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Generalized Predictive Control of Multi-Phase Induction Machine Supplied by Multi-Level Inverter

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Abstract: With more than three phases, multi-phase induction machines provide an alluring substitute for lowering the strains placed on the machine's switches and windings. The management of overly produced current is one of the most important issues when making quick and significant adjustments to the speed control of a multi-phase induction motor. Thus, if the speed controller lacks an output amplitude limitation, it may cause harm to both the motor and the power electronics converter. The speed control loop and the two internal current control loops are the first two areas in which this research suggests using polynomial predictive controllers to solve the saturation phenomena of the speed regulator. Then, by convexly optimizing the Youla parameter while accounting for time and frequency constraints, the external predictive speed controller is readjusted. This ensures that the speed response to the reference stays in an imposed model with minimal current control during transient periods, while also preserving the closed-loop functionalities that the initial predictive controller had achieved. The results of the simulation demonstrate how well the suggested control system controls speed under different multi-phase induction machine operating situations.

Keywords: Five-phase, Induction motor, Vector control, Generalized predictive control, Multi-level inverter.

Introduction

In some applications, multiphase drives have emerged as a viable substitute for their three-phase counterparts because of their inherent benefits, which include fault tolerance and the ability to divide power among more than three phases (Guo, 2021). These benefits are especially intriguing for propulsion and safety-critical applications all-electric ship propulsion (Yin, 2013). Electrical and hybrid vehicles (Kumar,2020; Gang, 2019). And more-electric aircraft (Guo, 2021). Where the rotating field in the three-phase machine cannot be maintained if one of the phases is lost. When one or more phases are lost, on the other hand, multiphase drives can still function with the rotating field. This is because a multiphase machine always needs just two degrees of freedom to produce a spinning field, regardless of the actual number of stator phases. Therefore, even with some derating, post-fault operation with a rotating field is feasible. Additionally, in some of the previously described applications, the low inverter DC link voltage supplied by batteries necessitates large phase current needs; thus, multiphase drives are particularly appropriate since they reduce the current per phase for the specified power (Liu, 2020).

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The five-phase machine is among the most intriguing multiphase devices for these uses (Yin, 2013). There are two distinct five-phase electrical machine architectures in the literature. A sinusoidal MMF distribution serves as the foundation for the first one. Because this multiphase drive only needs sinusoidal voltages, low order harmonics in the machine's input voltage are undesired. The stator windings in the second one are concentrated. In this instance, stator current low-order harmonic injection can be used to increase torque generation. This is especially true for the third harmonic, while evaluating reference voltage vectors places a heavy computational load on the real-time processing system (Qu, 2023). Although a five-phase machine with sinusoidal MMF distribution is used in this study as an example of a multiphase drive, the findings may be applied to a five-phase machine with concentrated windings.

Multiphase drives with high performance applications need particular control systems. Field Oriented Control (FOC) is the most widely used control structure. It is a cascaded method that has an outer speed control loop and an inner current control loop (Yin, 2013). A two-level multiphase voltage source inverter (MVSI) is usually controlled by switching signals produced by the inner control loop. A suitable carrier-based or space vector pulse width modulation approach (CPWM or SVPWM, respectively) is used to regulate the MVSI. Although CPWM techniques are easier to use, SVPWM provides a deeper understanding of the characteristics of multiphase drives and inverters.

An alternative to cascade PI control of electrical drives is Model Predictive Control (MPC), which is an optimization-based approach that computes the next control action by minimizing difference between the predicted output of a system and the specified reference. Many MPC design algorithms are available and, in general terms, can be categorized as: (i) transfer-function based, such as Generalized Predictive Control (GPC) (Clarke et al., 1987). (ii) step response model based, such as Dynamic Matrix Control (DMC) (Cutler & Ramaker, 1979). And (iii) state-space model based (Kerrigan, 2002).

