The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2023

Volume 26, Pages 295-305

IConTES 2023: International Conference on Technology, Engineering and Science

Generalized Predictive Control of the Active and Reactive Stator Powers of the DFIG for Wind Energy Generation

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Abstract: This paper proposes a Generalized Predictive Control (GPC) strategy for Wind Power Generation (WPG) based on a doubly fed induction generator (DFIG). The objective is to study and apply a robust active and reactive power control strategy based on GPC of the DFIG, this is likely to optimize the energy production and improve the quality of the energy produced. In order to maximize the amount of WPG taken even when the turbine is uncertain or the wind speed varies abruptly, the design is built utilizing the Maximum Power Point Tracking (MPPT) theory. Through numerical modeling with the aid of the Matlab/Simulink software, the predictive control (GPC) of the active and reactive stator powers of the DFIG was validated. A comparison between the GPC of the GADA and the indirect method based on a typical PI controller is developed in order to illustrate the viability of the suggested method. According to the simulation results of this comparison, the suggested method is viable and has promising results.

Keywords: Generalized predictive control (GPC), Wind power generation (WPG), Doubly fed induction generator (DFIG), Active and reactive power control (ARPC).

Introduction

Energy has become increasingly important throughout time as a result of the urgent need to combat climate change and lessen our reliance on fossil fuels. Hydroelectric power, wind power, and solar power are regarded as substitutes that can fulfil our energy needs. We can benefit from the addition of these energy sources by creating jobs and stimulating the economy, especially in rural and isolated places (VO et al., 2023). Due to the obvious advantages of variable speed wind turbines (VSWT) equipped with a double-fed induction generator (DFIG) compared to other wind turbines based on other electric machines, they have drawn more attention from researchers during the past two decades (Hansen, 2023).

Doubly-Fed Induction Generator (DFIG) or known as the "double-fed asynchronous machine'. The most common arrangement for this machine's wiring is to link the stator directly to the network while feeding the rotor through a controlled power converter. This method is more appealing for all situations where speed variations are constrained to those around synchronization. The main benefit of this machine is that the system's power converter only needs to handle 20–30% of the total system power (Mellah & Hemsas, 2012). This means that power converter losses—and hence, production costs—can be minimized in comparison to the converter's ability to handle all power. Additionally, the DFIG in generator mode enables the production of electrical energy at constant frequency and variable mechanical speed. Additionally, she provides a broad operational range in comparison to a squirrel cage induction generator (Cheng & Zhu, 2014; Simões et al., 2015). The interested reader is referred to ref for more information about different WES (Dani et al., 2023).

The advancement of highly integrated digital control systems and the advancement of power electronics have made room for a variety of control strategies (Bektache & Boukhezzar, 2018;Shiravani et al., 2022;Pradhan et al.,2022; Davanipour & Asadipooya, 2017). Among the many control strategies discussed in specialized literature, Field-Oriented Control (FOC) of the DFIG enables the design of alternate-current speed variations that are competitive and while maintaining the efficiency and simplicity of direct current drives (Omac & Erdem, 2023; Prasad & Mulla, 2020). GPC (Shiravani et al., 2022).

However, when really difficult performances are required, conventional control method quickly reveal their limitations. In fact, one of the biggest problems with controlling processes is the presence of delays. These delays are frequently the root of issues that arise during the real time implementation of conventional methods. The idea of predictive control was developed to address this kind of issue (Bektache & Boukhezzar, 2018; Pradhan et al., 2022; Shiravani et al., 2022). We focus on the generalized predictive control (GPC) in this paper.

This paper is structured as follows: the first section provides a general overview of the wind energy conversion systems. In the second section, a modeling study of a DFIG will be presented. The purpose of the study will be to focus on the control of active and reactive power using PI regulators. The third section introduces a fast description of generalized predictive control. In the fourth section we presented some simulations results and we conclude by a conclusion. The third section introduces a fast description of generalized predictive control. In the fourth section, we presented some simulation results and concluded this paper with a conclusion.

Wind Energy Conversion Systems

A device called WECS transforms wind energy into another kind of energy. WECS can be broadly classified into two categories: those that utilize wind turbines to produce energy, which we will discuss later, and those that use windmills to pump water. According to rotational speed control, we can distinguish between two types of WECS: fixed-speed and variable-speed WECS. The first type is called fixed-speed WECS, generally with a squirrel induction generator applied with a gearbox to avoid operation at high wind speeds so as not to damage the turbine.

