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Controlling Variable Speed Wind Turbines Which Have Doubly Fed Induction Generator by Using of Internal Model Control Method

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ABSTRACT: Doubly Fed Induction Generators (DFIG) are as the main generators which are used in the power generation systems of wind energy in Variable Speed-Constant Frequency (VSCF). Wind turbine model and dynamic mathematic model of DFIG have been presented in this article. Rotor currents control in internal loop and rotation speed in external loop have been accomplished according to the methods of Internal Model Control (IMC). A sample of Doubly Fed Induction Generators of VSCF with nominal capacity of 1.5 MW has been simulated in MATLAB software. The simulation results indicate quick dynamic response of system in different conditions and performance in hyper-synchronous and sub-synchronous speed.

KEYWORDS: Doubly fed induction generator, Sub-synchronous speed, Hyper-synchronous speed, Variable speed, Constant frequency, Simulink.

I.INTRODUCTION

In recent years, wind power generation systems of variable speed-constant frequency connected to the network have had significant progress. Existence of wind power generation system in power network has prepared important context for scientist's research of this domain [1, 2]. In comparison with wind turbines which have constant speed- constant frequency, using of wind turbines with variable speed- constant frequency and Doubly Fed Induction Generator has many advantages. Some of them are optimal performance in variable speed, separated control of active and reactive power, reduction of mechanical tensions and noise, improvement of power quality and using of power transformer with nominal power between 25-30 percent of the total power of the system [3]-[7]. Doubly Fed Induction Generators of a system with high rank are non-linear and have powerful relation between their different components. Search in the field of dynamic mathematic model, controlling methods of connection to the network and dynamic performance at the time of voltage collapse have been studied in the references [8] to [10]. In this article, the form of stator and rotor voltage waves, rotor currents and speed in different conditions such as performance in hyper-synchronous and sub-synchronous speeds have been analysed. In [11] study presents an overview and literature survey over past few decades on the different problems associated due to penetration of WT-DFIG in the power system and control aspects of DFIG. Also the dynamic behaviour for a DFIG Wind Energy Conversion system with fuzzy controller is simulated for different fault conditions and the results are compared to that of the system with PI Controllers in [12]. In a new case, the performance of DFIG is analyzed during the operation of sub-synchronous and super-synchronous generating modes using MATLAB/SIMULINK in [13].

Principles of wind turbines with variable speed-constant frequency which have Doubly Fed Induction Generators have been studied and accurate mathematical model of Doubly Fed Induction Generator with considering important details has been simulated. Also controlling has been accomplished according to the stator flux direction. Internal model control in the speed and currents control loops has been used. In order to simulate and do the analyses, a wind turbine system model with nominal capacity of 1.5 Megawatt has been used. Simulation has been done in MATLAB/Simulink software and simulation results indicate confirmation of theoretical analyses and effectiveness of control methods.

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II.PERFORMANCE PRINCIPLES OF DOUBLY FED INDUCTION GENERATORS OF VSCF

Wind turbines with variable speed-constant frequency which have Doubly Fed Induction Generator in a comprehensive look include wind turbine, gearbox for adjusting the speed, Doubly Fed Induction Generator rotor-side transformers and network-side transformers, transformer connected to the network and transmission line connected to the network. Diagram of a sample of wind turbine with doubly fed induction generator has been indicated in the Fig. 1.

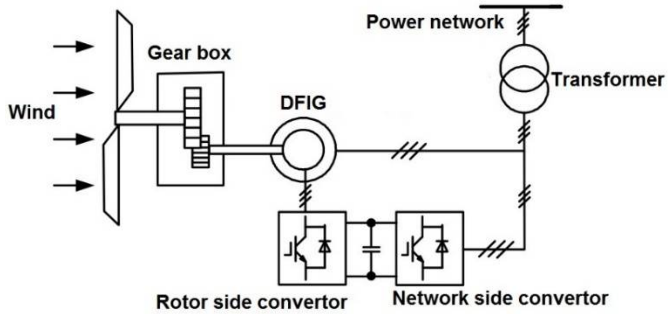

Fig. 1 Diagram of a sample of VSCF DFIG

When electric motor is stable in the performance conditions, the rotational fields of stator and rotor are rotating with synchronous speed. Therefore, the equation between rotational magnetic field of rotor and stator can be expressed as follows:

$$n_1 = n_2 + n_r \qquad (1)$$

Equation No. (1) Can be rewritten in the form of equation (2):

$$\frac{n_r P}{60} + f_2 = f_1 \qquad (2)$$

In above equations, n_1 is the magnetic fieldspeed of stator, n_2 is the magnetic field speed of rotor to stator, n_r is rotor speed, P indicates the number of poles, f_1 and f_2 indicate in order stator currents frequency and rotor currents frequency.

