A Study on Power Flow Analysis in Power Systems with the Participation of Double-Fed Induction Generators based Wind Turbine System

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ABSTRACT

This paper focuses on double-fed induction generator (DFIG) based wind turbine system (WTS) and evaluate its effect to the distribution of power flow in power system. The structure of DFIG based WTS will be make detailed, including a rotor, stator and back-to-back converters. Power flows in itself are analyzed in both over and under synchronous operating modes. Control structure of DFIG is shown corresponding to rotor-side controller and grid-side controller to harness wind power and synchronize to the power grid. Operating scenarios that can happen in a proposed grid with the participation of DFIG based WTS are also shown to analyze the distribution of power flows in whole system whenever there are variations of power consumption and power generation. Simulation process will be carried out by MATLAB software to demonstrate proposed operating scenarios. Simulation results will show the power flows in whole system, the power adaptability corresponding to variation of load steps, the decrease of power from DFIG based WTS and the variation of currents at buses. Moreover, power exchange between power source and considered grid and current going through main units also can be determined and provided to dispatch center to ensure system stability.

Keywords: DFIG, Control structure, Power flow analysis, Wind turbine, Wind generator, Wind speed.

INTRODUCTION

Generators can be classified into two main kinds, including asynchronous generator (ASG) and Synchronous Generator (SG). DFIG is a type generator of ASGs and considered as the most suitable generator with high rated power in wind power generations. To control and operate this type of generator, DFIG must be connected to a power grid that can absorb or provide power in all operating time [1-3].

DFIG can be designed by slip rings and two windings. Stator winding (static unit) connected to the grid works with fixed frequency and rotor winding (rotating unit) works with variable frequency. In wind power system, the rotor can be driven by blades of wind turbine (caused by wind energy). In real operating process, the variation of wind speed makes DFIG work at synchronous speed, over synchronous speed or under synchronous speed as depicted in Fig.1. These operating mode can cause different power flows in itself (rotor). In both these operating mode, power flow always from stator to the grid. In over synchronous speed, rotor will generate power to the grid. In under synchronous speed, rotor will absorb power from the grid to create magnetic rotating field, called reactive power. It means that reactive power must be met by the grid or a capacitor bank. DFIGs based WTG are often designed with rated power from some tens kW to some MW. To regulate energy flow, rated power of its inverter only equals to 1/3 rated power of other generators that work directly with lip rings in rotor. This advantage can help to reduce system cost remarkably. Furthermore, DFIGs also work in wide range of slip co-efficience to harness almost wind energy at all time [1-3].

