A new method of virtual direct torque control of doubly fed induction generator for grid connection

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ABSTRACT

Over the past few years, due to the shortage of fossil fuels and their unwanted environmental impacts, the use of renewable energy has vastly increased. Among them is wind power, which has been at the center of attention as one of the most important renewable energies. Many studies have been conducted regarding wind farms with variable speeds. Among these, the doubly fed induction generator (DFIG) has been of utmost importance due to its capability of separately controlling the active and reactive power, reducing the nominal converter capacity, maintaining constant variable speed frequency, and improving quality. The goal of this study is to control the synchronizing and network connection to the DFIG such that when connected to the network, no pulse is seen in the torque, rotor current, or stator. The method used in this study is known as virtual torque, which is derived from direct torque control, but instead of an electromagnetic torque, we use a virtual one. To implement this method, it is only required to measure the network voltage, current, and rotor position, and changing the control algorithm from synchronizing to grid connection only includes some changes in the flux references and torque, and calculating the electromagnetic torque instead of the virtual one.

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1. INTRODUCTION

The wind farm system has been at the center of attention over the past decade due to its challenging cost, lack of environmental impacts, and the use of renewable energy sources instead of fossil and nuclear fuels. In some countries, the nuclear option is not applicable due to extremely dangerous environmental impacts, and therefore the use of wind farms has been settled in their programs [1]. Generally, wind farms are categorized into two groups: Wind farms without the use of power electronic converters: Most of these farms use a squirrel cage induction generator and connect to the network via what is known as a soft drive. The soft drive is commonly used in order to decrease the inrush current while startup. As it can be seen in Figure 1, a capacitor bank is required in order to compensate for the reactive power needed by the machine [2].

By adding the power electronic converters to the wind farm system, the cost and complication of said farm would be increased but on the other hand the more accurate control of the active and reactive power and improved power quality gives us the capability of synchronizing and connecting to the network without any unwanted effects on the power system [2]. The use of doubly fed induction generator (DFIGs) is in higher priority due to its advantages in comparison to other machinery used in the wind farm systems. Connecting the doubly induction generator to the network is of utmost importance, and few studies have paid attention to it.

A successful synchronizing reduces the pressure forced upon different parts of the wind turbine. The mechanical pressure caused by the torque's transient terms is due to the big current when connecting to the network. A soft and fast connection of the doubly fed induction generator to the network, also small turbulence when connecting are important features when connecting the doubly fed induction generator to the network. When an error occurs in the power system and the wind farm is temporarily removed from the circuit, a swift synchronizing helps connect it to the circuit again after the error has been dealt with and before the induction generator's protection system takes it offline entirely [3].

In [4] vector control has been used for the means of synchronizing. The lack of voltage feedback leads to the voltage difference between the stator and network, and therefore prolongs the time required in order to connect to the network. In [5], [6] two rings have been implicated, one to control the rotor voltage and the other to minimize the network-stator voltage difference before connecting the doubly fed induction generator to the network. In [7] the stator voltage has been controlled directly and by reducing the integral proportional controllers, the control algorithm has been partially simplified. In this study, for the means of synchronizing in the doubly fed induction generator and connecting to the network, the virtual torque direct control method has been used. For this means, initially the virtual flux and virtual torque are explained, and afterwards we represent the virtual torque direct control method by using hysteresis controllers [8].

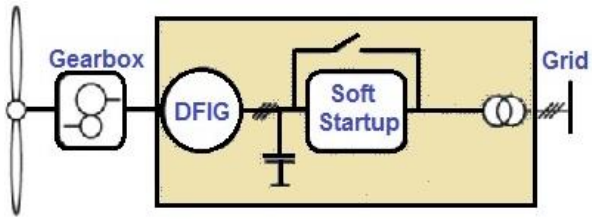

Figure 1. Wind farm based on the squirrel cage induction generator

2. DYNAMIC MODEL OF THE DFIG

First off, we explain the doubly fed induction generator in the stator reference frame. The rotor and stator voltage equations are represented as space vectors [9].

$$\overrightarrow{v_S^S} = R_S\overrightarrow{i_S^S} + \frac{d\overrightarrow{\varphi_S^S}}{dt} \tag{1}$$

$$\overrightarrow{v_r^r} = R_r\overrightarrow{i_r^r} + \frac{d\overrightarrow{\varphi_r^r}}{dt} \tag{2}$$

Which v_s^s is the stator's space vector, i_s^s the stator's space vector, and the space vector for the stator's flux. The (1) has been shown in shown in the stator frame. v_r^r is the rotor's space vector, i_r^r the rotor current's space vector, and φ_r^r is the space vector for the rotor's flux. In (2) has been shown in the rotor frame. On the other hand, the relation between currents and fluxes while in space vector form are as [10]:

$$\overrightarrow{\varphi_s^s} = L_{ss}\overrightarrow{i_s^s} + L_m\overrightarrow{i_r^s} = L_{ss}\overrightarrow{i_s^s}+L_m.e^{j\theta_m}.\overrightarrow{i_r^r} \tag{3}$$

$$\overrightarrow{\varphi_r^r} = L_m\overrightarrow{i_s^r} + L_{rr}\overrightarrow{i_r^r} = L_r\overrightarrow{i_r^r}+L_m.e^{-j\theta_m}.\overrightarrow{i_s^s} \tag{4}$$

which L_{ss} and L_{rr} are the stator and rotor's self-inductance, L_m is the stator and rotor's mutual inductance, and their relations with the stator and rotor's leaking inductance L_{sl} and L_{lr} is as:

$$L_{ss} = L_{ls} + L_m \tag{5}$$

$$L_{rr} = L_{lr} + L_m \tag{6}$$

consequently, the DFIG in the stator's reference frame $(d_s - q_s)$ could be achieved [10].

$$\overrightarrow{v_s^s} = R_s\overrightarrow{i_s^s} + \frac{d\overrightarrow{\varphi_s^s}}{dt} \tag{7}$$

$$\overrightarrow{v_r^s} = R_r\overrightarrow{\iota_r^s} + \frac{d\overrightarrow{\varphi_r^s}}{dt} - j.\omega_m.\overrightarrow{\varphi_r^s} \quad (8)$$

$$\overrightarrow{\varphi_s^s} = L_{ss}\overrightarrow{\iota_s^s} + L_m\overrightarrow{\iota_r^s} \quad (9)$$

$$\overrightarrow{\varphi_r^s} = L_m\overrightarrow{\iota_s^s} + L_{rr}\overrightarrow{\iota_r^s} \quad (10)$$

The electric power on the rotor and stator sides are calculated as (11)-(14).

