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Research Article

Dynamic Analysis of Current Loops Behavior in a Wind Turbine Based Doubly-fed Induction Generator

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Abstract

Recently, the doubly-fed induction machine is commonly utilized in wind generation system. A doubly-fed induction generator (DFIG) has been an extensively known machine compared to other types of the wind energy system. This paper presents, a detailed model that comprises a wind turbine (WT), DFIG, rotor side converter (RSC), power electronic components, and grid side converter (GSC) which are used to investigate the dynamic performance of a wind turbine based on DFIG. Vector control approach has been implemented to design the whole system. There are different control strategies for controlling the machines. However, in this paper, indirect speed control strategy has been performed and the dynamic characteristics of current loops in a wind turbine based on DFIG are analyzed. The entire system has been confirmed by MATLAB/Simulink software and detailed results are discussed.

Keywords: Wind turbine, Doubly-fed induction generator, Dynamic analysis, Vector control, Indirect speed control.

Çift Beslemeli Endüksiyon Jeneratör Tabanlı Rüzgar Türbini Mevcut Döngü Davranışının Dinamik Analizi

Öz

Son zamanlarda, çift beslemeli endüksiyon makinesi, rüzgar üretim sistemlerinde yaygın olarak kullanılmaktadır. Çift beslemeli endüksiyon jeneratörü (ÇBIJ), rüzgar enerjisi sisteminin diğer türlerine kıyasla yaygın olarak bilinen bir makine olmuştur. Bu makale, rüzgar türbini (WT), ÇBIJ, rotor tarafı dönüştürücü (RTD), güç elektroniği bileşenleri ve dinamik durumu araştırmak için kullanılan şebeke tarafı dönüştürücü (ŞTD) içeren ayrıntılı bir model sunmaktadır hemde ÇBIJ tabanlı rüzgar türbininin dinamik performansını araştırmak için kullanılır. Tüm sistemi tasarlamak için vektör kontrol yaklaşımı uygulanmıştır. Makineleri kontrol etmek için farklı kontrol stratejileri vardır. Ancak bu yazıda, dolaylı hız kontrol stratejisi uygulanmış ve ÇBIJ tabanlı rüzgar türbinindeki akım döngülerinin dinamik özellikleri analiz edilmiştir. Bu nedenle, akım döngülerinin çok doğru olduğu ve gerçek akım döngülerinin teorik olana oldukça uyduğu fark edilebilir. Tüm sistem MATLAB/Simulink yazılımı ile doğrulanmış ve detaylı sonuçlar tartışılmıştır.

Anahtar Kelimeler: Rüzgar türbini, Çift beslemeli endüksiyon jeneratörü, Dynamic analiz, Vektör kontrol, Dolaylı hız kontrolü.

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1. Introduction

Wind energy is among the most well-known renewable energy sources, and its use is increasing steadily around the world. In 2019, alone, more than 60 GW of wind energy capacity was installed globally, which is a 19% rise over installation in 2018, showing that wind energy is gradually dominating the energy industry. A doubly-fed induction generator (DFIG) has been an extensively known machine compared to other forms of the wind energy system. It contains a wind turbine attached to the shaft of an induction generator. A DFIG is built such that: the stator part connects to the power grid directly, whereas the rotor part links to the grid via a PWM converter that controls the slip energy. Moreover, it presents the mathematical modeling of the wind turbine system. The dynamic model of DFIG allows one to know the continual performance (not only under steady-state) of machine parameters, but also during various voltage providing situations. The doubly fed induction machine is commonly utilized in wind generation system.