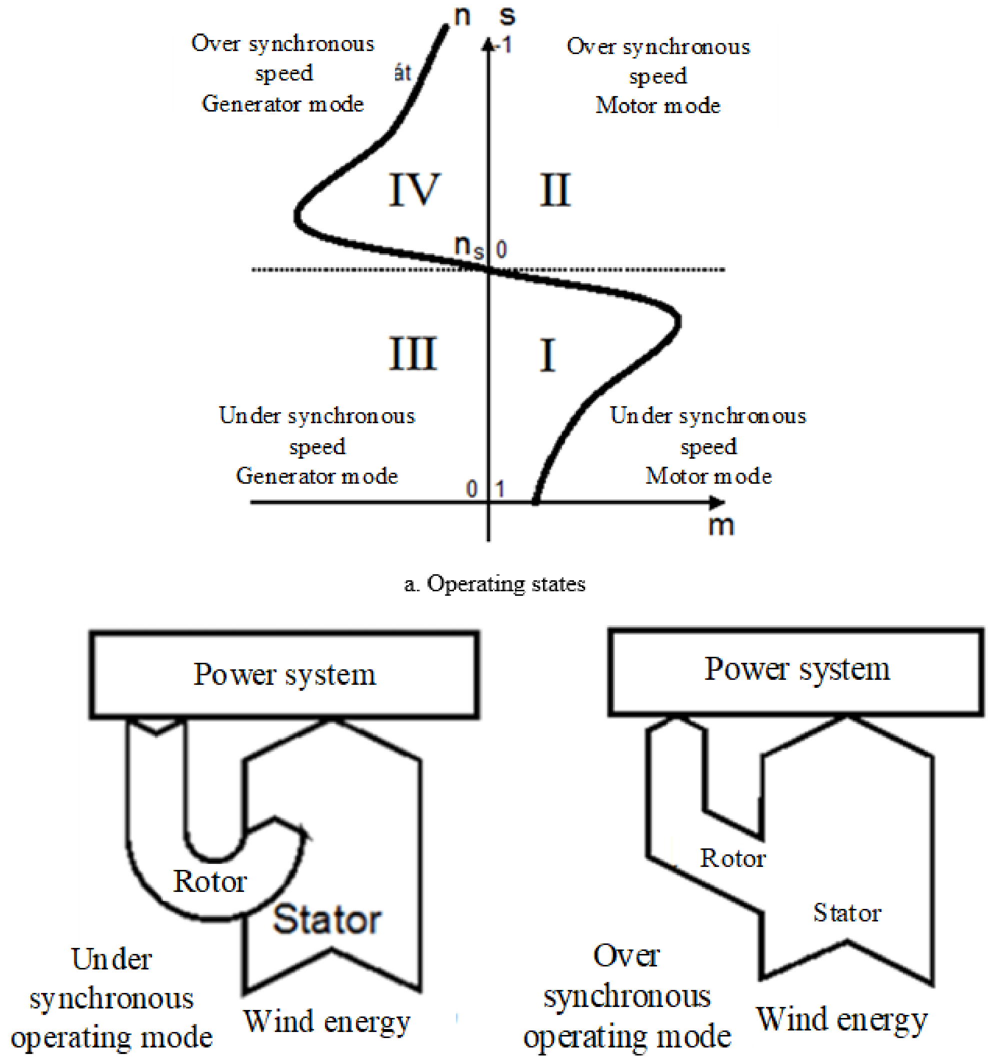

Fig.1 Operating modes and power flows of DFIG

In almost power systems, DFIGs are often considered as distributed generations if individually implemented or large power plants if implemented in wind farms. DFIGs will inject power to the grid depending on instantaneous wind speed if there isn't any energy storage. Sometime, power generating from DFIG can reach to maximum value if wind speed is equal or higher than rated wind speed of designed wind turbine. Moreover, power from DFIG also can be equal to zero if wind speed is smaller than v_{cut-in} or higher than $v_{cut-out}$. So, it must be create analysis to determine power flows distributed in whole system with the participation of DFIG. It can help to determine maximum value of power going through each unit in whole system and create suitable operating solutions. It means that power balance can be ensured and devices such as circuit breakers, transmission lines, etc., can be work stably in long time.

From above analysis, this paper will focus on control structure of rotor and grid-side converter and determine power flows in whole system with the participation of DFIG and the variation of electric loads. The next section will introduce general structure of WTG and control of the rotor and grid-side converters. The third section will present some scenarios of power flows in whole system and simulation results. The last section will show some conclusions and contributions of this paper.

CONTROL STRUCTURE OF DFIG

A. General structure of WTG

Systems of turbine and generator convert wind energy to mechanical energy on turbine axis. The general structure of this system is depicted in Fig.2 [1-3].

