



# PERFORMANCE INVESTIGATION OF WIND TURBINES BASED ON DOUBLY FED INDUCTION GENERATORS WITH BACK-TO-BACK CONVERTER

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## ABSTRACT

In the last decades, wind turbines have been extensively studied due to the increasing demand for renewable energy sources. Based on a very strong background of operational experience with wind turbine generators of varying sizes and the development of high-performance power electronics, these most recent wind turbine generators offer the requisite and enhanced performance for their safe integration into the power systems. In the past, wind turbine generators were simply connected to distribution networks; however, current projects and wind turbine generators sizes require a direct connection to the transmission system level through a project-specific substation. Due to these developments, an integrated strategy is needed to maximize the allocation of control responsibilities between substation control and wind turbine control. Dual-Fed Induction Generator (DFIG) systems can be used in many ways to make complex solutions. In this paper, the design and control of DFIG systems are presented to improve WT operating performance in different cases. Given the strong association between converter control strategies and working conditions, it is important to better understand to demonstrates the importance of developing an appropriate modelling approach. The key findings are discussed, and recommendations are provided for future research in this paper.

## KEYWORDS:

Wind turbines WT, Doubly-fed induction generators DFIG, Current controllers, back-to-back converter and rotor side control.

## 1. INTRODUCTION

Wind energy, as a renewable and sustainable energy resource, is at the top of the harvestable energy resources, and it has a reputation as a clean and free source of energy dating back over 2,500 years. However, its primary function is to utilize wind speed to rotate the moveable portion of a generator so that its stationary portion can produce electricity. However, the total installation for producing energy is plagued by challenges like environmental fluctuations, economic hurdles, device lifetimes, and network modification. Concerns like figuring out if something is possible, how much it will cost to install, how to control and model it, how it will affect the energy system and the environment are the main reasons why studies and research are done. Double-fed induction generators (DFIG) were utilized in multi-megawatt wind turbine generators more than 20 years ago (WTG). Because of the 1970s oil price crisis, both Germany and the United States invested heavily in connecting multi-MW WTG to their electrical transmission and distribution networks. One of the most well-known WTGs was the 3 MW GROWIAN. It was erected in 1983 in Marne, Germany, by three German utilities working together. (Warneke, 1983), (Braun, 1984) The Wind Energy Project Office of NASA Lewis Research Centre began designing a 3.5 MVA WTG based on the DFIG concept in the early 1980s. The so-called MOD-5B was erected and put into operation in Kahuku Village, Oahu, in July 1987 (NASA, 1988).

DFIG has been one of the most widely used methods of producing wind energy over the last decade. The evolution in energy conversion field allows various configurations of Wind-Energy-Conversion-Systems “WECSs” to be achievable; as a result, this evolution creates chances for implementing various designs of generators. These generators can be classified according to fundamental operating and installation methods in many and various categories, but our concern focus on the classification which distinguish between generators depending on fundamental principle of operation; hence it includes two main categories (Geng, 2012). The second one Variable Speed Generators “VSGs” attracts the concern the most because of their advantages and powerful points; especially that it is adopted widely in the energy and economic field (Burton, 2001). Manufactures and industrial companies are moving towards building and development of wind turbines with higher energy, which could reach to 6 MW (Ackermann, 2002). The wind turbines based on doubly fed induction generators “DFIG” has a powerful point that the energy electronic system has to deal with a range of fraction from 20% up to 32% of the overall energy of the system. This advantage points to reduction of the waste in the energy of the electronic system and save more (Hansen, 2001), (Morel, 1998) and (Xu, 1995).

The fundamental advantage of the double-fed induction generator is that the power electronics must only manage a tiny part of the overall system power. This means that the losses in the power electronic equipment are lower than they would be in a power electronic system handling full power. A smaller converter may save money, which is an important advantage. A doubly-fed induction machine's control, on the other hand, is more difficult than that of a standard induction machine, and it has a number of serious flaws, including problems with starting, synchronization, and oscillatory transients (Gallardo , 2004). There are several approaches for controlling DFIG (Arbi , 2009)- (Hughes , 2005) (Joshi, 2009) (Ling , 2007). Vector control in a d-q reference frame is a popular way of operating a DFIG because it allows for independent control of active and reactive power (Abo-Khalil, 2006). In this experiment, vector control is used to control the rotor side converter. The voltages of the DFIG stator must be matched to those of the grid before connecting it to the grid terminals. A few articles (Iwanski, 2007) discuss DFIG control for the synchronization process. The phase-locked loop (PLL) method is extensively used to extract and reconstruct phase and frequency information from electrical systems (Andreas, 2005).