Generalized Predictive Control (GPC)

Generalized predictive control (GPC) is one of the most popular predictive control algorithms developed by Clarke in 1987 (Ling, 2023; Feng, 2010). GPC retains the design flexibility and performance of GMV/PP technique. It also caters for offsets (since it uses integrated controlled auto regressive moving average (CARIMA) model), feed-forward signals, and multivariable plant without detailed prior knowledge of structural indices. The main difference between GPC and DMC is the model used to describe the plant and the formulation of the dynamic matrix. For satisfying the control objectives, it makes the use of a CARIMA model and various horizons. This model is more appropriate in industrial applications where disturbances are non-stationary. A CARIMA model is used to obtain good output predictions and optimize a sequence of future control signals to minimize a multistage cost function defined over a prediction horizon. The inclusion of disturbance is necessary to deduce the correct controller structure.

$$A(z^{-1})y(t)=B(z^{-1})u(t-1)+C(z^{-1})\,{}^{e(t)}\!\big/_{\Delta(z^{-1})} \tag{1}$$

In both cases (speed loop or current loops), the GPC control strategy uses for the prediction the CARIMA model (controlled autoregressive integrated moving average)

Whre $u(t-1)$ is the control, $y(t)$ is the process output, $e(t)$ is the zero mean white noise, $\Delta(z^{-1}) = 1- z^{-1}$, A and B are polynome in backward shift operator z^{-1} derived from (5). The predictive outputin the j-th prediction step over the costing horizons $N_1 \leq j \leq N_2$ is done by:

$$\underbrace{y(t+j)=F_j(z^{-1})y(t)+H_j(z^{-1})}_{Free\ response}\underbrace{\Delta u(t-1)\quad+G_j(z^{-1})\Delta u(t+j-1)+J_j(z^{-1})}_{Forced\ response}e(t+j) \tag{2}$$

F_j , G_j , H_j are polynomilas determined from soling intertively Diophantine equation. The GPC control law is obtained by minimizing the cost function given by:

To generate a set of predicted outputs $\hat{y}(t+j/t)$, the prediction model equation (2) is used. The value of $\hat{y}(t+j/t)$ for $j>t$ depent on future control signals $u(t+j)$. These control signals are used to achieve the objective in GPC by minimizing the cost function given as:

$$J(N_1,N_2,N_u)=\sum_{j=N_1}^{N_2}\delta(j)[\hat{y}(t+j/t)-w(t+j)]^2+\lambda\sum_{j=1}^{N_u}\lambda(j)[\Delta u(t+j-1)]^2 \quad (3)$$

$$\Delta u(t+1) = 0 \text{ for } j \geq N_u$$

GPC depends on the integration of assumption of a CARIMA plant model, use of LRPC, recursion of Diophantine equation, consideration of weighting of control increments in cost function and the choice of a control horizon (Nail, 2015; Clarke, 1987). GPC is applicable to non-minimum phase, open loop unstable and having variable dead time. It is capable of considering both constant and varying future set points. It is unaffected (unlike pole-placement strategies) if the plant model is over parameterized.

However, GPC has limitations with minimum phase processes for some of the most obvious choices of its design parameters (Duan, 1991). GPC shows better performance in cement mill, a spray-drying tower and compliant robot arms.

Mathematical Model for Five-Phase Induction Motor

The electric equation of a five-phase an asynchronous machine in the natural base is given by the following expression for each phase:

$$\begin{cases} [V_s]=[R_s].[I_s]+\dfrac{d[\phi_s]}{dt} \\ [V_r]=[R_r].[I_r]+\dfrac{d[\phi_r]}{dt} \end{cases} \quad (4)$$

Where

$[V_s] = [v_{sa}\ v_{sb}\ v_{sc}\ v_{sd}\ v_{se}]$; $[I_s] = [i_{sa}\ i_{sb}\ i_{sc}\ i_{sd}\ i_{se}]$; $[V_r] = [v_{ra}\ v_{rb}\ v_{rc}]$; $[I_r] = [i_{ra}\ i_{rb}\ i_{rc}]$;

$R_s = R_{sa} = R_{sb} = R_{sc} = R_{sd} = R_{se}$; $R_r = R_{ra} = R_{rb} = R_{rc}$;

$[\phi_s]=[\phi_{sa}\ \phi_{sb}\ \phi_{sc}\ \phi_{sd}\ \phi_{se}]$; $[\phi_r]=[\phi_{ra}\ \phi_{rb}\ \phi_{rc}]$