These paper presents the dynamic model and the performance analysis of the current loops behavior in a wind turbine based DFIG. The dynamic model of DFIG allows one to know the continual performance (not only under steady-state) of machine parameters, but also during various voltage providing situations. This section first develops the dynamic model of DFIG in abc stationary natural frame. The dynamics of the system is then converted to a rotating dq reference frame using Clarke and Park transformation method for cancellation of coupling between the two stator and rotor windings. The Clarke transform is a mathematical technique that converts a 3-phase abc natural frame into an orthogonally structure $(\alpha\beta)$ [1]. Let's consider a symmetric 3-phase induction generator having stationary abc axis with 120^0 apart. Then it's possible to convert the abc constituents into $\alpha\beta$ through the Clarke method. On the contrary, the Park transform technique was first introduced by an American engineer R.H. Park in the late 1920s to simplify a new strategy for the analysis of a 3-phase electrical machine. This method was introduced to transform a 2-phase $\alpha\beta$ reference frame into a rotating dq reference frame via a rotating transform $T_P(\theta)$ matrix. The dynamic model of DFIG in a rotating dq axis is very important for designing the properties of synchronous and hyper-synchronous operating system as well as implementing vector control strategy for controlling active and reactive output power. There are different strategies in the literature for controlling the DFIG [2-12]. In this paper, we only focus on the dynamic characteristic of the current loops.

This paper is organized as follows: Section II presents the wind turbine system. Section III and IV exhibits the vector control and control strategy of the system. Section V presents the results followed by the conclusion.

2. Wind Turbine System

The purpose of this section is to present some basic data and concepts for a wind turbine model. A practical wind turbine has a nominal output power of 1.5 to 3 MW. For this purpose, in this paper, a 2.4 MW of wind turbine has been chosen for the system simulation. The purpose of this section is to present some basic data and concepts for a wind turbine model. A practical wind turbine has a nominal output power of 1.5 to 3 MW. For this purpose, in this paper, a 2.4 MW of wind turbine has been chosen for the system simulation. aerodynamic model, a drive train model, and a generator. The corresponding wind speed supplied to the aerodynamic system is estimated using a wind speed model. [14]. The amount of rotational speed divided by the real wind speed (v_w) is called lambda. Wind speed, blade's pitch angle and speed of the rotor are together fed into the aerodynamic system. Output torque is fed to the drive train model along with the speed of the generator. Drive train model thereby generates electromagnetic torque on the high-speed shaft which is transmitted to the generator system [3, 6].

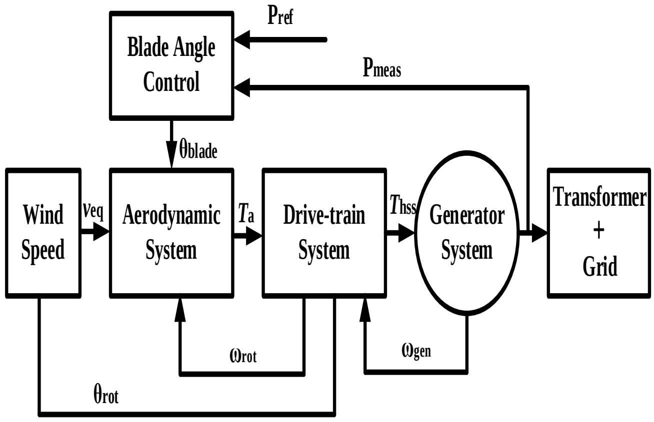

Figure 1. Typical block model of the wind turbine.

3. Control of DFIG Based Wind Turbine

In this paper, vector control (VC) which is also called field-oriented control (FOC) of electrical machines has been implemented. VC employs in both the rotor side and grid side converter. Using this control strategy, it is possible to decouple and construct the control of d component and q component separately [4, 5]. VC minimizes the control design complication and accomplishes various control goals. The main purpose of the RSC is to control the active and reactive power that allows the turbine to capture the maximum power from the wind, while also providing reactive power supports to the grid. Correspondingly, GSC aims to keep the DC bus voltage constant. In this section, the control of RSC is presented. In RSC control, we have the current loops of the DFIG and the mechanical speed (rotor speed controller). Direct current (i_{dr}) is proportional and controls the reactive power, whereas, the quadrature currents are proportional to the toque or stator active power. The GSC control includes the bus voltage references and controls the grid reactive power reference $(Q_{g\_}ref)$. It also includes the derivation of the transfer function of a closed-loop second order system for the rotor side and grid side of a DFIG. Moreover, an angle calculator also called phase-locked loop (PLL) is designed in both RSC and GSC control, in order to achieve a three-phase stator voltage grid synchronization. PLL offers the reliability to estimate and reject smaller harmonics. Furthermore, Proportional and Integral control and the maximum power point tracking (MPPT) approach using indirect speed controller has been applied in order for the mechanical torque (T_t) to follow the maximum power curve in response to the wind speed variations [7-9].

