system model i.e. A, B, C and E.

$$\underline{\mathbf{u}} = \mathbf{K_1}\underline{\mathbf{x}} + [\mathbf{K_1} - \mathbf{I}]\left[\mathbf{G_f^T}\,\mathbf{G_f}\right]^{-1}\left[\mathbf{G_f^T}\,\mathbf{H}\right]\begin{bmatrix}\underline{\mathbf{d}}\\ \underline{\mathbf{y_r}}\end{bmatrix} \tag{20}$$

Where

$$\mathbf{G_f} = \begin{bmatrix}\mathbf{A} & \mathbf{B}\\ \mathbf{C} & \mathbf{0}\end{bmatrix} \text{ and } \mathbf{H} = \begin{bmatrix}\mathbf{E} & \mathbf{0}\\ \mathbf{0} & -\mathbf{I}\end{bmatrix}$$

The combined feed forward and integral feedback control law becomes

$$\underline{\mathbf{u}} = \mathbf{K_1}\underline{\mathbf{x}} + \mathbf{K_2}\int_0^{\mathbf{t}}(\underline{\mathbf{y}} - \underline{\mathbf{y_r}})\mathbf{dt} + \mathbf{K_{FF}}\begin{bmatrix}\underline{\mathbf{d}}\\ \underline{\mathbf{y_r}}\end{bmatrix} \tag{21}$$

Where

$$\mathbf{K_{FF}} = [\mathbf{K_1} - \mathbf{I}]\left[\mathbf{G_f^T}\,\mathbf{G_f}\right]^{-1}\left[\mathbf{G_f^T}\,\mathbf{H}\right] = [\mathbf{K_3} \quad \mathbf{K_4}] \tag{22}$$

Note that the feed forward term is a function of reference and disturbance inputs, while the series integrator term makes the controller less sensitive to the system parameter variations [11].

Steps in Feed Forward Controller Design

1. Form $\mathbf{G_f}$ and $\mathbf{H}$ matrices from the system matrices $\mathbf{A}, \mathbf{B}, \mathbf{C}$ and $\mathbf{E}$.
2. Calculate $\left[\mathbf{G_f^T}\,\mathbf{G_f}\right]^{-1}\left[\mathbf{G_f^T}\,\mathbf{H}\right]$
3. Use $\mathbf{K_1}$ of (9) to obtain $\mathbf{K_{FF}}$ as given in (22).

The block diagram of the combined feed forward and integral feedback controller for the CSI-IM drive under investigation is shown in Fig. 3

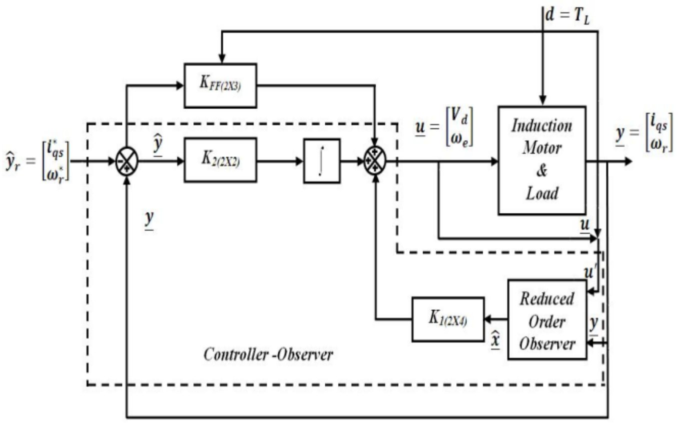

Figure 3: Proposed Feed Forward and Integral Feedback controller.

Table I: Induction Motor and DC link Parameters.

Name Plate Data 2.5 hp, 3-Phase, Star connected, 4 Poles, 110 V, 14 A, 50 Hz, Squirrel Cage Induction Motor			
Parameter	Name	Actual Value	Per-Unit Value
Stator Resistance	R_s	0.63 Ω	0.126
Rotor Resistance	R_r'	0.23 Ω	0.046
Stator and Rotor Leakage Inductances	$L_{ls} = L_{lr}'$	0.0028 H	0.176
Magnetizing Inductance	L_m	0.12446 H	7.800
DC chock Inductance	L_d	100 mH	6.280
DC chock Resistance	R_d	0.5 Ω	0.100

Simulation Results

To study the dynamic response of the drive systems shown in the Fig. 2 and Fig. 3, they have simulated using MATLAB simulation software with step changes in references stator current $\mathbf{I_s}$and speed $\boldsymbol{\omega_r}$ and load torque $\mathbf{T_L}$ (disturbance) for two cases (a) state feedback without feed forward control and (b) state feedback with feed forward control.