With changes of wind speed, the stator output frequency will remain constant so that VSCF functionality to be obtained. When DFIG is in super- synchronous mode, f_2 is larger than zero. Network provides AC stimulation of low frequency of positive succession and needed power for stimulation transformers. If f_2 is smaller than zero, network will create AC stimulation of low frequency of negative succession by stimulation transformers. In hyper-synchronous mode, slip is negative and in sub-synchronous mode, slip is positive.

III.DYNAMIC MATHEMATICAL MODEL

1. Wind turbine model

Wind turbine is the most important part of process of transforming energy in the power generation system of wind energy. Wind turbine is used for transforming the kinetic energy of wind to electric energy. Wind turbine output is influenced by wind input power. Therefore for safety, the stability and reliable performance should be planned. According to Betz theory, the power of wind turbine is as follows:

$$P_m = \frac{1}{2} C_p \rho S v^3 \qquad (3)$$

C_p is the coefficient of wind turbine power,ρ is the air density, S indicates sweep surface of turbine and v is the wind speed. The power coefficient of wind turbine is a function of deviation angle of blade (β) and the tip speed ratio (λ). We define λ as follows:

$$\lambda = \frac{\omega_{wt} R}{v} \qquad (4)$$

In equation (4), ω_{wt} is the mechanical angle of wind turbine blades and R is the radius of wind turbine blade. The numerical method for calculating the power coefficient of wind turbine (C_p) is in the form of equation (5) [14].

$$C_p(\lambda, \beta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right) e^{\frac{18.4}{\lambda_i}} \qquad (5)$$

In equation (5), λ_i is defined as follows:

$$\lambda_i = \left[\frac{1}{\lambda - 0.02\beta} + \frac{0.003}{\beta^3 + 1}\right]^{-1} \quad (6)$$

For reaching to the maximum power coefficient, there is always an optimal tip speed ratio (λ_{opt}) that can be determined with regard to the amounts of deviation angle of blade (β).

Output torque of wind turbine is proposed as an important parameter in calculations that its amount can be calculated as follows:

$$T_m = \frac{P_m}{\omega_{wt}} \quad (7)$$

2. Dynamic mathematical model of DFIG

Doubly Fed Induction Generator can be divided into two important parts of stator and rotor. Stator-side follows generator rules and rotor-side follows motor rules of electric machines. In other words, the positive direction of currents in stator has been considered in generator form and in rotor it has been considered in motor form. Voltage equations and stator and rotor flux in the reference frame of d-q are expressed as follows:

$$\begin{cases} v_{ds} = -R_s i_{ds} - p\psi_{ds} + \omega_1 \psi_{qs} \\ v_{qs} = -R_s i_{qs} - p\psi_{qs} - \omega_1 \psi_{ds} \end{cases} \quad (8)$$

$$\begin{cases} v_{dr} = R_r i_{dr} + p\psi_{dr} - \omega_s \psi_{qr} \\ v_{qr} = R_r i_{qr} + p\psi_{qr} + \omega_s \psi_{dr} \end{cases} \quad (9)$$

$$\begin{cases} \psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} - i_{dr}) = L_s i_{ds} - L_m i_{dr} \\ \psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} - i_{qr}) = L_s i_{qs} - L_m i_{qr} \end{cases} \quad (10)$$

$$\begin{cases} \psi_{dr} = L_{lr} i_{dr} + L_m (i_{dr} - i_{ds}) = L_r i_{dr} - L_m i_{ds} \\ \psi_{qr} = L_{lr} i_{qr} + L_m (i_{qr} - i_{qs}) = L_r i_{qr} - L_m i_{qs} \end{cases} \quad (11)$$