If more recent studies are examined, different solutions available in the literature to solve this problem have been reviewed. Input admittance modelling and stability analysis have been worked by (Biyun, 2022) An enormous amount of work has been carried out in optimum modelling of DFIG based WT systems (Yan, 2019, Ntuli, 2022, Huang 2021).

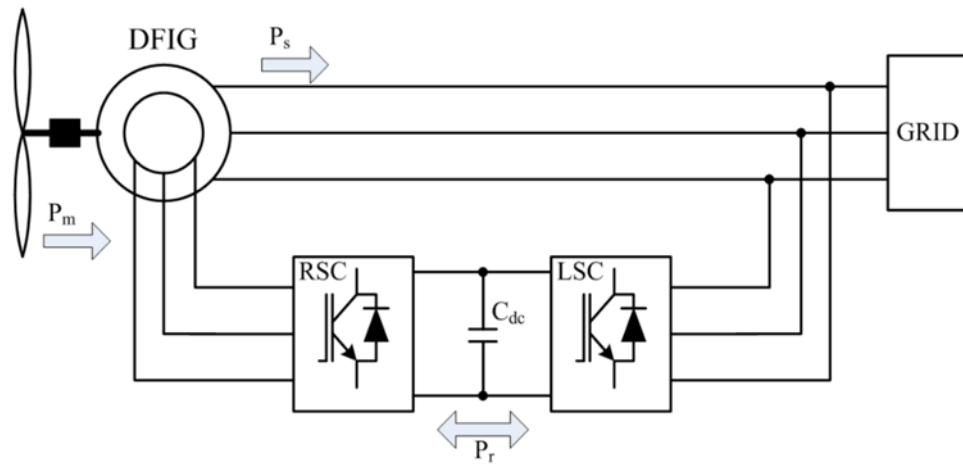
In grid-compatible power electronic systems, PLL can also be used to match grid voltages with controlled currents or voltages. The PLL mechanism used here allows for control of both the output frequency and the phase of the stator voltage. As a result, matching the voltage to the grid voltage and gently connecting it to the electrical grid is simple. The PLL technique is used in this work to synchronize all components. In order to attain more exact and equivalent dependable mathematical models for DFIG, researches and studies have been undertaken for proposing analysis and simulation of DFIG's properties. Moreover, DFIG's ubiquity in wind turbines area increases the absolute necessity of proper and acceptable model which supply an analogous performance of DFIG about fluctuating networks situations.

The approaches used in modeling control systems are very important in terms of examining the behavior of the system. From this point of view, appropriate modeling of DFIGs is vital in observing the behavioral effects of the system under different operating conditions. In this paper, it is aimed to create a suitable model for DFIG to examine the behavioral effects in different working conditions. Wind Turbine based on DFIGs is built with an equivalent

mathematical model which simulates the overall system. The process starts with building a model for wind turbine, taking into account the mathematical equations and equivalent circuits, while the ultimate model simulates the influence of DFIG on wind turbine. Simulation studies have shown that the model can effectively imitate system operation.

## 2. MATHEMATICAL MODEL OF DFIG

Wind Turbine System based on Doubly Fed Induction Generator (DFIGs) which is equivalent to constant frequency generator is presented. This method is illustrated in the following Fig. 1. This method has been adopted and considered widely over the last decades in different systems and applications in order to provide energy within a range of Mega-Watts. These systems based on Doubly Fed Induction Generator (DFIGs) have been manufactured and tested by various companies such as Nordex and Dewind (Abad, 2011).



