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Model Predictive Control of Linear Induction Motor Drive

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Abstract: This paper investigates the application of the Model Predictive Control (MPC) technique in order to control the speed and/or position of the Linear Induction Motor (LIM) drive. The main goal of this controller is to provide the optimal 3-phase primary voltages necessary for tracking a certain speed reference trajectory. Moreover, constraints over the flux and current could be imposed to keep them within permissible values. The main idea is to tighten the future output error to zero, with minimum input effort. The MPC controller produces its optimal output derived from a quadratic cost function minimization based on the linearized machine model. A PI controller may be used in order to eliminate the steady state error completely. Simulation results show that the MPC controller succeeded in well tracking all given speed reference trajectories at high speed as well as at low speed with almost no current and force ripples. It has been proved that the proposed controller has faster response than any traditional controller. Moreover, it shows more robustness against parameter uncertainty and load disturbance.

1. INTRODUCTION

Nowadays, the linear induction motor (LIM) has been widely used in a variety of applications like as transportation, conveyor systems, actuators, material handling, pumping of liquid metal, sliding door closers, curtain pullers, robot base movers, office automation, drop towers, elevators, etc. (Bucci *et al.*, 1994), (Zhang, *et al.*, 1995). This is attributed to the several advantages that the LIM may possess such as high starting thrust, alleviation of gears between motor and the motion devices, simple mechanical construction, no backlash and less friction, and suitability for low speed and high speed applications (Takahashi and Ide, 1993), (Boldea and Nasar, 1997).

The driving principles of the LIM are similar to those of the traditional rotary induction motor. However, the control characteristics of the LIM are more complicated. This is attributed to the change in operating conditions such as mover speed, temperature, and rail configuration. Moreover, there are uncertainties existing in practical applications of the LIM which is usually composed of unpredictable plant parameter variations, external load disturbance, and unmodeled and nonlinear dynamics. Therefore, the LIM drive system must provide high tracking performance, and high dynamic stiffness to overcome the above difficulties (Abdou and Sherif, 1991), (Gastli, 1998), (Gastli, 2000).

Modern control techniques have been used to control the speed and/or position of the induction motor drives. Among these techniques, the method of Direct Torque Control (DTC) is considered one of the latest and efficient techniques that are used for this purpose (Habetter *et al.*, 1992), (Lascu *et al.*, 2000). The advantages of DTC strategy are fast transient response, simple configuration, and low parameter dependence. However, the classical DTC has inherent drawbacks such as variable switching frequency, high torque and current ripples, high noise level at low speeds and also the difficulty to control torque and flux at low speeds.

Also the sliding mode control (Yan *et al.*, 2000), (Tursini *et al.*, 2000) is one of the effective methods that has many good features such as fast dynamic response, simplicity of design and implementation, and robustness to parameter variations or load disturbance. This method is combined with adaptive backstepping to control the mover position of a LIM drive (Lin *et al.*, 2002a). However, the implementation of the associated control switching will cause chattering which involves high control activity and may excite unmodeled dynamics.

In the past few years, there has been considerable interest in the applications of intelligent methods to deal with the nonlinearities and uncertainties of the LIM control system. Intelligent methods such as neural, fuzzy and genetic algorithm have been employed for this purpose (Lin and Wai, 2002), (Wai *et al.*, 2001), (Lin and Wai, 2001), (Lin *et al.*, 2002b), (Lin *et al.*, 2004).

A robust controller that combines the merits of integral-proportional (IP) position control and neural network has been designed for a LIM drive (Lin and Wai, 2002), where the secondary flux is estimated using the sliding mode flux observer. The feedback linearization theory is used to decouple the thrust and flux amplitude of the LIM, and the neural network is used to estimate the lumped uncertainty. However, the major drawback of this method is that their application domain is limited to static problems due to the feedforward neural network structure. This is in addition to the chattering problem associated with the sliding mode. These disadvantages could be avoided using intelligent backstepping control systems in order to control the mover of the LIM drive. The recurrent or recurrent-fuzzy neural networks (Lin and Wai, 2001), (Lin *et al.*, 2002b) have been employed for this purpose.

Also, an attempt to control the mover position of the LIM drive using real coded genetic algorithm has been reported in (Lin *et al.*, 2004).