The second type is called variable-speed WECS, generally with a DFIG or permanent magnet synchronous generator equipped with a power electronic device (Mellah & Hemsas, 2013). Figure 1 shows the WECS based DFIG configuration. Figure 1 shows the WECS based DFIG configuration. We note that there are many ways to get electricity from: marine current (TOLA et al., 2022), ocean wave energy (Rahuna et al., 2023), ocean current energy (Silva et al., 2023).

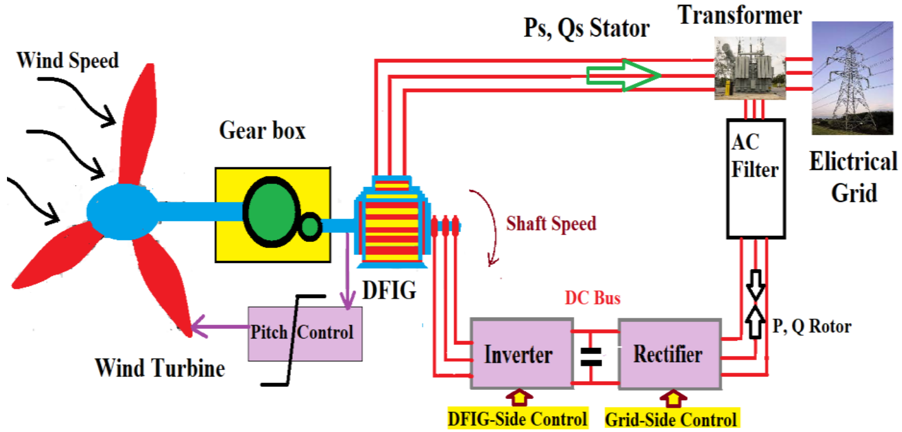

Figure 1. WECS based a DFIG configuration

Modeling of the DFIG

Modeling the electric machine is an essential step in its development. Advances in computer science and software engineering make it possible to carry out efficient modeling and to consider the optimization of electrical machines. The objective of this section is to give a short description of the modeling of the DFIG machine in the frame of reference linked to the rotating field, and it makes it possible to obtain a mathematical model adapted to the decoupled adjustment of the active and reactive powers at the level of the stator of DFIG.

Stator and Rotor Voltage Equations

In the previous conditions, the equations of the mathematical model of the DFIG in matrix form are written:
For the stator:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \Phi_{as} \\ \Phi_{bs} \\ \Phi_{cs} \end{bmatrix} + \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}\begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} \quad (1)$$

For the rotor:

$$\begin{bmatrix} V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \Phi_{ar} \\ \Phi_{br} \\ \Phi_{cr} \end{bmatrix} + \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix}\begin{bmatrix} I_{ar} \\ I_{br} \\ I_{cr} \end{bmatrix} \quad (2)$$

Magnetic Equations

The magnetic equations in matrix form are given by the following expressions:

$$\begin{bmatrix} \Phi_s \\ \Phi_r \end{bmatrix} = \begin{bmatrix} [l_s] & [M_{sr}] \\ [M_{sr}] & [l_r] \end{bmatrix} \cdot \begin{bmatrix} i_s \\ i_r \end{bmatrix} \quad (3)$$

With:

$$[\Phi_s] = \begin{bmatrix} \Phi_{sa} \\ \Phi_{sb} \\ \Phi_{sc} \end{bmatrix} \; ; \; [\Phi_r] = \begin{bmatrix} \Phi_{ra} \\ \Phi_{rb} \\ \Phi_{rc} \end{bmatrix}; [i_s] = \begin{bmatrix} i_{sa} \\ i_{ab} \\ i_{ac} \end{bmatrix} \; and \; [i_r] = \begin{bmatrix} i_{ra} \\ i_{ab} \\ i_{rc} \end{bmatrix}$$

Mechanical Equation

$$C_{e_m} - C_r = j\frac{d\omega_m}{dt} \Rightarrow \omega_m = \frac{1}{j}(C_{e_m} - C_r) \quad (4)$$

Park Transformation

This transformation, which allows the transition from the three-phase system to the two-phase system, is carried out by matching their homopolar, direct and quadrature components to the real variables. and applied to currents, voltages, and flux makes it possible to obtain differential equations with constant coefficients, the following equation represent the voltage equation.

$$\begin{cases} V_d = Ri_d + \dfrac{d\Phi_d}{dt} - \dfrac{d\theta}{dt}\Phi_q \\ V_q = Ri_q + \dfrac{d\Phi_q}{dt} + \dfrac{d\theta}{dt}\Phi_d \\ V_o = Ri_o + \dfrac{d\Phi_o}{dt} \end{cases} \quad (5)$$