3.1. RSC Control

In order to use the vector control approach, the dynamic equation of DFIM should be modelled, which provides the instantaneous voltages and currents in order to compute and control the parameters. The rotor currents cannot be determined with cage motors, thus the current is substituted by an appropriate amount expressed in a rotating dq representation by using a well-known technique called as Clarke and Park transformation.

The transfer function of RSC for both current control loops can be expressed as follows [9-11]:

$$TF = \frac{i_{dr}(s)}{i_{dr}^{*}(s)} = \frac{i_{qr}(s)}{i_{qr}^{*}(s)} = \frac{sk_p+k_i}{\sigma L_r s^2+(k_p+R_r)s+k_i} = \frac{sk_p+k_i}{L_f s^2+(k_p+R_f)s+k_i} \quad (1),$$

where: $k_p = 2\omega_n L - R$ is proportional gain; $k_i = \omega_n^2 L$ is integral gain; L_f, L_r – filters of inductance and resistance, respectively. Figure 2 shows the Bode plot diagram of dq closed loop transfer function for the rotor side converter.

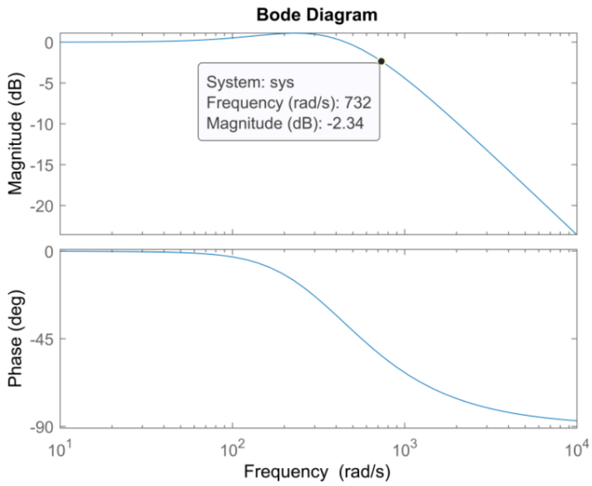

Fig. 2 Bode plot diagram of the closed-loop system of RSC.

3.2. GSC Control

It is very important to control some components in the GSC. Because it is impossible to make it operate effectively without controlling certain magnitudes in the grid side system. One of the purposes of the GSC control is to maintain the DC bus voltage constant, irrespective of the region of operation. It also operates at a unit power factor. The GSC is responsible for controlling parts of the power flow of the DFIG. The power produced by the three-blade wind turbine is partially supplied through the rotor of the DFIG. For instance, the power flow that passes through the rotor also passes through the DC-link and then sent to the grid by the GSC. The GSC is connected to the grid through an RL filter [12].

The transfer function of GSC is expressed as follows [9]:

$$\frac{i_{qs}(s)}{i_{qs}^{*}(s)} = \frac{sk_p+k_i}{s^2(L_f)+s(R_f+k_p)+k_i} \quad (2)$$

Bode plot diagram of the closed loop for both RSC and GSC is illustrated in Figure 3.