On the other hand, Model Predictive Control (MPC) appears to be an efficient strategy to control many applications in industry. It can efficiently control a great variety of processes, including systems with long delay times, non-minimum phase systems, unstable systems, multivariable systems, constrained systems (Camacho and Bordons, 1999), as well as complex and hybrid systems (Thomas *et al.*, 2004).

In this paper, the model predictive controller has been applied to control the speed and/or position of the LIM drive. Based on a linearized model for the LIM, the MPC controller offers an optimal 3-phase primary voltage necessary for tracking the speed trajectory. The controller calculates the optimal primary voltages while respecting the given constraints over the flux and current to keep them within permissible values. This optimal solution is calculated based on the current states of the system, the actual speed error and the predicted future output of the model.

Simulation results proved that the response of the proposed controller is very fast compared to the classical direct torque controller. Moreover, it shows more robustness against parameter uncertainty and load disturbance in the high speed as well as low speed ranges.

The paper is organized as follows: Section 2 briefly presents the dynamic model of the linear induction motor. General consideration about model predictive control and its cost function are presented in section 3. The implementation scheme of the LIM drive together with the MPC controller is described in section 4. Simulation results and general remarks are presented in section 5. Finally, the conclusions and future work are given in section 6.

2. LINEAR INDUCTION MOTOR

1.1 Dynamic Model of the LIM

The dynamic model of the LIM is modified from the traditional model of a three phase, Y-connected induction motor in $\alpha-\beta$ stationary frame and can be described by the following differential equations (Lin and Wai, 2002):

$$p\ i_{\alpha s} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{\alpha s} + \frac{Lm}{\sigma L_s L_r T_r}\lambda_{\alpha r} + \frac{n_p L_m \pi}{\sigma L_s L_r h}\upsilon\lambda_{\beta r} + \frac{1}{\sigma L_s}V_{\alpha s} \tag{1}$$

$$p\ i_{\beta s} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{\beta s} - \frac{n_p L_m \pi}{\sigma L_s L_r h}\upsilon\lambda_{\alpha r} + \frac{Lm}{\sigma L_s L_r T_r}\lambda_{\beta r} + \frac{1}{\sigma L_s}V_{\beta s} \tag{2}$$

$$p\lambda_{\alpha r} = \frac{L_m}{T_r} i_{\alpha s} - \frac{1}{T_r}\lambda_{\alpha r} - \frac{n_p \pi}{h}\upsilon\,\lambda_{\beta r} \tag{3}$$

$$p\lambda_{\beta r} = \frac{L_m}{T_r} i_{\beta s} + \frac{n_p \pi}{h}\upsilon\,\lambda_{\alpha r} - \frac{1}{T_r}\lambda_{\beta r} \tag{4}$$

$$p\upsilon = \frac{1}{M}F_e - \frac{D}{M}\upsilon - \frac{1}{M}F_L \tag{5}$$

Where : $T_r = \dfrac{L_r}{R_r}$, $\sigma = 1 - \dfrac{L^2{}_m}{L_s L_r}$.

- p : differential operator,
- D : viscous friction and iron-loss coefficient,
- F_e : electromagnetic force,
- F_L : external force disturbance,
- h : pole pitch,
- L_s : primary inductance per phase
- L_r : secondary inductance per phase,
- L_m : magnetizing inductance per phase,
- M : total mass of the moving element,
- n_p : number of pole pairs.
- R_s : primary winding resistance per phase,
- R_r : secondary resistance per phase,
- T_r : secondary time constant,
- υ : mover linear velocity,
- $\lambda_{\alpha r}, \lambda_{\beta r}$: $\alpha-\beta$ secondary flux components,
- $i_{\alpha s}, i_{\beta s}$: $\alpha-\beta$ primary current components,
- $V_{\alpha s}, V_{\beta s}$: $\alpha-\beta$ primary voltage components,
- σ : leakage coefficient,

The electromagnetic force can be described in the $\alpha-\beta$ fixed frame as (Lin *et al.*, 2002a):

$$F_e = k_f\left(\lambda_{\alpha r} i_{\beta s} - \lambda_{\beta r} i_{\alpha s}\right) \tag{6}$$

Where k_f is the force constant which is equal to:

$$k_f = \frac{3 n_p L_m \pi}{2 L_r h} \tag{7}$$

3. MODEL PREDICTIVE CONTROL

3.1 General Consideration

Predictive control was first developed at the end of 1970s, and noted by the work done by (Richalet *et al.*, 1978). In 1980s, many methods based on the same concepts are developed. Among them, the Generalized Predictive Control (GPC), developed by David Clarke and his team (Clarke *et* *al.*, 1987), that become the most utilizing technique after that. Those types of control, are now grouped under the name Model Predictive Control (Camacho and Bordons, 1999).