The voltage homopolar component is zero for a balanced system. From the above we obtain the following equations:

$$\begin{cases} V_{ds} = R_s i_{ds} + \dfrac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} \\ V_{qs} = R_s i_{qs} + \dfrac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} \\ V_{dr} = R_r i_{dr} + \dfrac{d\Phi_{dr}}{dt} - (\omega_s - \omega_m)\Phi_{qr} \\ V_{qr} = R_r i_{qr} + \dfrac{d\Phi_{qr}}{dt} + (\omega_s - \omega_m)\Phi_{dr} \end{cases} \quad (6)$$

Park Transformation Applied to the Flux

We apply the Park transformation, then we eliminate the homopolar component, and we obtain:

$$\begin{bmatrix} \Phi_{ds} \\ \Phi_{qs} \\ \Phi_{dr} \\ \Phi_{qr} \end{bmatrix} = \begin{bmatrix} L_S & 0 & L_m & 0 \\ 0 & L_S & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} . \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (7)$$

State-Space Representation of the Electrical Equations

After simple mathematical operations, we get the following state space representation of the DFIG model:

$$\dot{X} = \begin{bmatrix} -(\frac{R_S}{\sigma} + \frac{L_m^2}{L_r \sigma T_r}) & (\omega_s) & (\frac{L_m}{\sigma T_r L_r}) & (\omega_m \frac{L_m}{\sigma L_r}) \\ -(\omega_s) & -(\frac{R_S}{\sigma} + \frac{L_m^2}{\sigma T_r L_r}) & -(\omega_m \frac{L_m}{\sigma L_r}) & (\frac{L_m}{\sigma T_r L_r}) \\ (\frac{L_m}{T_r}) & 0 & -(\frac{1}{T_r}) & (\omega_s - \omega_m) \\ 0 & (\frac{L_m}{T_r}) & -(\omega_s - \omega_m) & -(\frac{1}{T_r}) \end{bmatrix} X + \begin{bmatrix} (\frac{1}{\sigma}) & 0 & -(\frac{L_m}{\sigma L_r}) & 0 \\ 0 & (\frac{1}{\sigma}) & 0 & -(\frac{L_m}{\sigma L_r}) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} U \quad (8)$$

Where: $\dot{X}' = [\frac{di_{ds}}{dt}, \frac{di_{qs}}{dt}, \frac{d\Phi_{dr}}{dt}, \frac{d\Phi_{qr}}{dt}]$, X' = [$i_{ds}$, i_{qs}, Φ_{dr}, Φ_{qr}], U' = [V_{ds}, V_{qs}, V_{dr}, V_{qr}], $\sigma = (L_S - \frac{L_m^2}{L_r})$ and $T_r = \frac{L_r}{R_r}$

DFIG Torque

The DFIG electromagnetic torque's expression:

$$T_{e_m} = np.\frac{L_m}{L_r}.(\Phi_{dr} i_{qs} - \Phi_{qs} i_{ds}) \quad (9)$$

So, the mechanical equation becomes:

$$\frac{d\omega_m}{dt} = \frac{1}{j}.[np(\frac{L_m}{L_r}).(\Phi_{rd} i_{sq} - \Phi_{rq} i_{sd}) - C_r] \quad (10)$$

Expressions of Active and Reactive Powers

The expressions of the active and reactive powers are given by:

$$\begin{cases} P_s = \frac{3}{2}(v_{ds}.i_{ds} - v_{qs}.i_{qs}) \\ Q_s = \frac{3}{2}(v_{qs}.i_{ds} - v_{ds}.i_{qs}) \end{cases} \quad (11)$$

Field Oriented Control Strategies

There are two methods for carrying out power control of the DFIG:

-The direct method consists of independently regulating each axis for power control. The regulators of this method directly control the rotor voltages, hence the explicit name of this type of control.
-The indirect method consists of indirectly regulating the rotor currents. The setpoint for this type of regulation is estimated from the reference powers and the feedback to the comparators will be made from the measured direct and quadrature rotor currents.

Direct Vector Control

This method requires a good knowledge of the flux module and its phase; this must be verified whatever the transitional regime carried out. It is therefore necessary to carry out a series of measures available within the process. This control mode is so called because a regulation of the stator flux is introduced by a feedback loop requiring the measurement or estimation of these variations. In its essence, direct vector control must be carried out by measuring the flux which requires the use of the sensor placed in the air gap of the machine, an operation which is generally delicate to carry out.