**Fig. 1. Wind Turbine System based on (DFIGs) with back-to-back converter.**

As shown in Fig. 1, a DFIG is just a wound-rotor induction machine with the stator windings connected directly to the grid and the rotor windings connected to the grid through a back-to-back converter. A back-to-back converter is made up of a line-side converter (LSC) and a rotor-side converter (RSC). A dc-link capacitor is put between the two converters to store energy and stop the dc-link voltage from spiking up and down. The LSC controls the dc-link voltage while the RSC controls the torque or speed of the DFIG and the power factor at the stator terminals. In systems that are connected to the grid, the power-factor correction control of the LSC is also used a lot. By adding a new function in place of an already-defined function, the LSC can be used as either a reactive power compensator or an active filter. A simple three-phase diode rectifier can be used instead of the LSC to work at sub synchronous rates. DFIG has been written about in many papers. Numerous sources describe DFIG modeling. In this section, we'll talk

about only the most important parts of the model. The DFIG can be shown by the following d-q equations:

$$v_{sd} = R_s i_{sd} + \frac{d}{dt} \lambda_{sd} - \omega_d \lambda_{sq} \quad (1)$$

$$v_{sq} = R_s i_{sq} + \frac{d}{dt} \lambda_{sq} + \omega_d \lambda_{sd} \quad (2)$$

$$v_{rd} = R_r i_{rd} + \frac{d}{dt} \lambda_{rd} - \omega_{dA} \lambda_{rq} \quad (3)$$

$$v_{rq} = R_r i_{rq} + \frac{d}{dt} \lambda_{rq} + \omega_{dA} \lambda_{rd} \quad (4)$$

Where  $v_{sd}, v_{sq}$  in d – q reference frame Stator winding voltages,  $v_{rd}, v_{rq}$  in d-q reference frame Rotor winding voltages,  $i_{sd}, i_{sq}$ , in d-q reference frame, Stator winding currents,  $i_{rd}, i_{rq}$  in d-q reference frame Rotor winding currents,  $\lambda_{sd}, \lambda_{sq}$ , in d-q reference frame Stator flux linkages, Wb-turn  $\lambda_{rd}, \lambda_{rq}$  in d-q reference frame Rotor flux linkages, Wb-turn.

Also, the different in speed shown in equation (5),

$$\omega_{dA} = \omega_d - \omega_m \quad (5)$$

$\omega_m, \omega_d$  Actual speed and Reference, rad/s,

Also, the electromagnetic torque calculated by equation (6)

$$T_{em} = \frac{P}{2} (\lambda_{rq} i_{rd} - \lambda_{rd} i_{rq}) \quad (6)$$

where  $T_{em}$  Electromagnetic in (Nm).

$$J_{eq} \frac{d}{dt} \omega_m + B \omega_m = T_{em} - T_L \quad (7)$$

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd} \quad (8)$$

$$\lambda_{sq} = L_s i_{sq} + L_m i_{rq} \quad (9)$$

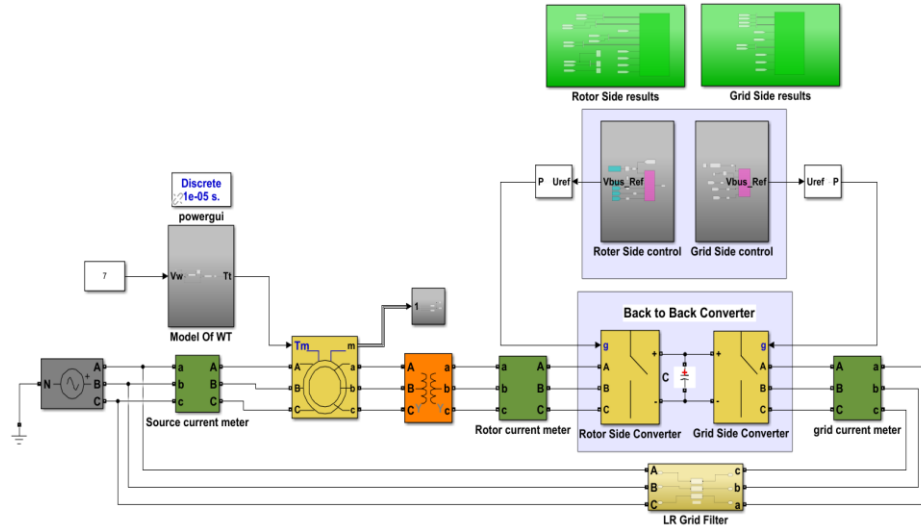
$$\lambda_{rd} = L_r i_{rd} + L_m i_{sd} \quad (10)$$

$$\lambda_{rq} = L_s i_{rq} + L_m i_{sq} \quad (11)$$

Where  $J_{eq}$  moment of inertia (kgm/s<sup>2</sup>).  $B$  Friction constant.  $R_r, R_s$  Rotor and Stator winding resistance (  $\Omega$  ).  $L_r, L_s$ , and  $L_m$  are rotor, stator self-inductance and mutual inductance between rotor and stator windings (Henry).