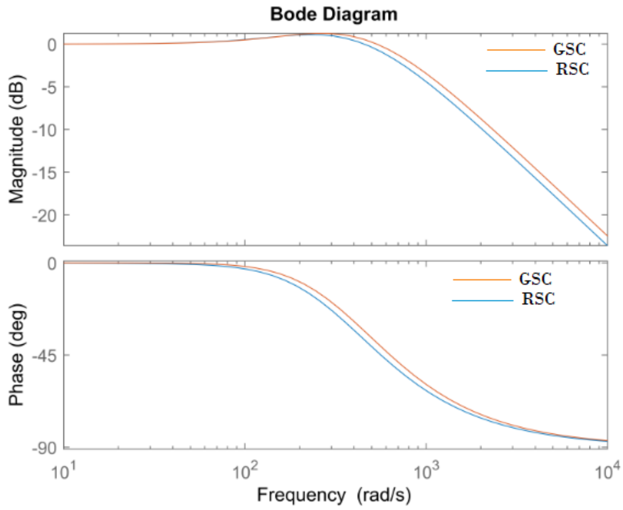

Fig. 3 Bode plot diagram of both RSC and GSC.

In Figure 3, the red line indicates GSC current loops and blue one shows RSC current loops. Current loops of both GSC and RSC with a band width are very similar. Figure 4 shows the step response for the grid side, and it reaches the steady state in 15 milliseconds.

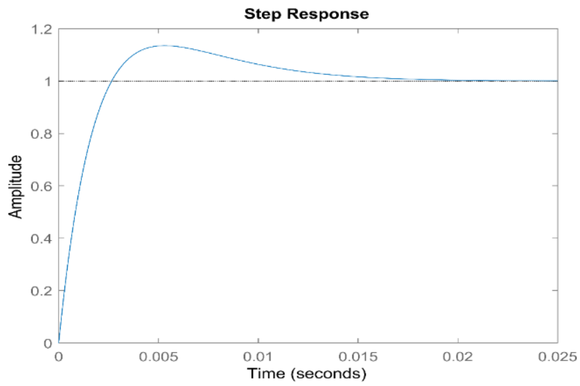

Fig. 4 Step response of the GSC.

4. Control Strategy

4.1. PI Controller

The PI controllers are some kinds of regulators that combines proportional and integral operation in one unit [15]. It is important to create a PI regulator, in order to assure that the rotor speed, generated torque, the direct (i_{dr}) and quadrature (i_{qr}) rotor currents follow their references. The torque coefficient and output power curve of the wind turbine are shown in Figure 5. The proposed output power curve has been confirmed by comparing with the output of the generated power for various wind speed.

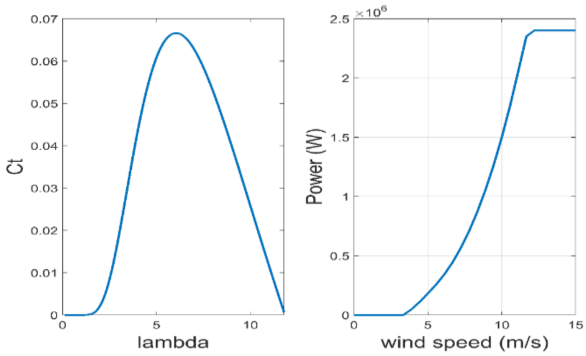

Fig. 5 Torque coefficient versus lambda and power curve.

4.2. Indirect Speed Control

Different strategies have been presented in the literature to control the wind turbine under partial load while tracking the maximum power extraction. At this point, there are two types of speed control: direct and indirect speed control. In this paper, MPPT by indirect speed control is considered. This approach is important because it ensures a variable speed operating system, to optimizes the power output across a given wind speed. The power generated by the three blades becomes maximum by maximizing the power coefficient (C_p). As a result, lambda (λ) should be maximum such that the blades capture the maximum amount of wind energy. Assume the variable speed turbine is functioning at a level of the curve with speed of the wind and rotor torque unchanged (Figure 6). When the rotor speed is lowered to Ω_{t-b}, the operational level shifts to level b, and torque becomes T_{t-b}. Mechanical torque is held at the previous level relating to T_{t-a}, thus T_{t-b} is greater than electromagnetic torque T_{em} and rotor speed rises till it stabilizes near Ω_{t-a} level once again. The technical parameters of DFIG are presented in Table 1.

