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A RELIABLE MATRIX CONVERTER FED INDUCTION MOTOR DRIVE SYSTEM BASED ON PARAMETER PLANE SYNTHESIS METHOD

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Abstract

The paper presents a novel technique for designing Proportional Integral (PI) controller parameters for a reliable closed loop operation of Matrix Converter (MC) fed Induction Motor Drive (IMD). Parameter plane synthesis method is used to find the stable region in PI parameter plane. Small signal stability of the system is tested by perturbation along the stable point. The frequency scanning technique is used to confirm the stability of the region in parametric plane. The theoretical investigations have been carried out for analyzing the steady state and transient behavior of the proposed drive system and compared with the conventional Ziegler-Nichols method.

Key Words: Matrix Converter, Reliability, Induction Machine, D-Partition Technique.

1. Introduction

With the progress in automation, there has been a need for reliable step-less variable-speed drives which have the ability to respond quickly and accurately to external speed and torque demands. They should also have the capability of giving long term stability and good transient performance. With rapid developments in the technology of power electronics and solid state devices, electric drives with solid state control have been increasingly popular and are replacing all types of conventional drives.

The induction motor, in particular the squirrel cage induction motor, has many inherent advantages for industrial applications because of its ruggedness, simplicity, low inertia rotor, low cost, robust construction, absence of sliding contacts, high power/weight ratio, low maintenance, availability in ratings over the wide range, efficient operation and capacity to work in the hazardous environment [1]. Unlike the dc motor, it is having a coupled structure therefore the separate control of the field and armature is not easily possible. With vector control, the decoupling of d-q axes is possible in ac drives. The input current of motor is decoupled into two components, one producing flux, and the other, producing torque, and then controlling them independently.

The speed control of induction motor can be accomplished by supplying a variable voltage variable frequency (VVVF) source which can be achieved by using MC. The MC is a single stage process which converters fixed ac supply into variable ac supply by modulating nine bi-directional switches [2,3]. The main features of MC include bi-directional power flow, controllable input power factor and sinusoidal input current. The MC fed induction machine drive system as higher efficiency, better stability and a wide range of speed control.

Mathematics is a precise and concise language, with well-defined rules for manipulations and helps us to formulate ideas and underlying assumptions [4]. To maintain the system stability under all operating conditions and to maintain drive speed constant irrespective of the disturbance, precise and accurate design of closed loop PI controller is necessary. Some conventional techniques for controller design are discussed in [5-7]. The application of matrix converter in vector controlled drive is studied in [8,9]. In this work, plane parameter synthesis method [10-12] also known as D-partition is used. The plane parameter synthesis method has been used earlier in a number of processes [13-16].

In the present study, a rigorous mathematical model has been developed for analyzing the steady state and transient behavior of MC fed induction motor drive system. The PI parameters have been designed using parameter plane synthesis method. An idealized model describing the behavior of the system has been developed based on the concept of coupled circuit approach. The system has been analyzed in synchronously rotating reference frame.

2. System Overview

The drive system comprises of three phase ac supply, MC, induction machine, current and speed transducers. System components are modeled mathematically in terms of the transfer function. The MC is operated using Modified-Venturini algorithm. The induction machine speed control is done using vector control methodology. The steady state equations of the system are obtained by setting the time rate of change of all currents to zero in the generalized system equations.

2.1. Converter-drive Specification

The complete mathematical model of the drive system developed in the synchronous rotating frame of reference in terms of d-q variables is shown in Figure 1. The delay in the firing unit of the MC is approximated by a simple first order time lag with a time constant equal to the period between two consecutive firing pulses. The MC transfer function is represented as:

$$V_{out} = \frac{1}{1 + pT_S} V_S^* \tag{1}$$

2.2. Current and Speed Transducers

For closed loop control of the drive, current and speed sensors are used to measure the corresponding quantities. A low pass filter is used to reduce the ripples both in sensed current and speed. The current and speed feedback signals are taken as:

$$w_{rf} = \frac{1}{1 + pT_g} w_r \tag{2}$$

$$i_{sf} = \frac{1}{1 + pT_f} i_s \tag{3}$$

2.3. Proportional Integral Controllers

The speed and current PI controllers are used to process the speed and current error respectively. The flux in the system is assumed to be constant. The PI controllers are represented as follows:

$$i_s^* = \frac{k_2\left(1 + pT_2\right)}{pT_2}(w_r^* - w_{rf}) \tag{4}$$

$$V_s = \frac{k_1\left(1 + pT_1\right)}{pT_1}(i_s^* - i_{sf}) \tag{5}$$

2.4. Induction Machine

The squirrel cage induction motor is represented as a fourth order equation in d-q reference frame as:

$$\begin{bmatrix} V_{qs}^e \\ V_{ds}^e \\ V_{qr}^e \\ V_{dr}^e \end{bmatrix} = \begin{bmatrix} R_s + \frac{p}{w_b} X_s & \frac{w_e}{w_b} X_s & \frac{p}{w_b} X_m & \frac{w_e}{w_b} X_m \\ -\frac{w_e}{w_b} X_s & R_s + \frac{p}{w_b} X_s & -w_e \frac{X_m}{w_b} & \frac{p}{w_b} X_m \\ \frac{p}{w_b} X_m & \frac{w_{sl}}{w_b} X_m & R_r + \frac{p}{w_b} X_r & \frac{w_{sl}}{w_b} X_r \\ -\frac{w_{sl}}{w_b} X_m & \frac{p}{w_b} X_m & -\frac{w_{sl}}{w_b} X_r & R_r + \frac{p}{w_b} X_r \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix} \tag{6}$$

The simplified transfer function for the induction machine is derived by assuming constant flux operation given as:

$$i_{qs}^e = \frac{V_{qs}^e - w_r L_s i_{ds}^e}{R_s + \frac{R_r L_s}{L_r} + L_a p} = \frac{K_{a1}}{(1 + sT_{a1})}(V_{qs}^e - w_r L_s i_{ds}^e) \tag{7}$$

where, $R_a = R_s + \frac{R_r L_s}{L_r}$, $K_{a1} = \frac{1}{R_a}$ and $T_{a1} = \frac{L_a}{R_a}$.

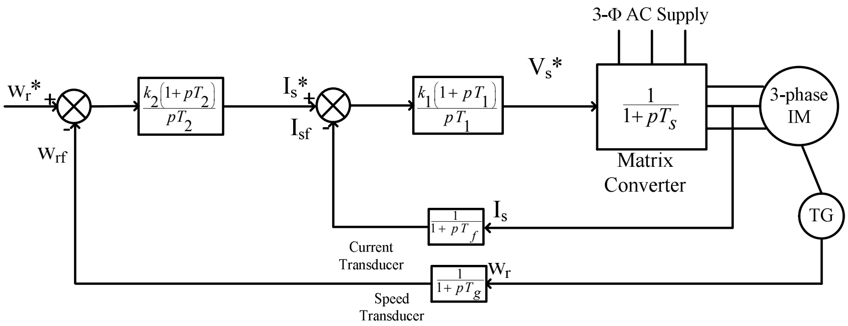


Figure 1: Mathematical model of the proposed drive system

3. Ziegler- Nichols Method

This is an experimental formula which was proposed by Ziegler and Nichols in early 1942. The open loop characteristic of the proposed system is obtained by step change in the input parameters and corresponding parameters k, L and T are obtained. The transient characteristic is shown in Figure 2. The controller parameters are calculated using the Table 1 and the corresponding parameter values are listed in Table 2.