In fact MPC received a very favourable echo in the industry because it is recognized as a simple and effective control technique. It has proved to efficiently control a wide range of applications in industry, among them the chemical process, that was the first application for this type of control, petrol industry, electromechanical systems like controlling robot axes and many other applications. It is capable to control a great variety of processes, including systems with long delay times, non-minimum phase systems, unstable systems, multivariable systems, constrained systems and hybrid systems.

3.2 Principal ideas of predictive control

The main idea of predictive control is to use a model of the plant to predict future outputs of the system. Based on this prediction, at each sampling period, a sequence of future control values is elaborated through an on-line optimization process, which maximizes the tracking performance while satisfying constraints. Only the first value of this optimal sequence is applied to the plant, the whole procedure is repeated again at the next sampling period according to the 'receding' horizon strategy (Dumur and Boucher, 1998).

A simple block diagram characterizing the MPC is shown in Fig. (1). It should be noted that the predicted output from the system model and the actual error are used to obtain the control signal.

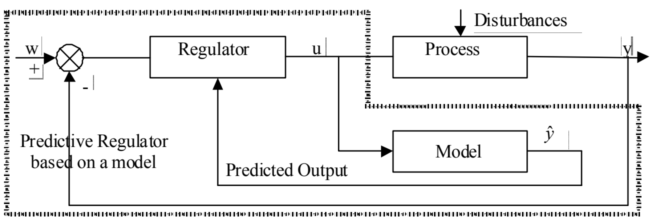

Figure 1 : A simple block diagram describing the MPC.

Model predictive control is based on the system model and the principles of receding horizon control (RHC). The control signal at instant t is obtained by solving, at each sampling instant, an on line open loop optimal control problem over a finite horizon using the current state of the system as initial states.

The interesting of this control technique becomes obvious when the trajectory to be followed by the system is known in advance, as for example in the robot, chemical process or machine tools, where the anticipation action takes place.

The general object is to tighten the future output error to zero, with minimum input effort. The cost function to be minimized is generally a weighted sum of square predicted errors and square future control values, e.g. in Generalized Predictive Control (Clarke *et al.*, 1987):

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} \beta(j)\left[\hat{y}(k+j|k) - w(k+j)\right]^2 + \sum_{j=1}^{N_u} \lambda(j)\left[u(k+j-1)\right]^2 \tag{8}$$

Where N_1, N_2 are the lower and upper prediction horizons over the output, N_u is the control horizon, $\beta(j), \lambda(j)$ are weighting factors. The control horizon permits to decrease the number of calculated future control according to the relation: $\Delta u(k+j) = 0$ for $j \geq N_u$. $w(k+j)$ represents the reference trajectory over the future horizon N.

Constraints over the control signal, the outputs and the control signal changing can be added to the cost function:

$$\begin{aligned} u_{\min} &\leq u(k) \leq u_{\max} \\ \Delta u_{\min} &\leq \Delta u(k) \leq \Delta u_{\max} \\ y_{\min} &\leq y(k) \leq y_{\max} \end{aligned} \tag{9}$$

Solution of (8) gives the optimal sequence of control signal over the horizon N while respecting the given constraints of (9).

Model Predictive Control have many advantages, in particularly it can pilot a big variety of process, being simple to apply in the case of multivariable system, can compensate the effect of pure delay by the prediction, inducing the anticipate effect in closed loop, being a simple technique of control to be applied and also offer optimal solution while respecting the given constraints.

On the other hand, this type of restructure required the knowledge of model for the system, and in the present of constraints it becomes a relatively more complex regulator than the PID for example, and it takes more time for on-line calculations when the constraints intervene. MPC parameters, including prediction and control horizon as well as weighting factors, are designed based on successive iterations (trial and error); no mathematical or theoretical forms have been developed yet to determine the best configuration of MPC parameters.

