

Article

Design of Vector Control Strategies Based on Fuzzy Gain Scheduling PID Controllers for a Grid-Connected Wind Energy Conversion System: Hardware FPGA-in-the-Loop Verification

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Abstract: This paper presents a hardware implementation upon a Field Programmable Gate Array (FPGA) of improved Vector Control Strategies (VCSs) based on a Fuzzy Logic System (FLS) of a grid-connected wind energy conversion system. Usually, the classical VCS is based on fixed-gain Proportional Integral Derivative (PID) controllers, which are known to exhibit limited performance against the nonlinear behavior of wind systems, such as rapid fluctuations of the wind speed and uncertainties of the system parameters. In order to overcome this limitation, an improved VCS based on Fuzzy Gain Scheduling PID controllers (VCS-FGS-PID) is suggested in this work to guarantee good tracking, high accuracy and good robustness under system parameter variations. Indeed, the PID controller gains are tuned, in real-time, by the FLS. In addition, the proposed VCS-FGS-PID methods are implemented on the FPGA in order to reduce the delays and the period of the system of the control loop, thanks to its parallel processing. In fact, the performance of the suggested VCS-FGS-PID approaches are proved by digital simulation with the Xilinx system generator tool under Matlab/Simulink, in addition to an experimental hardware-in-the-loop implementation using the FPGA. The obtained results demonstrate that the proposed VCS-FGS-PID techniques offer better performance as regards good tracking and high accuracy and good robustness against stator resistance variability compared to VCS-PI.

Keywords: wind energy conversion system; fuzzy logic; Xilinx system generator; field programmable gate array; proportional integral derivative controller



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1. Introduction

The rise in global electrical energy demand and the depletion of fossil energy sources has led to an urgent need for renewable energy sources. The development and optimization of renewable energy technologies, such as solar, wind and hydropower, has emerged as a viable solution. In particular, several studies have focused on using remote sensing data to assess land cover changes and their impact on ecosystem services [1–3]. Geospatial analysis has also been utilized to enhance precision agriculture and optimize animal husbandry practices [4,5]. Additionally, climate change impacts on various sectors, including agriculture and animal production, have been investigated through the integration of remote-sensing, geospatial and modeling approaches [6,7]. These efforts have led to

improved understanding of environmental processes and informed decision-making for sustainable resource management. Hence, integrating the power grid of renewable energy sources such as Photovoltaic (PV) and wind energy has become a relevant solution [8]. To solve the issues of global warming as well as greenhouse gas emissions, the energetic transition should pass through the multiplication of installations of PV and wind generators [9]. Today, the electricity flow produced by renewable energy sources, such as PV and wind sources, is considered an important alternative solution to compensate the increase in electricity demand [10].

For the last few years, wind turbine technologies have generally featured novel construction, performance and operation aspects. Currently, the variable-speed Wind Energy Conversion System (WECS) is the most used. It has been given significant consideration, and its extent of cross-country energy has risen more quickly in the last few decades. Indeed, compared to fixed-speed WECSs, the variable-speed WECS features some advantages such as reduced mechanical stress, good quality of the produced electrical energy and the existence of a maximum power point with a variable position that depends on wind speed [11]. Despite the benefits of variable-speed WECSs that are based on a Permanent Magnet Synchronous Generator (PMSG), the main problem of this wind system consists of wind speed fluctuations. Power generated from the WECS is directly proportional to the wind profile. As a result, a small variation in the wind speed has a big impact on the extracted power. In fact, the latter is inconsistent with the power grid for the reason that the grid voltage should have an acceptably stable amplitude and frequency. A wind turbine is an intermittent power source that can cause fluctuations such as communication delays and cyber-attacks in the power demand and frequency of the power system. Any change in the power requirements of the grid can cause deviations from the nominal frequency, leading to potential damage to the devices connected in the grid. However, in order to improve the stability and reliability of power systems, much effort has been devoted to studying them [12–14].

Recently, PMSGs have been progressively used for variable-speed wind turbines given their good performance, high efficiency, high-power density, low heat generation and small size. The wind turbine is connected to the power grid by the use of one power electronic interface and one Resistor-Inductor (RL) filter. The power electronic interface is made up of an Alternative Current (AC)/Direct Current (DC) rectifier, a DC/AC inverter and a common DC bus, which are controlled by two vector control strategies. Thus, determining adequate control strategies is a very important aspect of this system. Generally, the most known control technique is the conventional Vector Control Strategy integrating a control loop based on Proportional Integral (VCS-PI) controllers or Proportional Integral Derivate (PID) controllers [15]. A PID controller can be used to control some aspects of a nonlinear system, especially if the nonlinearity is small or can be approximated by a linear model over a certain operating range [16,17]. In this case, a PID controller can be used to control the system within that range, and the control performance will be acceptable. Indeed, PI and PID controllers are more suitable for linear systems, but these controllers can be utilized for controlling nonlinear systems such as electrical machines, wind turbines, etc. [18–21]. However, WECSs based on PI or PID controllers provide poor performance in terms of tracking, accuracy and robustness since they are exposed to various internal and external disturbances, such as fluctuations in the wind speed, changes in the turbine blade angle, variations in the generator speed and changes in the stator resistance due to temperature variations or other factors [22,23]. Consequently, the linearity of VCS-PI controllers is not designed to withstand the complex nonlinear behavior of WECSs, since the inadequate choice of the controller gains can lead to the instability of the system [24].

Therefore, the VCS of the WECS is usually based on a Proportional Integral (PI) controller for controlling the generator currents, the grid currents and the DC voltage [25]. Furthermore, the linear PI controller cannot be adequate against parameter variations and external disturbances [26], which consequently affect the tracking accuracy, stability and

dynamics of the controlled system [27]. Thus, the negative effects of these disturbances cannot be mitigated utilizing the VCS-PI controllers with fixed gains [27].

As the WECS is a non-linear system, a well-developed non-linear controller can overcome the limitations of PI and PID controllers and achieve superior control performance in the face of uncertainties and external disturbances [28]. Researchers have proposed various advanced non-linear control techniques for the variable-speed WECSs in recent years, including back-stepping-based control [29], adaptive control [30], predictive control [31], intelligent control based on artificial neural networks and fuzzy logic systems [32–36] and Sliding Mode Control (SMC) [25,37,38]. SMC has been deemed the most suitable control method for the WECS because of its strong robustness. However, the primary drawback of first-order SMC is the chattering phenomenon, which causes high oscillations around the equilibrium point and vibrations in the electrical machines and mechanical parts of the system due to the discontinuous nature of the control action [39,40]. This issue has led to SMC's rejection by designers for certain industrial applications. Therefore, various improvement studies have focused on reducing chattering, which is considered the main issue of SMC. Saturation or sigmoid functions can be used instead of the discontinuous control action to attenuate chattering, ensuring continuous control. However, this control law drives the system state trajectories towards the sliding surface's vicinity rather than towards the sliding surface itself, affecting control robustness under disturbances [41,42]. In addition, the higher-order sliding mode algorithm is deployed in order to reduce the chattering phenomenon. However, this method requires higher-order real-time derivatives of the outputs [43]. In [25], the authors put forward an SMC for a grid connected to a WECS based on a PMSG. Indeed, the SMC was suggested to replace the PI controllers used in the wind generator control strategies. The SMC would offer good performance in terms of stability, good dynamic and fast response, but it would cause high oscillations in the electromagnetic torque, the quadratic stator current, the direct grid current and the injected active and reactive power. In [30], the authors proposed a Classical Tip Speed Ratio technique with PI (CTSR-PI) controller for a wind turbine generator. The performance of the CTSR-PI controller was tested using simulation studies, and it offered good performance in terms of dynamic response and under wind condition variations, but it had limitations such as poor tracking accuracy. In the same context, the authors put forward Adaptive Control Tip Speed Ratio Integral Backstepping (AC-TSR-IBS) in order to overcome the limitations of the CTSR-PI controller, but its performance was not evaluated under parameter variations. In [44], the authors suggested a Neuro Second-Order SMC (SOSMC) technique based on artificial-neural-network controllers with Fuzzy Space Vector Modulation (NSOSMC-FSVM) to control the reactive and active power of the doubly fed induction generator. These controllers were compared with the SOSMC-control-based traditional space vector technique, and the performances of the two controllers were tested with simulation studies. The NSOSMC-FSVM offered good performance compared to SOSMC in terms of robustness under wind condition variations and tracking accuracy, but it had limitations such as the complexity of algorithm implementation. Moreover, the implementation of large neural networks required an important processing time. In addition, the SOSMC needed information about the sliding surface and its derivate [45]. In [46], the authors proposed two neural networks to automate the tuning of PID parameters; the creation of the data took approximately 120 h to generate million samples of data. It spent a significant amount of time training, which made the implementation in real-time more complex.

Moreover, combining fuzzy logic technology with a PI controller can guarantee tracking quality even with high model uncertainties. In [47], the authors comparatively studied PI linear and fuzzy logic controllers for an active grid-interfacing inverter in order to compensate the harmonic produced by the nonlinear system. The harmonics induced by the PI controller were high when compared to the FLC-based controller. In fact, fuzzification can help mitigate the effect of nonlinearities and disturbances in several ways [48]. Firstly, it allows for the representation of complex nonlinear relationships between the

input and output variables. This means that the control system can handle nonlinearities that may be difficult to model using traditional control methods. Secondly, fuzzification allows handling uncertainties and imprecise information. In traditional control systems, uncertainties and disturbances can cause the system to behave unpredictably. Fuzzy logic can handle uncertainties by representing the input and output variables as fuzzy sets, which allows for reasoning with degrees of membership. Finally, the FLC can adjust the controller parameters dynamically based on the changes in the input signals. Fuzzy rules can be designed to modify the control output based on the magnitude and direction of the disturbance, which can reduce the sensitivity of the control system to external disturbances. Fuzzy Gain Scheduling (FGS) combined with PID control is a powerful method for controlling complex and nonlinear systems such as the WECS. Fuzzy logic allows the controller to adapt in real-time to changing operating conditions, which is critical for ensuring the optimal performance and stability of the system [48].

In this context, the first contribution of this paper consists of combining Vector Control Strategies with FGS based on a PID (VCS-FGS-PID) to control higher performance of a grid-connected WECS. The control system is divided into three parts: (i) VCS-FGS-PID for the PMSG-side converter, (ii) VCS-FGS-PID for the grid-side converter and (iii) a FGS-PID for regulating the DC bus voltage. The VCS-FGS-PID for the PMSG-side converter consists of controlling the electromagnetic torque, the PMSG speed, the quadratic stator current and the direct stator current. It uses the electromagnetic torque reference as an input, which is generated by a Maximum Power Point Tracking (MPPT) algorithm. Moreover, the VCS-FGS-PID of the grid-side converter is used for controlling the active and reactive power injected to the grid. It is also used to adjust the voltage and frequency in order to achieve a satisfactory level of security of the power system. The FGS-PID is suggested in this paper thanks to its robustness under external disturbances such as sudden wind speed variations and internal disturbances. As an advanced approach, the VCS-FGS-PID approach is distinguished by its good performance under the aforementioned disturbances. This is done in real-time by tuning gains of PID controllers [47]. The aforementioned three parts of the control system, which are designed and implemented in hardware using a Field-Programmable Gate Array (FPGA), differ from other published work.

Currently, the control algorithms of electrical systems are implemented usually on two programmable-technology types: FPGAs and Digital Signal Processing (DSP). The DSP has a limiting factor of short execution time, and this is because of the control algorithm's serial processing. In order to overcome the limitations of DSP, FPGAs can be considered a preferred solution. The benefits of using hardware FPGAs are multiple: (i) rapid prototyping, (ii) reduced execution time due to parallel processing and (iii) ability to use too-heavy control methods as regards computing time [49]. Thus, FPGAs have been used in varied research work [49–52]. Two main methods have been used to implement control algorithms on FPGAs, namely the Xilinx System Generator (XSG) and programming Very-high-speed integrated circuit Hardware Description Language (VHDL) [53–56]. For the suggested control algorithm, a VHDL code is generated by the XSG tool. The XSG tool is chosen because it is flexible, simple and rapid.

Within this framework, the second contribution of this paper is to design, with the XSG, and implement, on an FPGA board of the suggested VCS-FGS-PID algorithm for the PMSG-side converter, the suggested VCS-FGS-PID of the grid-side converter and the FGS-PID for regulating the DC bus voltage. Concerning the WECS, it is composed of a wind turbine that derives a PMSG and is connected to the power grid via an RL filter and a power electronics interface containing two converters interconnected by one common DC bus. The novelty and the main contributions of this paper theoretically, by simulation and by hardware in the loop co-simulation, are as follows:

- (i) Robust VCS-FGS-PID approaches are proposed for controlling the electromagnetic torque, the stator current's quadratic component, the DC injected into the grid, the active and the reactive power injected into the grid and the DC bus voltage. The suggested approach can ensure good performance in terms of tracking and accuracy, as well as high robustness under stator resistance variations. The proposed control strategies will guarantee excellent robustness under stator resistance variations and good tracking accuracy of the controlled variables even under high fluctuations of the wind speed;
- (ii) The algorithms of the suggested VCS-FGS-PID and the FGS-PID of DC bus voltage are designed utilizing the XSG tool in order to verify the WECS behaviors via simulation and to automatically generate a VHDL code;
- (iii) A real Hardware co-simulation of the suggested VCS-FGS-PID algorithms using an FPGA Zed-Board AES-Z7EV-7Z020-G is carried out before the final experimental validation step in order to avoid damage risks and guarantee the experimental operation. It also reduces the overall time allowed for the experimentation, the prototyping time, the time to market and the designed system cost.

The rest of the article is organized as follows. The various system elements are modeled in Section 2. In Section 3, the conventional VCS-PI and the VCS-FGS-PID are discussed to ensure robust control of the WECS. The FPGA hardware architecture of the VCS-PI and the proposed VCS-FGS-PID, as well as their synthesis and implementation, are described in Section 4. In Section 5, the two control methods are implemented and simulated under the XSG, and a comparison between both controllers with and without parameter variations is presented, followed by a comparison with other studies. Finally, Section 6 concludes this work and opens new perspectives.

2. Description and Modeling of the WECS

In this study, a variable-speed grid-connected WECS is presented. It is composed of a wind turbine as a main source that derives a PMSG. The power grid is linked to the WECS through an RL filter and a power electronic interface. The power electronic interface is made up of a three-phase rectifier (converter 1 AC/DC) and an inverter (converter 2 DC/AC) interconnected by a common DC bus, as depicted in Figure 1. The RL filter is utilized for reducing the inverter harmonics in its output power.

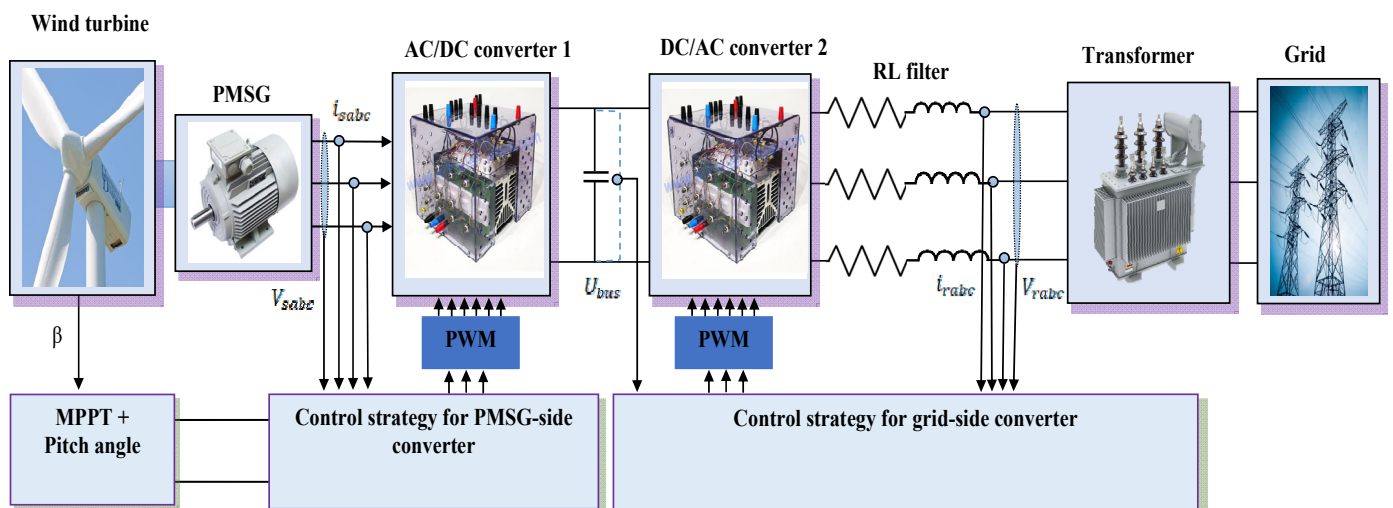


Figure 1. WECS architecture.