With change of flux equations to voltage, voltage-current equations in the reference frame of d-q are obtained as follows:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} -R_s - L_s p & \omega_1 L_s & L_m p & -\omega_1 L_m \\ -\omega_1 L_s & -R_s - L_s p & \omega_1 L_m & L_m p \\ -L_m p & \omega_s L_m & R_r + L_r p & -\omega_s L_r \\ -\omega_s L_m & -L_m p & \omega_s L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (12)$$

Electromagnetic torque is also expressed as follows:

$$T_L - T_e = T_L - \frac{3n_p}{2} L_m (i_{ds} i_{qr} - i_{qs} i_{dr}) = \frac{J}{n_p} \frac{d\omega_r}{dt} \quad (13)$$

In above equations, R_s and R_r are armature winding resistors of stator and rotor, L_s, L_r, L_m و L_{ls}, L_{lr} are in order insider inductances of stator and rotor, reciprocal inductance and leaky inductance of rotor and stator. $v_{ds}, v_{qs}, v_{dr}, v_{qr}$ are in order the voltages of d and p axes of stator and rotor. $i_{ds}, i_{qs}, i_{dr}, i_{qr}$ are in order the currents of d and p axes of stator and rotor and $\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr}$ are in order the fluxes of d and p axes of stator and rotor. ω_1 is the synchronous speed, ω_r is rotor speed and $\omega_s = \omega_1 - \omega_r$ is the slip speed. P in above matrix is the differential operator. Above equations indicate full mathematical model of DFIG.

IV.APPLICATION OF INTERNAL MODEL CONTROL (IMC) IN DFIG

Control system of IMC not only is accounted for modelling the inaccurate disturbances of efficiency system, but also for non-linear models, it is one of very proper options. Also non-linear IMC includes integral operator and can guarantee the output convergence of system to the reference of stable state. Non-linear IMC has very interesting features. Designing IMC can be used for controlling the currents or speed of all alternate currents machines [15]. In this article which has been reformed based on non-linear IMC and it is a proper method of analysis, a new solution has been designed and implemented for control of DFIG. This method confirms the effectiveness of internal loop control of

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currents and the external loop controller of speed and indicates that the accomplished simulation from the controlling view is stable.

1. Application of IMC in currents loop
IMC controlling diagram of rotor current loop of wind power generation system of DFIG has been indicated in the Fig. (2):

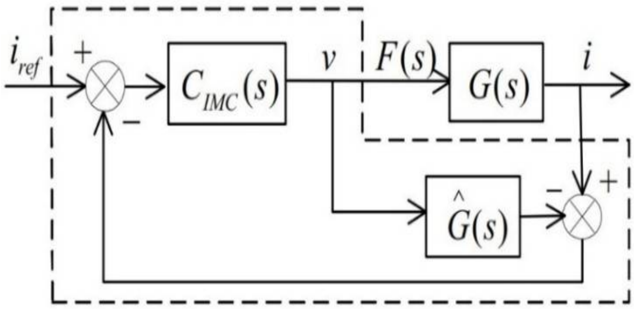

Fig. 2IMC controlling diagram of rotor currents loop of wind power generation system of DFIG

In the Fig.2, $C_{IMC}(s)$is the controller transformer function, G(s) is the controlled system, i_{ref} is the control system input, i is the output currents of system, $\hat{G}(s)$ is the internal model of controlled system and F(s) is the systematic equivalent transformer function which has been drawn in dotted form. For selecting the currents transformer function for $C_{IMC}(s)$, controller designing has high importance. A designing method is as follows [15]:

$$C_{IMC}(s) = \left(\frac{\alpha}{s+\alpha}\right)^n \hat{G}^{-1}(s) \qquad (14)$$

that n and α are determining for designing$C_{IMC}(s)$. α is in the form of $\alpha = \frac{ln9}{t_{rise}}$. The closed loop transformer function is as follows:

$$G_c(s) = \frac{G(s)C_{IMC}(s)}{1 + C_{IMC}(s)[G(s) - \hat{G}(s)]} \qquad (15)$$

If $G_c(s) = G(s)$, equation (15) will be simplified as follows:

$$G_c(s) = \left(\frac{\alpha}{s+\alpha}\right)^n \qquad (16)$$

With similar method, F(s) can be obtained in the following form:

$$F(s) = \frac{C_{IMC}(s)}{1 - C_{IMC}(s)\hat{G}(s)} \qquad (17)$$

Designing IMC with above method has slow dynamic response. For solving this problem, a feed forward feedback is used. By exerting this feedback, improved system diagram of IMC has been indicated in the Fig. 3.