4. SYSTEM CONFIGURATION

The block diagram of the linear induction motor controlled with the proposed MPC controller is shown in Fig. (2). The system consists mainly of LIM, speed encoder, voltage source inverter, MPC controller, and secondary flux estimator. The motor speed signal is measured and compared with a reference one. A PI controller on the speed error is fed to the MPC controller in order to reduce the steady state error. The signals input to the MPC controller are the system states, speed reference, output of the PI controller, and feedback of the control signal. The system states are $\left[i_{\alpha s} \;\; i_{\beta s} \;\; \lambda_{\alpha r} \;\; \lambda_{\beta r} \;\; v_r\right]^T$; primary currents, estimated secondary fluxes and motor speed respectively. The secondary flux components are estimated using the voltage and current signals as follows:

$$\lambda_{\alpha r} = (L_r / L_m)(\lambda_{\alpha s} - \sigma L_s\, i_{\alpha s})$$
$$\lambda_{\beta r} = (L_r / L_m)(\lambda_{\beta s} - \sigma L_s\, i_{\beta s}) \qquad (10)$$

Where : $\lambda_{\alpha s} = \int (V_{\alpha s} - i_{\alpha s} R_s)dt, \quad \lambda_{\beta s} = \int (V_{\beta s} - i_{\beta s} R_s)dt$

A linearization for the LIM model is made to be used as the linear model of the MPC controller. This linearization is made on-line at each sampling instant, due to the continuous change of the operating points, around the current states and the last control signal $\mathbf{x}_k, \mathbf{u}_{k-1}$. The control signal is memorized and fedback to the input of the MPC for the linearization purpose.

After successive iterations, the parameters of the MPC controller that give a good response are as follows:

Prediction horizon $N = 50$, control horizon $N_u = 50$,
Weights on manipulated variables = 0 ,
Weights on manipulated variable rates = 0.1 ,
Weights on the output signals = [0 0 0 0 2000],
Sampling interval = 0.0001 sec.
Gains of the PI controller are: $K_p = 5, \quad K_I = 300$.

The weights on the output currents and fluxes are set to zero because the reference trajectories of those signals are unknown, thus they have no effect on the minimization of the cost function J. Instead, maximum and minimum constraints are taken into account in the MPC controller so that the currents and fluxes do not exceed certain values. The load force is taken as unmeasured disturbance input to the system.

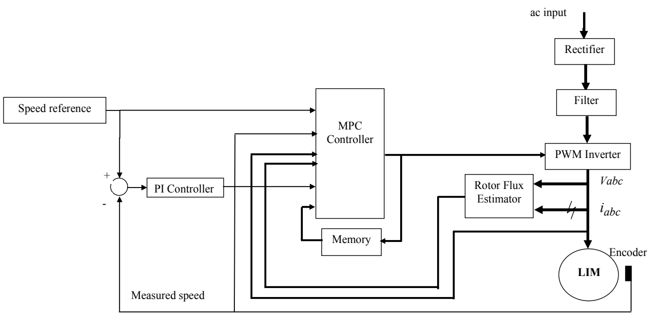

Fig. 2. Block diagram of the LIM drive controlled with the MPC controller.

5. RESULTS AND DISCUSSIONS

Computer simulations have been carried out in order to validate the robustness of the proposed scheme. The Matlab / Simulink software package has been used for this purpose. Different operating conditions including load change, various speed trajectories and mismatched parameter have been assumed. The data of the LIM used for simulation procedure are (Lin and Wai, 2002): 3-phase, Y-connected, 2-pole, 3-kW, 60-Hz, 180-V, 14.2 A. The motor detailed parameters are listed below in table (1).

Figure (3) shows the speed responses of the proposed MPC controller and also that obtained with the classical DTC. The LIM is assumed to start at t=0 and accelerated up to 2 m/sec in the first 0.2 second, then the motor speed is kept constant at this value during the remaining simulation period. It is worthy to note that the acceleration period (0.2 sec) is thought to be enough for the motor to attain the desired speed (2 m/sec). This is because the tested motor has a smaller size and less weight and thereby lower mechanical time constant (0.077 sec.). The load force is stepped from 350 N. to 700 N. at t = 0.5 seconds. Nominal motor parameters are assumed.