The model of five-phase an asynchronous machine is as follows after converting Phase variables into *d-q* variables:

$$\begin{cases} V_{sd}=[R_s].i_{sd}-\omega_s\phi_{sq}+\dfrac{d\phi_{sd}}{dt} \\ V_{sq}=[R_s].i_{sq}+\omega_s\phi_{sd}+\dfrac{d\phi_{sq}}{dt} \\ V_{rd}=[R_r].i_{rd}-(\omega_s-\omega_r)\phi_{rq}+\dfrac{d\phi_{rd}}{dt} \\ V_{rq}=[R_r].i_{rq}+(\omega_s-\omega_r)\phi_{rd}+\dfrac{d\phi_{rq}}{dt} \end{cases} \quad (5)$$

The electromagnetic torque for asynchrounous machine is equal to:

$$T_e=\frac{5}{2}pL_m(\phi_{rd}.i_{sq}-\phi_{rq}.i_{sd}) \quad (6)$$

On the other hand, the mechanichal equation of the machine is:

$$J\frac{d\Omega_r}{dt} = T_e - T_r - f_m.\Omega_r \tag{7}$$

This set of equations allows characterizing the electromechanical behaviour of a five-phase PMSM machine.

Indirect Vector Control for Five-Phase Asynchronous Motor Drive

Vector control technique aims to make equivalence between the five-phase asynchronous motor drive and DC motor. This objective can be achieved by controlling the q-axis flux component to zero. Stator flux and rotor flux orientation are examples of field oriented control techniques for an asynchronous machine. The stator current space vector for an asynchronous machine has two components i_{sd} and i_{sq}.

The i_{ds} produces the rotor flux component and i_{qs} produces the torque-producing component in rotor flux orientation. The rotary flow direction control model is given by the following equation:

$$\begin{cases} i_{rq} = 0 \\ i_{rd}^{*} = \phi \end{cases} \tag{8}$$

The simplified model of the machine as follows:

$$\begin{cases} \sigma L_s \dfrac{di_{sd}}{dt} = -\left(R_s + \dfrac{L_m^2}{L_r^2}R_r\right)i_{sd} + \sigma L_s \omega_s i_{sq+} \dfrac{L_m}{L_r.T_r}\phi_r + V_{sd} \\ \sigma L_s \dfrac{di_{sq}}{dt} = -\left(R_s + \dfrac{L_m^2}{L_r^2}R_r\right)i_{sq} - \sigma L_s \omega_s i_{sd} - \dfrac{L_m}{L_r.T_r}\omega_r \phi_r + V_{sq} \\ \dfrac{d\phi_r}{dt} = \dfrac{L_m}{T_r} i_{sd} - \dfrac{1}{T_r}\phi_r \\ T_e = p\dfrac{L_m}{T_r}\phi_r i_{sq} \\ \omega_r = \dfrac{M}{T_r}.\dfrac{1}{\phi_r}.i_{sq} \\ J\dfrac{d\Omega_r}{dt} = T_e - L_r - f\Omega_r \end{cases} \tag{9}$$

With $T_s = L_s / R_s$: stator time constant ; $T_r = L_r / R_r$: rotor time constant ; $\sigma = 1 - \dfrac{L_m^2}{L_r.L_s}$: Total leakage coefficient.

Dynamic Model of Flux and Torque

The rotor flux and the electromagnetic torque can be estimated from the currents i_{sd} and i_{sq} , stator quantities accessible from the measurement of real currents stator subject to the realization of the Park transformation.

$$\begin{cases} \hat{\phi}_r + T_r\dfrac{d}{dt}\hat{\phi}_r = L_m i_{sd} \\ \hat{T}_e = p\dfrac{L_m}{T_r}\hat{\phi}_r i_{sq} \\ \hat{\omega}_s - \omega_r = \dfrac{L_m}{T_r}.\dfrac{1}{\hat{\phi}_r}.i_{sq} \\ \hat{\theta}_s = \int \hat{\omega}_s dt \end{cases} \Rightarrow \begin{cases} \hat{\phi}_r = \dfrac{L_m}{1+T_r} i_{sd} \\ \hat{T}_e = p\dfrac{L_m}{T_r}\hat{\phi}_r i_{sq} \\ \hat{\omega}_s - \omega_r = \dfrac{L_m}{T_r}.\dfrac{1}{\hat{\phi}_r}.i_{sq} \\ \hat{\theta}_s = \int (p\Omega_r \dfrac{L_m}{T_r}.\dfrac{1}{\hat{\phi}_r}.i_{sq})dt \end{cases} \tag{10}$$

Decoupling by Compensation

The decoupling principle amounts to defining two new control variables v_{sd1} and v_{sq1} such as v_{sd1} only acts on i_{sd} and v_{sq1} on i_{sq}.