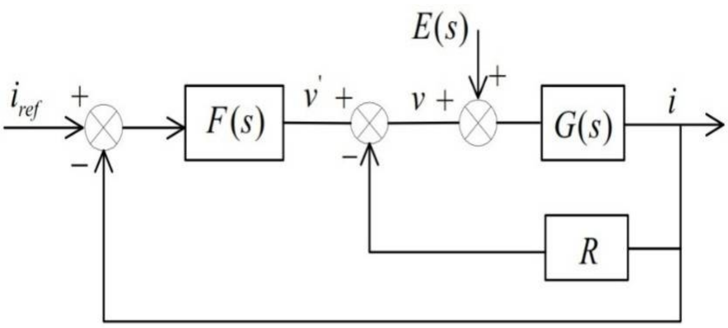

Fig. 3 Improved system diagram of IMC

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The transformer function of this system is as follows:

$$G_E(s) = \frac{G(s)}{1 + G(s)[F(s) + R]} = \frac{\alpha}{s + \alpha} \frac{1}{G^{-1}(s) + R} \quad (18)$$

For a first degree system by selecting $R = \alpha L_r - R_r$, the above transformer function will be as follows:

$$G_E(s) = \frac{s}{L_r(s + \alpha)^2} \quad (19)$$

By doing it, the disturbances effect can be reduced. The transformer function of rotor currents loop will be as follows:

$$G(s) = \frac{i}{\acute{v}} \frac{i}{v + Ri} = \frac{1}{\frac{v}{i} + R} = \frac{1}{L_r s + R_r + R} \quad (20)$$

For the first degree system, n=1, it is enough that currents controller to be designed in the form of a PI controller and equation (21):

$$F(s) = \frac{\alpha}{s} \hat{G}^{-1}(s) = \frac{\alpha}{s}(L_r s + R_r + R) = k_P + \frac{k_I}{s} \quad (21)$$

that k_P and k_I are in order proportional and integral interests. By selecting $R = \alpha L_r - R_r$, two interests will be in the forms of $k_P = \alpha L_r$ and $k_I = \alpha^2 L_r$.

2. IMC application in the speed loop

With regard to the generator torque equation and assuming that the internal loop of currents is quicker than external loop of controllable speed, T_L will be considered as disturbance in electromagnetic torque. In the Fig. (4), the speed loop has been indicated according to IMC.

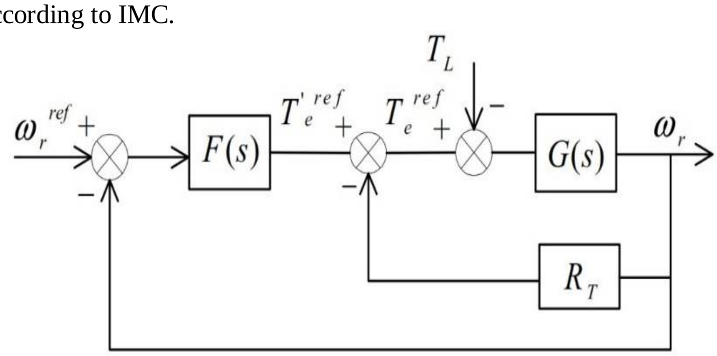

Fig. 4 The speed loop according to IMC

With regard to the Fig. 4, the transformer function of $G_{T_L}(s)$ can be calculated as follows:

$$G_{T_L}(s) = \frac{\omega_r}{T_L} = \frac{s}{\frac{2J}{P}s^2 + (R_T + k_P)s + k_I} \quad (22)$$

that $R_T = \frac{2\alpha_\omega J}{P}$ can be simplified as follows:

$$G_{T_L}(s) = \frac{Ps}{2J(s + \alpha_\omega)^2} \quad (23)$$

With regard to the equation (23), the torque disturbance effect has been reduced. Therefore for simplifying the equations, the disturbance can be withdrawn. In these conditions, the transformer function will be obtained as follows:

$$G(s) = \frac{\omega_r}{T_e^{ref}} = \frac{1}{\frac{2J}{P}s + R_T} \quad (24)$$

Using of IMC rule for a first degree system obtains the speed controller as follows:

$$F(s) = \frac{\alpha_\omega}{s} \hat{G}^{-1}(s) = \frac{\alpha_\omega}{s}\left(\frac{2J}{P}s + R_T\right) = k_P + \frac{k_I}{s} \quad (25)$$

that the proportional and integrator interests will be in the forms of $k_P = \alpha_\omega \frac{2J}{P}$, $k_I = \alpha_\omega R_T$.