2.1. Wind Turbine Modeling

The wind turbine captures the aerodynamic power P_{aer} , as described in (1) [57]:

$$P_{aer} = C_p P_w = \frac{1}{2} C_p(\lambda, \beta) \rho A V_v^3, \quad (1)$$

where ρ denotes air density (kg/m^3), $A = \pi R^2$ represents that area swept by the blades of the wind turbine (m^2), V_v is the wind speed (m/s), β denotes the blades' pitch angle ($^\circ$), λ represents the speed ratio and C_p is the power coefficient.

As a function of the aerodynamic power, T_{aer} is the wind turbine's aerodynamic torque expressed as follows [23]:

$$T_{aer} = \frac{P_{aer}}{\Omega_{mec}}, \quad (2)$$

where Ω_{mec} is the wind turbine's rotational speed (rad/s).

The C_p power coefficient indicates the wind turbine's characteristics, and its effectiveness can be expressed in terms of orientation angle and λ speed ratio of blades β as follows [23]:

$$C_p = 0.5 \left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 10 \right) e^{-\frac{18.4}{\lambda_i}}, \quad (3)$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1}}. \quad (4)$$

The ratio between the wind speed and the blade speed defines the tip speed ratio λ as follows:

$$\lambda = \frac{\Omega_{mec} R}{V_v}. \quad (5)$$

The wind turbine is controlled with the aim of extracting the maximal available wind power. Based on Betz theory, the power coefficient should not exceed 0.593 (Experimentally) [57].

Finally, the diagram in Figure 2 summarizes the wind turbine model. The inputs are the pitch angle β , the wind speed V and the electromagnetic torque. The output is the mechanical speed.

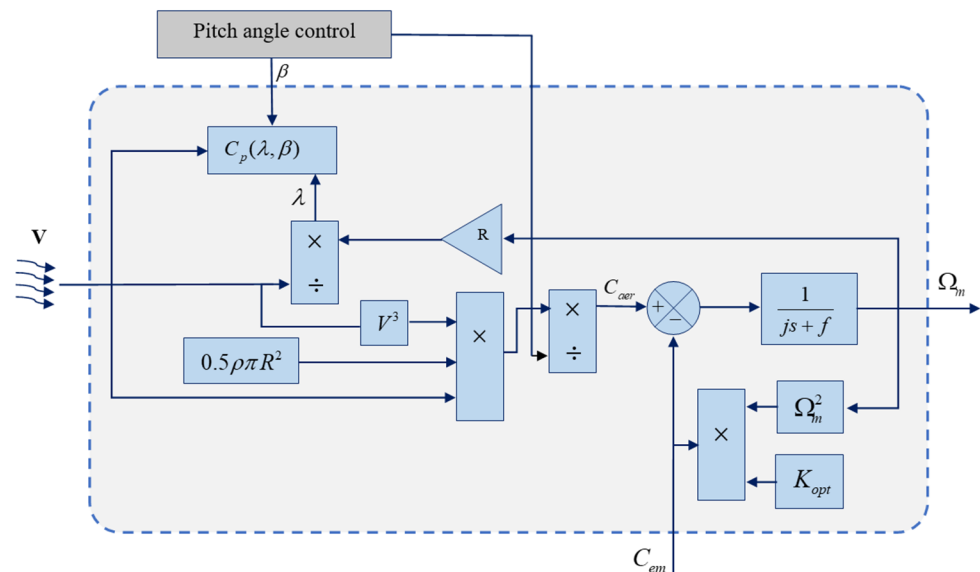


Figure 2. Diagram of wind turbine model.

Figure 3 depicts the C_p variation concerning λ and β , which presents the optimal value of the $\lambda_{opt} = 8.15$ speed ratio, corresponding the maximal value of the $C_{pmax} = 0.4794$ power coefficient, with $\beta = 0$. In view of this fact, Equation (6) gives the maximum power that we can obtain through the MPPT algorithm [25]:

$$P_{MPPT} = \frac{1}{2} \frac{\rho C_{pmax} R^5 \Omega_{mec}^3}{\lambda_{opt}^3} \quad (6)$$

$$T_{em_{MPPT}} = \frac{1}{2} \frac{\rho C_{pmax} R^5 \Omega_{mec}^2}{\lambda_{opt}^3}.$$

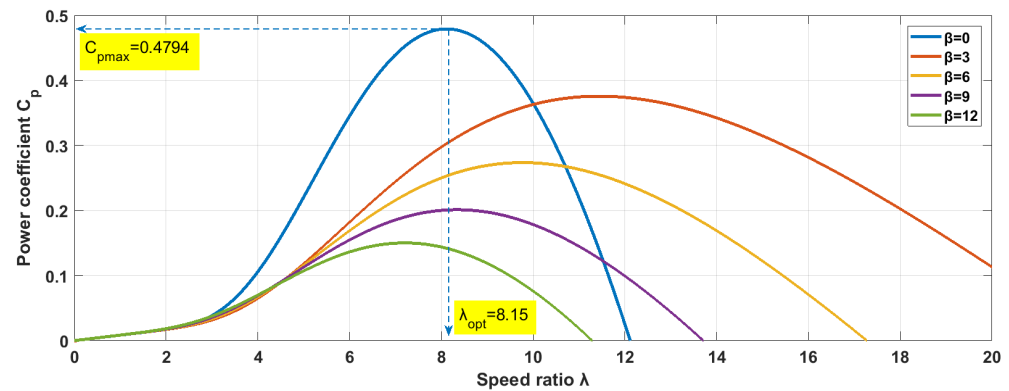


Figure 3. C_p versus λ .

To recuperate the maximum amount of the available kinetic wind power, the blade pitch angle is zero, which corresponds to optimal C_p and λ values for the operation in an MPPT mode. However, it is important to limit the turbine's rotational speed in case the wind speed exceeds the nominal speed to protect the system from mechanical problems. In this work, the control system, called "pitch control", should be added to jointly control the speed as well as the power of the wind turbine and necessarily limit them once the rated value of the wind speed is exceeded. Figure 4 describes the pitch control system operation.

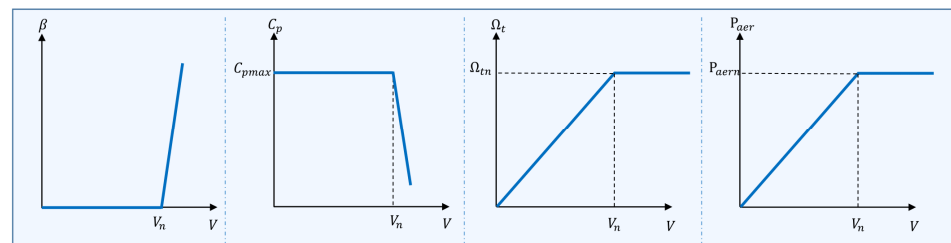


Figure 4. Evolution of different wind turbine characteristics.

2.2. Interest of Variable Speed

The WECS's variable speed is plausible because of the interface of power electronic converters, which allows for the partial or complete decoupling—with the power grid—of wind generators. The available power is given by all characteristics that concern the generator's rotational speed. Figure 5 illustrates the varied wind speed. Accordingly, when we drove the generator at a fixed speed, we could not exploit any theoretical maximum power curve. That is why, for optimizing the operating point, the generator shaft's rotation speed must be adjusted by the extracted power depending on the wind speed. Let point A for wind speed V_2 correspond to the aerodynamic power peak of coordinates $(P_1, 1)$. If the turbine speed is not basically altered and if the wind speed changes from V_2 to V_3 , power P_2 becomes in another point B other than the peak of the second characteristic. To extract the maximum power, the generator speed needs to be different from the other rotation speed which is larger compared to the previous one, thus requiring varying this rotation speed as a function of the wind in order to reach the maximum power (point C).

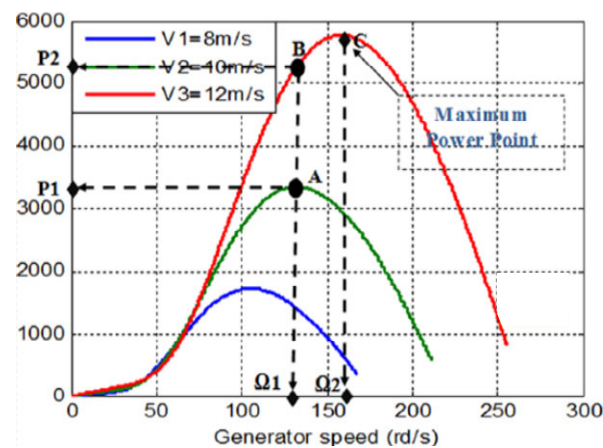


Figure 5. Aerodynamic power for different wind speed values as a function of mechanical speed.

2.3. Modeling of PMSG and Connection with Power Grid

We connected the wind turbine to the PMSG to transform mechanical energy into electrical energy. This PMSG is modeled in the d - q frame as follows [58]:

$$\begin{cases} V_{sd} = R_s i_{sd} + L_{sd} \frac{d}{dt} i_{sd} - \omega L_{sd} i_{sq} \\ V_{sq} = R_s i_{sq} + L_{sq} \frac{d}{dt} i_{sq} + \omega (L_{sq} i_{sd} + \varphi_m) \\ T_{em} = p \varphi_m i_{sq} \end{cases} \quad (7)$$

where R_s is the stator resistance, L_s is the stator inductance, p represents the pole pair number, φ_m denotes the permanent magnet flux (Wb) and ω is the electrical speed.

To connect the wind generator to the power grid, a three-phase RL was used before a transformer. The expressions in the d - q frame model are (8) [23]:

$$\begin{cases} L_r \frac{d}{dt} i_{rd} = V_{id} - R_r i_{rd} + L_r \omega_R i_{rq} - V_{rd} \\ L_r \frac{d}{dt} i_{rq} = V_{iq} - R_r i_{rq} - L_r \omega_R i_{rd} - V_{rq} \end{cases} \quad (8)$$

where ω_R is the grid frequency, R_r is the grid resistance, and L_r is the grid inductance.

3. Control Strategy of the WECS

This work aims to present VCS-FGS-PID controllers for the power-grid-connected variable-speed WECS. The VCS-FGS-PID control design basically focuses upon tuning the gains of the PID controllers using fuzzy logic technology as a solution to overcome the issues of uncertainties of the system parameters.

3.1. Conventional Vector Control Technique of the WECS

Conventional VCS-PIs are proposed in this part for controlling the WECS. The main objective of these controllers is to prove their sensitivity versus highly enormous ranges of wind speed variations and internal system non-linearities. Indeed, the classical vector control technique is developed to evaluate the main contribution of this work.

The reference currents of this vector control strategy applied to the PMSG, are determined as [25]:

$$\begin{cases} i_{sd-ref} = 0 \\ i_{sq-ref} = \frac{C_{emMPPT}}{\omega \phi} \end{cases} \quad (9)$$

The wind turbine is controlled by the conventional control technique applied for the PMSG to extract the maximal available power. We master the controller on the DC bus voltage to keep its voltage to a fixed value that is totally irrespective of the wind speed variations.

A control vector strategy is applied to converter 2 (DC/AC) as a function of the control of the active power and the reactive one, where both are exchanged with the production system and the power grid. Two control loops are constructed for controlling both elements of currents i_{rd-ref} and i_{rq-ref} . As a consequence, they can regulate the grid connection's active power and reactive power, respectively. Currents i_{rd-ref} and i_{rq-ref} are given by the active and reactive power of references P_r^* and Q_r^* as:

$$\begin{cases} i_{rd-ref} = \frac{P_r^* V_{rd} + Q_r^* V_{rq}}{V_{rd}^2 + V_{rq}^2} \\ i_{rq-ref} = \frac{P_r^* V_{rq} + Q_r^* V_{rd}}{V_{rd}^2 + V_{rq}^2} \end{cases} \quad (10)$$

To ensure the operation of the WECS's unity power factor, the reactive power reference can be fixed to zero ($Q_r^* = 0$). As a result, both active power P_r and reactive power Q_r will be functioning based on the power grid current's direct and quadratic components. The problem in this case is to how to control active and reactive power in a separate way. For this, orienting reference (d, q) is enough for repealing the quadratic ($V_{rq} = 0$) voltage's component. According to this, $V_r = V_{rd}$. Therefore, the connection model with the power grid given by Equation (9) and the references of the power grid current's direct and quadratic components become [25]:

$$\begin{cases} L_r \frac{d}{dt} i_{rd} = V_{od} - R_r i_{rd} + L_r \omega_r i_{rq} - V_r \\ L_r \frac{d}{dt} i_{rq} = V_{oq} - R_r i_{rq} + L_r \omega_r i_{rd} \end{cases} \quad (11)$$

$$\begin{cases} i_{rd-ref} = \frac{P_r^*}{V_{rd}} \\ i_{rq-ref} = 0 \end{cases} \quad (12)$$

The same characteristic variables for every phase must be possessed by the converter output voltage to guarantee that renewable energy generators are properly connected to the power grid. If the voltage phase angle is appropriately adjusted, this effect is attained. The Phase Locked Loop (PLL) is the most typical approach utilized for synchronizing the main energy supply with the grid-side converter outputs. Thus, it is important in this study to construct one PLL (Figure 6) able to correctly analyze a voltage phase angle of one ideal power grid.

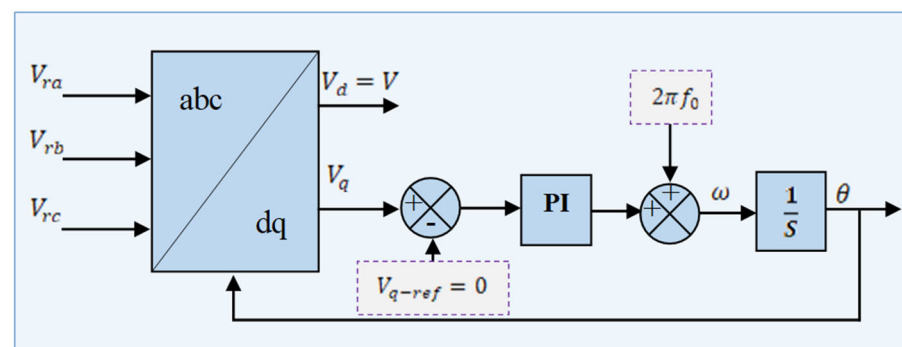


Figure 6. PLL algorithm.

The conventional vector technique control laws of the PI have better results for linear systems having constant parameters. On the other hand, these laws for nonlinear systems such as wind systems are not adequate enough, especially when system accuracy is needed, and other dynamic characteristics will be hard to obtain during wind speed variability [59]. To overcome this drawback, the VCS-FGS-PID controller approach is proposed in this paper.

3.2. Fuzzy Gain Scheduling-PID Controller

The conventional VCS-PI cannot determine the variation in increasing and decreasing errors while only being capable of responding to the immediate error value. Consequently, it is not appropriate for nonlinear systems such as wind generators. The VCS-FGS-PID controllers are proposed to overcome this problem. The structure of this control strategy is detailed in Figure 7.