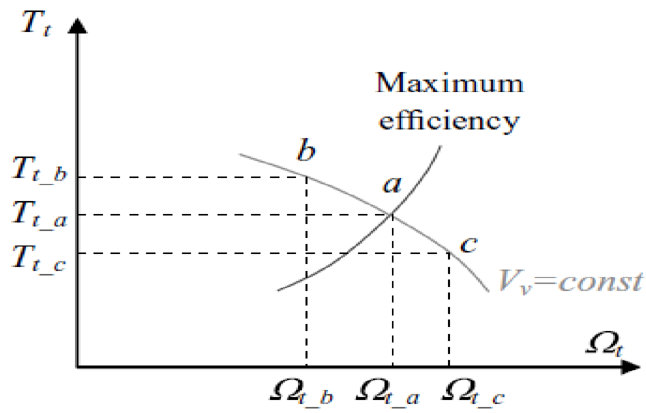

Fig. 6 MPPT stability curve [14]

Table 1. Doubly-fed induction generator parameters

Parameters	**Values**
Rated power	2 MW
Nominal voltage	690 V
Electromagnetic torque	12732 Nm
Rotational speed	1800 rpm
Stator resistance	2.6m Ω
Stator inductance	2.6m H
Rotor resistance	2.9m Ω
Rotor inductance	2.6m H
Number of poles	2

5. Results and Discussion

The overall simulation system has been carried out in MATLAB 2019a software. Three-blade wind turbine of 2.4 MW power has been chosen for the system simulation. The switching frequency for the whole simulation is set at 4 kHz. Quadrature rotor currents behavior is illustrated in Figure 7. It is noted, that the quadrature rotor current component is very accurate.

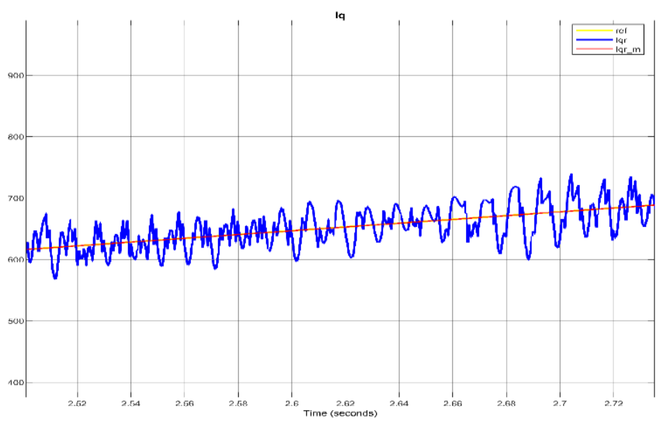

Fig. 7 Quadrature rotor currents behavior

In Figure 8, it can be realized that, the theoretical model (idr_m) has been a little bit degraded but thanks to the compensation, the theoretical model fits quite well with the actual one (idr).

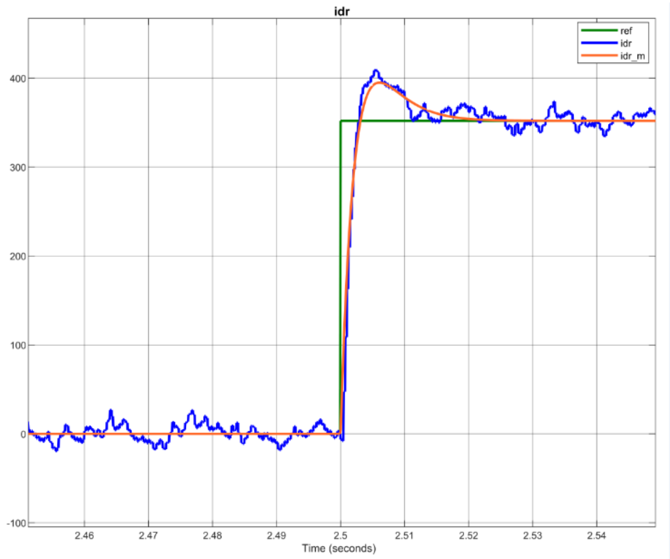

Fig. 8 Direct rotor current behavior

Figure 9 demonstrates the grid reactive power reference.