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V. RESULT AND DISCUSSION

In this part, simulation of a real system is considered. Wind turbine parameters with variable speed- constant frequency in the simulation are as follows:

Table 1- real system features

Quantity	Size	Sign
Nominal power of generator, DFIG	1.5 MW	P_e
Nominal voltage	690 V	V
Frequency	50 Hz	f
Stator resistor	0.023 p.u.	R_s
Stator inductance	0.18 p.u.	L_s
Rotor resistor	0.016 p.u.	R_r
Rotor inductance	0.16 p.u.	L_r
Reciprocal inductance	2.9 p.u.	L_m
Poles number	6	p
Inertia invariable of wind turbine	0.685 s	H
Wind speed	11 m/s	v

This wind turbine has been connected to a transmission line with length of 30 Km. The simulated model of system in Simulink part of MATLAB software is in the form of Fig. 5.

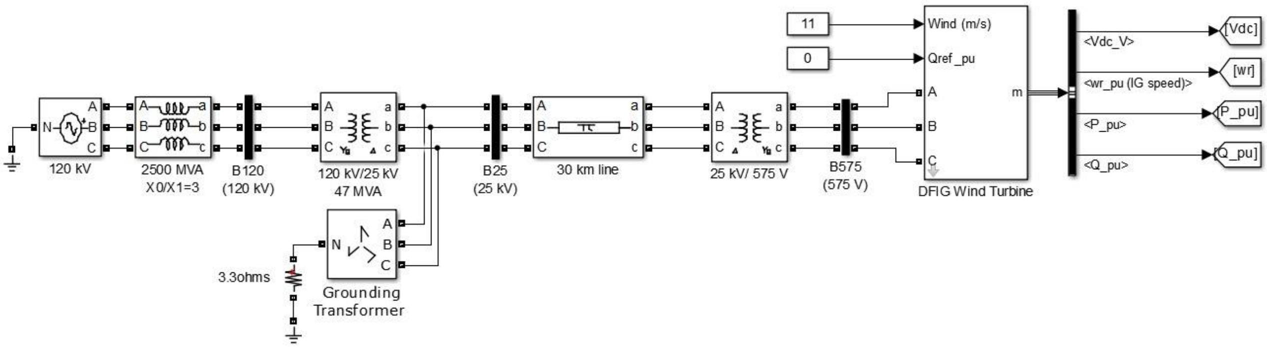

Fig. 5 Simulink model of simulated system

120%rotor speed of synchronous speed has been regulated in p.u. at the time of launch, and after 0.05s it is placed in the torque control situation. The voltage wave of stator and rotor voltage and also the wind speed changes have been brought in the Fig. s 6 to 8.