The simulation result graphs from Fig. 4. to Fig. 10. shows that the transient response of the drive system is considerable improved in speed $\boldsymbol{\omega_r}$ and current $\mathbf{I_s}$ in terms of rise time $\mathbf{t_r}$ in ms and settling time $\mathbf{t_s}$ in ms, that can be seen when feed forward control is added, while there is an increase of $\mathbf{M_p}$ in each case.

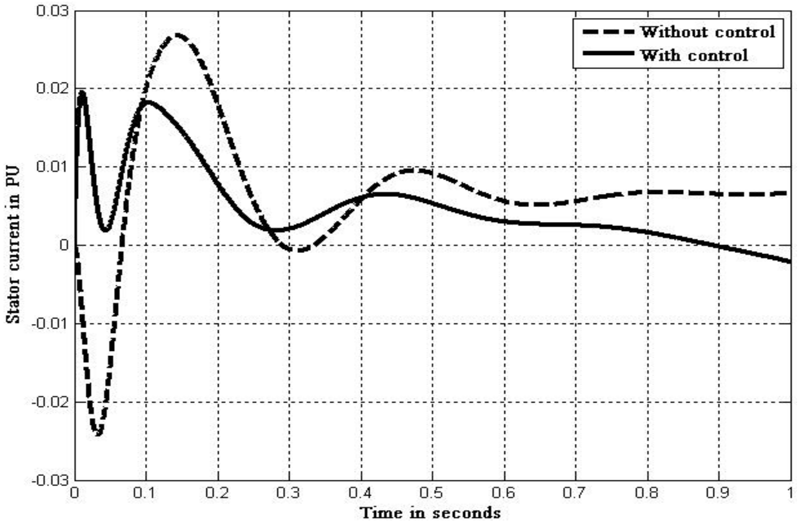

Figure 4: I_s for 0.01 pu step change in motor speed at No-Load.

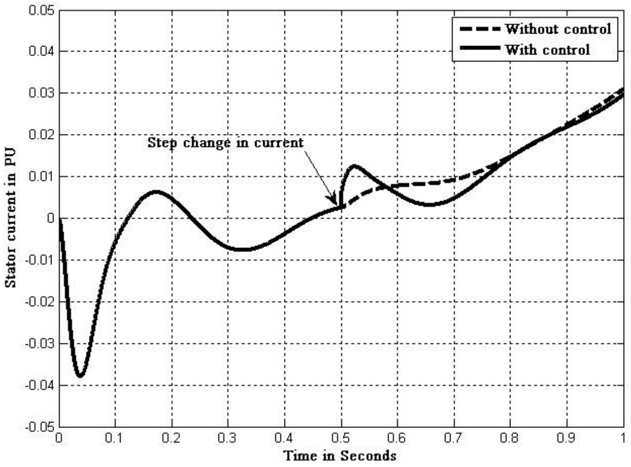

Figure 5: I_s for 0.01 pu step change in stator current at No-Load

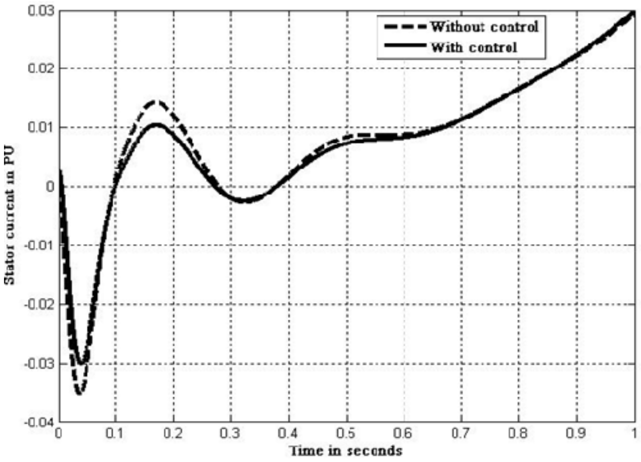

Figure 6: I_s for 0.01 pu step change in stator current at Constant Load.