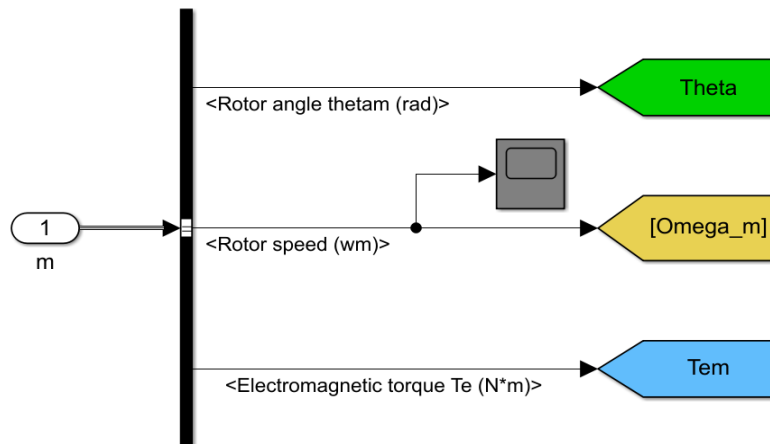
### 3. EXPERIMENT IMPLEMENTATION

The design is implemented using the MATLAB/Simulink. Wind turbine based DFIG model complete modelled which includes the control loops of rotor current and DFIG connection beside the control loops of grid side as shown in Fig. 2.



**Fig. 2. Wind power system based on DFIG.**

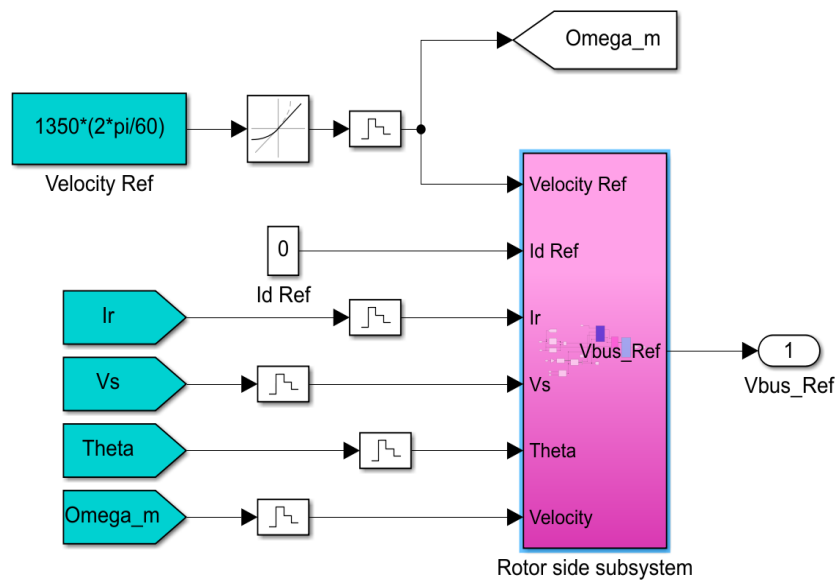
The output torque of the wind turbine model represents the input torque of the asynchronous machine. As indicated in Fig. 3 the acquisition block holds the important output parameters (Rotor Angle Theta, Rotor Speed, and Electromagnetic Torque) of the asynchronous machine that are utilized by the Rotor Side Control Subsystem.