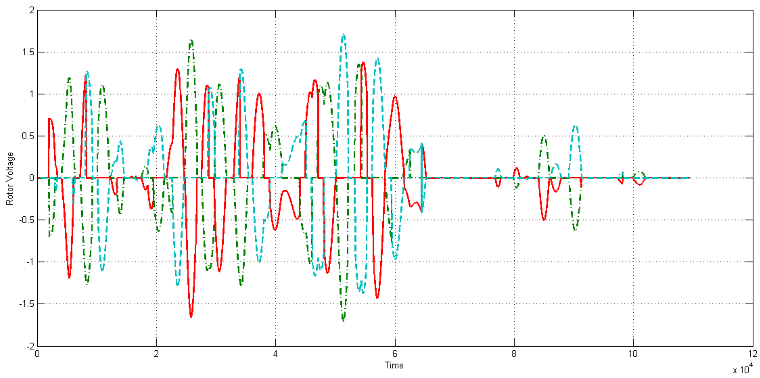

Fig. 6 Wave shape of rotor voltage

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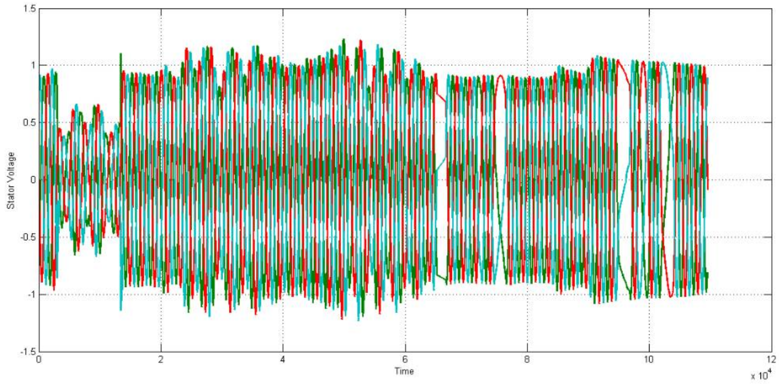

Fig. 7 Wave shape of stator voltage

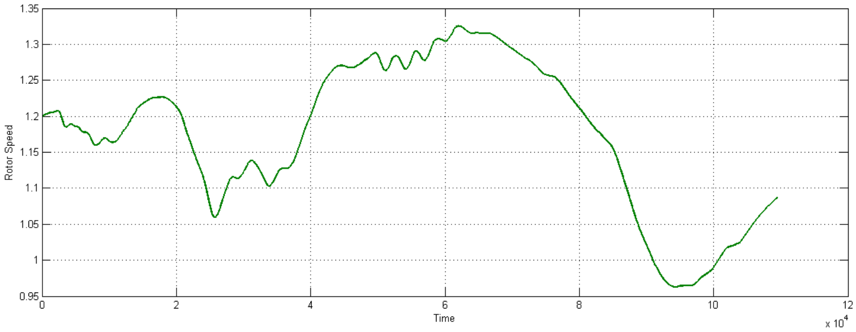

Fig. 8 Wind changes

When rotor speed changes from sub-synchronous to synchronous and hyper-synchronous speed, rotor current frequency changes with turbine speed. Wind turbine with variable speed- constant frequency which has Doubly Fed Induction Generator has been connected to 25-Kv bus-bar by 30-Km transmission line. Bus-bar voltage and currents of 25 kV have been indicated in the Fig. 9.

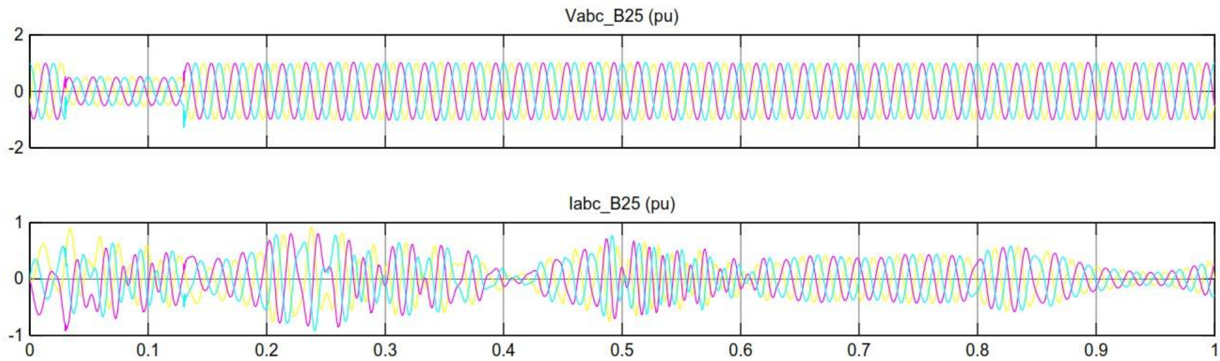

Fig. 9Bus-bar voltage and currents of 25 kV

During the simulation process, analysis of the waves form and comparing it with numerical analyses can lead to design and select the amounts correctly.

VI.CONCLUSION

In this article, the performance of a wind turbine with variable speed-constant frequency which has Doubly Fed Induction Generator was studied and the results which have been obtained from numerical analysis of data were

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simulated on a real system. The effect of proper designing of controllers, IMC and its effects on currents loops and speed were studied. The effects of methods which have been implemented on the system were also considered in final simulation. It was indicated that the presented model due to the quick dynamic response in different speeds can be used for analysing and designing the wind turbine connected to the network.

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BIOGRAPHY

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