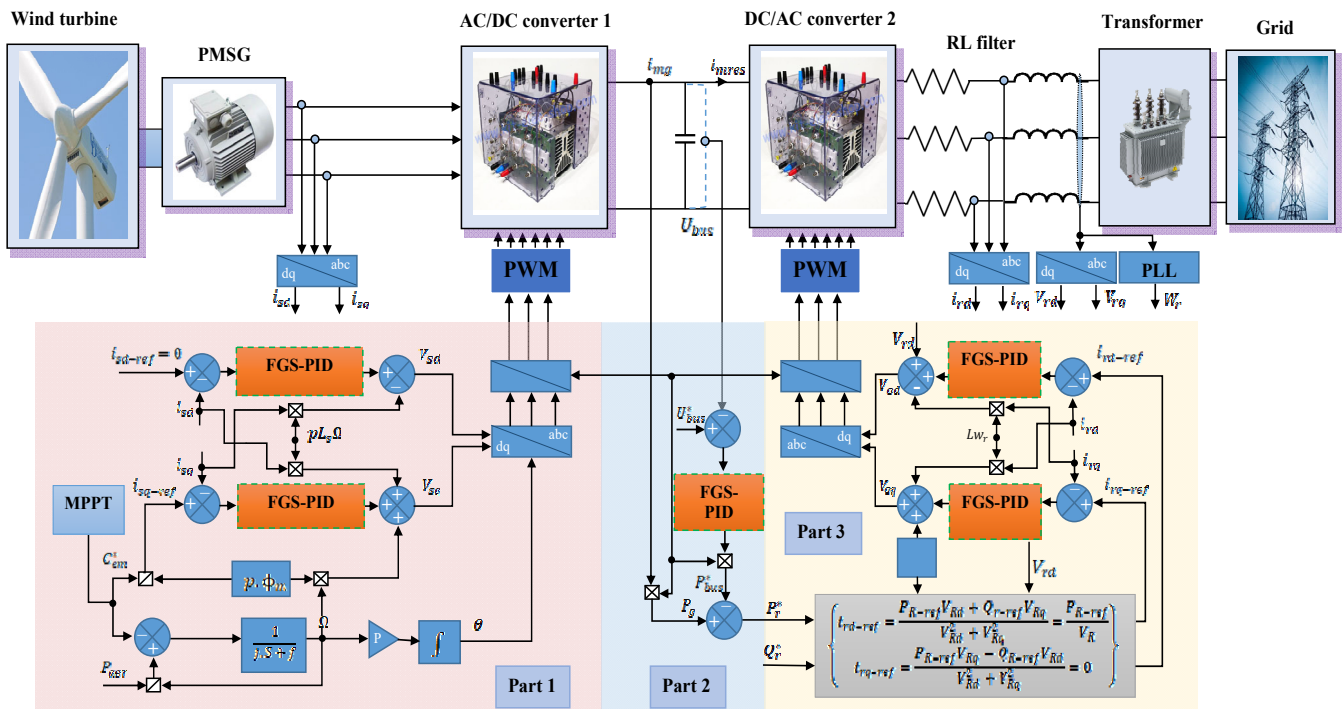


Figure 7. Schematic of WECS VCS-FGS-PID controller.

As shown in Figure 8, the VCS-FGS-PID is based on three steps: fuzzification, inference and defuzzification [60]. Fuzzification is an important aspect of FGS-PID controllers, as it allows them to handle nonlinearities and uncertainties in the system. Fuzzification involves representing the system inputs and outputs as fuzzy sets, which allows the controller to reason about the system in a more flexible and robust way. However, FGS-PID controllers can adjust their parameters in real-time based on the current state of the system, which allows them to handle these nonlinearities and uncertainties more effectively [48].

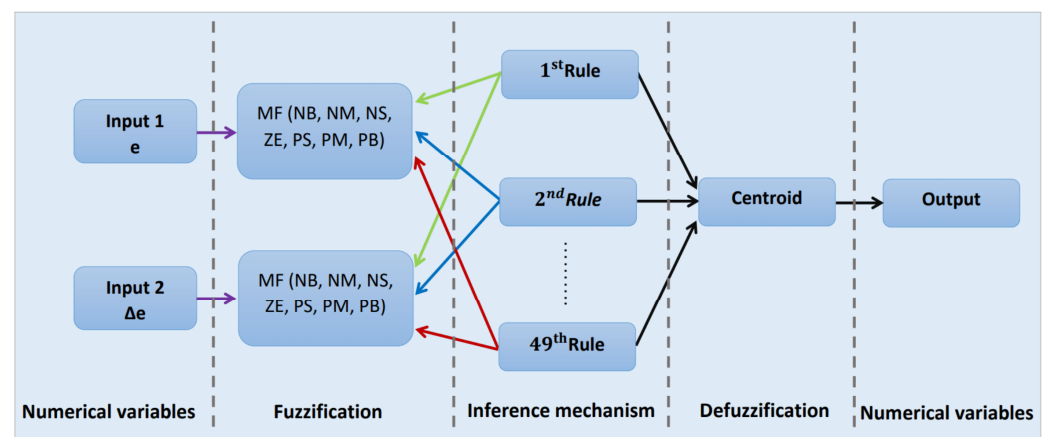


Figure 8. Fuzzy logic controller block diagram.

In comparison with conventional tuning techniques, fuzzy logic tuning does not depend on well-defined or precise mathematical formulas. However, it manipulates inferences through the use of several fuzzy rules based on fuzzy operators: AND, OR, THEN, etc., applied to linguistic variables. This VCS-FGS-PID controller is made up of a conventional PID control system, a fuzzy reasoning mechanism and a set of fuzzy rules, as summarized in Figure 9.

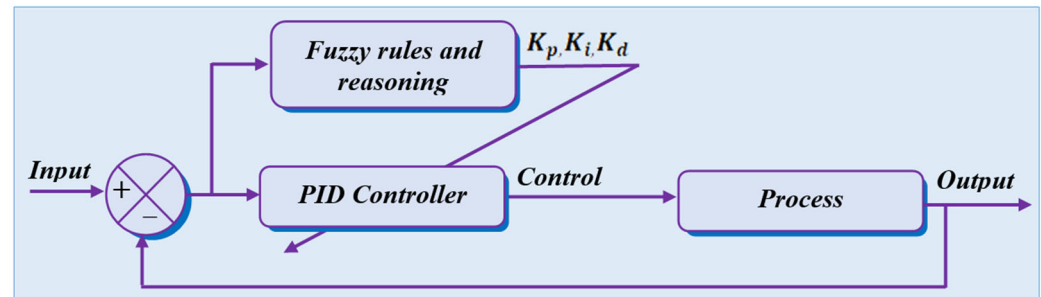


Figure 9. PID control system with fuzzy logic controller.

The PID gains are tuned in real-time as regards the fuzzy inference and the knowledge base. After that, the control signal is generated by the PID controller. The VCS-FGS-PID controller is characterized by three corrective actions, which are K_p , K_d and K_i [56]. We can assume K_p and K_d to be always in the $[K_{pmin}, K_{pmax}]$ and $[K_{dmin}, K_{dmax}]$ range, so that the following equations will be defined as:

$$\begin{aligned} K'_p &= \frac{(K_p - K_{pmin})}{(K_{pmax} - K_{pmin})} \\ K'_d &= \frac{(K_d - K_{dmin})}{(K_{dmax} - K_{dmin})}. \end{aligned} \quad (13)$$

The PID parameters are determined by the proposed scheme according to the current error and its derivate. In fact, the integral time constant is determined as a function of the derivative time constant:

$$T_i = \alpha T_d. \quad (14)$$

Therefore, we can obtain the integral gain as follows:

$$K_i = \frac{K_p}{(\alpha T_d)} = \frac{K_p^2}{(\alpha K_d)}. \quad (15)$$

Once K'_p , K'_d and K_i , α have been determined, the PID controller parameters are determined through the use of Equations (13) and (15):

$$K_p = (K_{pmax} - K_{pmin})K'_p + K_{pmin}, \quad (16)$$

$$K_d = (K_{dmax} - K_{dmin})K'_d + K_{dmin}, \quad (17)$$

$$K_i = \frac{K_p^2}{(\alpha K_d)}. \quad (18)$$

A basic rule to determine the K_p and K_d range is based on extensive simulation research that is performed on various processes, as follows:

$$\begin{aligned} K_{pmin} &= 0.32K_u, K_{pmax} = 0.6K_u \\ K_{dmin} &= 0.08K_u T_u, K_{dmax} = 0.15K_u T_u' \end{aligned} \quad (19)$$

where K_u and T_u denote, at the stability limit, the gain and period of the oscillation, respectively. Figure 10 and Tables 1–3 show the fuzzy controller's membership functions designed with E and dE inputs. The outputs of the fuzzy set are K'_p , K'_d and α . In this case,

we have: PB: Positive Big, PM: Positive Medium, PS: Positive Small, ZO: Zero (zero), NS: Negative Small, NM: Negative Medium and NB: Negative Big.

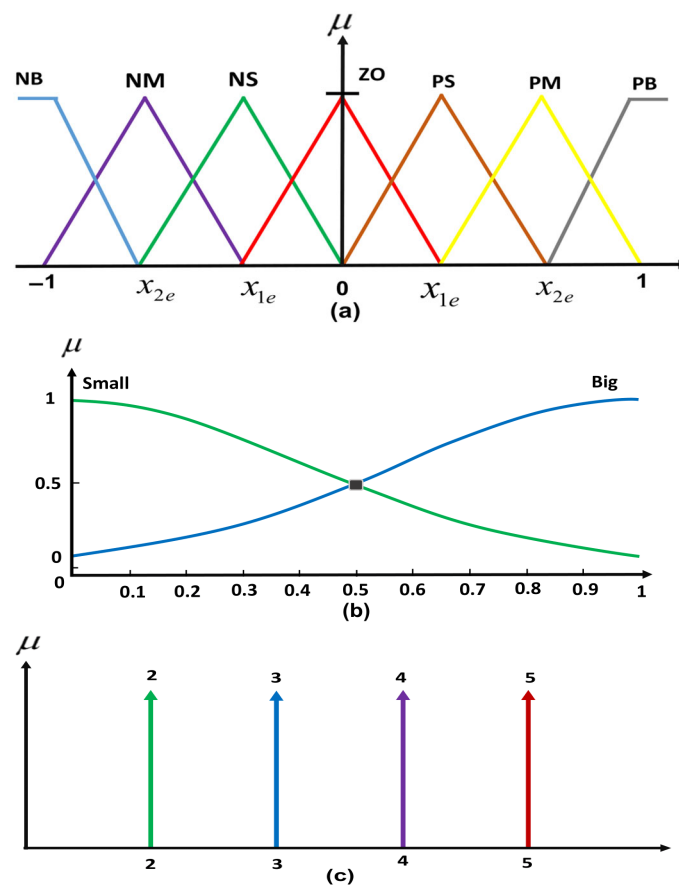


Figure 10. (a) Membership function of E and dE. (b) Membership function of K_p and K_d . (c) Membership function of α Table.

Table 1. Fuzzy tuning rules for K'_p .

		dE						
E	NB	NB	NM	NS	ZO	PS	PM	PB
	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

Table 2. Fuzzy tuning rules for K'_d .

		dE						
E	NB	NB	NM	NS	ZO	PS	PM	PB
	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 3. Fuzzy tuning rules for α .

		dE						
E		NB	NM	NS	ZO	PS	PM	PB
	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

4. Materials and Methods

4.1. XSG Architectures of Control Techniques

Xilinx always provides its designers with tools for the simplification of the digital systems' description phase. In fact, the XSG is a developed and excellent graphics tool for the creation, simulation, verification, implementation and validation of highly performant systems on Xilinx FPGA targets [61]. It is also a modeling tool for designing FPGA-based systems. It features a library of different blocks that may be compiled into an FPGA automatically [62]. The XSG was utilized in this work to design and implement the vector control strategies based on the suggested VCS-FGS-PID of the variable-speed WECS connected to the grid on an FPGA. First, we used the XSG blocks from the Simulink package to implement the recommended architectures. If the designed architecture was verified by digital simulation and achieved the desired results, the VHDL code was generated in an automatic way using the XSG tool [63].

Moreover, the XSG is a system-level modeling tool which smooths the way for the FPGA hardware design. Matlab/Simulink was used for providing a high-level flexible modeling environment well-suited for hardware designs. This tool provides high-level abstractions which can be systematically compiled into an FPGA through the simple use of commands. We created such a system in a Simulink modeling environment using a specific library given by Xilinx. As a matter of fact, the XSG designs data control and data-paths well. To simulate FPGAs, Xilinx provides a "hardware co-simulation" technique for the verification of the system on an FPGA board utilizing the PC. The routing, placement, synthesis and programming file generation steps were performed in a systematic way by the Xilinx Vivado tool. It is shown in Figure 11 that the hardware design flow opted for the XSG. We used in this work a Vivado/XSG 2018.1 version, which works on a Matlab/Simulink 2017b version, our computer GF63 thin 9RCX intel I7-9750H and an FPGA ZedBoard AES-Z7EV-7Z020-G. After designing the system and obtaining necessary simulation results, the bitstream file could be generated following the generation of the VHDL code and synthesis. The configuration files were then used to program the FPGA [63,64].

4.1.1. Designed Architecture of VCS-PI Using XSG

The PI control used is mathematically expressed by (20) [60]:

$$G_c(s) = K_p \left(1 + \frac{1}{T_i s} \right), \quad (20)$$

where $T_i = \frac{K_p}{K_i}$, and K_p and K_i are the proportional and integral gains, respectively.

Figures 12–14 present the hardware design of the VCS-PI controllers for the PMSG-side converter, the VCS-PI controller hardware design for the DC bus voltage and the hardware design of the VCS-PI controllers for the grid-side converter, respectively.

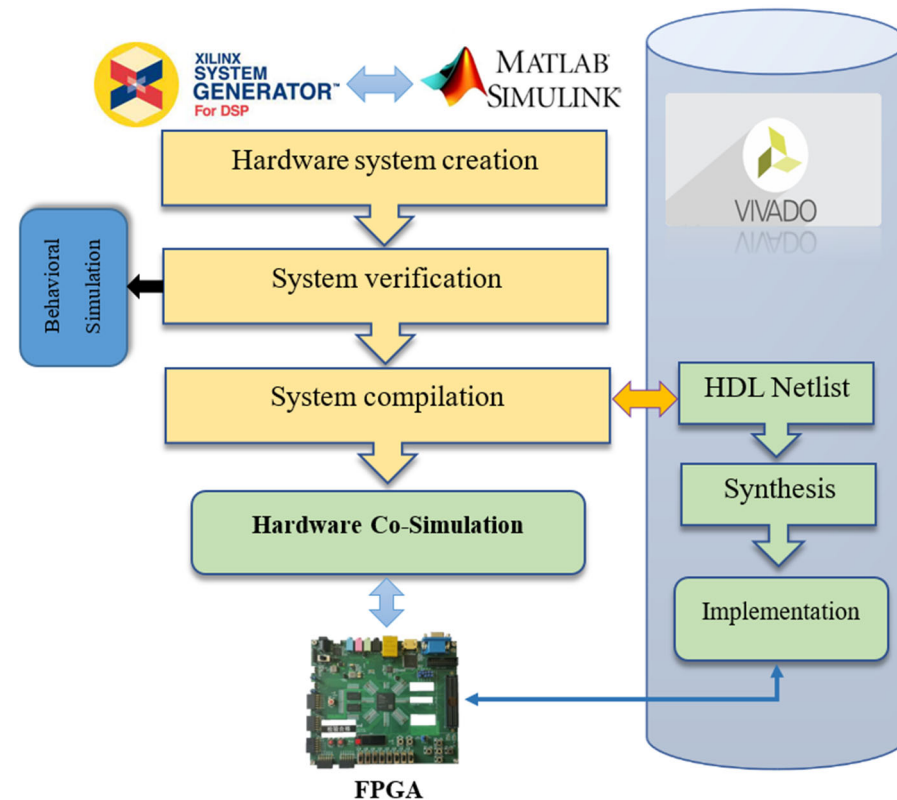


Figure 11. XSG-based design flow.

4.1.2. Implementation of VCS-FGSPID Controllers Using XSG

Figures 15–17 present the VCS-FGS-PID controllers' hardware design for the PMSG-side converter (part 1 of Figure 7), the VCS-FGS-PID controllers' hardware design for the V_{dc} bus voltage (part 2 of Figure 7) and the VCS-FGS-PID controllers' hardware design for the grid-side converter (part 3 of Figure 7), respectively.