Table 1. Parameters and data of the LIM

Rs (Ω)	5.3685	Pole pitch, h (m)	0.027
Rr (Ω)	3.5315	Total mass of the mover, M (kg) .	2.78
Ls (H)	0.02846	Viscous friction and iron-loss coefficient, D (kg/s)	36.0455
Lr (H)	0.02846	Force constant, Kf (N/wb.A)	148.35
Lm (H)	0.02419	Rated secondary flux, (wb)	0.056

It is worthy to indicate that the DTC needs to about 0.5 sec. in order to attain the steady state value either from start or after the load disturbance took place. On the other hand, the MPC controller takes less than 0.03 sec. only. It has been noticed that with the MPC controller, the reference and actual speeds are aligned and good tracking performance has been achieved. At t=0.5 sec. there is a small dip in the speed response due to the load change, but the controller succeeded in restoring the speed reference very quickly.

It can be said that the MPC controller response is much faster than that of the DTC response and able to deal with load changes more efficiently.

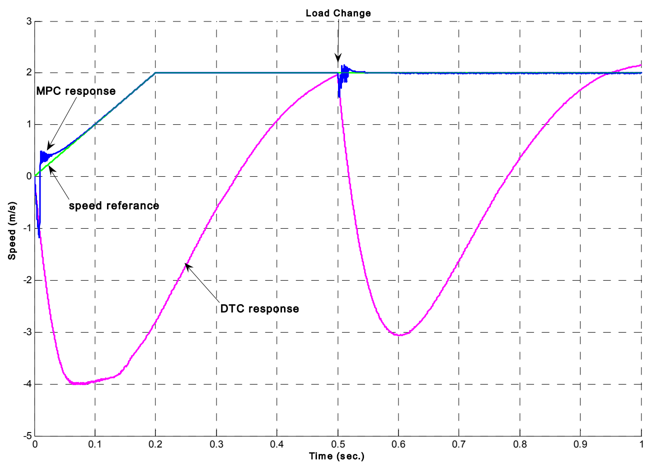

Fig. (3) MPC response versus DTC response

The performance of the MPC controller is tested also at low speed (0.1 m/s), with the same load change of the previous scenario. Figure (4) shows the simulation waveforms obtained. They are from top to bottom: speed response, developed force and three phase primary currents. The later is enlarged during the period from t= 0.45 to 0.55 sec. in which the load change occurs. Again the controller responds quickly to the load disturbance and behaves well at low speed except for the first few milliseconds at the beginning of simulation. This is attributed to the large difference between the given initial states and the actual states which affect the linearization model.

It is clear that the 3- phase currents and the electromagnetic force do not contain ripples as usually with the DTC technique for such low speed.

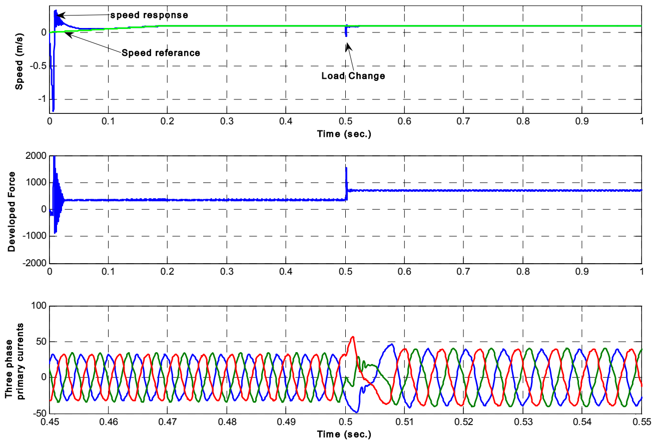

Fig. 4. Simulation results obtained with the MPC controller at low speed.

The robustness of the MPC controller has also been tested against parameters uncertainty. Only, the primary resistance detuning is considered in this test because it has significant effect on the flux estimation especially at low speeds, the value of primary resistance is increased by 50% in the LIM model while it is kept at its nominal value in the controller. The load is kept constant at the level of 350 N. Figure (5) illustrates the simulation waveforms in this case of uncertainty at low speed (0.1 m/s). It has been indicated that very fast response has been achieved using the MPC controller. Thus, the reference speed is attained in 0.1 sec. only. Also, the waveforms of the developed force and primary currents are free of any ripples.