So, we can write the voltages v_{sd} and v_{sq} as a function of v_{sd1} and v_{sq1} as follows:

$$\begin{cases} v_{sd} = v_{sd1} - e_1 \\ v_{sq} = v_{sq1} - e_2 \end{cases} \tag{11}$$

With:

$$\begin{cases} e_1 = \sigma L_s \omega_s i_{sq} + \dfrac{L_m R_r}{L_r^2} \phi_r \\ e_2 = -\sigma L_s \omega_s i_{sd} - \dfrac{L_m}{L_r} \omega_s \phi_r \end{cases} \tag{12}$$

Defluxing

The defluxing block are written as follows

$$\phi_r^* = \begin{cases} \phi_{rn} & if \quad \Omega_r < \Omega_{rn} \\ \dfrac{\phi_{rn}\Omega_{rn}}{\Omega_r} & if \quad \Omega_r > \Omega_{rn} \end{cases} \tag{13}$$

A system illustration of the vector control of five-phase an asynchronous motor is given in figure 1.

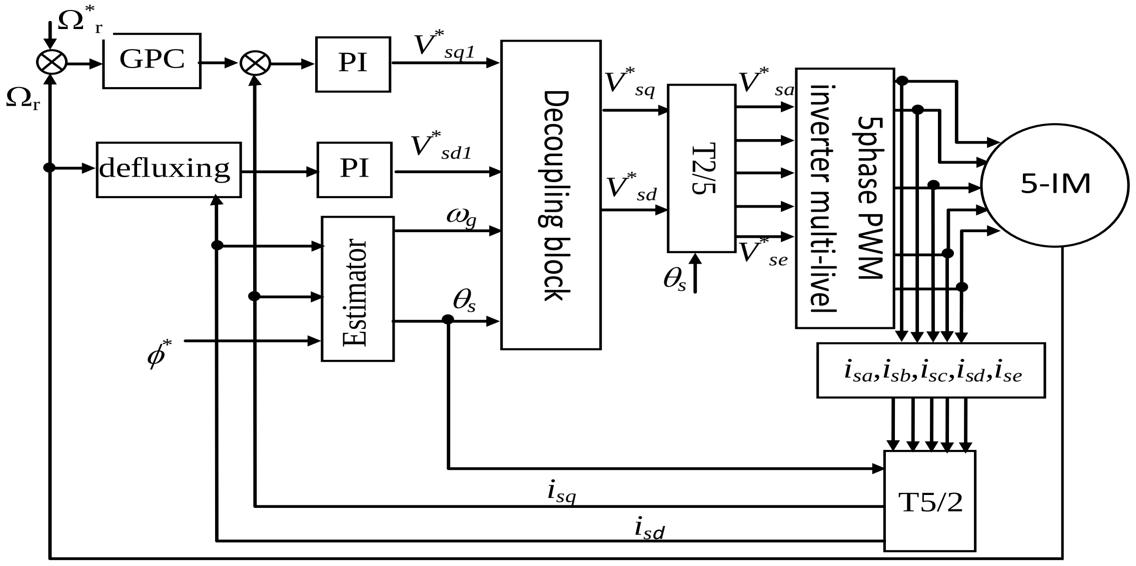


Figure 1. Vector control for a five-phase an asynchronous machine.

Results and Discussion

The simulations have been performed in a MATLAB envi-ronment writing the differential equations for the evolution of the five induction motor and load. Figures 2 and 3 illustrate respectively the rotor speed, rotor flux magnitude, components currents (i_{ds},i_{qs}), Flux and the real stator current i_{as} control by PI regulator. To illustrate the performance of the predictive control applied to the speed control, the five induction motor was simulated with a reference speed of 157 rad/s vacuum and then applying a nominal load of 10 N.m at t = 1s (Figure 4).