4.1.3. Design of Membership Functions Using XSG

Fuzzification, an inference engine and defuzzification are described in this section as part of the XSG design, in order to implement the VCS-FGS-PID controller architecture on FPGAs. The XSG tools, representing in general the graphical interface library for Matlab/Simulink that can be utilized to design and simulate a dynamic system process, allow for highly implementing digital algorithms on FPGA boards. Figure 18 shows the hardware design of the FGS-PID controllers where the inputs include the error and its derivative. In addition to that, the outputs are the optimal values K_p , K_i and K_d . As previously stated, fuzzy sets are represented in triangular and trapezoidal shapes. Predefined blocks manipulated by fuzzy logic are not included in the XSG library. As a result, several VCS-FGS-PID controller sections were mathematically developed and described. The first step consisted of determining all membership functions through the use of the equation systems that relate to them. In the following part, using the XSG for each input, designing an example of membership functions is presented.

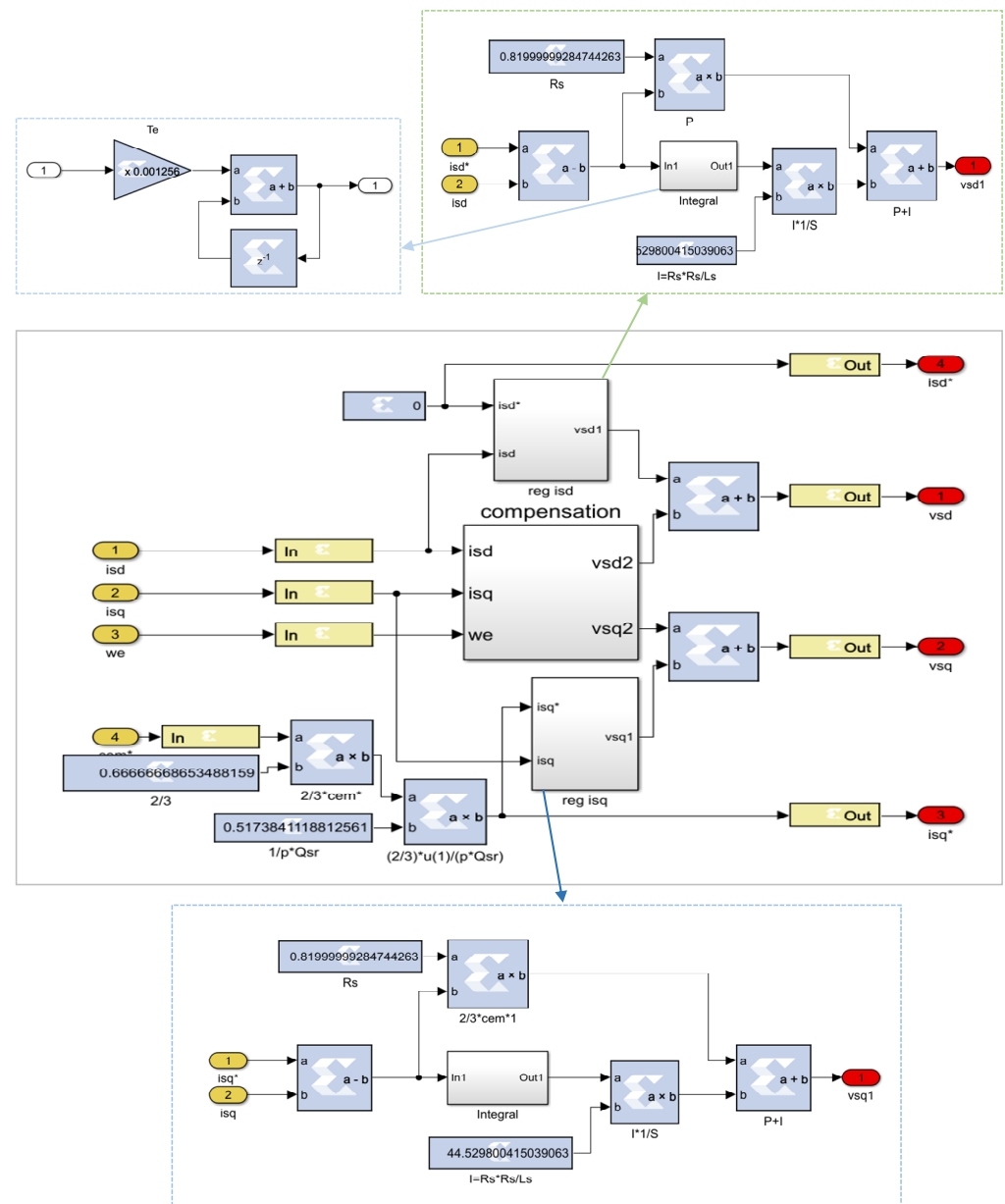


Figure 12. Hardware design of VCS-PI controllers for PMSG-side converter. Where (*) is added to distinguish between the actual and the references variables.

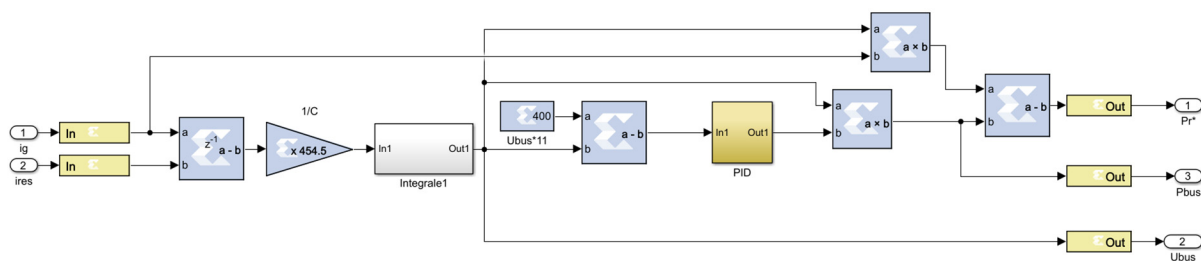


Figure 13. Hardware design of VCS-PI controllers for DC bus voltage. Where (*) is added to distinguish between the actual and the references variables.

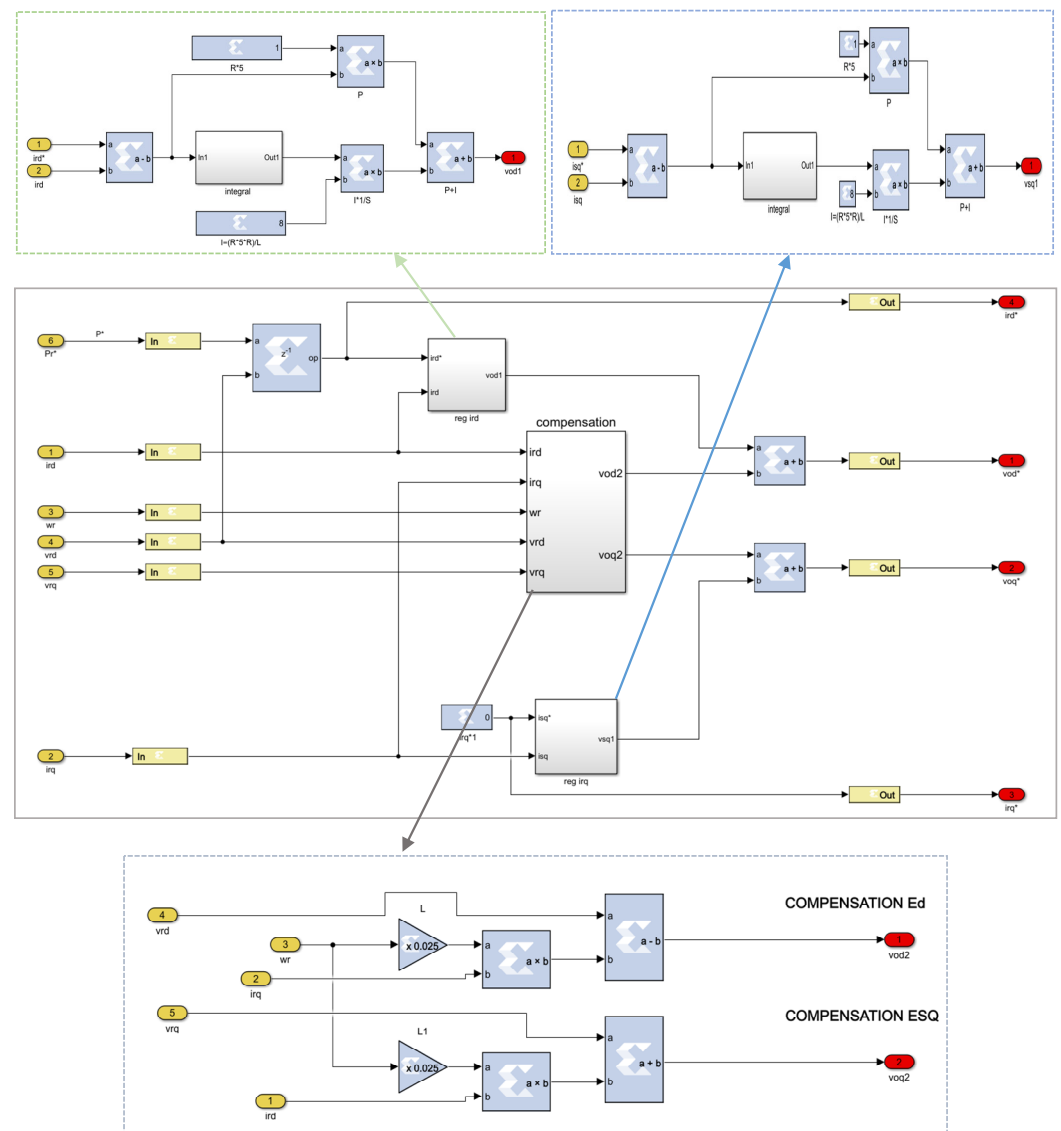


Figure 14. Hardware design of VCS-PI controllers for grid-side converter. Where (*) is added to distinguish between the actual and the references variables.

- Fuzzy membership function of error

Accordingly, an error was given by seven fuzzy sets, which are actually presented by seven mathematical functions, named: PB, PM, PS, ZE, NS, NM and NB. For example, the membership named NS is given by Equation (21), and it is illustrated using the XSG in Figure 19.

$$\left\{ \begin{array}{l} \text{if } e(t) > 0 \text{ or } e(t) > -x_{2e} \text{ then } y(t) = 0 \\ \text{if } e(t) > -x_{1e} \text{ then } y(t) = -3 \times e(t) \\ \text{else } y(t) = 3 \times e(t) + 2 \end{array} \right\} \quad (21)$$

- Fuzzy membership

The ZE-membership error derivative function is given by (22) and it is depicted using the XSG in Figure 20.

$$\left\{ \begin{array}{l} \text{if } de(t) < -x_{1e} \text{ or } de(t) > x_{1e} \text{ then } y(t) = 0 \\ \text{if } de(t) < 0 \text{ then } y(t) = 3 \times de(t) + 1 \\ \text{else } y(t) = -3 \times de(t) + 1 \end{array} \right\} \quad (22)$$

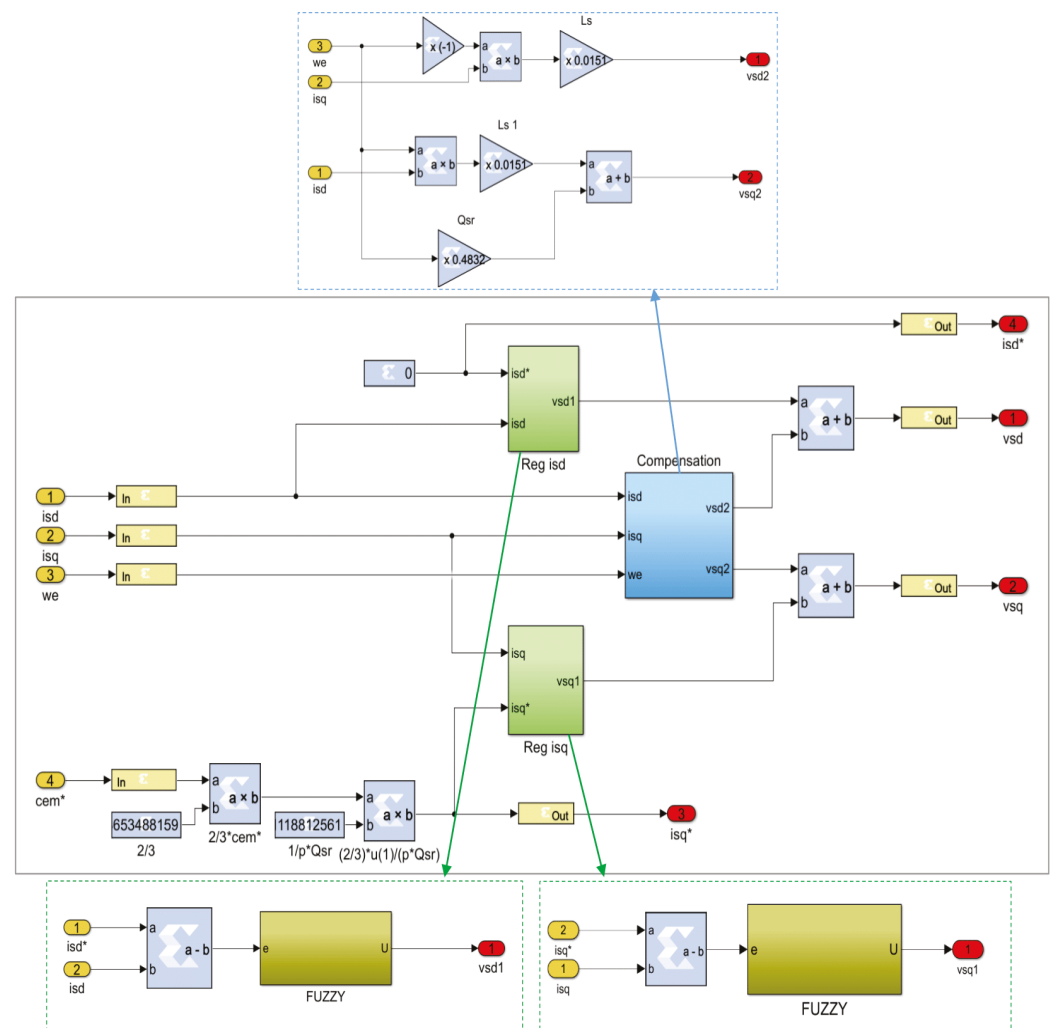


Figure 15. Hardware design of VCS-FGS-PID controllers for PMSG-side converter. Where (*) is added to distinguish between the actual and the references variables.

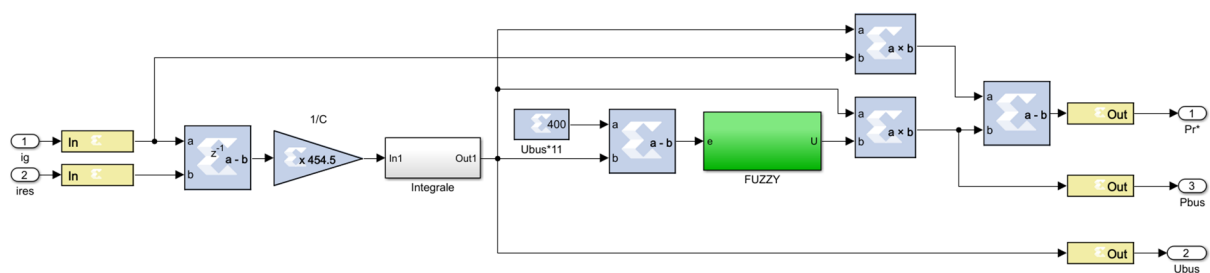


Figure 16. Hardware design of VCS-FGS-PID controllers for DC bus voltage. Where (*) is added to distinguish between the actual and the references variables.