$$\mathrm{P_s} = \frac{3}{2}\mathrm{Re}\{\overrightarrow{\mathrm{v_s}}.\overrightarrow{\mathrm{i_s^*}}\} = \frac{3}{2}(\mathrm{v_{s\alpha}}.\mathrm{i_{s\alpha}} + \mathrm{v_{s\beta}}\mathrm{i_{s\beta}}) \quad (11)$$

$$P_r = \frac{3}{2}Re\{\overrightarrow{v_r}.\overrightarrow{\iota_r^*}\} = \frac{3}{2}(v_{r\alpha}.i_{r\alpha} + v_{r\beta}i_{r\beta}) \quad (12)$$

$$Q_s = \frac{3}{2}Im\{\overrightarrow{v_s}.\overrightarrow{\iota_s^*}\} = \frac{3}{2}(v_{s\beta}.i_{s\alpha} - v_{s\alpha}i_{s\beta}) \quad (13)$$

$$Q_r = \frac{3}{2}Im\{\overrightarrow{v_r}.\overrightarrow{\iota_r^*}\} = \frac{3}{2}(v_{r\beta}.i_{r\alpha} - v_{r\alpha}i_{r\beta}) \quad (14)$$

Eventually, the torque equation is calculated via (15).

$$T_{em} = \frac{3}{2}.p.Im\{\overrightarrow{\varphi_r^*}.\overrightarrow{\iota_r}\} = \frac{3}{2}.p.Im\{\overrightarrow{\varphi_s}.\overrightarrow{\iota_r^*}\} = \frac{3}{2}.p.Im\{\overrightarrow{\varphi_s^*}.\overrightarrow{\iota_s}\} = \frac{3}{2}.\frac{L_m}{L_s}.p.Im\{\overrightarrow{\varphi_r}.\overrightarrow{\iota_s^*}\} = \frac{3}{2}.\frac{L_m}{2\sigma.L_{rr}.L_{ss}}p.Im\{\overrightarrow{\varphi_r^*}.\overrightarrow{\varphi_s}\} \quad (15)$$

Which in the equation mentioned above $\sigma = 1 - \frac{L_m{}^2}{L_{ss}.L_{rr}}$ is the leaking factor and P is the count of machine pole pairs. It must be noted that for the means of writing simplification, the S superscript has been omitted from the power and torque [10], [11].

3. IMPLEMENTATION OF THE VIRTUAL DTC METHOD

For the means of synchronizing the doubly fed induction generator with the network, and preventing mechanical and electrical stress, it is required to have these conditions before connecting the DFIG to the grid: The stator voltage must have the same domain as the network voltage. The stator and network voltage frequency must be equal. And the stator and network voltages are to be on the same phase. Only in such conditions when we connect the DFIG to the network, no severe fluctuation would occur in the torque and inrush current within the stator and rotor [12].

3.1. The concepts of virtual direct torque control

Direct torque control is a very efficient vector control method for induction machine drives that has been used for the last two decades. In this method, machine flux and electromagnetic torque are considered as reference quantities that are directly controlled by the voltage vector related to the inverter. Since direct torque control (DTC) is a vector control method of induction machine, in addition to the frequency and amplitude, it has the ability to control the instantaneous angular position of the voltage spatial vectors. As a result, this method is able to control and maintain the correct and optimal angular position between the effective spatial vectors in the behavior of the induction machine in the stable and transient state. The virtual torque control is derived from the direct torque control, with the difference that instead of the electromagnetic torque, we use a virtual torque which is calculated from the byproduct of the rotor's flux and the network's virtual flux [13].

3.2. Virtual flux

The term "virtual flux" is used because such a flux does not physically exist, and its mathematical concept is used for controlling purposes. The virtual flux is acquired from the network voltages [14]:

$$\theta_g = \tan^{-1}\left(\frac{\overline{V}_{\beta g}^{g}}{\overline{V}_{\alpha g}^{g}}\right) - \frac{\pi}{2} \quad (16)$$

$$\theta_g = \tan^{-1}\left(\frac{\overline{V}_{\beta g}^{g}}{\overline{V}_{\alpha g}^{g}}\right) - \frac{\pi}{2} \quad (17)$$

$$\left|\bar{\varphi}_g\right| = \frac{|\bar{V}_g|}{\omega_s} \tag{18}$$

which ω_s is the network's angular velocity and is acquired from:

$$\omega_s = \frac{d\theta_g}{\mathrm{dt}} \tag{19}$$

which $\bar{V}^{\mathrm{g}}_{\alpha\mathrm{g}}$ and $\bar{V}^{\mathrm{g}}_{\beta\mathrm{g}}$ are the network's voltage vectors in the network's reference frame with an ω_s angular speed. As it is observed in (17) and (18), alike the stator flux in the direct torque control, the virtual torque has a constant domain and frequency. The virtual flux is always 90 degrees behind the network voltage. Because the virtual torque is constant in both amount and frequency, it could be easily calculated from the network amounts [15].

3.3. Virtual torque

As mentioned before, the virtual torque could be acquired from the rotor's true flux and the network's virtual flux [16], [17]:

$$T_v = K\left|\bar{\varphi}^r_g\right|\left|\bar{\varphi}^r_r\right| sin\acute{\delta} \tag{20}$$

where δ′ is the angle between the rotor flux and the virtual network flux. The K coefficient is acquired from:

$$K = \frac{3}{2}p\frac{L_m}{L_{ss}L_{rr}\sigma} \tag{21}$$

where L_m, L_{rr}, and L_{ss} are respectively are the magnetizing inductance, rotor self-inductance, and the stator self-inductance. σ is the leaking factor which could be acquired from the (22) [18].

$$\sigma = 1 - \frac{L_{\mathrm{m}}^2}{\mathrm{L_{rr}L_{ss}}} \tag{22}$$

4. SYNCHRONIZING AND CONNECTING THE DFIG TO THE GRID

In the DFIG turbine-generator, the generator is a wound rotor induction (WRI) type, and the rotor winding is fed by a power electronic converter. The power electronic converter consists of two converters: one converter on the rotor side and the other converter on the grid side. These two converters are controlled independently. The duty of the converter on the rotor side is to control the real and reactive power that the generator exchanges with the network. In fact, by means of the converter on the rotor side, the speed of the generator can be adjusted along with the changes in the wind speed so that the aerodynamic power transferred to the turbine shaft is the highest. The grid side converter controls the DC link voltage and can also be used for reactive power injection and voltage control. Connecting the DFIG to the grid requires synchronizing the stator and the grid voltage. In this paper, we have used the rotor side converter in order to fulfill this condition [19]. The function of the grid-side converter in the DFIG generator is to stabilize the DC link voltage by exchanging real power with the grid. In addition, this converter can play a role in setting the power factor and exchanging reactive power with the network. The duty of the converter on the rotor side is to control the real power and speed of the generator. By means of the converter on the rotor side, it is also possible to control the reactive power that the generator exchanges with the network.