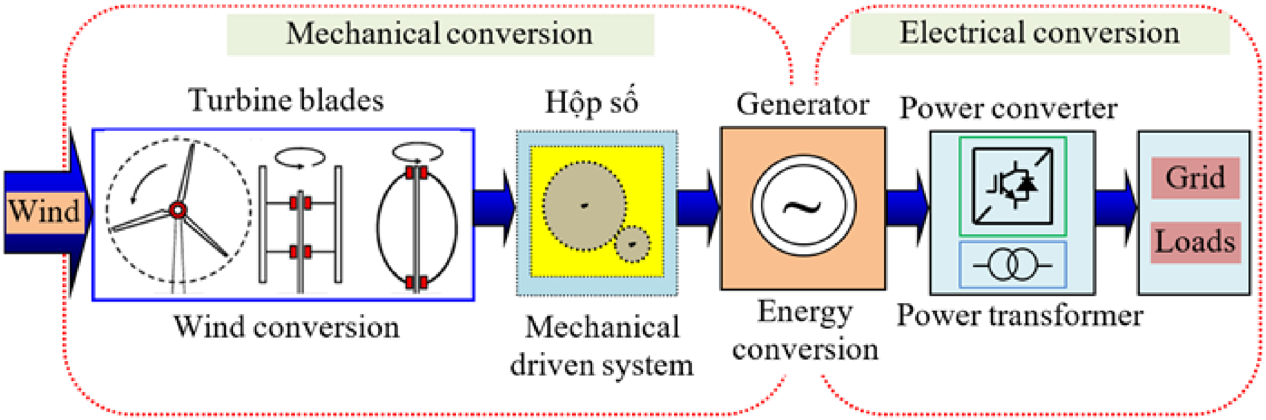

Fig.2 General structure for WTG

Turbine blades are designed in horizontal or vertical axis types to convert wind kinetic energy to rotating movements on turbine axis. They must be designed to stand high wind speed, sudden change of wind direction or many different harsh operating conditions.

The gearbox is coupled to turbine and generator axis. It converts low speed of turbine axis (about (30÷60) round/min) to high speed of generator axis (about (1200÷1500) round/min).

The generator converts magnetic rotating field on generator axis to electric energy.

Power converters and transformers help to regulate working modes for the generator, step up voltage and synchronize to the grid.

DFIG based WTS with partly scale power converter is still the most widely used variable speed wind turbine. The stator side of the DFIG is directly connected to the grid, while a partial-scale power converter is responsible for the control of the rotor frequency as well as the rotor speed. The power rating of the partial-scale converter settles the speed range (typically ±30 % around the synchronous speed). Moreover, the converter performs as a reactive power compensator and a smooth grid interconnection. Smaller power converters have been the benefits of this concept from economic point of view. The configuration of DFIG based WTS partial-scale back-to-back power converters is described in Fig.3.

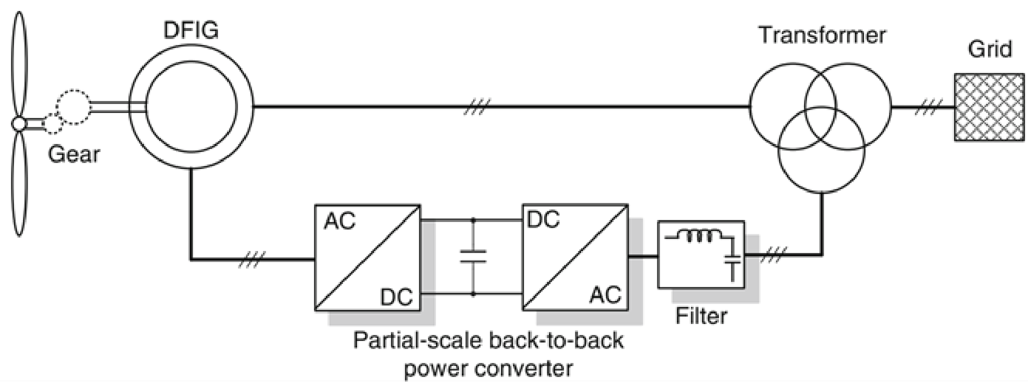

Fig.3 DFIG based WTS configuration with partial-scale back-to-back power converters

B. Control of the rotor and grid-side converters

Vector control is one of the most widely used control schemes for the DFIG based WTS. The dq-reference frames in a vector control can be aligned either to the grid voltage or to the stator flux. The model of the DFIG under grid voltage oriented dq-reference frames can be expressed as equations (1) and (2) [3-10].

$$\begin{cases} u_{sdq} = R_s i_{sdq} + \frac{d}{dt}\psi_{sdq} + j\omega_0\psi_{sdq} \\ u_{rdq} = R_r \dot{i}_{rdq} + \frac{d}{dt}\psi_{rdq} + j\omega_s\dot{\psi}_{rdq} \end{cases} \quad (1)$$

$$\begin{cases} \psi_{sdq} = L_s i_{sdq} + L_m i_{rdq} \\ \psi_{rdq} = L_r i_{rdq} + L_m i_{rdq} \end{cases} \quad (2)$$

where $u_{sdq} = u_{sd} + ju_{sq}$ and $u_{rdq} = u_{rd} + ju_{rq}$ are the stator and rotor voltages;

i_{sdq} and i_{rdq} are the stator and rotor currents;

ψ_{sdq} and ψ_{rdq} are the stator and rotor flux linkage;

L_m, L_s, and L_r are the magnetizing inductance, stator inductance and rotor inductance;

R_s and R_r are the stator and rotor resistances.