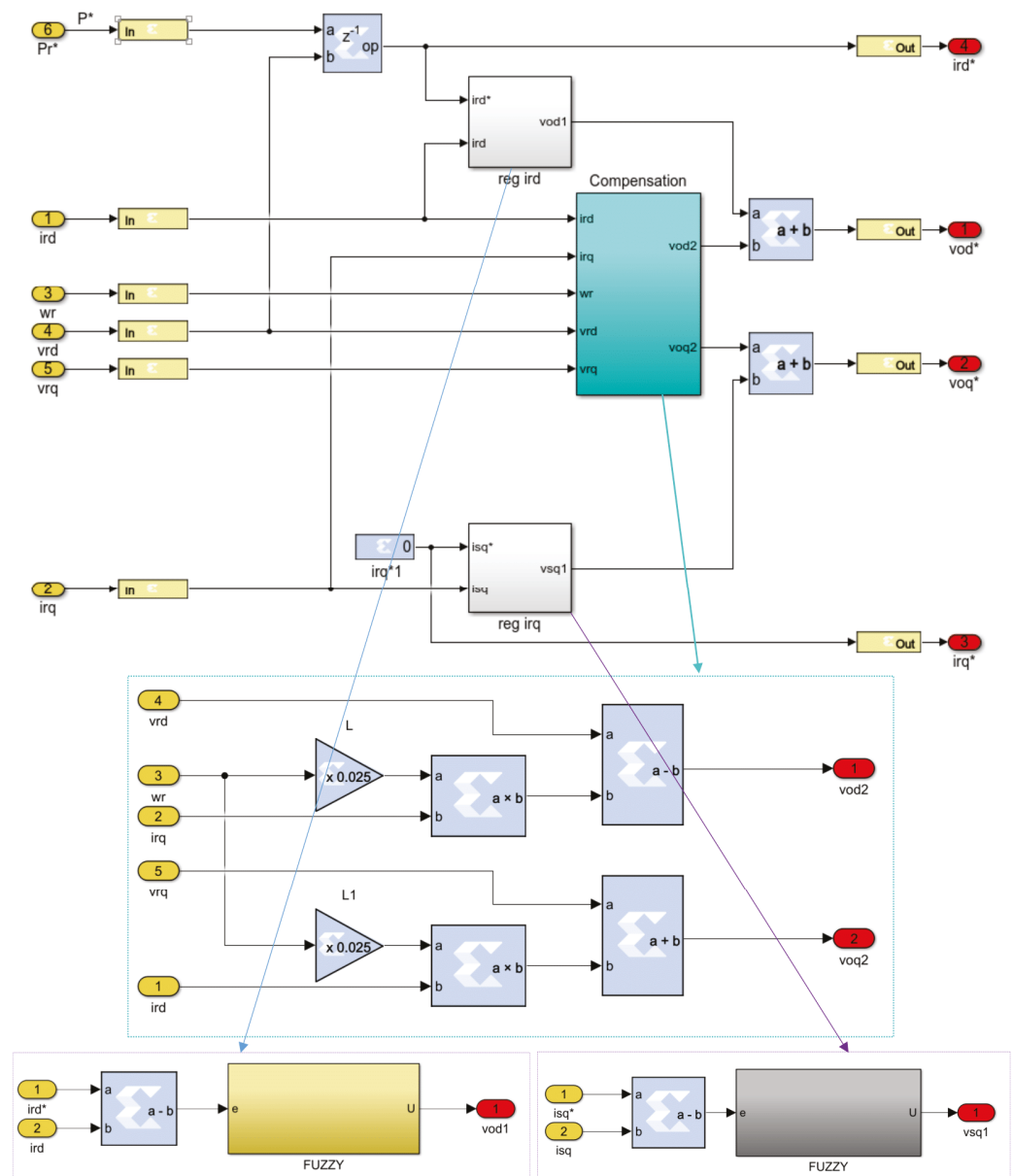


Figure 17. Hardware design of VCS-FGS-PID controllers for grid-side converter. Where (*) is added to distinguish between the actual and the references variables.

4.1.4. Design of Rules

Sugeno developed such a fuzzy logic controller, which was a MIN function, used to find the minimal value in our research work between the membership functions of the two inputs, which are the error and its derivative. This controller reflects the AND operator that links between various fuzzy functions. A rule example is provided in Figure 21:

$$\text{if } (e \text{ is } NS) \text{ and } (deisPB) \text{ then } \begin{Bmatrix} K_p' & \text{is} & S \\ K_d' & \text{is} & B \\ \alpha & \text{is} & 4 \end{Bmatrix}. \quad (23)$$

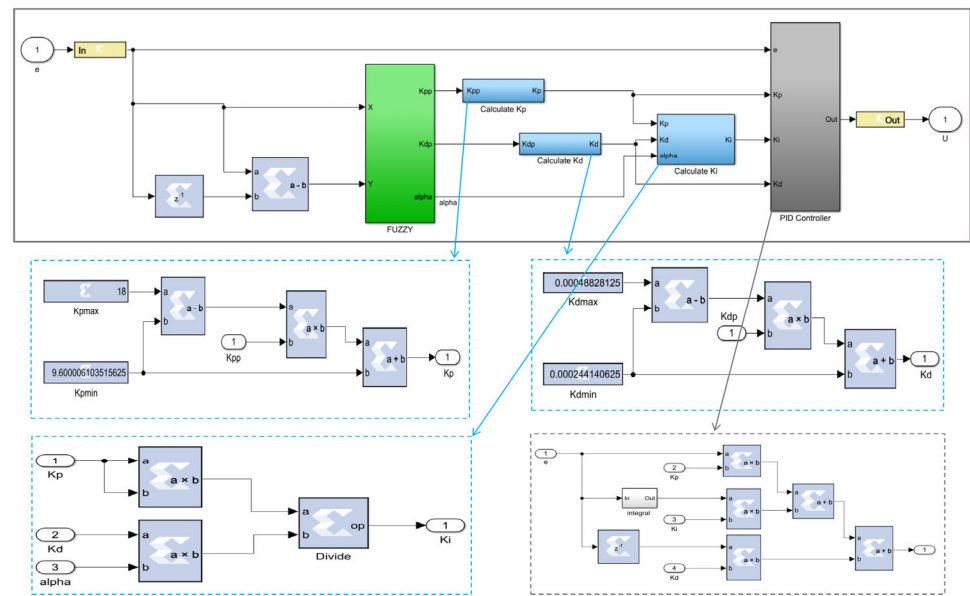


Figure 18. Hardware design of FGS-PID.

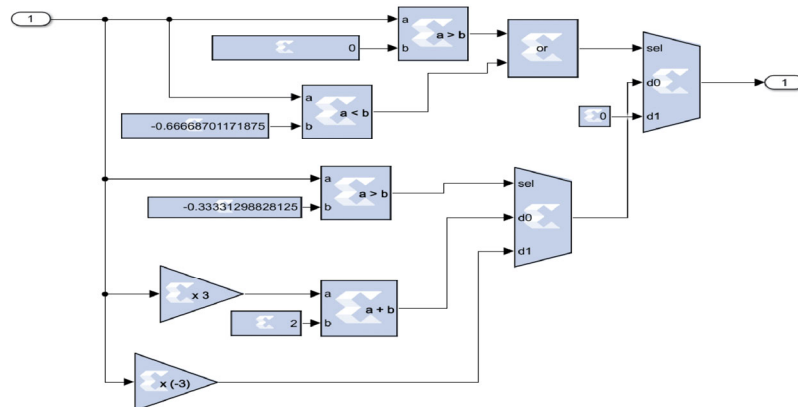


Figure 19. Design of membership function NS from XSG.

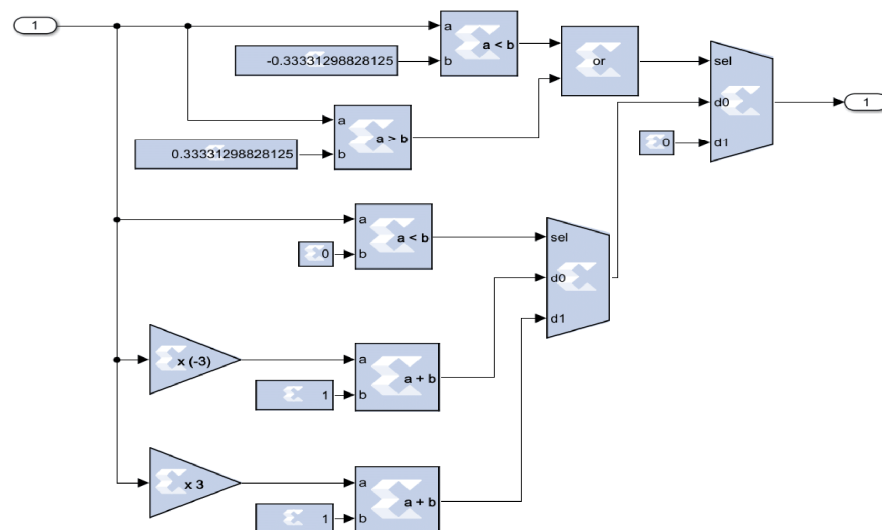


Figure 20. Design of ZE membership function from XSG.

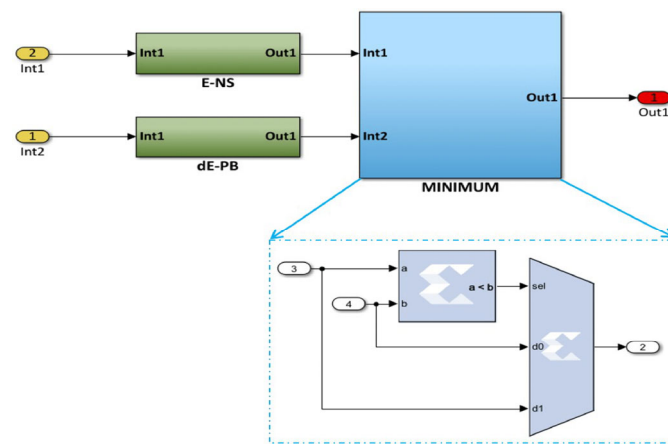


Figure 21. Rule design example from XSG.

Because the membership functions are singletons, we applied a weighted-height technique for defuzzification, where the variation in the output variable is specified as follows [60]:

$$y = \frac{\sum W_{ij} \times Z_{ij}}{\sum W_{ij}} \quad (24)$$

5. Results and Discussion

5.1. Simulation and Implementation Results

The WECS and its control algorithms were developed and simulated with MATLAB/Simulink through the use of the XSG tool. The system parameters are summarized in Tables 4–6, which are used to validate the control schemes suggested in this work. Under 10 s of simulation time, the wind profile shown in Figure 22a was applied to the wind turbine model.

Table 4. Parameters of power grid.

Parameters	Value
Grid-side filter resistance R_r	0.2 Ω
Grid voltage V_r	380 V
Grid-side filter inductance L_r	25 mH
DC capacitance C_{bus}	2200 μ F
U_{bus}^* reference voltage	400 V

Table 5. Parameters of PMSG.

Parameters	Value
Resistance of stator R_s	0.82 Ω
Inductance of stator L_s	0.0151 mH
Number of pole pairs p	2
Flux of permanent magnet φ_m	0.4832 Wb
Resistance of stator R_s	0.82 Ω

Table 6. Wind-turbine parameters.

Parameters	Value
Number of blades	3
Air density ρ	1.22 kg/m ³
Rated power P_{col}	3.5 kW
Blade radius R	2 m
Rated wind speed V_{vn}	13 m/s

A wind turbine was constructed to revolve at a particular speed and produce a certain energy amount. A control mechanism named “pitch angle” was used to control the power output of the wind turbine, being increased if the wind speed is high. Figure 22b presents the PMSG mechanical speed, while Figure 22c indicates the pitch angle variation. The following is a summary of the control systems’ performance: the orientation angle increased if the wind speed’s nominal value was surpassed. As a result, the C_p power coefficient dropped, as represented in Figure 22d. Thus, the generated power was limited, as depicted in Figure 23. A comparison study between the VCS-FGS-PID controller and the VCS-PI controller is presented to prove the superior VCS-FGS-PID performance.

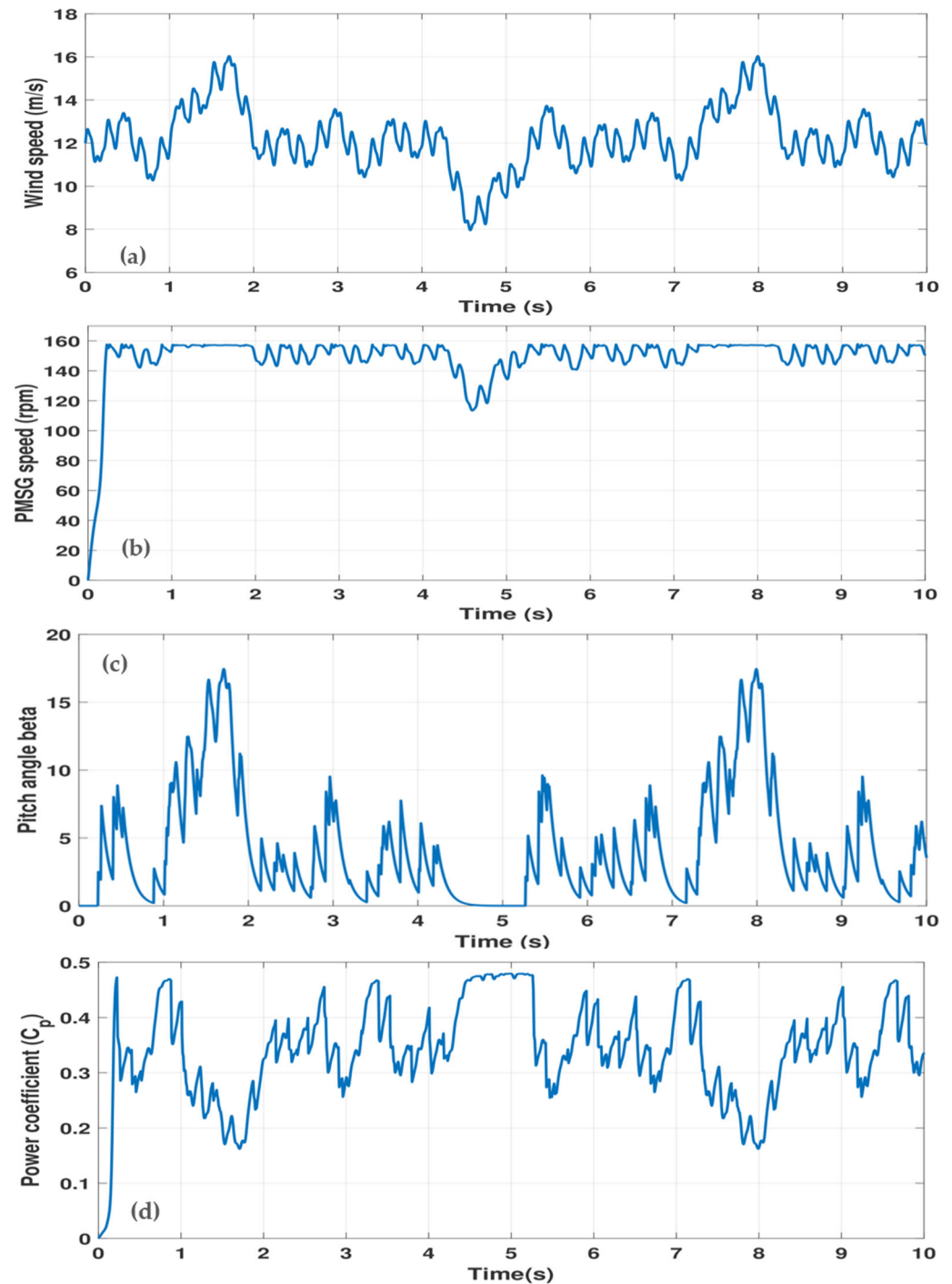


Figure 22. (a) Wind speed, (b) mechanical speed, (c) pitch angle β and (d) power coefficient.