**Fig. 3. Acquisition block in the DFIG model.**

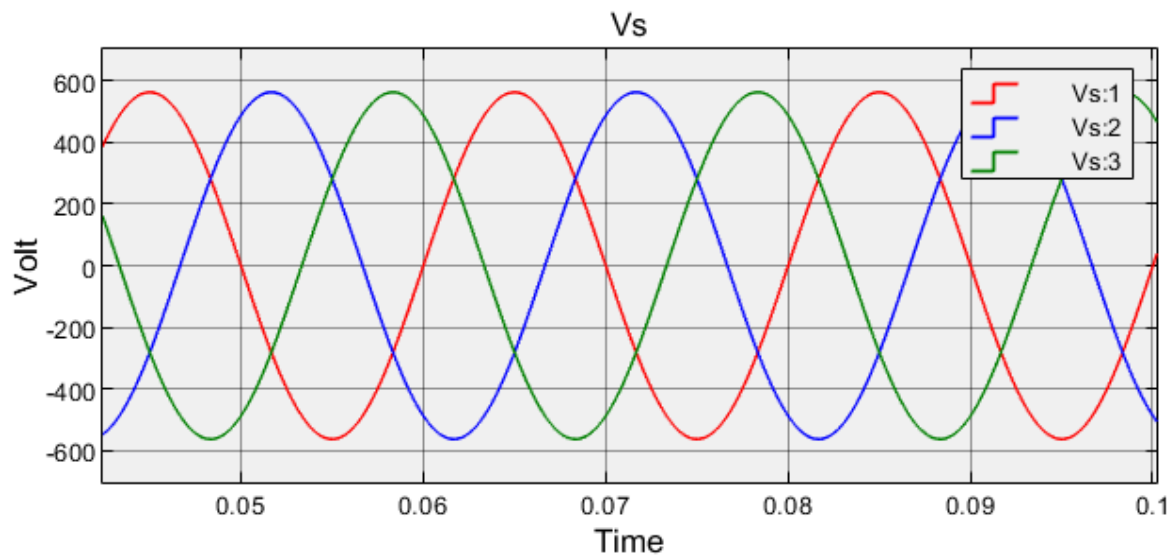
In Fig. 4, the input parameters of rotor side control system contained of; rotor speed, reference speed, estimated value of rotor current, rotor angle theta and source voltage) while the output

is the voltage of bus which is the input of the PWM generator. Eventually, the loops of control are applied regarding those currents of rotor are relative to the stator.



**Fig. 4. Rotor side control system.**

In the same way, the line side control algorithm applied to get constant voltage and frequency. Input signal of three phase programmable voltage source shown in Fig. 5.



**Fig. 5. Input signal of three phase programmable voltage source.**

#### 4. RESULTS AND DISCUSSION

In order to test the validity of the realized model, simulation studies were tried in which different study subjects were discussed. The results obtained for different wind speed conditions are presented below.

#### 4.1. Rotor side result and performance

The reference or objective speed is entered as a ramp signal with an initial value of 0 m/sec and 147 m/sec as a final value as shown in the following Fig. 6. According to the machine adopted, we computed the synchronous speed as 147 m/sec. The control process is done zero final error after the system is stable. The control loop is responsible for chasing the reference or objective speed even with the change in the value. On the other hand, the control process of the current is done as shown in the following Fig. 7, while the method of zero value of the d component related to the rotor current is adopted and implemented in the stable phase of the system.

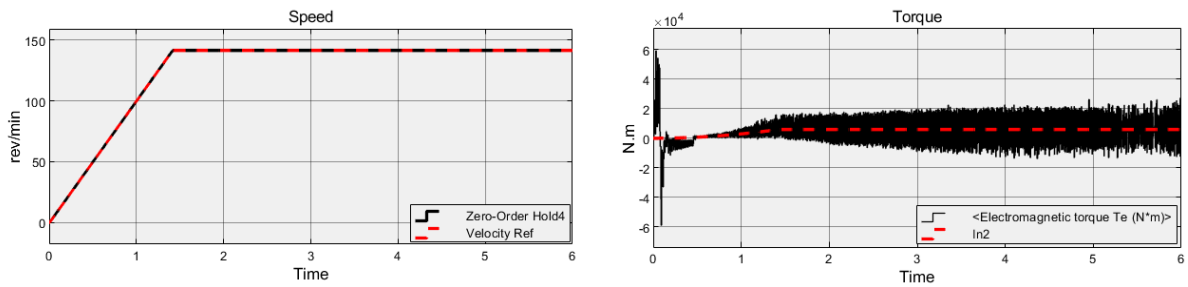


Fig. 6. Objective speed and torque curve.