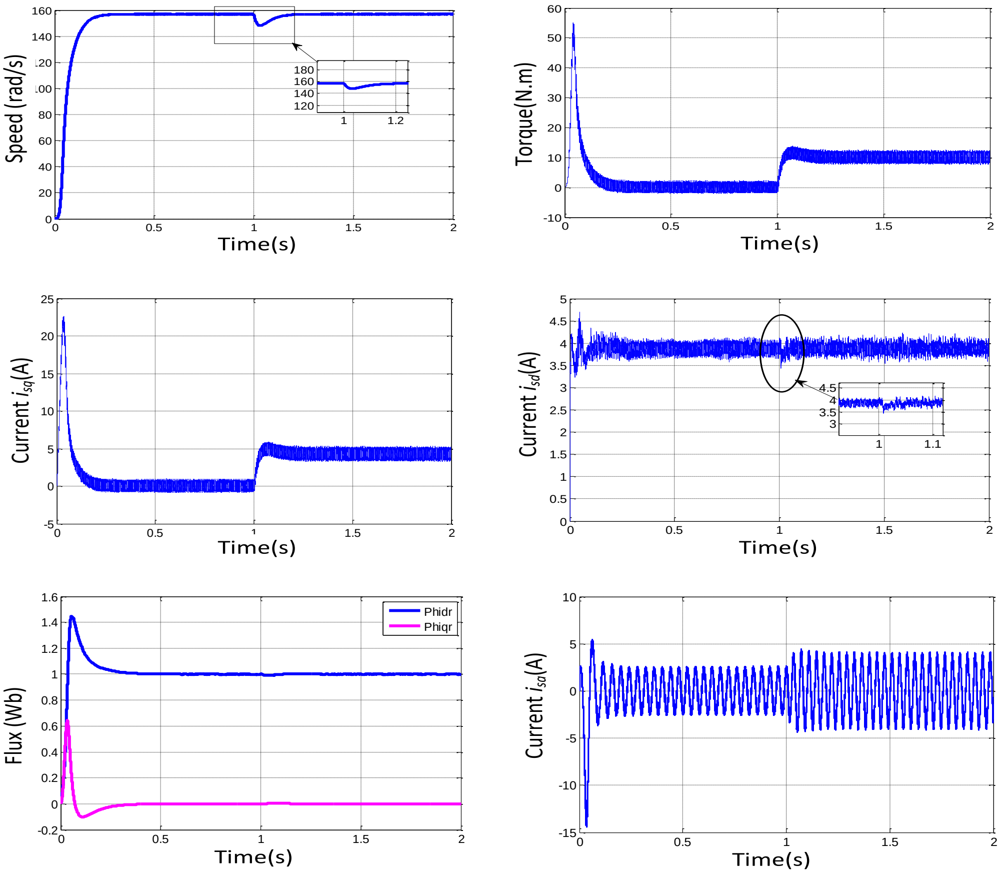


Figure 2. Indirect vector control performance of the five-phase IM with PI regulators.