Controller Type	Step response		
	Kp	Ti	Td
P	1/a	-	-
PI	0.9/a	3L	-
PID	1.2/a	2L	L/2

Table 1: Ziegler- Nichols tuning formulae

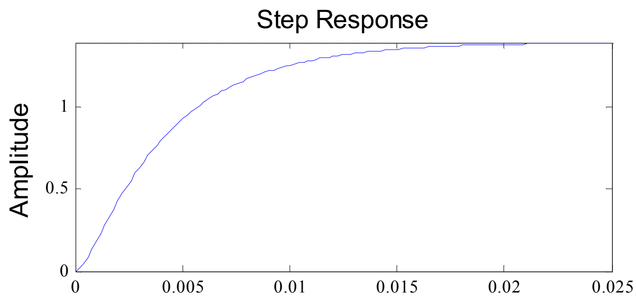


Figure 2: Open loop step response of the system

4. Parameter Plane Synthesis Method

For a reliable operation of drive, stable closed loop performance is extremely important, which depends on the controller parameters. This arise the accurate design of PI controller. Two PI controllers are used in the present study, one for torque control and other for speed control. Parameter plane synthesis method is used to find the stable region in the parameter plane. The performance of drive system based on the PI controller parameters designed is investigated in Matlab/Simulink environment. Further, frequency scanning technique is used to validate the designed PI controllers.

4.1. Design of Torque Controller

The parameter plane synthesis method (D-partition technique) is used for finding the region in parameter plane as continuous data system which ensures high damping ratio and degree of relative stability. The mathematical model shown in Figure 1 is considered. The system equations (6) can be rewritten as:

$$w_{sl}V_{qs}^{e} = w_{sl}\left\{R_s + \frac{p}{w_b}(X_s - \frac{X_m^2}{X_r})\right\}i_{qs}^{e} + \left(w_{sl} * w_e \frac{X_m}{w_b} + p\frac{X_m R_r}{X_r} + p^2\frac{X_m}{w_b}\right)i_{dr}^{e}$$
$$0 = w_{sl}\left(-\frac{X_m R_r}{X_r}\right)i_{qs}^{e} + \left\{w_{sl}\frac{X_r^2}{w_b} + \frac{w_b * R_r^2}{X_r} + p(2R_r) + p^2\frac{X_r}{w_b}\right\}i_{dr}^{e} \quad (8)$$

To design the current controller parameters (K_1 and T_1), motor flux and speed are assumed to be constant. The perturbed quantities can be expressed as:

$$V_{qs}^{e} = V_{qso}^{e} + \Delta V_{qs}^{e}$$
$$i_{qs}^{e} = i_{qso}^{e} + \Delta i_{qs}^{e}$$
$$i_{dr}^{e} = i_{dro}^{e} + \Delta i_{qs}^{e} \quad (9)$$

The characteristics equation of the current loop is given as $D(p)=0$ which is rewritten as:

$$\alpha pF_2(p) + \beta F_1(p) + pF_1(p) = 0 \quad (10)$$

where $\alpha=1/K_1$ and $\beta=1/T_1$.

$$F_1(p) = \frac{w_{slo}}{\left(1+pT_f\right)*\left(1+pT_s\right)}\left(w_{slo}\frac{X_r^2}{w_b} + \frac{w_b * R_r^2}{X_r} + p(2R_r) + p^2\frac{X_r}{w_b}\right) \quad (11)$$

$$F_2(p) = w_{slo}\left(R_s + p\frac{X}{w_b}\right)\left(w_{slo}\frac{X_r^2}{w_b} + \frac{w_b * R_r^2}{X_r} + p(2R_r) + p^2\frac{X_r}{w_b}\right)$$
$$+\left(w_{slo} * w_{eo}\frac{X_m}{w_b} + p\frac{X_m R_r}{X_r} + p^2\frac{X_m}{w_b}\right)\left(w_{slo}\frac{X_m R_r}{X_r}\right) \quad (12)$$

Putting p = σ+*jw* and varying, *w* from -∞ to +∞ for a constant σ. The D-partition boundary curve in α-β plane for σ =0 is shown in Figure 3. The curve is shaded according to the sign of the denominator of Δ which is given as:

$$\Delta = I_m\left[F_1(p)\right] * R_e\left[pF_2(p)\right] - I_m\left[pF_2(p)\right] * R_e\left[F_1(p)\right] \quad (13)$$

Moving into the direction of increasing *w*, the boundary curve is shaded twice on left side if Δ>0 and on the right side if Δ<0. The inner most region is the most probable stable region. To ensure the maximum relative stability, D-partition curves are plotted for different values of σ and varying ω from –∞ to +∞ as shown in Figure 4. As σ is increased, the stable region with higher degree of stability shrinks. The locus of the vector *D(p)* is plotted in the real and imaginary plane with the variation in w for an operating point lying inside the probable region and other lying outside the region as shown in Figure 5(a) and 5(b) respectively. It is clear that the point lying inside the probable stable region is giving stable response.