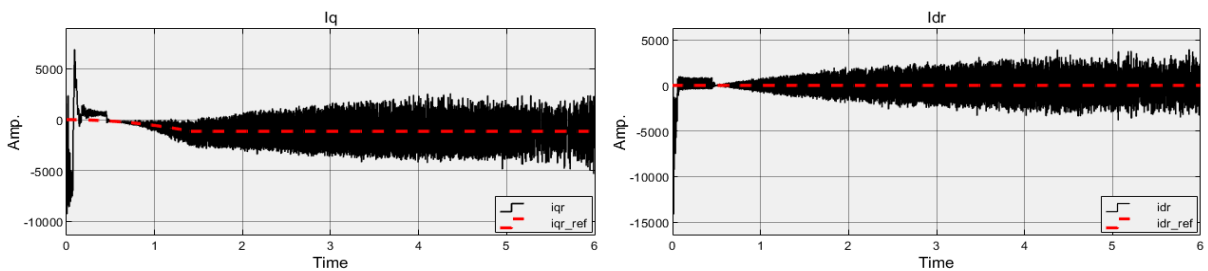


Fig. 7. Id and Idr control.

The current of the rotor and stator in accordance with the input step of the objective speed, as shown in Fig. 8 referring to the transition phase, we observe that the stator current increases until it returns to its stable phase, assuming the speed remains constant.

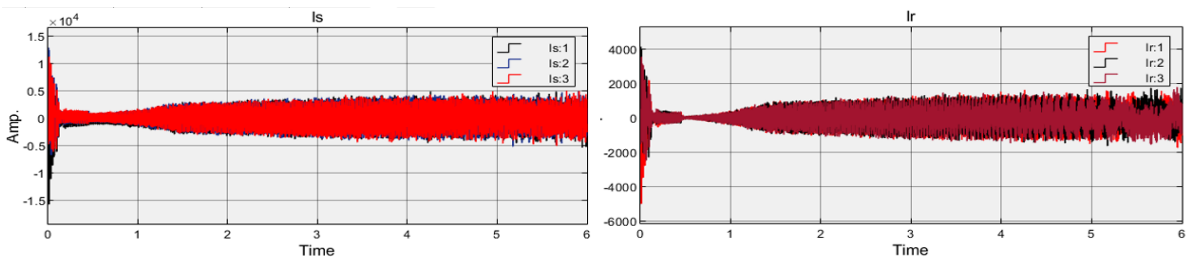


Fig. 8. Currents for the stator and rotor of the whole DFIG model.

### 4.2. Line side result and performance

The difference between the controlled signal of the grid voltage and the assumed reference or objective signal of 1150 Volts. Once the system is stable, we may notice that the control procedure is done with no final errors. No matter what the value is, the control loop is in charge of chasing the goal or reference grid voltage. Fig. 10 shows how the grid's reactive power is always worth the same amount. Fig. 10 shows the grid-side curves of the DFIG model, which is based on the wind turbine model. These curves are the most typical ones. Fig. 11 shows that we also offer the grid current based on the objective voltage input step. If the speed stays the same, we can look at the transition phase and see that the stator current goes up until it goes back to its stable phase.

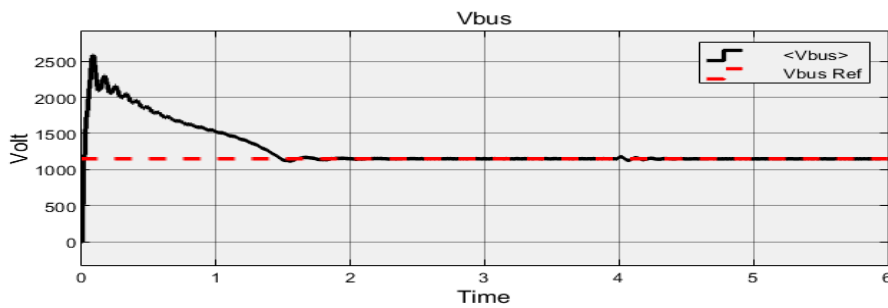


Fig. 9. Controlled signal of the grid voltage beside the objective signal.

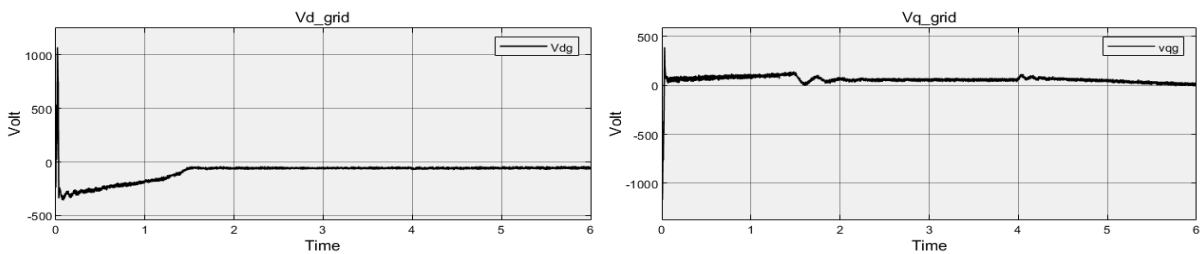


Fig. 10. Vd and Vq on the grid side.