4.1. Classic virtual direct torque control

During the idle time, which the stator is separated from the network, we could represent the relation between the stator's flux and voltage as (23) and (24) [20].

$$V_s = \frac{d\varphi_s}{dt} \tag{23}$$

$$\theta_s = \tan^{-1}\left(\frac{V_{s\beta}}{V_{s\alpha}}\right) - \frac{\pi}{2} \tag{24}$$

The subtitle *S* indicates the stator frame. Based on (16), (17), (23), and (24) the voltage's phase and frequency in both the network and stator is only achieved is the network's virtual flux would be equal to the stator's flux in both phase and frequency. As it could be seen in Figure 2, the required conditions in order to line up the network's and stator's flux vectors is to reset the $\acute{\delta}$ angle to zero. Because the *d* axis in the network's reference frame (d_g) is in line with the voltage's vector (V_{ga}), and the d axis in the stator's reference frame (α) is in line with (V_{sa}), therefore in order to line up these two voltage vectors is to line up d_g and α. On the other hand, the angle between the rotor's flux and the network's virtual flux according to Figure 2, (17) and (24) are also $\acute{\delta}$ [21], [22].

During the idle time before connecting to the network, the stator is an open circuit, therefore the torque created by the machine and the angle between the stator's and rotor's flux are 0, therefore the stator's and rotor's flux are lined up. We could conclude from what was said that the rotor's flux being lined up with the network's virtual flux is the same as the stator's flux being lined up with the network's virtual flux. Meaning that in order to satisfy the condition of the stator's flux and network's virtual flux vectors to be lined up, we could analyze if the network's virtual flux is lined up with the rotor's flux. Based on (20) the requirement for $\acute{\delta}$ to be 0 is that the virtual torque T_v which was introduced before, be 0 as well. We could ensure the virtual torque to be 0 by introducing the reference signal 0 into the torque control ring during the direct virtual torque control. By applying the 0-reference signal for T_{v-ref}, two out of three conditions required for synchronization are satisfied. The third condition is the equality of the network and stator voltage domains, which would be satisfied through the flux control ring in the direct virtual torque control. In the direct virtual torque control method, the stator voltage domain is indirectly controlled by the flux control ring. In other words, by introducing the proper flux into the hysteresis controllers, we could ensure the voltage domain required by the stator. In order to acquire the rotor's flux reference, we show the doubly fed induction generator's equations once more during the idle time and according to the stator's current being 0 [23].

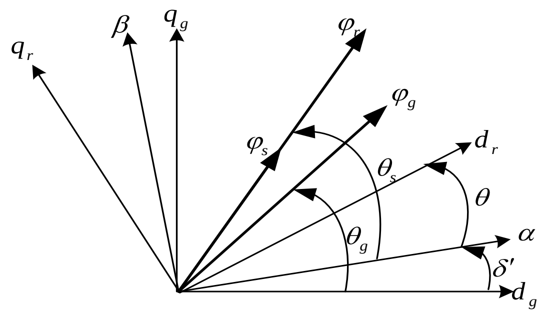

Figure 2. The stator, rotor, and network's flux vectors

$$\vec{V_s} = R_s\vec{I_s} + \frac{d\vec{\varphi}_s}{dt} \xRightarrow{I_s=0} \vec{V_s} = \frac{d\vec{\varphi}_s}{dt} \tag{25}$$

$$\vec{V_r} = R_r\vec{I_r} + \frac{d\vec{\varphi}_r}{dt} - j\omega_r\vec{\varphi}_r \tag{26}$$

$$\vec{\varphi}_s = L_s\vec{I_s} + L_m\vec{I_r} \xRightarrow{I_s=0} \vec{\varphi}_s = L_m\vec{I_r} \tag{27}$$

$$\vec{\varphi}_r = L_r\vec{I_r} + L_m\vec{I_s} \xRightarrow{I_s=0} \vec{\varphi}_r = L_r\vec{I_r} \tag{28}$$

As it was mentioned before, we could see in (27) and (28) that during the idle time, the rotor and stator flux vectors are lined up. Based on (27) and (28):

$$|\vec{\varphi}_r| = \frac{L_r}{L_m}|\vec{\varphi}_s| \tag{29}$$

on the other hand, $\vec{V_s}$ while idle is:

$$\vec{V_s} = j\omega_s\vec{\varphi}_s \tag{30}$$

therefore $|\vec{\varphi}_s|$ would be:

$$|\vec{\varphi}_s| = \frac{|\vec{V_s}|}{\omega_s} \tag{31}$$

hence the equation between the stator and rotor voltage domains while idle is acquired by (32).

$$|\vec{\varphi}_r| = \frac{L_r}{L_m}\frac{|\vec{V}_s|}{\omega_s} \tag{32}$$

In order to acquire the proper rotor flux reference, $|\vec{V}_s|$ must be equal to the network's voltage $|\vec{V}_g|$, therefore:

$$|\vec{\varphi}_r|_{ref} = \frac{L_r}{L_m}\frac{|\vec{V}_g|}{\omega_s} \tag{33}$$

The basic block diagram of the virtual direct torque control is shown in Figure 3. In order to estimate the rotor's flux, we use the common way used in the direct torque control method. Although calculating the rotor's flux is based on the machine's parameters, but this relation is minor in comparison to the relation to the integral proportional controllers of the vector control method, and therefore the lesser output is affected by the machine parameters' fluctuations [24].

The switching table using for this method, is the same as the switching table using for the direct torque control, and this is an advantage of the direct virtual torque control for synchronization which does not require to change the switching table when changes the state from idle to network connected. As it is shown in Figure 3, the converter on the rotor's side during idealization, is responsible for synchronizing the stator and network voltages [25].