In order to access information concerning the amplitude and phase of the flux, it is necessary to use “hall effect” sensors previously placed under the teeth of the stator. They are mechanically fragile and cannot work in severe conditions such as vibration and excessive heating. The signals captured are tainted by harmonies and their frequency varies with speed, which requires automatic adjustable filters.

Indirect Vector Control

This method consists of estimating the rotor voltage values from the active and reactive power values. Thus, the rotor currents will be regulated indirectly. This method is so called because it does not use a flux regulation loop, and therefore it does not require the use of the sensor or estimation of the stator flux. In this method the flux vector is estimated from the measurement of the rotor currents and the rotor speed, based on the equations of the rotor circuit of the asynchronous motor in a reference system rotating in synchronism with the vector of the stator flux.

The major disadvantage of this method is the sensitivity of the estimation towards the variation of the machine parameters due to magnetic saturation and the temperature variation especially for the rotor time constant Tr. The control is based on the inversion of the of equation.

$$V_{dr} = (R_r + L_r \delta S) I_{dr} + \frac{MS}{L_s} \Phi_s - W_r L_r \delta I_{qr} \tag{12}$$

$$V_{qr} = (R_r + L_r \delta S) I_{qr} + W_r \frac{M}{L_s} \Phi_s + W_r L_r \delta I_{dr} \tag{13}$$

$$I_{dr} = \frac{\Phi_S}{M} \tag{14}$$

$$I_{qr} = \frac{Cem}{K_t \Phi_s} \tag{15}$$

Indirect Control without Power Loop

The block diagram of indirect control without power loops is presented in Figure2.

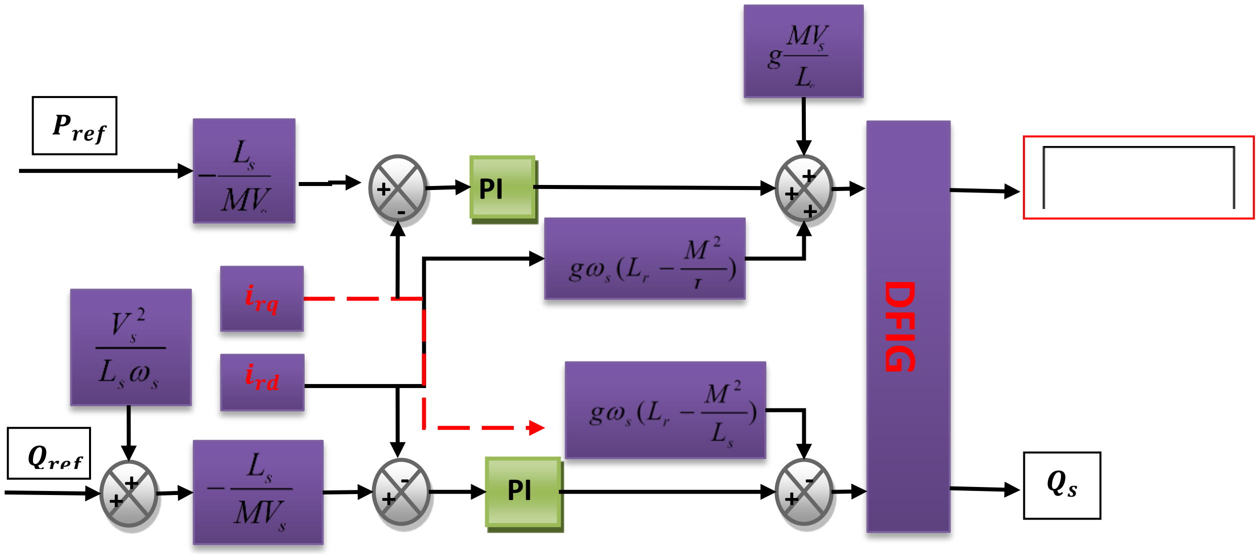

Figure 2. Block diagram of indirect control without power loops

Indirect Control with Power Loop

In order to improve the previous command, we will incorporate an additional regulation loop at the power level in order to eliminate the static error while preserving the dynamics of the system. We arrive at the block diagram presented in Fig.3 on which we clearly distinguish the two regulation loops for each axis, one controlling the current and the other the power.