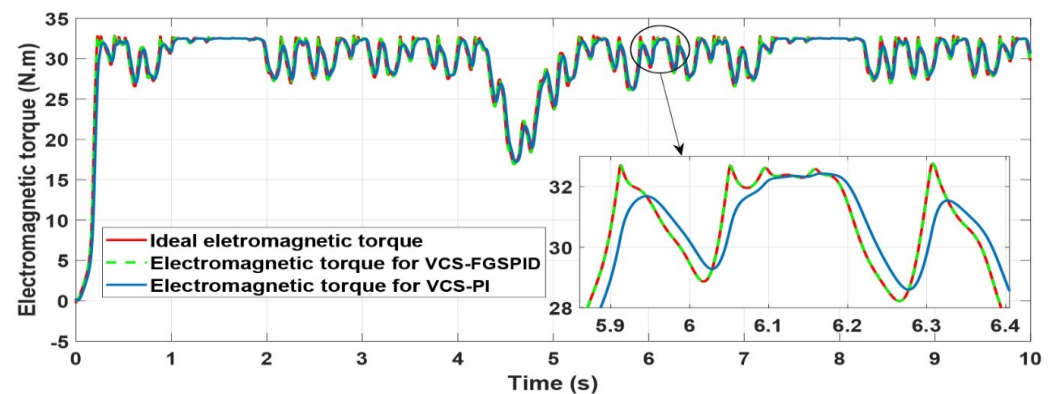


Figure 23. Electromagnetic torque.

Performance Comparison between VCS-PI and VCS-FGS-PID Controllers

To prove our VCS-FGS-PID controller performance, two tests are presented, without and with parameter variations. In the latter case, due to the heating-up of the generator, the values of resistor R_s gradually increased, because of the saturation assumption, as well as those of the inductances specific to the PMSG.

(a) System performance without parameter variation

This test was carried out for proving the system control robustness in response to changes in the wind speed. The responses obtained with both control kinds basically showed that the system controlled by the VCS-FGS-PID controller was more robust than the classical VCS-PI.

The errors of the electromagnetic torque, which is depicted in Figure 23 and the quadratic component of the stator current, which is shown in Figure 24, and which is produced by the speed change, were very high for the classical VCS-PI controller, wherein there was no instantaneous response from the torque and the current. To address this problem, the VCS-FGS-PID controller is suggested, which is characterized by good performance in terms of tracking error and response time.

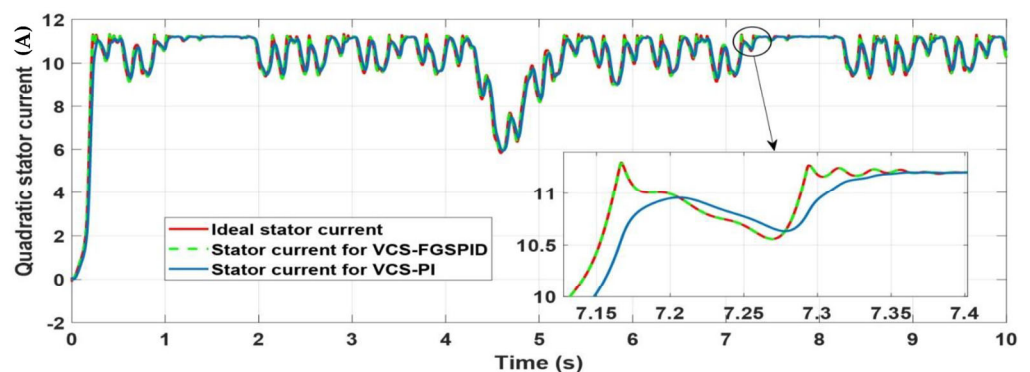


Figure 24. Stator current's quadratic component.

The direct component of the current, which is particularly injected to the grid, and its evolution are illustrated in Figure 25. The response of these curves demonstrates the fact that the VCS-FGS-PID controller is better than the VCS-PI in terms of response time and the disturbance rejection. Compared to the proposed VCS-FGS-PID control method, the high wind speed change had an effect on the conventional vector control. The profile of the active power injected to the grid is shown in Figure 26.

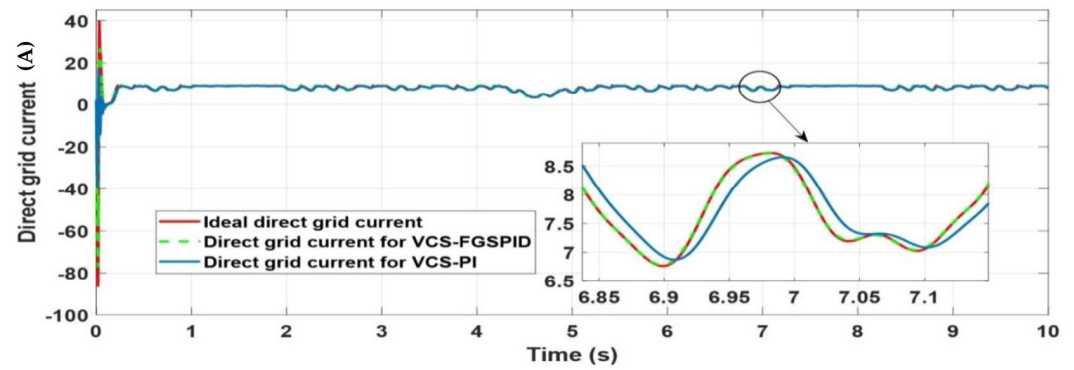


Figure 25. DC component injected into grid.

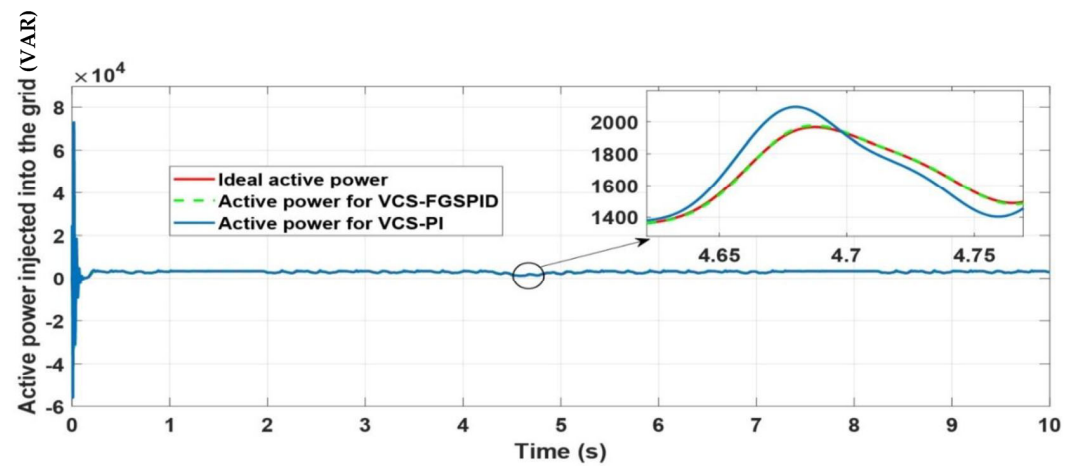


Figure 26. Active power injected into grid.

Figure 27 generally presents the simulation result of the reactive power, which was injected to the grid as well. The system functioned at a unity power factor. VCS-FGS-PID controllers clearly ignored the error while maintaining robustness qualities and finite-time convergence. Figure 28 shows the DC bus voltage simulation results. It is remarkable that the VCS-FGS-PID controller minimized the error compared to the VCS-PI controller while maintaining robustness.

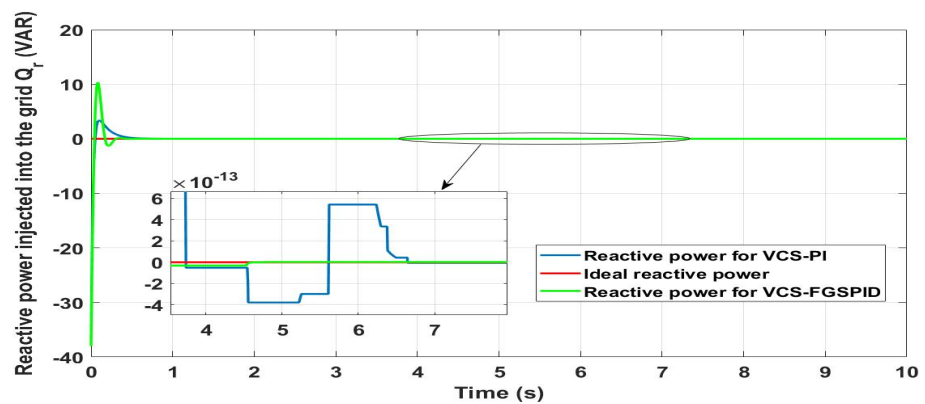


Figure 27. Reactive power injected into grid.

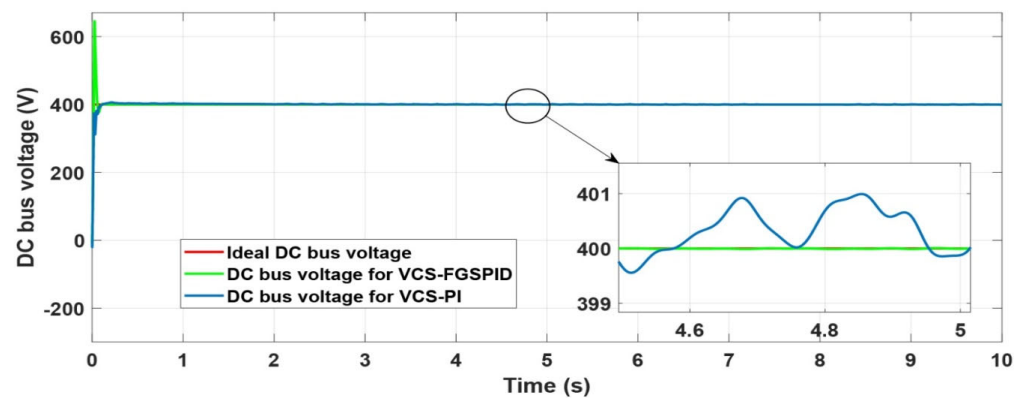


Figure 28. DC bus voltage.

(b) Performance of control system under parameter variation

To test the proposed control strategy performance as regards parameter variation, the PMSG started with the nominal stator resistance. Afterwards, it displayed variations in resistance values as follows:

- At $t = 2$ s, resistance increases by 50%;
- At $t = 4$ s, resistance rises by 100%;
- At $t = 8$ s, resistance goes up by 200%.

The variation in the stator resistance is summarized in Figure 29.

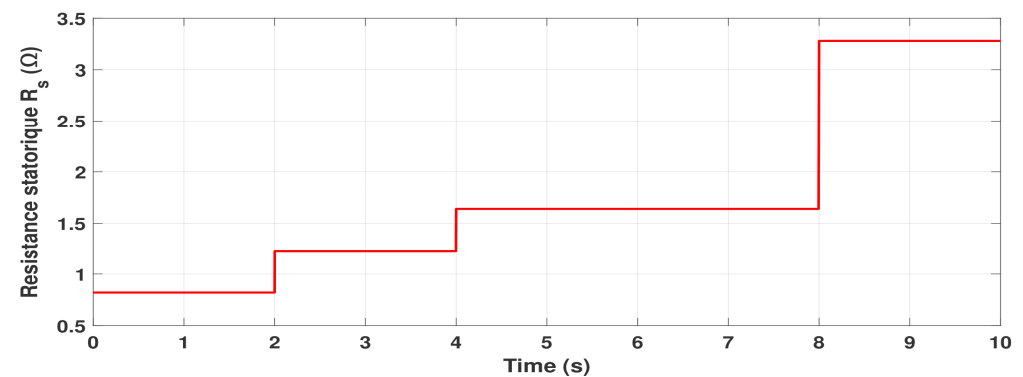


Figure 29. Variations in resistance as a function of time (s).

Figure 30 presents the electromagnetic torque simulation results with the variation in the stator resistance. As shown in this figure, a variation in the resistance of 50%, 100% and 200% resulted in the deviation of the conventional VCS-PI controller, while the VCS-FGS-PID controller maintained a stable behavior. As a consequence, the stator resistance variation test proves that the VCS-FGS-PID controller is more robust and more efficient compared to the VCS-PI controller.

5.2. Comparative Study between Suggested FGS-PID and a Nonlinear Controller

In order to highlight the effectiveness of the proposed FGS-PID, a comparative study with a SMC controller was carried out. As shown in Figure 31, the electromagnetic torque response when the WECS is controlled using the VCS-FGS-PID approaches offered better performance in terms of tracking accuracy and oscillation around the reference value. However, the electromagnetic torque presented a chattering phenomenon followed by high oscillation, which can lead to several undesirable effects on the quality of electrical energy produced and the overall system. Moreover, Figures 32 and 33 show the evolution of the quadratic component of stator current and the direct current component injected into the grid, respectively. These figures show that the advantage of VCS-FGS-PID is that it allows for excluding any phenomenon of chattering that may be caused by SMC while

maintaining the robustness properties. This suggests that VCS-FGS-PID algorithms may be more suitable control methods for industrial energy systems thanks to their ability to provide excellent accuracy and robustness without the issues of chattering that may be present in the SMC control technique. Figure 34 shows the simulation result of active power injected into the grid. It can be seen that the VCS-FGS-PID approaches allowed for the reduction or even the elimination of the chattering phenomenon while keeping the robustness properties and convergence in finite time.

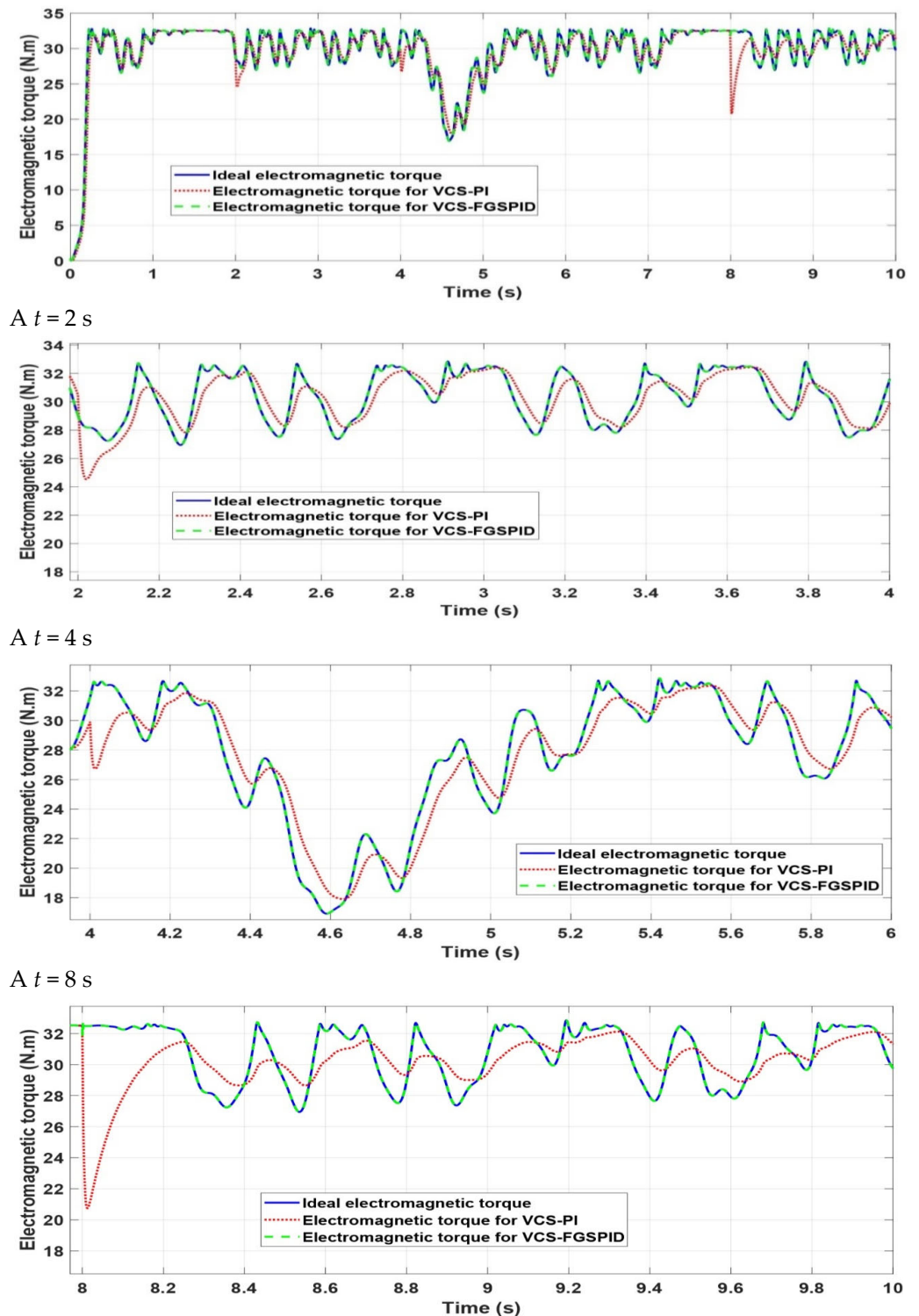


Figure 30. Electromagnetic torque response under parameter variations.