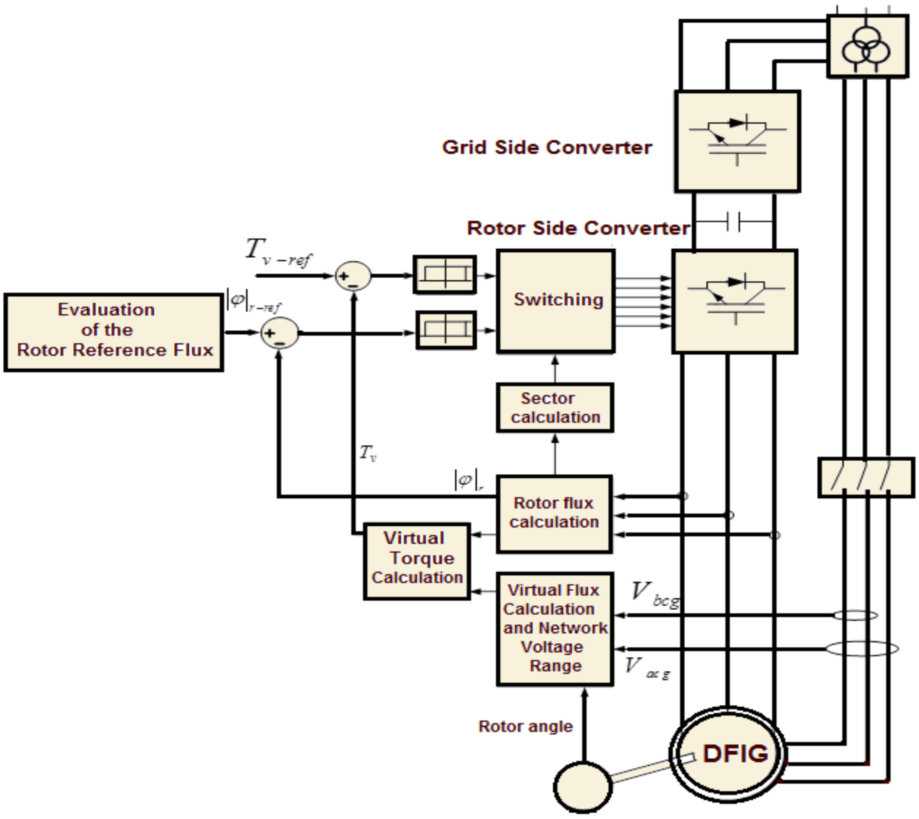

Figure 3. Block diagram of the basic virtual DTC for synchronizing and DFIG connection to the grid

4.2. Connecting the DFIG to the grid

After the DFIG stator voltage was completely synchronized with the network's voltage, then we could connect the generator to the network via a triple-phased switch. After connecting to the network, the direct virtual torque control would be replaced by the direct torque control so that it would control the doubly fed induction generator's performance during normal conditions (after connecting to the network). As mentioned before, the switching table for the direct virtual torque control is the same as the switching table for the direct torque control. Therefore, in order to connect to the network, there is no need to change the switching, and the entirety of the required changes refer to the hysteresis controller inputs. There is no need to calculate the virtual torque for the direct torque control, and instead we must calculate the machine's actual torque and the rotor's reference flux would also be calculated via the classic direct torque control method. After analyzing the synchronization, the machine's stator is connected to the network. Switching from the virtual torque to the electromagnetic torque does not negatively impact the controlling method, because during the transient state of connecting to the network, both the true and virtual torques are zero. The virtual torque is 0 in order to satisfy the synchronization condition between the stator and network voltages, and the electromagnetic torque is not applied during the moment of swift connection to the DFIG. Meaning that during the initial moments of connected to the network, the electromagnetic torque is still zero. The situation is also favorable regarding the stator's current, because before connecting to the network, the stator is an open circuit. And its current is zero, and also the electromagnetic torque is zero during the first moment of connection to the network, and the stator and network voltages are synchronized. Therefore we could expect that stator's current would remain zero on close to it [24], [25]. Figure 4 shows the switching process. One can note that the change in the torque reference of torque control loop is seen by the overall control as a reference step independently of the nature of the estimated torque. In the same way, the switching from the rotor reference calculation of mode 1 to the one of mode 2 is equivalent to the rotor flux reference step [26].

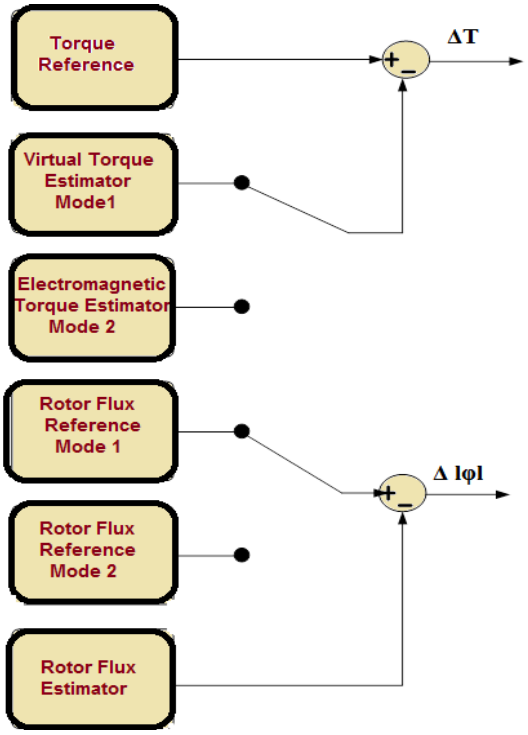

Figure 4. Principle of transition from no-load mode to grid-connection mode

5. RESULTS AND DISCUSSION

A direct virtual torque control (DVTC) for the grid connection of DFIG to the grid has been proposed. This new control method is based on the control of the generator rotor flux and newly defined virtual torque in order to meet synchronization conditions between grid and stator voltages. The previous analysis allows one to state that the transition from mode 1 to mode 2 requires the following.

1) The switching from the virtual torque estimator needed for the DVTC in mode 1 to the generator electromagnetic torque used in the DTC algorithm of mode 2.
2) The switching from the rotor flux reference calculation in mode 1 to the one based on the stator reactive power command as mentioned.

Furthermore, the rotor flux estimator is naturally the same for the two modes. Simulations were carried out under MATLAB-Simulink and PSIM environments in order to prove the effectiveness of the proposed overall control system. The simulated parameters for the DFIG are noted in the Table 1. Based on these parameters, the nominal power of DFIG is equal to 15 kW, the number of pole pairs is equal to 4, the nominal torque of the machine is equal to 95 Nm and the network's frequency is at 50 Hz.

Table 1. The simulated parameters for the DFIG

DFIG nominal power	$\boldsymbol{P = 15kW}$
Effective nominal power (line to line)	$V_n = 220\sqrt{3}$
Stator's leakage inductance	$L_{ls} = 0.005H$
Stator's resistance	$R_s = 0.168\Omega$
Stator's self-inductance	$L_{ss} = 0.05$
Rotor's leakage inductance	$L'_{lr} = 0.005H$
Rotor's resistance	$R'_r = 0.199\Omega$
Rotor's self-inductance	$L'_{rr} = 0.05H$
Magnetizing inductance	$L_m = 0.045H$
Number of pole pairs	$p = 4$
Frequency	$f_s = 50Hz$
Nominal torque	$T = 95N.m$

5.1. Synchronizing the stator's voltage with the grid

In this section, we represent the simulation results from the basic direct virtual torque control method which was based on the hysteresis controllers. The sampling frequency was at 40 kHz, and the DFIG was kept at a constant of 900 rpm. Simulation results indicate that by using said method we could smoothly and swiftly synchronize the doubly fed induction generator with the network. For the means revealing the suggested method, initially virtual torque was set at 40 N so that network and stator voltages would have some phase and frequency difference, and the virtual flux would be set at 0.8 Wb so that the stator voltage's domain would be different from the network's voltage. Afterwards at 0.4s the synchronization control is applied; the reference virtual torque would be set at 0 and the rotor's flux would be at 1.1004 Wb.