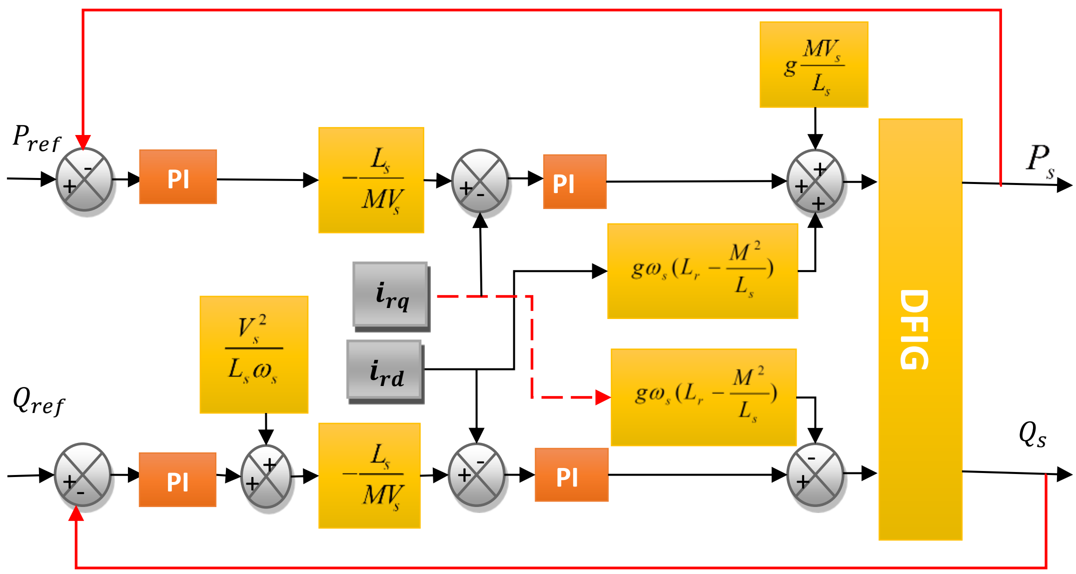

Figure 3. Block diagram of indirect control without power loops

Generalized Predictive Control (GPC)

The GPC was introduced at the end of the 1980s and is regarded as the most widely used prediction method, particularly for industrial processes (Domański, 2020). It is based on the minimization of a quadratically weighted horizon-flying criterion and depends on four parameters: the horizon of the command, the command's horizon and the factor of ponderation. However, the optimal adjustment is not guaranteed, Fig.5 show the diagram of the GPC method principle. The GPC cost function computes the performance by means of predicted errors between the reference output and the output of the system and predicted output increments (Rodrigues et al., 2020) as represented in eq.16, the interested reader is reffred to ref (Clarke et al., 1987a, 1987b)for more information.

$$J = E\left[\sum_{j=N1}^{N2} \left[y(t+j) - w(t+j) \right]^2 + \sum_{j=1}^{Nu} \lambda(j) \left[\Delta U(t+j-1) \right]^2 \right] \quad (16)$$

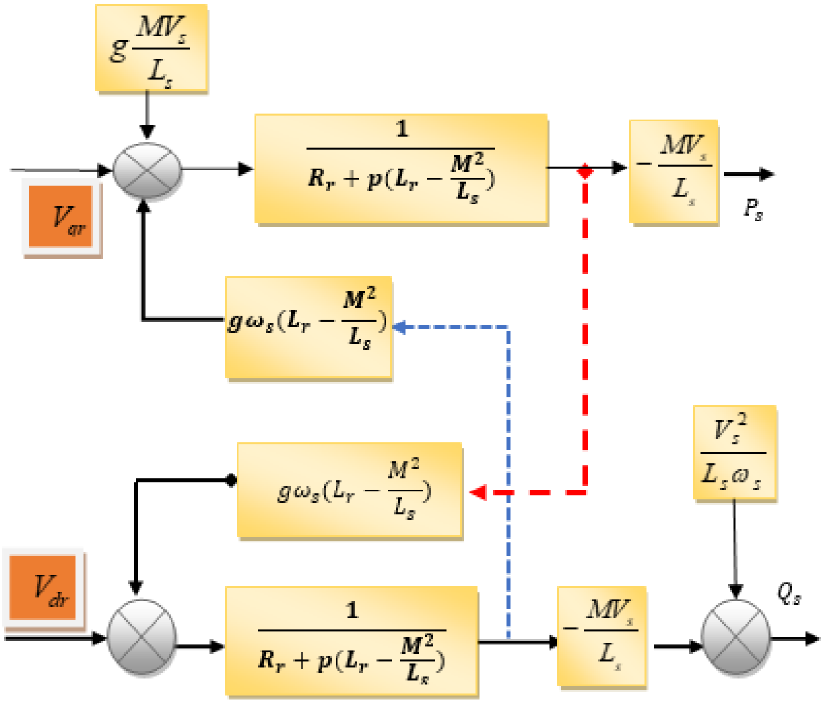

Figure 4. Block schematic of stator active and reactive power as function of rotor current of the DFIG