The transient response of the control loop is obtained for step variation in reference torque current from 1.0 p.u. to 1.05 p.u. of rated current value using Matlab/ Simulink blocksets. The transient response is plotted for different sets of K_1 and T_1, the values are chosen from the stable region as shown in Figure 6. The percentage over shoot and settling time corresponding to these chosen values of K_1 and T_1 are summarized in Table 3.

The comparison of various transient response curves shows that for K_1= 1/15 and T_1= 1/150, the settling time is fast enough and overshoot is within considerable limit. Therefore, the transfer function of the torque current controller is selected as $\frac{10(1+0.0067p)}{p}$.

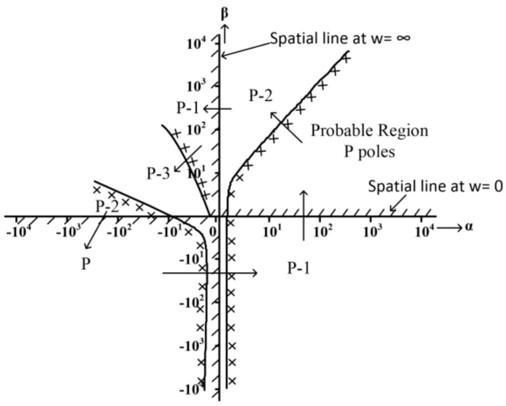


Figure 3: D-partition boundary for current controller (torque loop) design for absolute stability

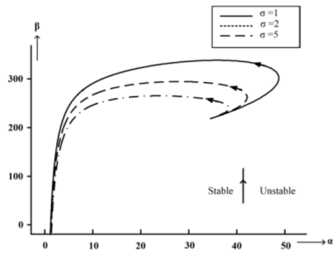


Figure 4: D-partition boundary for current controller (torque loop) design for different values of σ

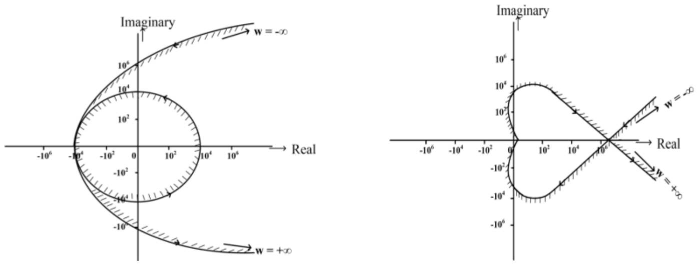


Figure 5: Frequency scanning technique for torque controller loop parameters (σ constant) (a) Stable Region; σ = 0.0, α= 15.0, β= 150.0 (b) Unstable Region; σ = 0.0, α= 1.0, β= 500.0

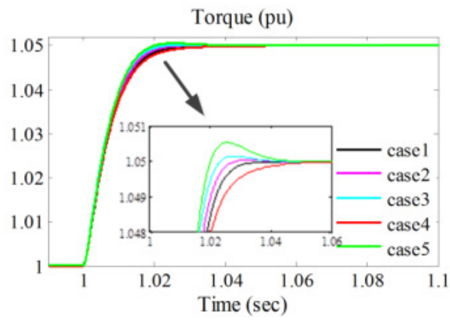


Figure 6: Transient response of Torque loop

4.2. Design of Speed Controller

For designing the outermost loop, the earlier determined torque and flux loop current parameters are used. The speed PI controller is designed using the same steps followed for the design of current control PI controller. The D-partition boundary obtained is shown in Figure7. Further, the D-partition curves plotted for different values of σ and varying w from –∞ to +∞ is shown in Figure 8. The stable and unstable response of the system for appropriate PI values is shown in Figure9(a) and (b) respectively.