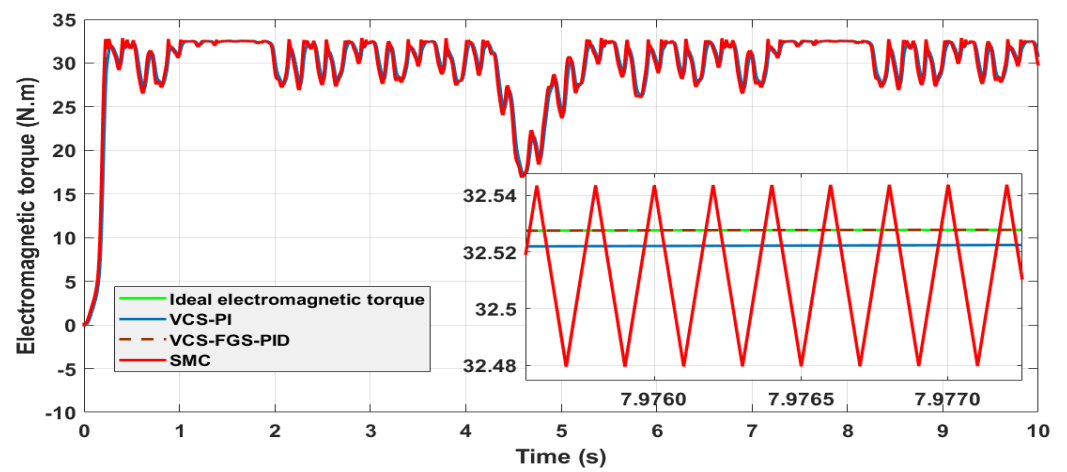


Figure 31. Electromagnetic torque.

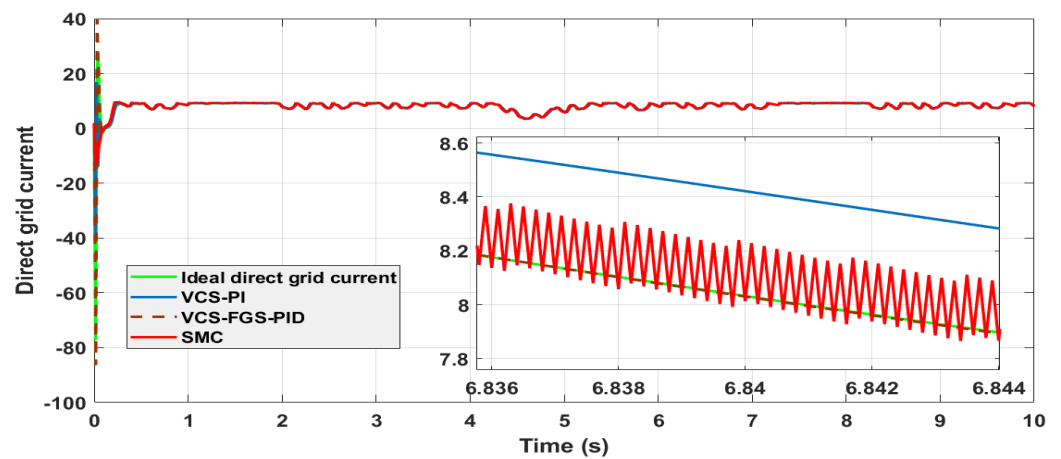


Figure 32. Direct grid current.

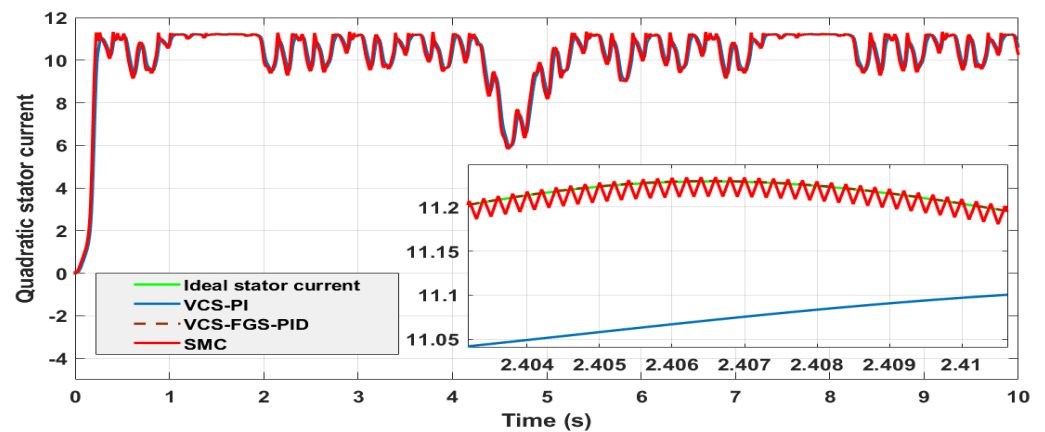


Figure 33. Quadratic stator current.

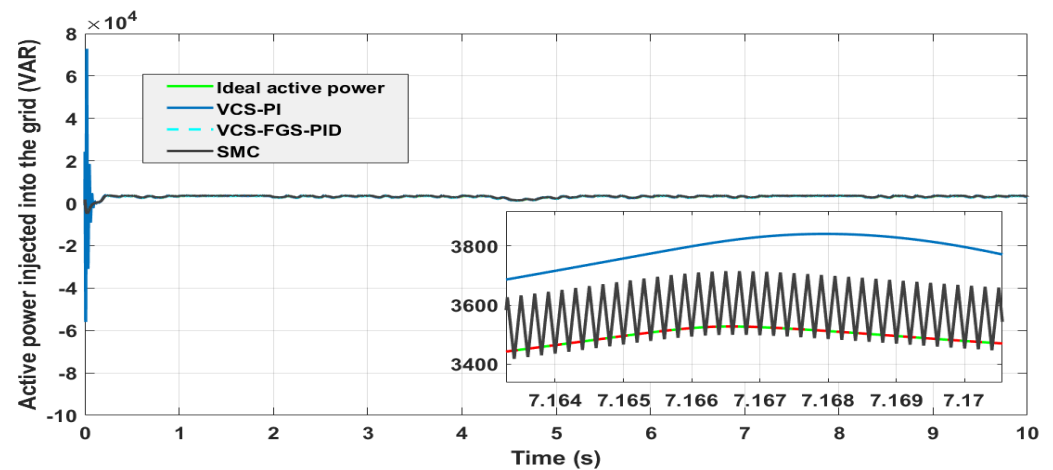


Figure 34. Active power injected into the grid.

The proposed controller performance was also evaluated through various performance indices using the Mean Absolute Error (MAE), the Mean Square Error (MSE) and the Root Mean Square Error (RMSE). The errors of electromagnetic torque, quadratic stator current, direct grid current and active power injected into the grid are defined as:

$$\begin{cases} e_{T_{em}} = T_{em_{ref}} - T_{em_{actual}} \\ e_{i_{sq}} = i_{sq_{ref}} - i_{sq_{actual}} \\ e_{i_{rd}} = i_{rd_{ref}} - i_{rd_{actual}} \\ e_{P_r} = P_{r_{ref}} - P_{r_{actual}} \end{cases}, \quad (25)$$

where $T_{em_{ref}}$ is the reference electromagnetic torque, $T_{em_{actual}}$ is the actual electromagnetic torque, $i_{sq_{ref}}$ is the reference stator current, $i_{sq_{actual}}$ is the actual stator current, $i_{rd_{ref}}$ is the reference direct grid current, $i_{rd_{actual}}$ is the actual direct grid current, $P_{r_{ref}}$ is the reference active power injected into the grid and $P_{r_{actual}}$ is the actual active power injected into the grid. The MAE, MSE and RMSE are defined as follows [65]:

$$\begin{aligned} MAE &= \frac{1}{n} \sum_{i=1}^n |e_i| \\ MSE &= \frac{1}{n} \sum_{i=1}^n e_i^2 \\ RMSE &= \sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2} \end{aligned} \quad (26)$$

where n is the number of data points.

To summarize while making reference to Table 7, it can be seen that the suggested VCS-FGS-PID offers better performance utilizing the MAE, MSE and RMSE, which demonstrates that the latter controller can be considered a contribution for controlling the industrial grid-connected WECS.

Table 7. Comparison between studied controllers.

Controllable Variable	Criteria	VCS-PI	SMC	VCS-FGS-PID
Electromagnetic torque	MAE	0.6007	0.0320	4.5179×10^{-4}
	MSE	0.8641	0.0013	5.7214×10^{-6}
	RMSE	0.9296	0.0364	0.0024
Quadratic stator current	MAE	0.2072	0.0110	1.5583×10^{-4}
	MSE	0.1028	1.5725×10^{-4}	6.8069×10^{-7}
	RMSE	0.3206	0.0125	8.2504×10^{-4}
Direct grid current	MAE	0.7756	0.1476	0.0574
	MSE	40.1864	0.0417	0.5022
	RMSE	6.3393	0.2043	0.7086
Active power injected into the grid	MAE	294.7217	56.0731	21.8005
	MSE	5.8029×10^6	6.0249×10^3	2.7075×10^3
	RMSE	2.4089×10^3	77.6199	52.0336

5.3. Comparison between Proposed Approach and Other Existing Schemes

In order to highlight the effectiveness of the proposed control method, it is important to compare it with other techniques presented in the literature. However, it should be noted that the comparison is limited by the fact that it is rare to find similar work performed under the same conditions. Table 8 clearly shows that the suggested control method yields a significantly neglected state error compared to other techniques. Furthermore, the proposed method exhibits favorable performance in terms of accuracy, robustness, dynamics, etc., compared to other methods. To summarize, the obtained results emphasize the superiority of the suggested control method in mitigating harmonic distortions and achieving accurate and fast control.

Table 8. Comparison between studied controllers.

Comparison Criteria	[25]		[66]		SMC [67]	FOC [68]	NSOSMC [44]	CTSR-PI [30]	Our VCS-PI	VCS-FGS-PID Proposed
	PI	FOSM	PI	RST						
Complexity of tuning and implementation	Low	High	Low	-	Low	High	Medium	Simple	Low	Low
Dynamic	Limited	Good	Low	-	Good	Medium	-	Fast	Limited	Very good
Stability features	Low	Good	Low	-	Good	-	-	-	Low	Excellent
Response time	High	Low	0.03	0.028	Low	-	Medium	-	High	Very low
Steady state error	-	-	1.25%	0.06%	0.15%	-	-	High	High	Neglected
Robustness under parameter variation	Not processed	Not processed	Not processed	Not processed	Not processed	Not processed	Not processed	Not processed	Very low	Excellent robustness
Tracking and performance	+	++	+	++	+++	++	++	++	+	++++
Perturbations	High	Chattering	-	-	-	-	-	-	High	Neglected
Study Nature	Simulation	Simulation	Simulation	Simulation	Simulation	Simulation	Simulation	Simulation	Simulation and Hardware in the loop	Simulation and Hardware in the loop

With (+): Low, (++): Medium, (+++): Good, and (++++), Excellent.

5.4. Implementation of Vector Control Strategy on FPGA

Hardware Co-Simulation

The XSG architecture description language provides important features that allow for communication with Simulink. As a result, a virtual operation scenario can be created for approximating and making a quick validation to the hardware implementation method,

which is known as the co-simulation test, and which has a significant role in validating the synthesized control strategy. In addition to this, it reduces the overall time that is required for accomplishing the experimental tests as well as improves the implementation efficiency. As a consequence, the hardware co-simulation of the suggested VCS-FGS-PID controller can be based on:

- Simulation step: The numerical simulation performed in the Matlab/Simulink environment is used for validating as well as confirming the implementation of the VCS-FGS-PID control algorithm;
- XSG simulation step: This step verifies that the results provided by the XSG simulation are similar to those obtained using Matlab/Simulink;
- Hardware co-simulation step: We implement the XSG model on an FPGA board. In fact, simulation is also called hardware-in-the-loop simulation. Therefore, the designed XSG architecture should be compatible with the characteristics of the FPGA board to be implemented.

It should be noted that a Joint Test Action Group (JTAG) co-simulation module, known as “JTAG co-sim”, is automatically generated between the gateway-in and gateway-out of the XSG blocks during the hardware co-simulation process. Figure 35 displays a broad block schematic of the implementation architecture of the suggested co-simulation procedure.

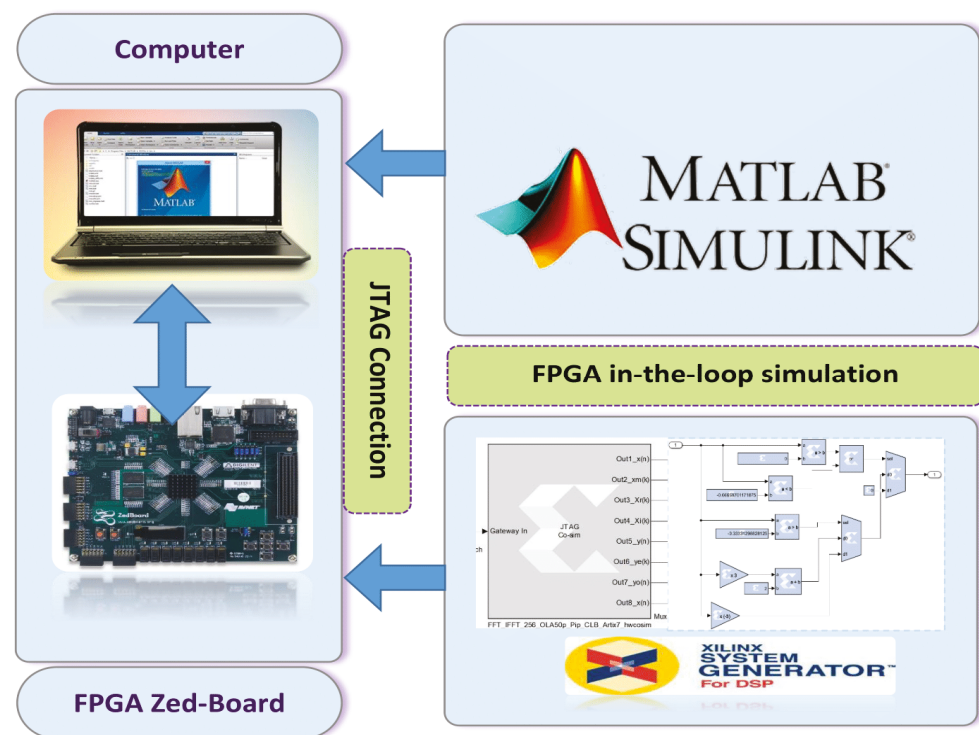


Figure 35. Hardware co-simulation.

A library of logic cores that is designed specifically for FPGA implementation can be obtained, which is ready to be configured and utilized as a function of the designer’s specifications. Following that, the Xilinx Integrated Software Environment (VIVADO) is utilized for generating “netlist” files for the implementation of system generator blocks. These files are responsible for the conversion of the logic design to a physical file. They also generate a bitstream to be transferred to a target tool using the typical JTAG connection. Simulation in MATLAB XSG allows the FPGA application to be tested under the same conditions as physical devices while having a similar variable and operator data width.