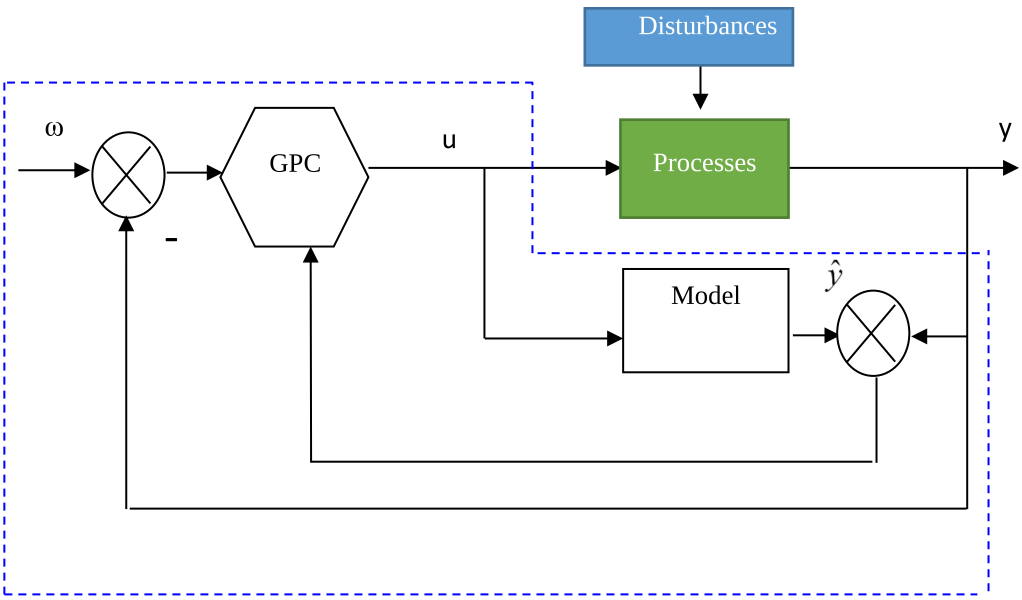

Figure 5. Diagram of the GPC Method Principle

Simulation Results

The generalized predictive control (GPC) of the active and reactive stator powers was validated by numerical simulation in the Matlab/Simulink environment. We used the same specifications for the FOC method. A comparison of the robust predictive control of the DFIG with the indirect method of classic PI is established using the same graph. Figure 6. illustrate the profile of the DFIG's enforced rotational speed.