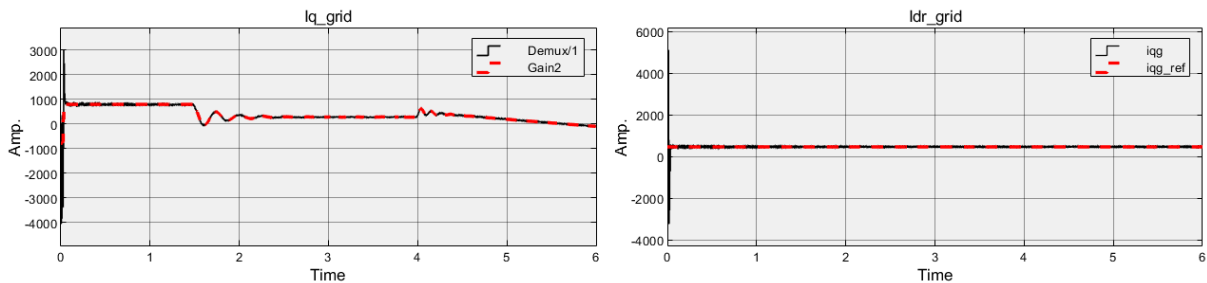
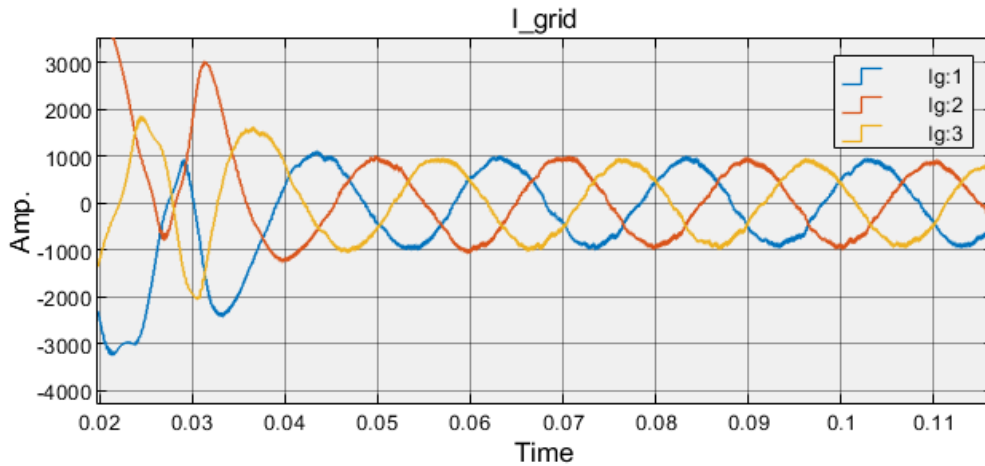


Fig. 11. Controlled Id and Iq signal of the grid side.



**Fig. 12. Grid current proportional to the input step of the target voltage.**

The obtained results confirmed that the developed model gives extremely realistic results. With this aspect, it shows that a modeling that can be useful in the design and control of large-scale systems such as DFIG has been made.

## 5. CONCLUSION

In this study, we have implemented and assessed the previously discussed theoretical notions for DFIG system control. Implementation was accomplished through a series of sequential steps and subsystems in order to implement the entire controlling system while evaluating and discussing various difficulties during the modulation process. In addition, the modulation procedure was conducted using the MATLAB/Simulink system. We found that the control process has a 0.15-second response time, a 2.5% override, and zero final error. Regardless of the change in value, the control loop was responsible for chasing the reference or objective speed. In the transition phase and for the rotor current at the synchronous speed, a DC current has developed in the rotor current, indicating that the synchronization phase in the DFIG system has ignored the initial reaction at the onset. The implementation of the DFIG System (control loops of rotor current, DFIG connection) was performed with the steady state evaluation in mind. A random operating point has been chosen for evaluation reasons, and the associated values and parameters of the theoretical model and the DFIG model have been compared.

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