Following the simulation and timing analysis of the proposed control algorithm architecture, the hardware co-simulation phase is used in order to confirm the design performance on an FPGA ZedBoard. As shown in Figure 35, the bitstream file is generated

and synthesized through hardware co-simulation, which is utilized for programming an FPGA and generating a novel JTAG block. The latter will replace the XSG design of the VCS-FGS-PID controller. Through the JTAG cable, the FPGA board can read the stator current, the electromagnetic torque, the mechanical speed, the grid current and the grid voltage. Finally, the generated JTAG block will be linked to the three-phase rectifier, the bus voltage and the inverter. In addition, the hardware co-simulation phase is initiated when the FPGA board is connected to the PC using a JTAG programming cable (USB-II cable). As depicted in Figure 36, the JTAG cable will be used to execute the bitstream download phase. After that, all Matlab tools are used to simulate and visualize the results. As shown in Figures 37–42, the hardware co-simulation results have the same precision as the results obtained from Simulink Matlab, which proves the efficiency of the proposed approach. Indeed, Figure 37 presents the evolution of the electromagnetic torque when the WECS is controlled by both control techniques, namely the VCS-FGS-PID and the VCS-PI. It can be seen that the suggested VCS-FGS-PID provides better performance in terms of tracking accuracy. Figure 38 demonstrates that the ideal quadratic stator current converges towards its reference value with excellent tracking and accuracy in the case of the suggested VCS-FGS-PID. However, when the WECS is controlled with the VCS-PI, the ideal quadratic stator current follows its reference values with remarkable error. Figures 39 and 40 present the evolutions of the direct grid current and the DC bus voltage. It can be seen that the suggested controller provides better performance in terms of accuracy relative to the VCS-PI. The active and reactive power injected to the grid is illustrated in Figures 41 and 42, which demonstrate that the actual power converges towards its reference with high accuracy.

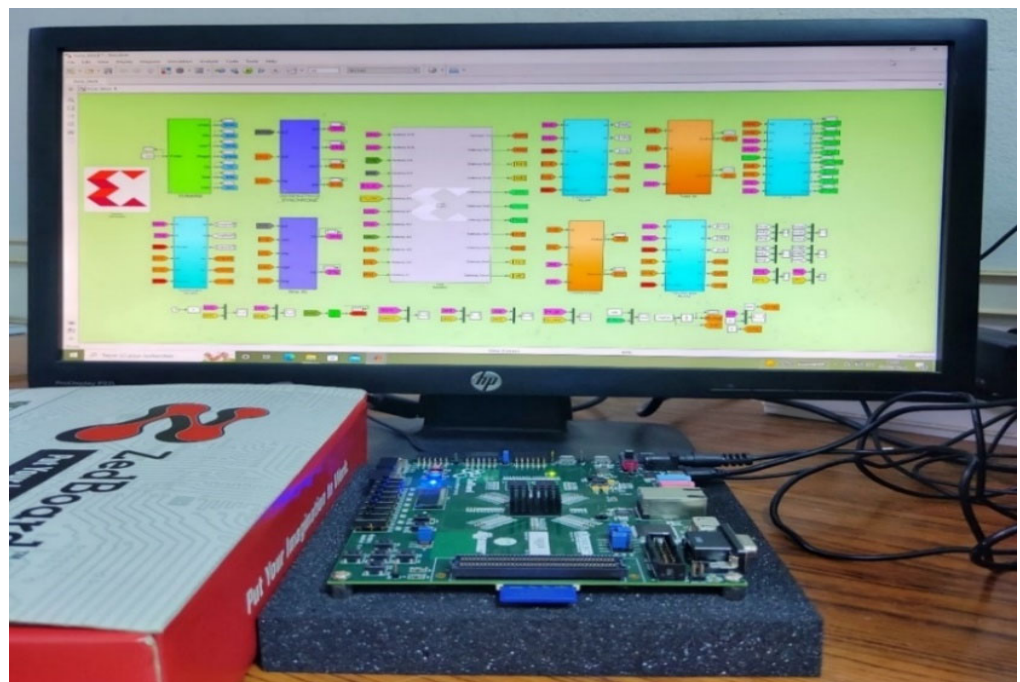


Figure 36. Hardware co-simulation for VCS-FGS-PID controllers.

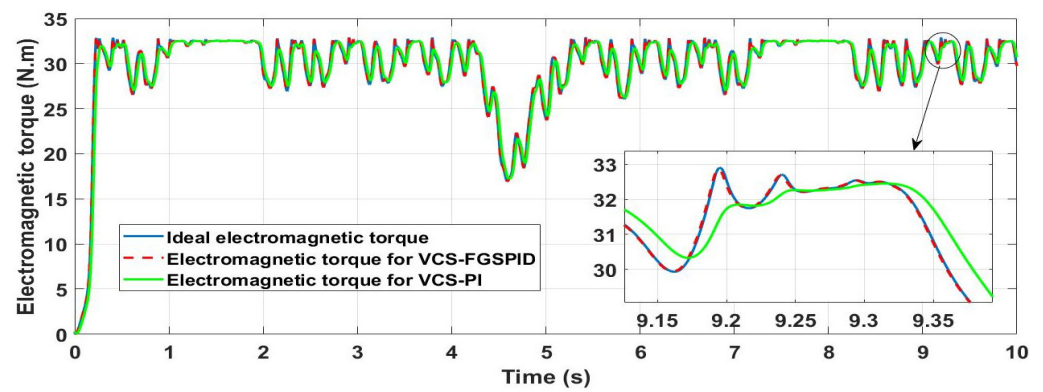


Figure 37. Hardware co-simulation for electromagnetic torque.

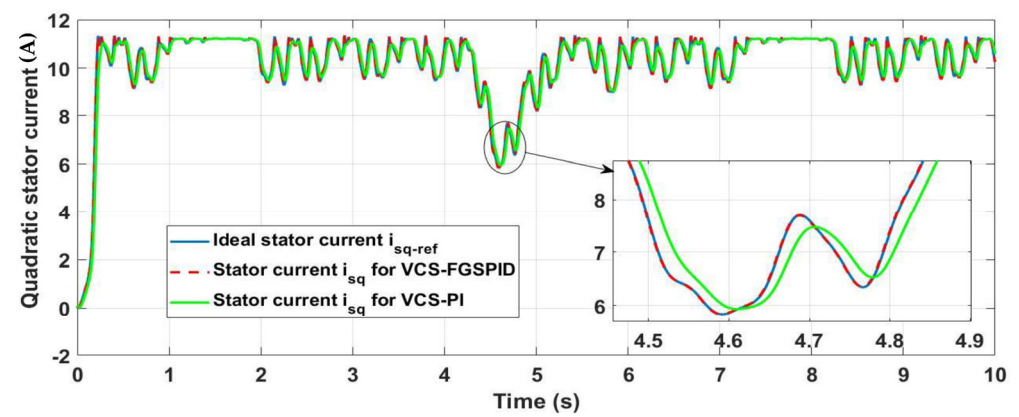


Figure 38. Hardware co-simulation for quadratic stator current.

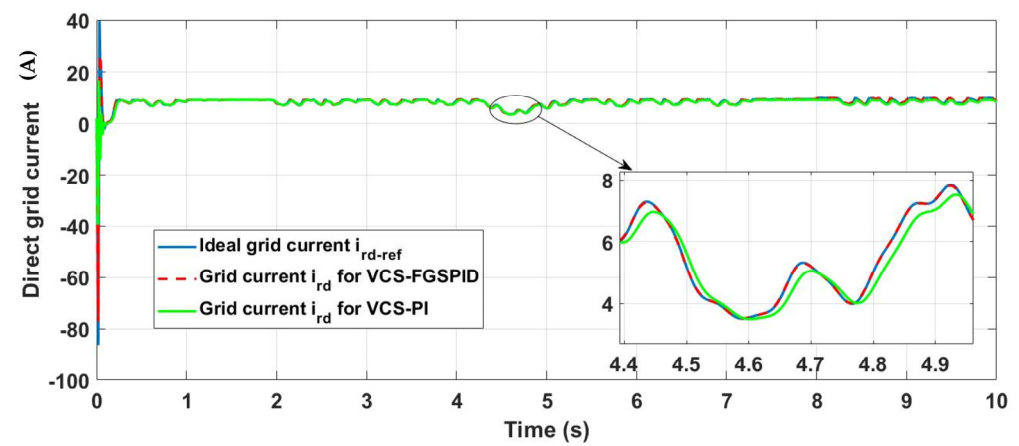


Figure 39. Hardware co-simulation for direct grid current.

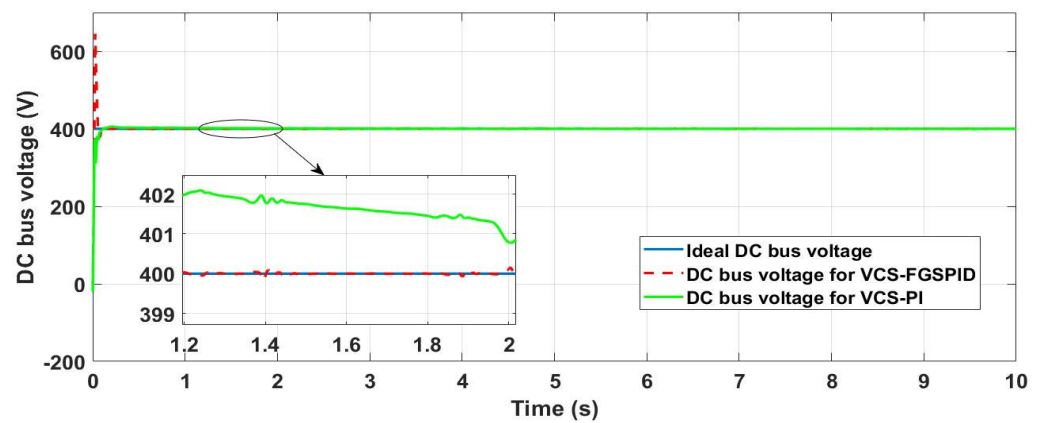


Figure 40. Hardware co-simulation for DC bus voltage.

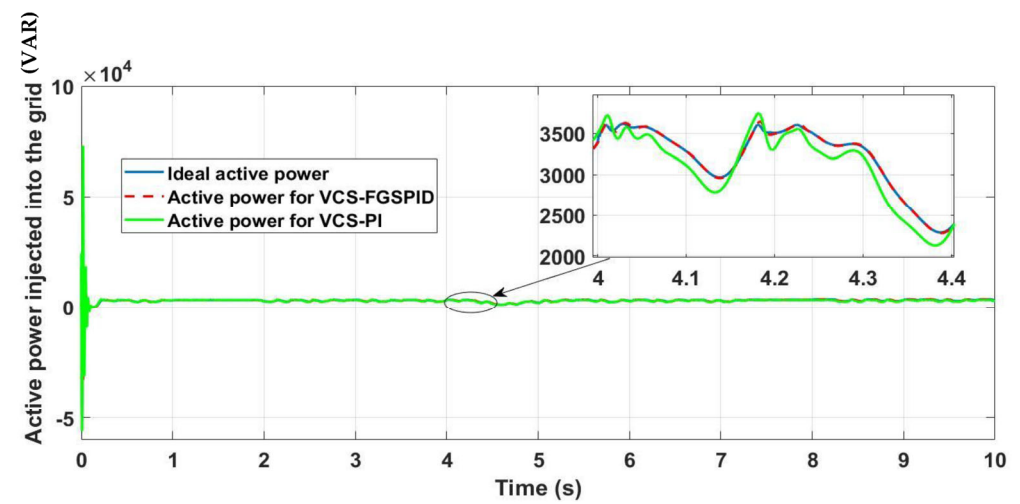


Figure 41. Hardware co-simulation for active grid-injected power.

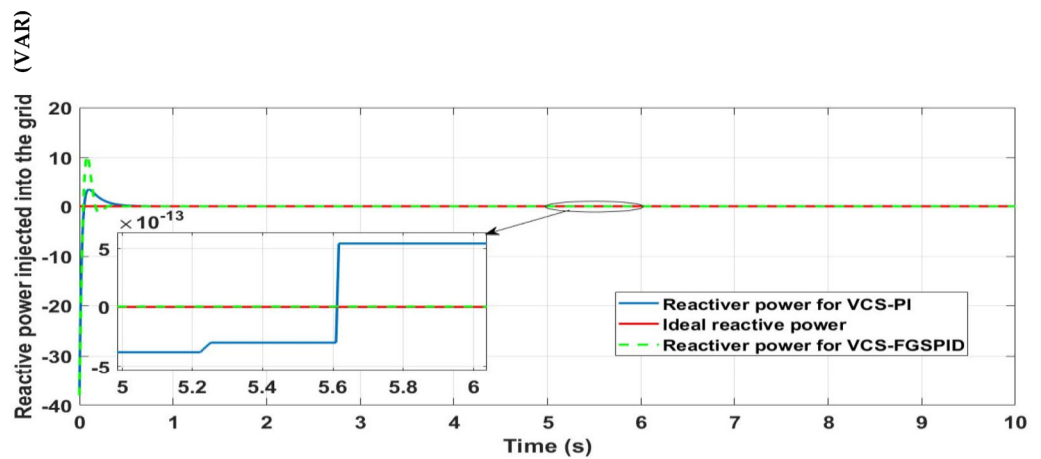


Figure 42. Hardware co-simulation for reactive grid-injected power.

Table 9 details the FPGA resource utilization of the proposed design. The suggested implementation uses between 0.2% and 59% resources. Moreover, the results show the low-cost benefits through the FPGA implementation. Indeed, the architecture of the proposed design occupies a reduced area while providing favorable performance. In fact, the FPGA real-time implementation can be utilized in various industrial processes for the WECS.

Table 9. Hardware resource consumption synthesis.

Resources	Utilization	Available	Utilization %
LUT	31,774	53,200	59.725563
LUTRAM	48	17,400	0.27586207
FF	22,139	106,400	20.807331

6. Conclusions

In this article, the development and hardware implementation of two control schemes (VCS-FGS-PID and VCS-PI) applied to a grid-connected variable-speed WECS have been discussed. There are two major aims for the control of the WECS. The first one is the PMSG-side converter control, which allows the wind turbine to extract the maximal power. The second one is the grid-side control, which aims to maintain the operation in a unity power factor by controlling the reactive and active power transferred into the power grid. This controller also regulates the DC bus voltage. The first control scheme based on the FGS-PID controller has been compared to the second one based on the conventional PI controller. For a better evaluation of varied control technique performance, a comparative study has been extended under varied stator resistance. The VCS-FGS-PID controller has been developed for solving any limit of the conventional VCS-PI controller as regards performance and stability under the nonlinearity behavior of the WECS.

For the hardware implementation, the XSG has been utilized for implementing the suggested control technique on the FPGA. The proposed approach hardware implementation is simple and quick thanks to a novel method based on the XSG. The various simulation results show the superior performance of the VCS-FGS-PID controller when compared to the conventional VCS-PI controller in terms of response time, stability properties, dynamics, tracking and accuracy under the high fluctuation of the wind speed and the varied stator resistance. The implementation result shows the FPGA efficiency in terms of execution time. Indeed, it has been quite short when compared to the dSPACE execution time, owing to parallel processing. The short execution time increases the machine performance and reduces the torque, as well as stator current disturbance, allowing more complicated algorithms to be implemented. Finally, the XSG implementation approach may be thought of as an important tool for implementing real-time hardware FPGAs as well as complicated and preferred WECS control algorithms.

Nevertheless, there are other challenges remaining to be solved in our future work such as the verification of the suggested VCS-FGS-PID method performance according to real experimental results. Moreover, the authors will focus on the integration of a battery energy storage system for the WECS. This could involve developing new control strategies and power management systems to optimize the output power, and subsequently obtain a perfect wind system able of ensuring a continuous load supply without fluctuations.

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Nomenclature

P_{aer}	aerodynamic power (W)
T_{aer}	aerodynamic torque
ρ	density of air (kg/m ³)
V_o	wind speed (m/s)
β	pitch angle (°)
λ	the speed ratio
C_p	power coefficient
Ω_{mec}	mechanical speed (rad/s)
R_s, L_s	inductance (mH) and resistance of the stator (Ω)
R_r, L_r	grid inductance (mH) and resistance (Ω)
p	pole pair number
φ_m	permanent magnet flux (Wb)
ω	electrical speed
ω_R	grid frequency (Hz)
V_{sd}, V_{sq}	direct and quadratic of the stator voltages (V)
i_{sd}, i_{sq}	direct and quadratic of the stator currents (A)
V_{rd}, V_{rq}	direct and quadrature voltages of the grid (V)
i_{rd}, i_{rq}	direct and quadratic currents of the grid (A)

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