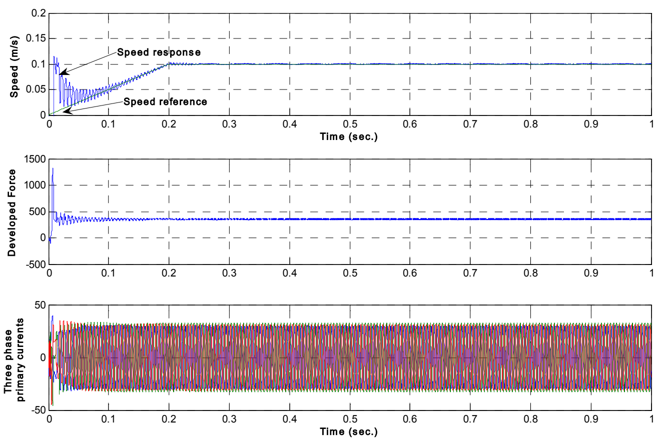

Fig. 5. Simulation results obtained with the MPC controller at low speed and mismatched primary resistance.

In order to check the tracking performance of the MPC controller, it has also been investigated with sinusoidal variation of the speed reference. This means that the reference position of the mover is also sinusoidal. Figure (6) shows the result of the MPC response as well as the DTC response with sinusoidal speed command having frequency = 5 Hz and amplitude 1 m/s. It is clear from the figure that the DTC response is not able to track the speed reference while the MPC controller succeeded in following the reference trajectory.

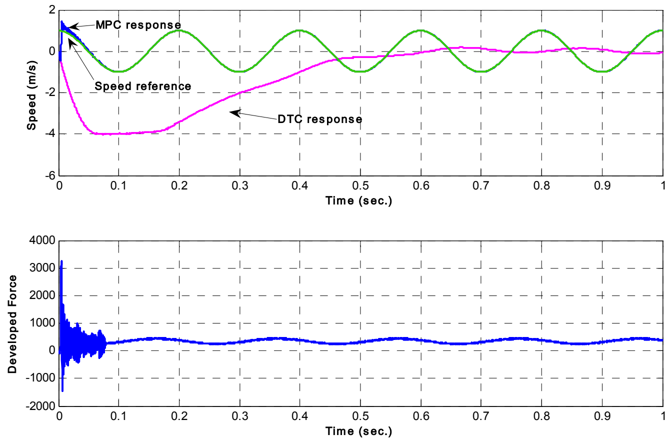

Fig. (6) MPC response versus DTC response with sinusoidal speed reference.

Previous simulation results prove the success of the presented technique; it gives good performance on speed tracking and good robustness against parameter variation and load changes. The main drawback of this technique is its computation load related to the on-line optimisation and the on-line linearization. Each sample data takes about few milliseconds on computer time, using the qpsolver Matlab code, on a 1.8 MHz PC with 256 kram. However using a higher PC features and faster commercial optimisation tools like *CPLEX* (ILOG, Inc., 2000) and *XPRESS-MP* (Dash Associates, 1999) will allow the real time implementation.

6. CONCLUSIONS

This paper presents the successful application of the model predictive controller to control the speed and/or position of the Linear Induction motor drive. This controller provides the optimal primary voltages necessary for tracking a certain reference speed trajectory while fulfilling the constraints over the flux and current to keep them within permissible values.

The proposed MPC controller response has many advantages; very fast response, robustness against parameter uncertainties and load changes, well tracking of speed trajectory at all speeds and has almost no current and force ripples. However, it has relatively high computation load which include the on-line linearization and the optimal solution computation.

It has been shown that the MPC controller offers better response than that of the classical direct torque control. It has been thought that the proposed controller is the fastest at all among the existent traditional controllers.

Future work should include experimental works to validate this technique practically. Also, the recurrent neural control will be used to overcome the computational load problem of the MPC controller. Finally, the same technique will be applied to control other machines like rotary induction motor, and permanent magnet synchronous motor.

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