Since the d-axis is aligned with stator (grid) voltage vector, the following is valid,

$$u_{sd} = U_g \text{ and } u_{sq} = 0 \quad (3)$$

Based on (1) and (2), the equivalent circuit of the DFIG can be obtained, as it is shown in Fig.4, where L_{ls} and L_{lr} are the stator and rotor leakage inductances and $L_s = L_m + L_{ls}$, $L_r = L_m + L_{lr}$ [3-10].

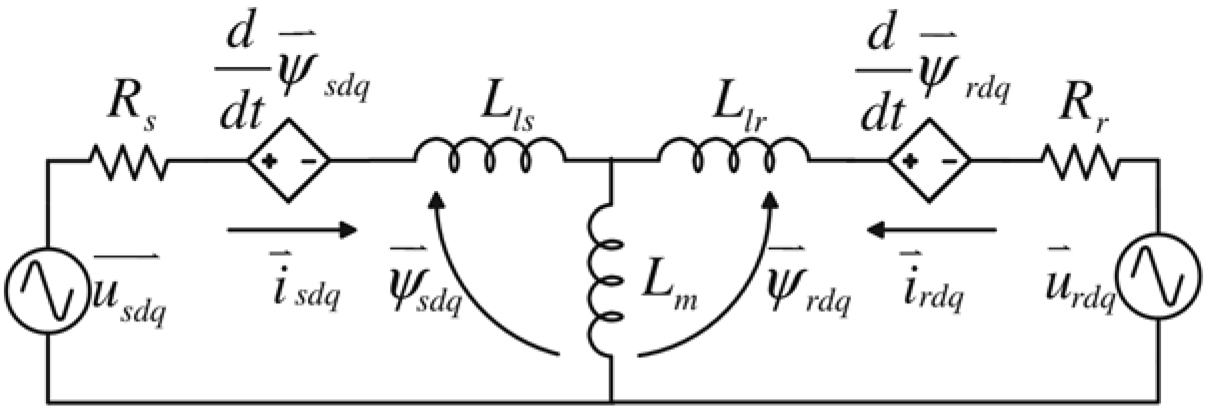

Fig.4 Equivalent circuit of the DFIG in the dq frame

The active power and reactive power output from the stator side of DFIG can be derived from (1) and (2), and can be expressed as equation (4) [3-10].

$$\begin{cases} P_S = -U_g \frac{L_m}{L_S} i_{rd} \\ Q_S = U_g \frac{L_m}{L_S} i_{rq} + \frac{U_g^2}{\omega_1 L_S} \end{cases} \quad (4)$$

It can be concluded that the stator output active power is related to the rotor d-axis current and the reactive power is related to the rotor q-axis current only. As a result, the active and reactive power can be adjusted separately by controlling the rotor dq currents. The grid voltage-oriented vector control scheme for the RSC of the DFIG is shown in Fig.5, which consists of a inner current loop and a outer power loop [3-10].