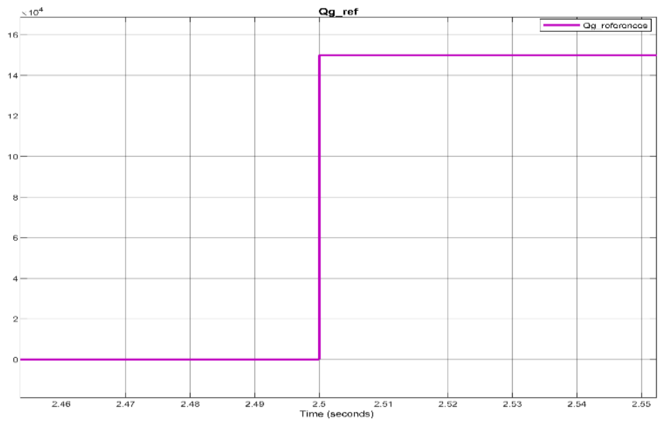

Fig. 9 Grid reactive power reference

Figure 10 and 11 represents quadrature and direct rotor voltage references, respectively. It should be noted that to follow properly dynamic performance of DFIG it is not required to reach the saturation of the voltage references.

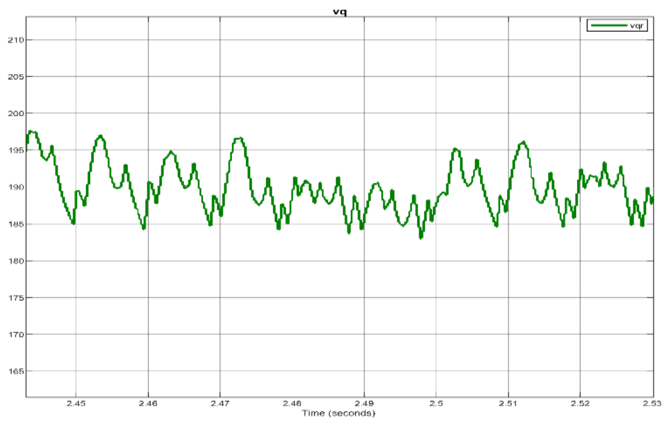

Fig. 10 Quadrature rotor voltage reference

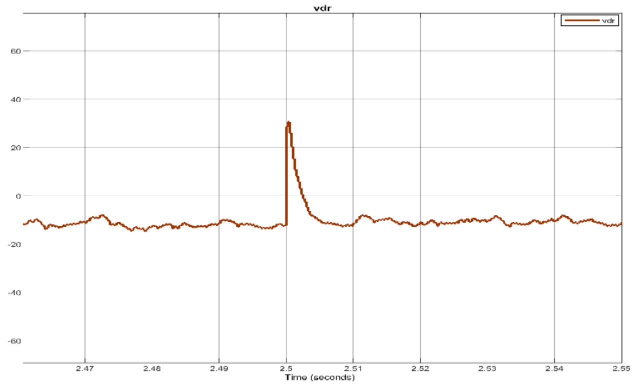

Fig. 11 Direct rotor voltage reference

DC bus voltage in the grid side is shown in Figure 12. We can see that DC bus voltage reaches its steady-state at 1150 V.

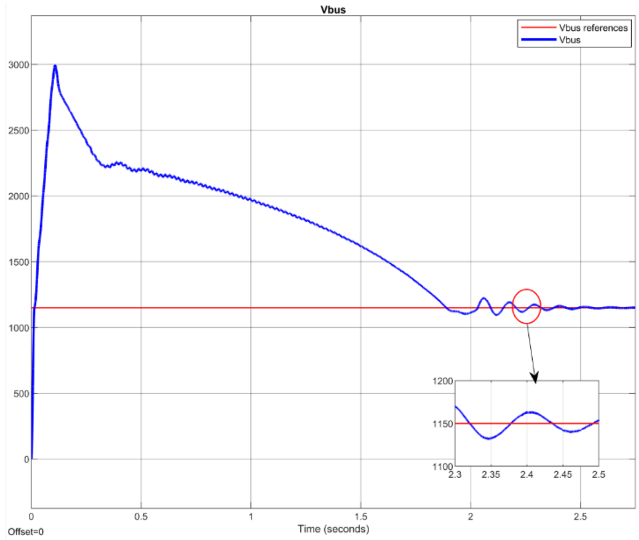

Fig. 12 DC bus voltage

Direct and quadrature grid currents behavior are presented in Figure 13 and 14, respectively. The behavior of the direct grid current is very accurate. The performance of 3-phase grid currents is demonstrated in Figure 15.