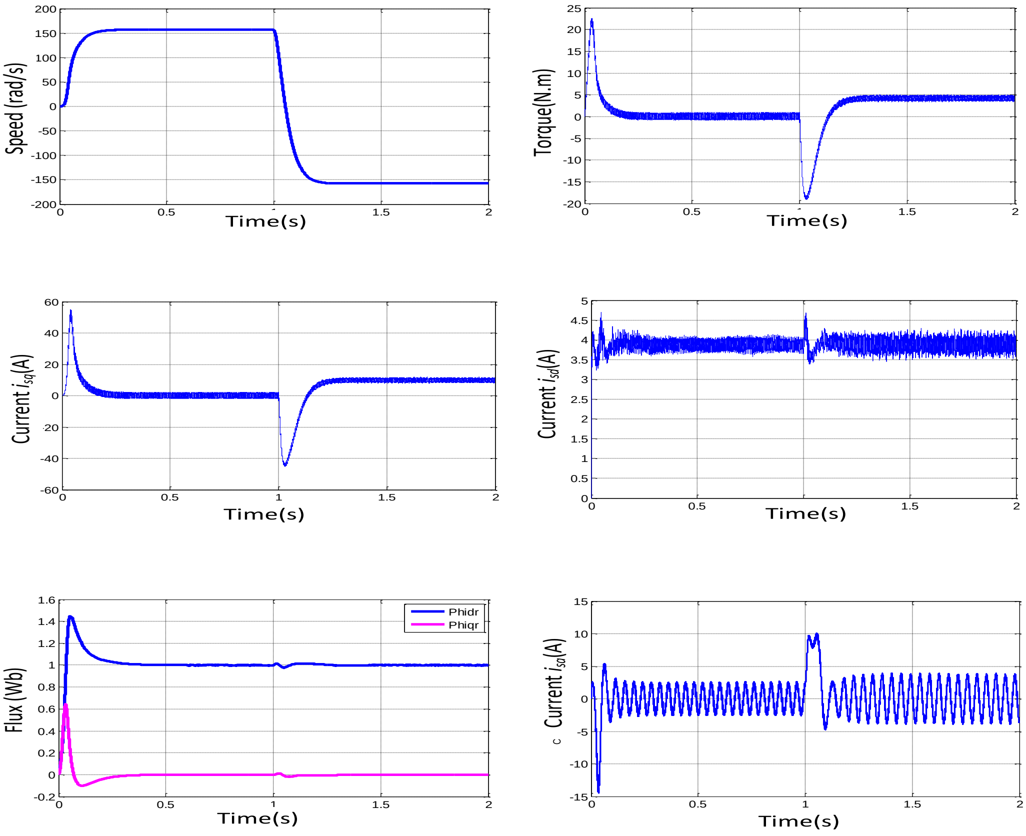


Figure 3. Indirect vector control performance of the five-phase IM with PI regulators in speed reversal

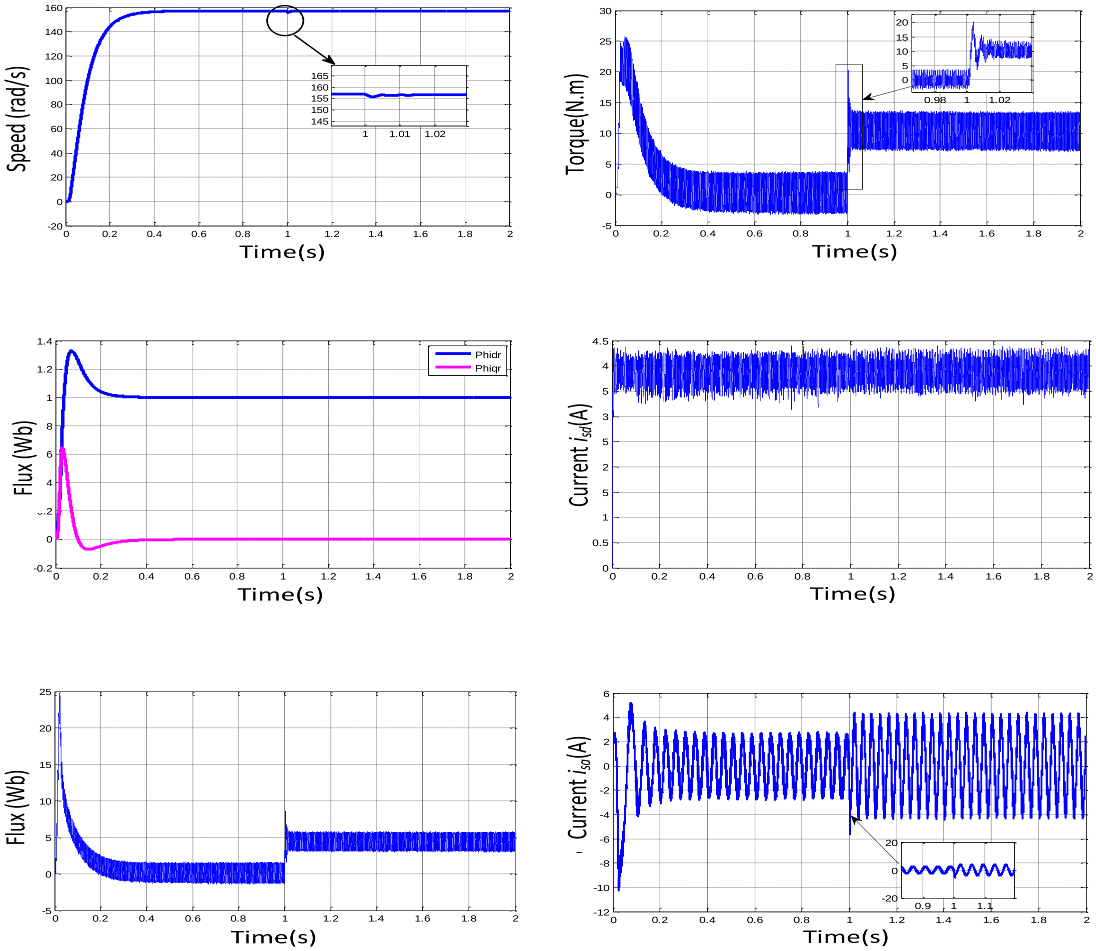
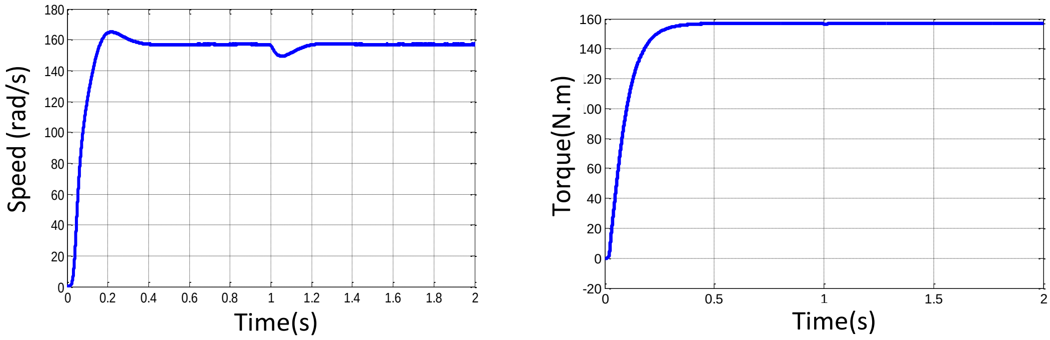