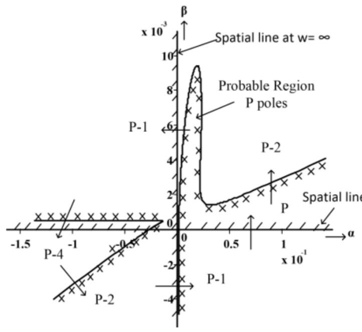


Figure 7: D-partition boundary for current controller (speed loop) design for absolute stability

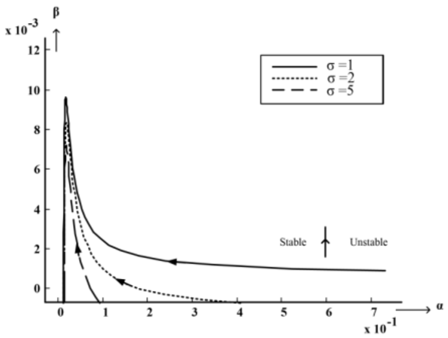
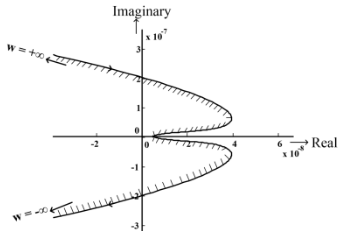
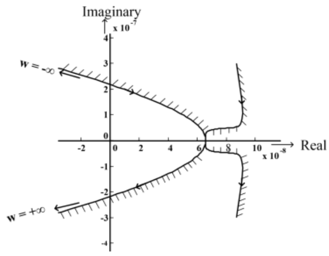


Figure 8: D-partition boundary for current controller (speed loop) design for different values of σ.

The percentage over shoot and settling time corresponding to some chosen values of K_3 and T_3 are summarized in Table 4. The comparison of various transient response curves shows that for K_3= 20 and T_3= 100, the settling time is 0.8 seconds and overshoot is 1.61% which is in considerable limit. Therefore, the transfer function of the torque current controller is selected as $\frac{0.2(1+100p)}{p}$.





(a) **(b)**

Figure 9: Frequency scanning technique for speed controller loop parameters (σ constant) (a) Stable Region; σ = 0.0, α = 1e-2, β = 8.0(b) Unstable Region; σ = 0.0, α= 1e-1, β= 15.0

Loop	Optimization Technique	K_p	k_i
Torque (First)	Conventional PI	0.0788	0.00875
	D-partition technique	0.0677	0.0067
Speed (Second)	Conventional PI	16.89	0.15
	D-partition technique	20	0.20

Table 2: Tuning Results of PI Controller (pu system)

Case	Gain (K_1)	Time Constant (T_1)	Overshoot (%)	Settling Time (sec)
1	0.05263	0.00667	-	0.047
2	0.06667	0.007143	0.195	0.048
3	**0.06667**	**0.00667**	**0.238**	**0.04**
4	0.09090	0.00667	0.286	0.042
5	0.07143	0.00667	0.952	0.05
6	0.04762	0.005	0.342	0.04

Table 3: Overshoots and settling times for step change in reference torque

Case	Gain (K_3)	Time Constant (T_3)	Overshoot (%)	Settling Time (sec)
1	10	50	4.19	0.9
2	**20**	**100**	**1.61**	**0.8**
3	10	100	3.23	0.8
4	5	83.33	4.09	1.0
5	3.33	125	5.14	>1.0

Table 4: Overshoots and settling times for step change in reference speed

5. Conclusion

The small signal stability of an indirect vector controlled MC fed IMD has been presented. The suitability of plane partition method for PI controller design for a reliable operation of drive has been suggested. The proposed controller based on D-partition technique has superior performance as compared to the conventional Ziegler- Nichols method. Further, the proposed technique is capable for coordination of parameters in parametric plane irrespective of the system order. The system non-linearity is linearized and characteristic equations for current and speed controllers are developed in terms of PI controller parameters. The results of frequency scanning technique validate the stable region identified by plane partition method. It is also noted that the PI controller design is invariant to change in the system perturbation.

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