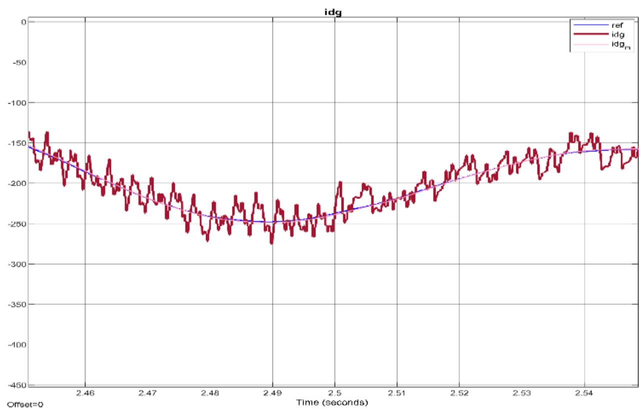

Fig. 13 Direct grid current behavior

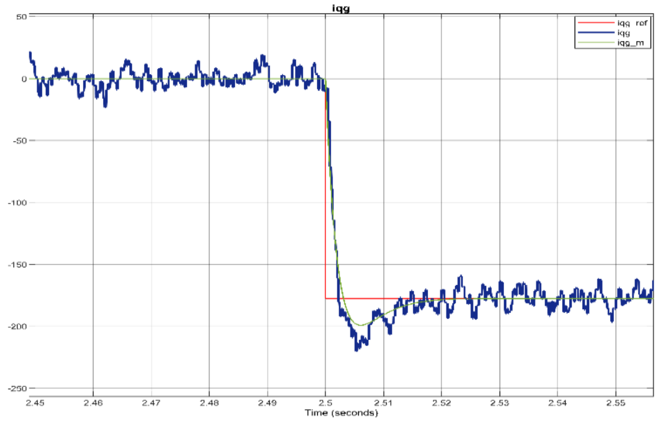

Fig. 14 Quadrature grid current behavior

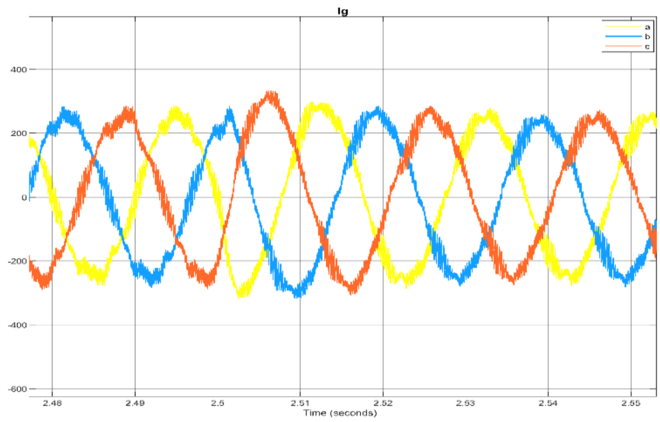

Fig. 15 Three-phase grid currents

6. Conclusion

This paper employs vector control strategy of a wind turbine based on DFIG. From the simulation results, it can be observed that the RSC controls the rotor current loops, and rotor voltage references, while, the GSC controls the DC bus voltage and grid reactive power. On the other hand, stator flux-oriented technique is applied to regulate the current loops in the rotor side. Likewise, the grid voltage-oriented technique is implemented to regulate grid reactive power as it varies according to the grid code. The simulated results demonstrates that the accuracy and the similarities of the actual and theoretical current components for both RSC and GSC.

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