As it could be seen in Figures 5 and 6, at 0.4 s the virtual flux and torque references are applied. The rotor and virtual fluxes could well enough follow their own references. Figure 7 indicates the network and stator voltages, which were expected to be different in domain, frequency, and phase before applying the proper virtual torque and flux references. After adjusting the appropriate virtual torque and rotor flux references in the system, the stator and network voltages become synchronized in less than one period.

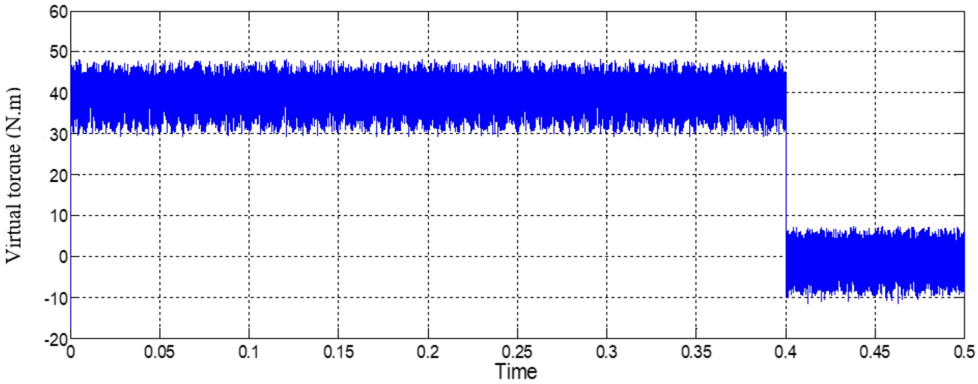

Figure 5. The virtual torque figure in the basic virtual DTC method

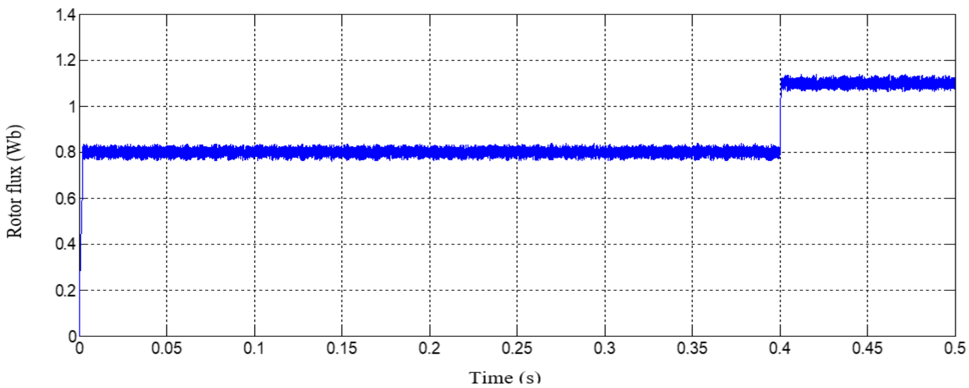

Figure 6. The rotor flux in the basic virtual direct torque control method

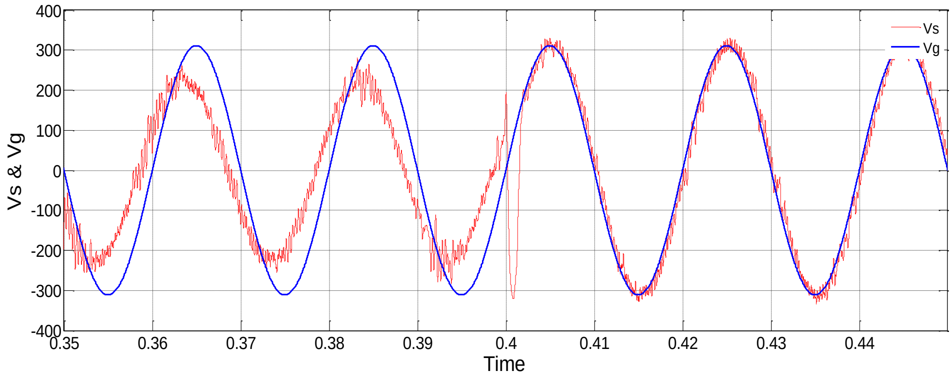

Figure 7. The stator and network voltage in the basic direct virtual torque control method

In Figure 7, it is completely shown that during the synchronization point, the stator voltage indicates a jump. For the means of a smoother synchronization with the network, instead of applying a sudden step, the virtual torque and rotor flux references are brought to their proper amount in 0.01 s. Therefore, the stator voltage fluctuations would be smoother.

Figures 8 and 9 indicate the virtual torque and rotor flux for the mode that their references would change via a slop limiter. In these conditions, as shown in Figure 10 the stator and network voltages would synchronize much more smoothly. Moreover, only the simulation results with the slop limiter would be shown in Figure 11 the rotor current has been shown in the basic direct virtual torque control method. As it could be seen, the rotor’s current domain and phase change in order to compensate the stator voltage and phase.

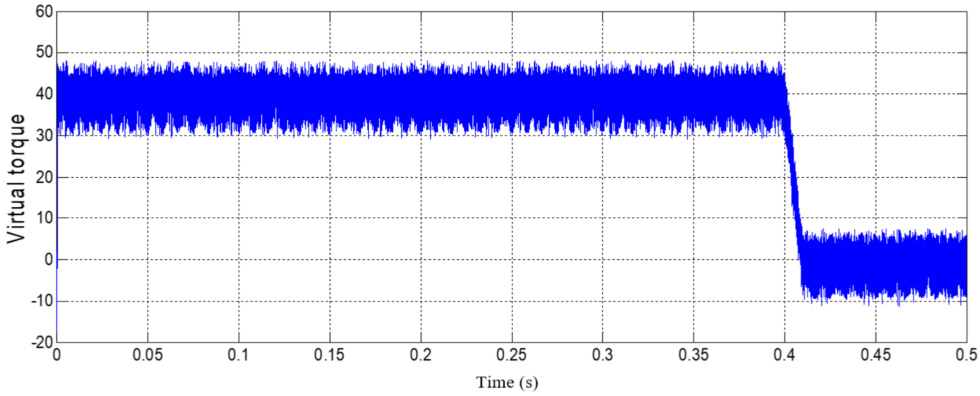

Figure 8. The virtual torque in the basic direct virtual torque control method with a slope limiter