Figure 4. Indirect vector control performance of the five-phase IM with GPC regulators

System Robustness

Variation of Rotor Inertia J=200% Jn



a) b)

Figure 5. Comparison between GPC and PI conventional - a) PI, b) GPC -

Figs. 5, the five-phase an asynchronous IM driver controlled by predictive control and conventional PI of the system under variation of the load and inertial moment (200% J_n). At the bottom of the Fig.5, it shows that with GPC, the process is less disturbed by an external disturbance than by compared to the conventional control (PI). In addition, it is noted that the GPC provides means to better control the transient error due to external disturbance. Finally, the speed response is without overshoot, without static error and with very fast disturbance rejection. Despite internal and external disturbances, the predictive control maintains the desired performance.

Conclusion

A novel approach to preventing five-phase induction motor speed controller saturation during transient periods which are brought on by rapid and significant step changes in the speed reference has been proposed in this study. The machine was then driven using the GPC approach in polynomial form, with an outer machine to regulate speed and two inner ones to regulate currents. The Youla parameterization has been used to fine-tune the outer GPC speed controller in the next stage. The resultant controller has two benefits and maintains the same RST form. In the transient regime without saturation, it may first decrease the current command. Secondly, it maintains the system's temporal response from before the alteration without altering the behavior of disturbance rejection. Simulations support these findings. Predictive control's effectiveness has been evaluated. The simulation's findings demonstrate how resilient GPC is to disruptions brought on by changes in the load and moment of inertia. Despite the disruptions, the speed response accurately adheres to the selected reference model.

Induction Motor Data

Rated power P_n= 3kW, nominal currant I_n= 3.6/6.2A, stator resistance R_s= 2.5Ω, rotor resistance R_r=1.9Ω, stator inductance L_s= 0.24H, rotor inductance L_r= 0.24H, mutual inductance L_m= 0.226H, rated phase stator voltage V_n = 380V, pole pair number P=2, rotor speed N = 1499tr/min, viscous friction coefficient K_f= 0.0006Nms/rad, Rotor inertia J= 0.031kg.m2.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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