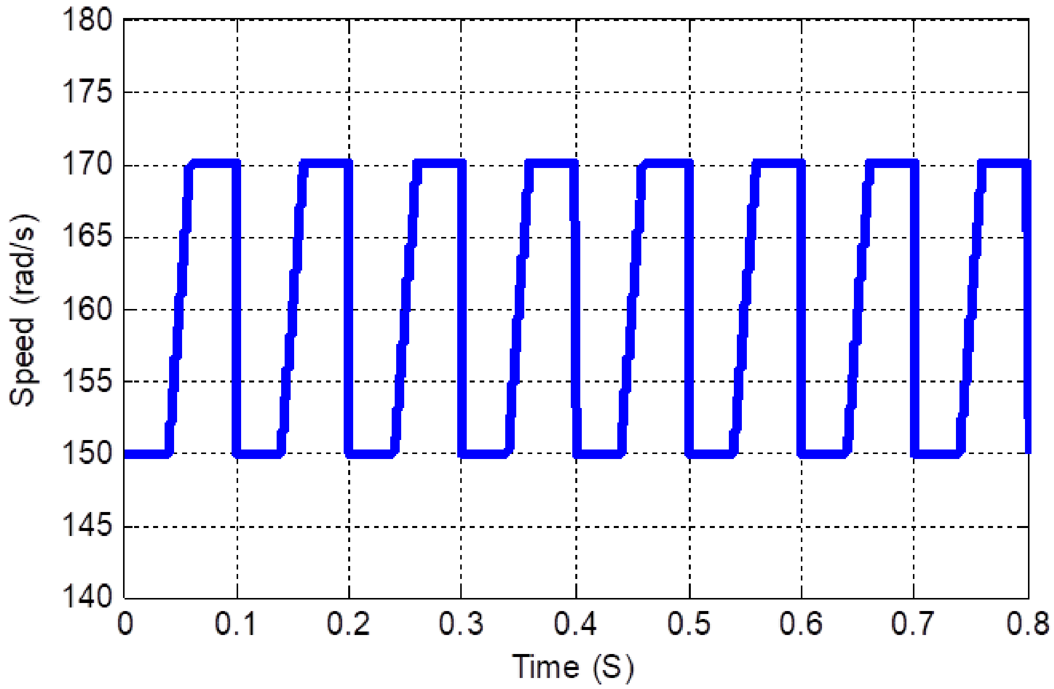

Figure 6. Profile of the DFIG's enforced rotational speed

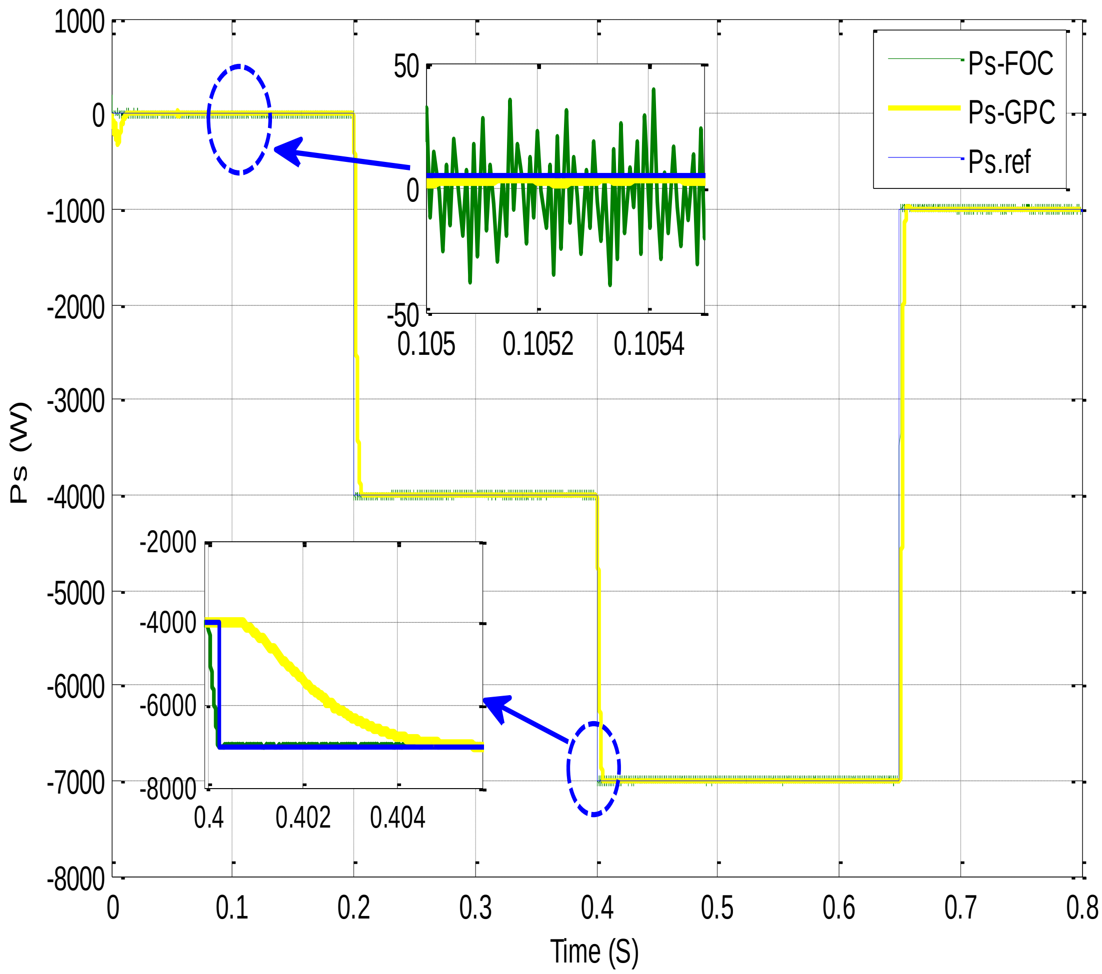

Figure 7. DFIG active power integrated to grid for the both control strategies FOC and GPC under wind variation.

Figure 7 shows the DFIG active power integrated to grid for the both control strategies FOC and GPC under wind variation, and Figure 8 shows the DFIG reactive power integrated to grid for the both control strategies FOC and GPC under wind variation. According to the simulation result, in transient-state, the FOC method quickly reaches the reference compared to the GPC for both powers, unlike in steady-state.