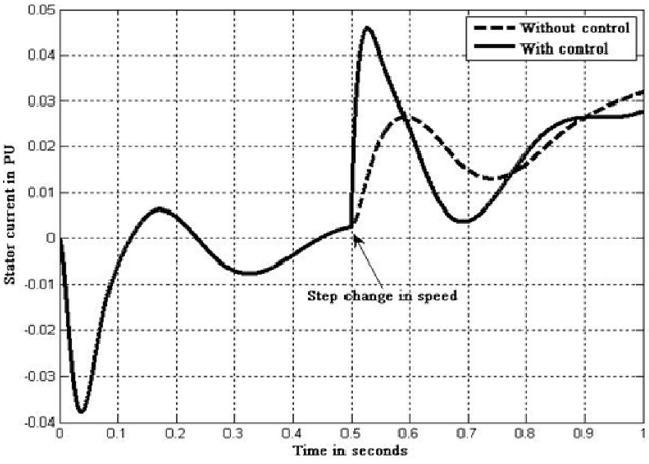

Figure 7: I_s for 0.01 pu step change in motor speed at Constant Load.

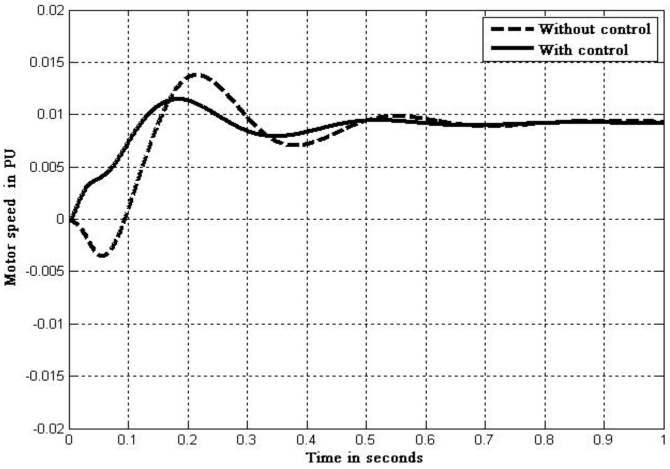

Figure 8: ω_r for 0.01 pu step change in motor speed at Constant Load.

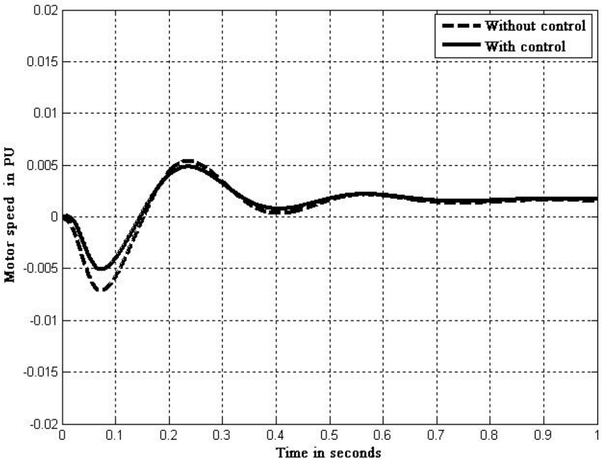

Figure 9: ω_r for 0.01 pu step change in stator current at No-Load.

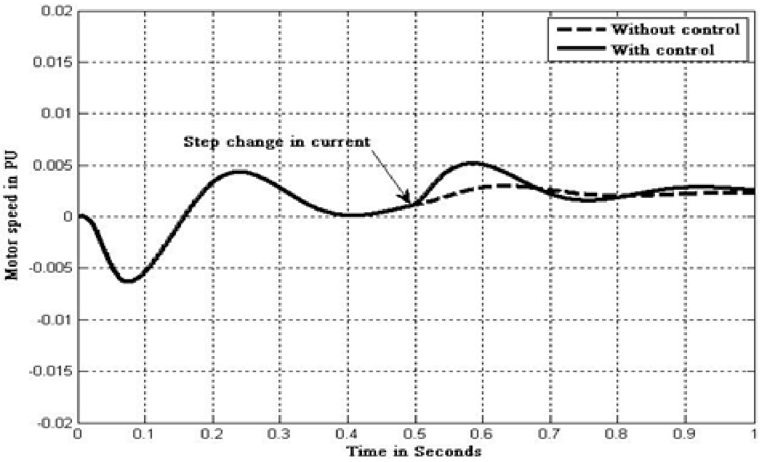

Figure 10: ω_r for 0.01 pu step change in stator current at Constant Load.

Table II: Simulation Results.