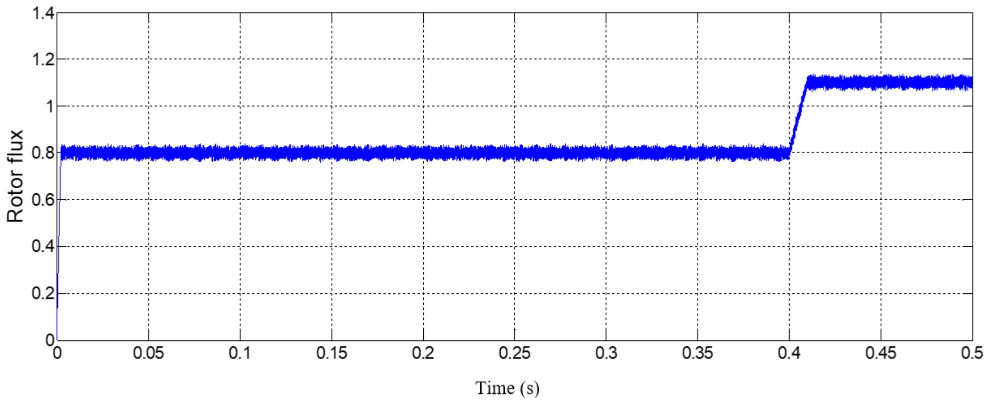

Figure 9. The rotor flux in the basic direct virtual torque control method with a slope limiter

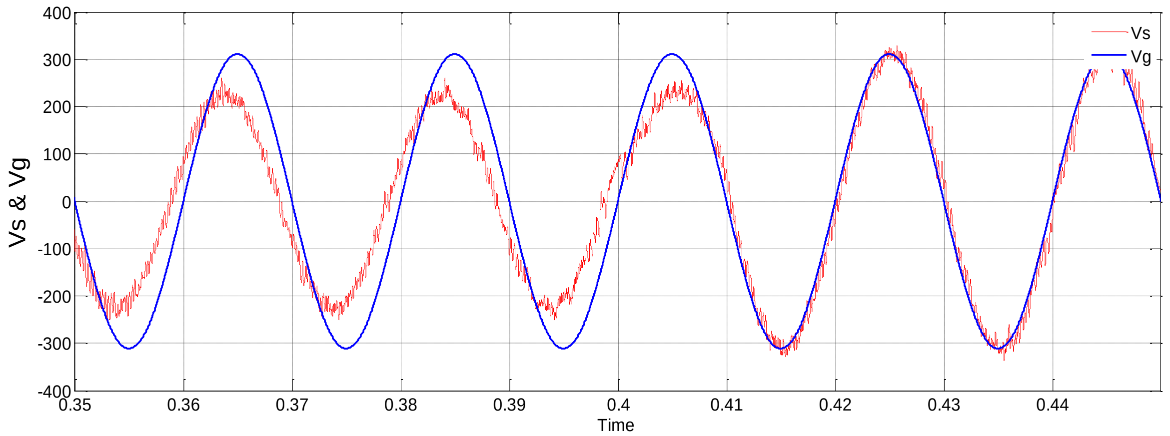

Figure 10. The network and stator voltage in the direct virtual torque control method with a slop limiter

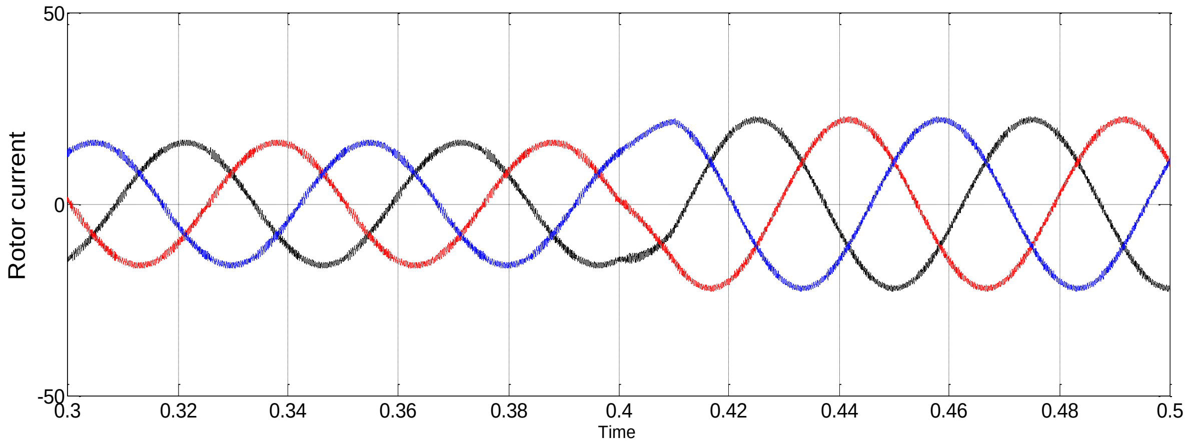

Figure 11. The rotor current in the basic direct virtual torque control method

5.2. Connecting the DFIG to the grid using the basic virtual direct torque control

In this section, the doubly fed inductor generator's connection to the network is shown via the basic direct virtual torque control method. As it was said before, in order to connect to the network and work in loaded conditions, it is only needed to change the rotor flux and torque references, and estimate the machine's electromagnetic torque instead of the virtual torque. In this section, initially in the moment of 0.1 s, the direct virtual torque control is applied for the means of synchronization. At 0.3 s, the DFIG is connected to the network, and the classic direct torque control takes over instead of the direct virtual torque control. In this stage the generator is not instantly loaded and still the electric torque is kept at 0. Afterwards at 0.4 s, a torque of -100 N is introduced into the DFIG. As seen in Figure 12, before synchronization the flux was set at 0.65 Wb. Afterwards at 0.3 s, the rotor flux is adjusted to 1.1004 (proper amount for synchronization), and at 0.4 s the rotor flux is set to 0.8 Wb for the means of functioning in loaded conditions. Figure 13 indicates the virtual flux DFIG until connected to the network, because after connecting to the network, DFIG is replaced by the machine's true torque. Figure 14 indicates the machine's actual torque. Until 0.3 s the stator is an open circuit and the electromagnetic torque is 0. When connected to the network, the direct torque control takes over instead of the direct virtual torque control, and the reference torque is still regulated at 0 while the stator is connected to the network.

As shown, the moment the generator is loaded and when connected to the network, no overshooting is indicated in the torque, while it was shown before that without synchronization, the torque could have an overshot of nearly 500%. In Figure 15, the stator current is shown. As it was expected, the current is 0 during synchronization. When the nominal torque is applied to the DFIG, a nominal current of 45 A is created in the stator. Figure 16 shows the stator current (zoom) at the moment when the DFIG is loaded; No overshoot current is observed at this time.