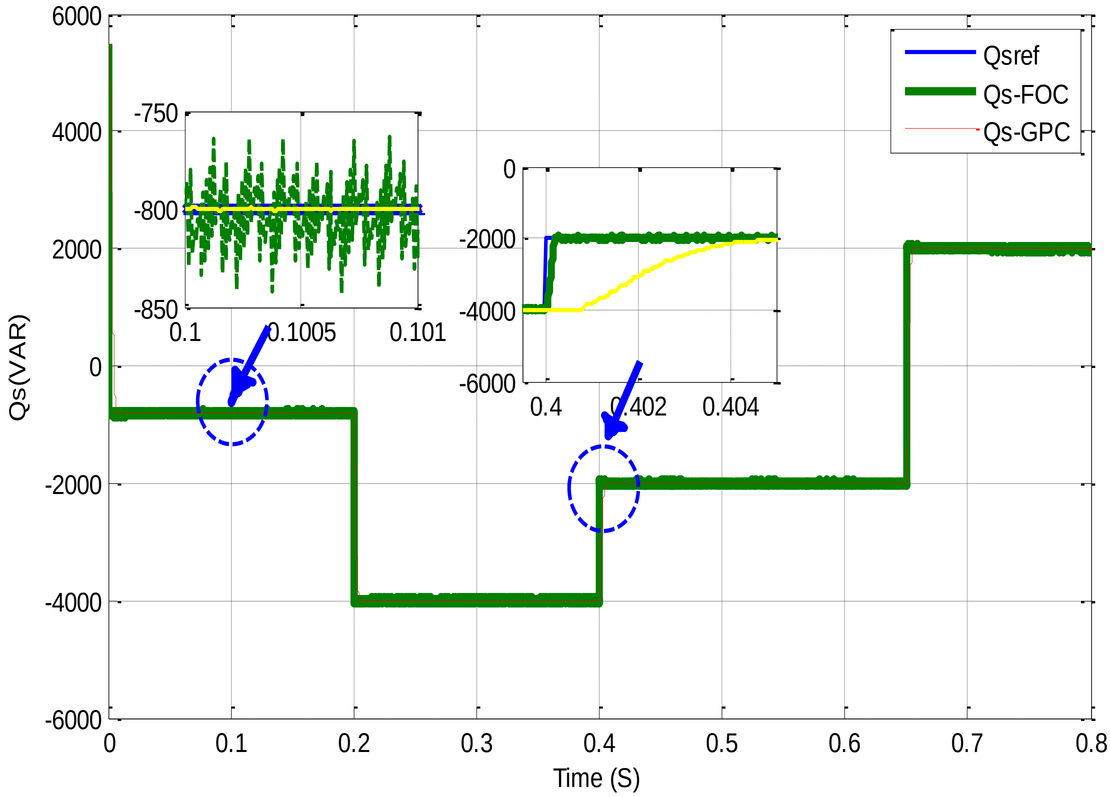

Figure 8. DFIG reactive power integrated to grid for the both control strategies FOC and GPC under wind variation.

Conclusion

In this study, we looked at a generalized predictive control method used with DFIG. We first provided the vector control based on flux orientation, then we used the Park model to represent the DFIG. Perfect understanding of the model of the system that needs to be adjusted is necessary for the vector control of the DFIG using a traditional adjustment method like PI regulators. This method produces control laws whose effectiveness is highly correlated with the accuracy of the dynamic model that characterizes the system's behavior. Since they directly affect the control computation, modelling errors or system parametric fluctuations can worsen the adjustment performance. Next, we looked at DFIG-specific generalized predictive control. According to the simulation results, performance was largely satisfactory throughout the load intervention and setpoint inversion. We produced power controls that are immune to variations in the parameters and demonstrated that adjusting the regulator's design and adjustment parameters can enhance the control process's output performance. As a result, the way the system behaves is determined by these factors. However, determining the ideal values for these factors is not always simple.

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

* This article was presented as an oral presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Turkey on November 16-19, 2023.

*The authors would like to thank the MESRS (Ministère de l'enseignement supérieur et de la recherche scientifique), Algeria. We also would like to thank the University of Bouira and Bouira and Hassiba Benbouali de Chlef for their assistance.

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To cite this article:

Mellah, H., Maafa, A., Sahraoui, H., Yahiou, A., & Smail, H. (2023). Generalized predictive control of the active and reactive stator powers of the DFIG for wind energy generation. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 26*, 295-305.