Slip 1% and 1% step increase in stator current						
	Without feed forward control					
	Constant Load			Full Load		
	t_r (ms)	t_s (ms)	M_p (%)	t_r (ms)	t_s (ms)	M_p (%)
I_s	98	987	18.76	97	987	8.8
ω_r	62	895	2.9	66	900	5.5
	With feed forward control					
	Constant Load			Full Load		
	t_r (ms)	t_s (ms)	M_p (%)	t_r (ms)	t_s (ms)	M_p (%)
I_s	50	976	35.56	49	974	41
ω_r	59	870	0	6	872	50.5
Slip 1% and 1% step increase in motor speed						
	Without feed forward control					
	Constant Load			Full Load		
	t_r (ms)	t_s (ms)	M_p (%)	t_r (ms)	t_s (ms)	M_p (%)
I_s	78	986	4.2	87	987	1.5
ω_r	25	892	13.47	45	898	72.0
	With feed forward control					
	Constant Load			Full Load		
	t_r (ms)	t_s (ms)	M_p (%)	t_r (ms)	t_s (ms)	M_p (%)
I_s	44	965	56	46	968	52.8
ω_r	34	870	9.26	48	872	64.2
Slip 1% and 1% step increase in load torque						
	Without feed forward control					
	Constant Load			Full Load		
	t_r (ms)	t_s (ms)	M_p (%)	t_r (ms)	t_s (ms)	M_p (%)
I_s	107	987	0	98	988	2.9
ω_r	6	899	52.7	56	875	15.9
	With feed forward control					
	Constant Load			Full Load		
	t_r (ms)	t_s (ms)	M_p (%)	t_r (ms)	t_s (ms)	M_p (%)
I_s	49	977	34.8	56	689	10.8
ω_r	6	871	536	3	417	4.2

The tabular presentation of the simulation results (Table II) also shows that the integral square speed error is reduced considerably with addition of feed forward control.

Experimental Setup

The experimental setup consists of two parts, the data acquisition part and the remotely control of the system through World Wide Web are shown in Fig.11, Fig.12

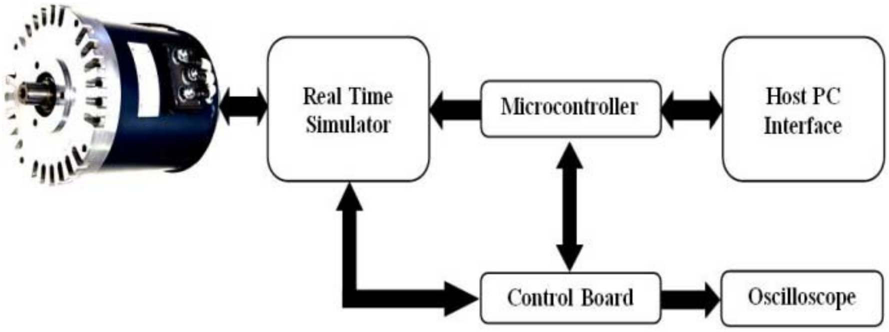

Figure 11: Arrangement of Data Acquisition and Drive Control.

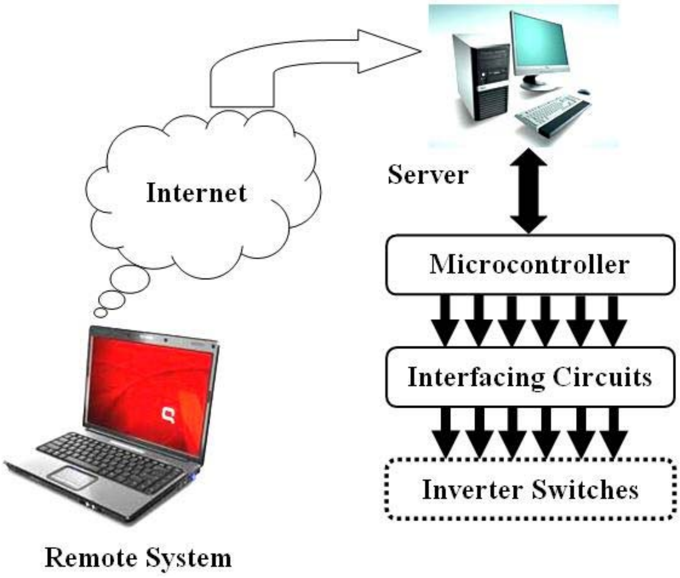

Figure 12: Diagram for control through WAN/wLAN.

Data Acquisition

The Data Acquisition part is used to measure the system outputs (the stator current and the speed), and load torque. The microcontroller reads the outputs $\mathbf{I_s}$, $\boldsymbol{\omega_r}$ and $\mathbf{T_L}$, through the real time simulator, estimates the d-q axes rotor currents through the observer and calculates the controller outputs which control the firing angle of the converter and the output frequency of the inverter.