The DFIG rotor's current is shown in Figure 17. When connecting to the network (0.3 s), no fluctuation or overshot is seen in the rotor's current, and it indicates that connecting to the network has no effect on the rotor current while the DFIG is not loaded yet. This figure indicates the completely smooth DFIG connection to the network. At 0.4 s, which the DFIG would be loaded, the rotor's current reaches 32 A.

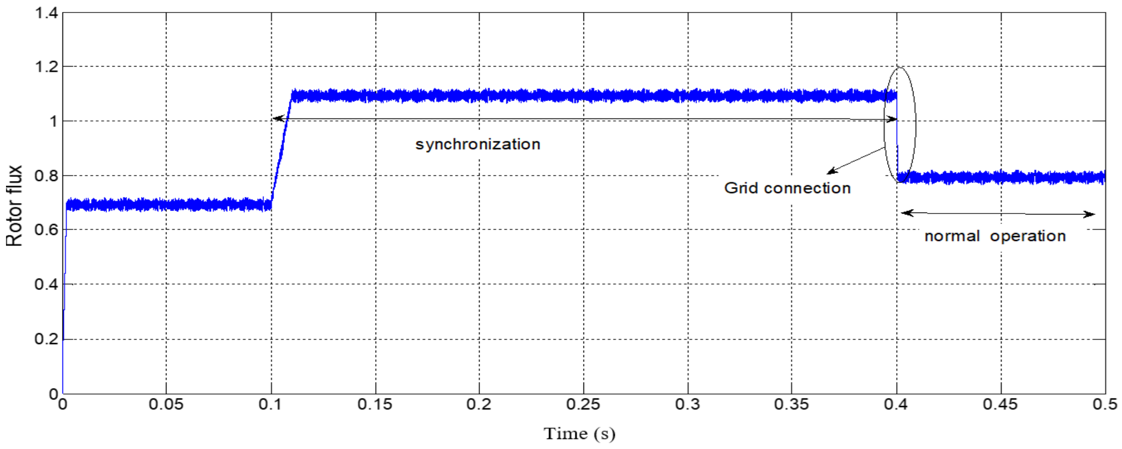

Figure 12. The rotor flux domain in the virtual direct torque control in order to connect DFIG to the grid

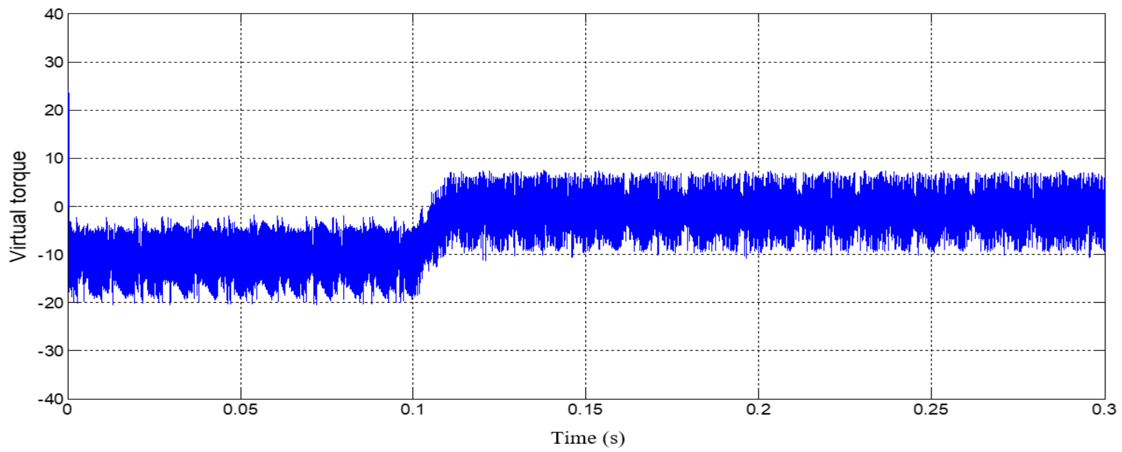

Figure 13. Virtual torque in the virtual direct torque control in order to connect DFIG to the grid

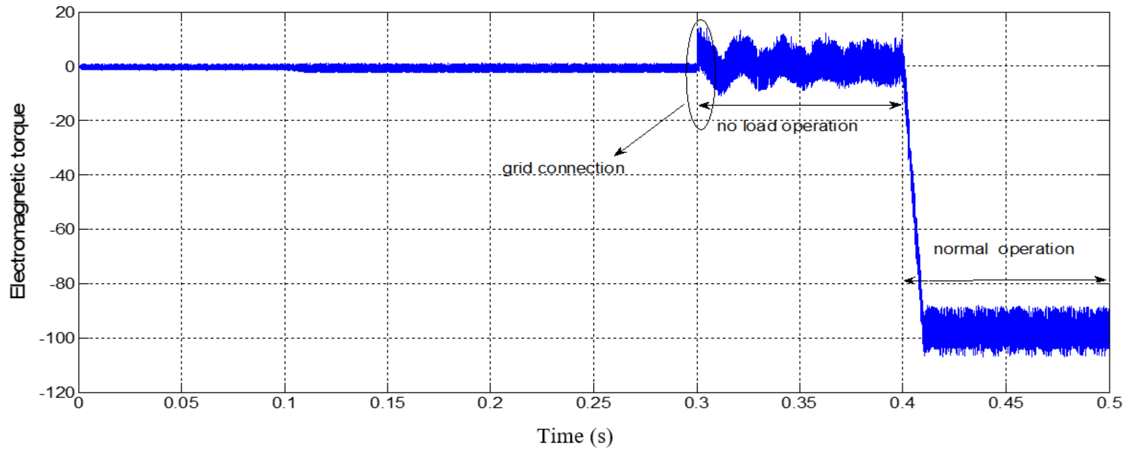

Figure 14. Electromagnetic torque of DFIG

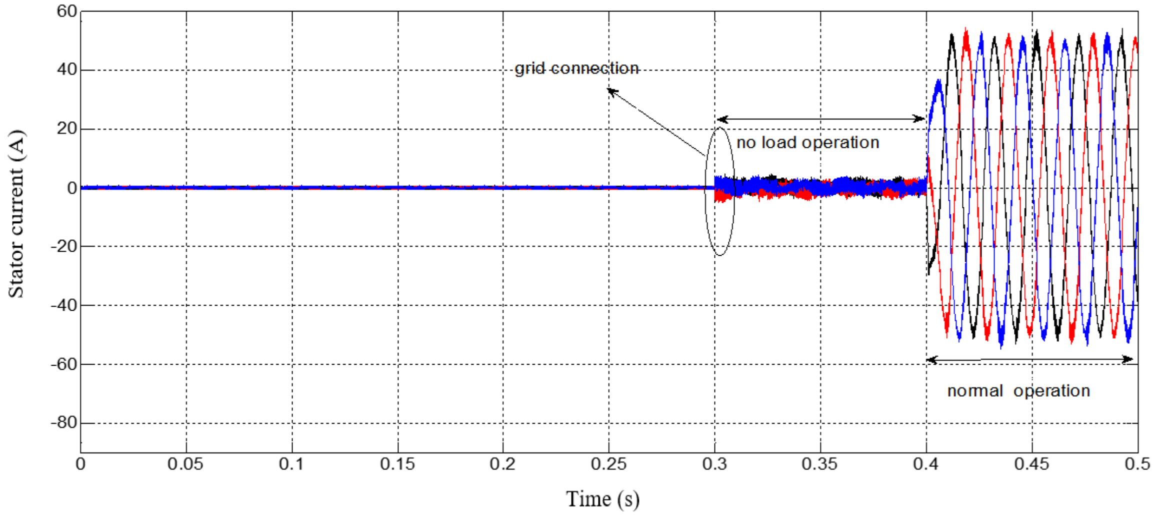

Figure 15. Stator current of DFIG in the virtual direct torque control method

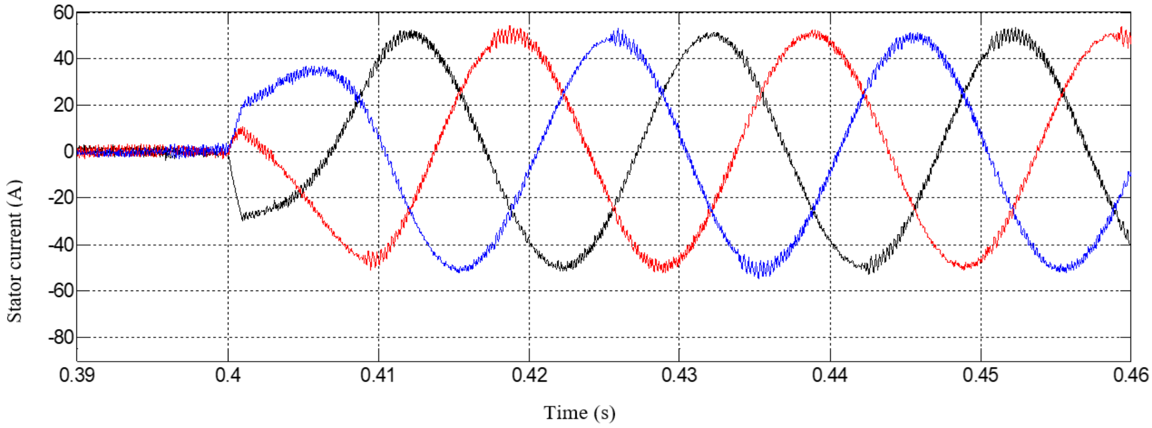

Figure 16. Stator current (zoom) when loading DFIG

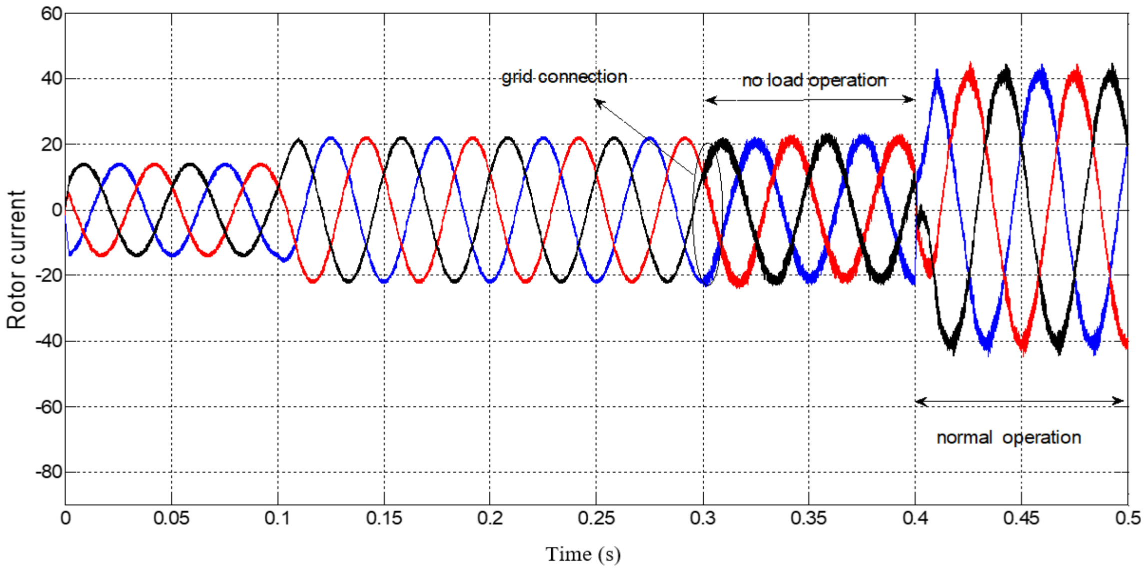

Figure 17. Rotor current of DFIG in the virtual direct torque control method while connecting to the grid

6. CONCLUSION

The use of wind energy is of utmost importance due to being clean and its competitiveness with other sources of renewable energy. Till now, many controlling methods have been represented in the field of wind energy via the DFIG. One of the prevalent methods in controlling the DFIG is the direct torque control, which many studies have taken place in order to improve its effectiveness, reduce the torque and flux fluctuations, and switching with a constant frequency. But connecting the DFIG to the network is of utmost important, while few studies have discussed it. A successful synchronization reduces the pressure applied to various parts of the wind turbine. The mechanical pressure caused by the torque's transient conditions is due to the enormous current at the moment of connecting to the network. A swift and smooth connection of the DFIG to the network and also little turbulence when connecting to the network, are important focal points when connecting said generator to the network. One of the most important reasons for the necessity of a swift connection of the DFIG to the network is that after dealing with the occurred error in the system, it is required to be able to connect the wind farm to the network before it is taken completely offline. In this paper, we have used the direct virtual torque control for the means of synchronization and connecting the DFIG to the network. Initially the basic direct virtual torque control method was represented and simulated. The use of the direct virtual torque control has advantages such as a swift synchronization and connection to a smooth network, which compared to the other methods that accomplish this goal over several periods, synchronization is achieved in this method in less than half a period. In addition to a swift synchronization, this method only requires to measure the network voltage, rotor current and rotor position, and does not require the stator voltage. Due to the virtual torque and the machine's electromagnetic torque being 0, connecting to the network has no impact on the controlling method's quality. Also, an easy implementation of this method is another one of its advantages.

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