Control through WAN

The software like Lab VIEW is provides very good graphical interface and also a very powerful tool for interfacing and controlling the connected system via serial port [13]-[16]. The main advantage of using this kind of softwares is the built-in web server, which can publish the Human Machine Interface (HMI) on internet by using web publishing tool. While publishing the HMI on internet, the administrator on server computer can also set rights to access. For the remotely access, its IP address must be included in the access list on the server computer. The type of access can also be set i.e. for controlling the HMI or just for monitoring. If the remote computer gets controlling access, then it can be observed on server that full control of the HMI is transferred to remote PC and even the server can’t control the system unless it disconnects the client first. If the HMI is being accessed remotely, the server computer also displays the IP addresses of the remote computer with the type of access either monitoring or controlling.

Conclusion

A microcontroller and WAN/wLAN based controller which involve state feedback feed forward control as well as a reduced order observer to estimate rotor currents for a CSI-IM drive has been designed and typical simulation results are presented. Though the controller design has been based on a linearized induction motor model and for a specific operating point, as has been done by many others and implemented with the help of a simple microcontroller kit, it has been observed to be stable within a considerable working zone around the operating point. However, with a sophisticated WAN/wLAN microcomputer based control system, the system model can possibly be identified in real time basis and the controller parameters can then be adapted to achieve pole placement control for a self-tuning controller with varying parameters (to be reported in a future paper). The robustness analysis of the state feedback controller is also left out of the scope of the present paper. The robustness analysis of an advanced motion control technique in robotics based on a sensitivity index of a general robust system with feed forward compensation loop employing a disturbance torque observer has been presented in some papers. In this paper the load torque is given as disturbance, detected directly and the effectiveness of the feed forward compensation in improving the dynamic response is demonstrated by the simulation results. The controller provides fast regulation and ensures stability of the drive in the face of disturbance. In the modern world, man is going for simpler technology rather than the latest one so as to avoid the unnecessary consequences and safety risks due to latest technologies. So this paper proposed a control in WAN/wireless LAN, that the load can be controlled anywhere in the world only if the computer acts as a server. This provides a controller with less man power, more reliability, fast dynamic response, simplicity and low cost.

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Appendix

$$\underline{\mathbf{x}} = [\,\Delta\mathbf{i}_{\mathbf{qs}}\ \Delta\mathbf{i}'_{\mathbf{qr}}\ \Delta\mathbf{i}'_{\mathbf{dr}}\ \Delta\boldsymbol{\omega}_{\mathbf{r}}/\boldsymbol{\omega}_{\mathbf{b}}\,]^{\mathbf{T}}$$

$$\underline{\mathbf{y}} = [\,\Delta\mathbf{i}_{\mathbf{qs}}\ \Delta\boldsymbol{\omega}_{\mathbf{r}}/\boldsymbol{\omega}_{\mathbf{b}}\,]^{\mathbf{T}}$$

$$\underline{\mathbf{u}} = [\,\Delta\mathbf{V}'_{\mathbf{d}}\ \Delta\boldsymbol{\omega}_{\mathbf{e}}/\boldsymbol{\omega}_{\mathbf{b}}\ \Delta\mathbf{T}_{\mathbf{L}}\,]^{\mathbf{T}}$$

$$\mathbf{A} = \begin{bmatrix} -x'_r r_0\omega_b/D_a & x_m r'_r\omega_b/D_a & -\omega_{e0}x'_r x_m(1-s)/D_a & -x_m x'_r i'_{dr0}\omega_b/D_a \\ \omega_b x_m r_0/D_a & x_0 r'_r\omega_b/D_a & \omega_{e0}(x_m^2 - s\,x_0 x'_r)/D_a & x_0 x'_r i'_{dr0}\omega_b/D_a \\ s\omega_{e0}x_m/x'_r & s\omega_{e0} & \omega_b r'_r/x'_r & -\omega_b/x'_r(x_m i_{qe0} + x'_r\ i'_{qr0}) \\ x_m i'_{dr0}/2H & 0 & x_m i_{qe0}/2H & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} x'_r\omega_b/D_a & 0 & 0 \\ -x_m\omega_b/D_a & -\omega_b(x_m i_{qe0} + x'_r\ i'_{qr0})/x'_r & 0 \\ 0 & -\omega_b & 0 \\ 0 & 0 & -1/2H \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$D_a = x_0 x'_r - x_m^2$$

$$s = (\omega_e - \omega_r)/\omega_b$$

$$v'_d = (\pi/3\sqrt{3})v_d$$

$$r_0 = r_s + \pi^2 r_d/18$$

$$x_0 = x_s + \pi^2 x_d/18$$

and H is inertia constant

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