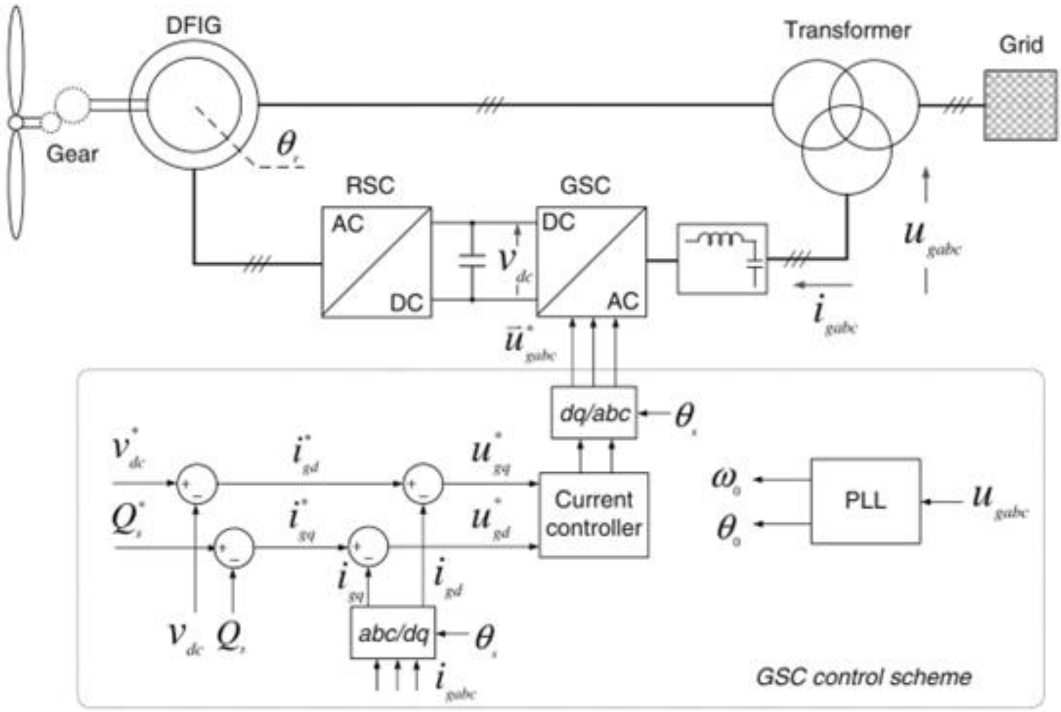

Fig.5 Voltage oriented vector control scheme for the RSC of a DFIG based WTS

The control scheme of the GSC in a DFIG based WTS is similar to that in a full-scale back-to-back WTS. As it is shown in Fig.6, the GSC is controlled by regulating the DC-link voltage and the reactive power [3-10].

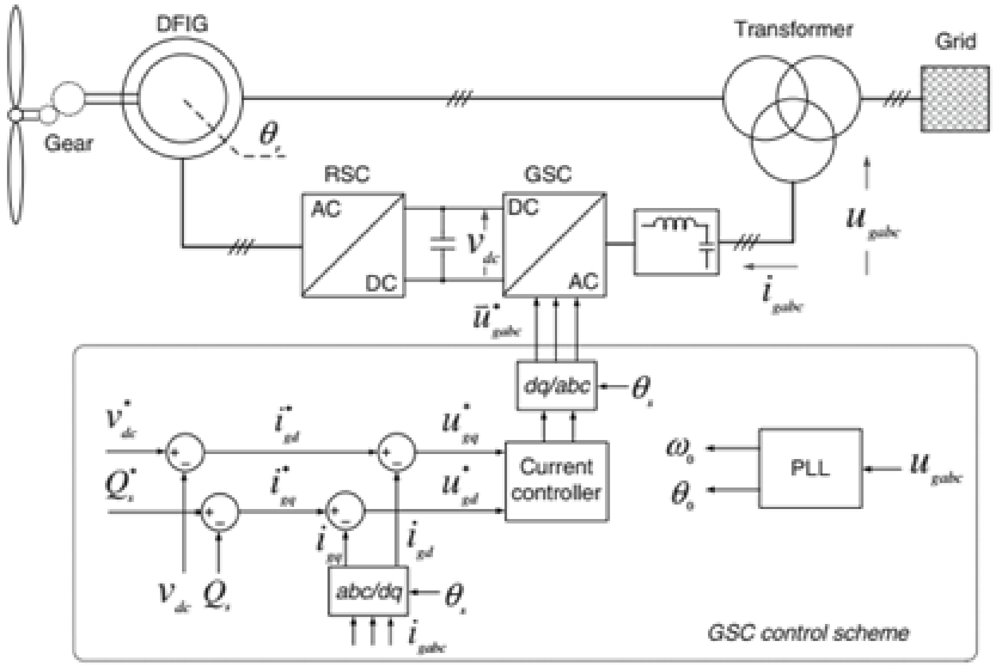

Fig.6 Control scheme for the GSC of a DFIG based WTS

POWER FLOW ANALYSIS AND SIMULATION RESULTS

A. Power Flow Analysis

A DFIG based WTS Plant and two electric loads (Load B4.2 and Load B4.1) are connected at the end of transmission line L1 as depicted in Fig.7. In this system, an electric load (Load B2) is also coupled to at the begining of the L1 transmission line (power-source side).

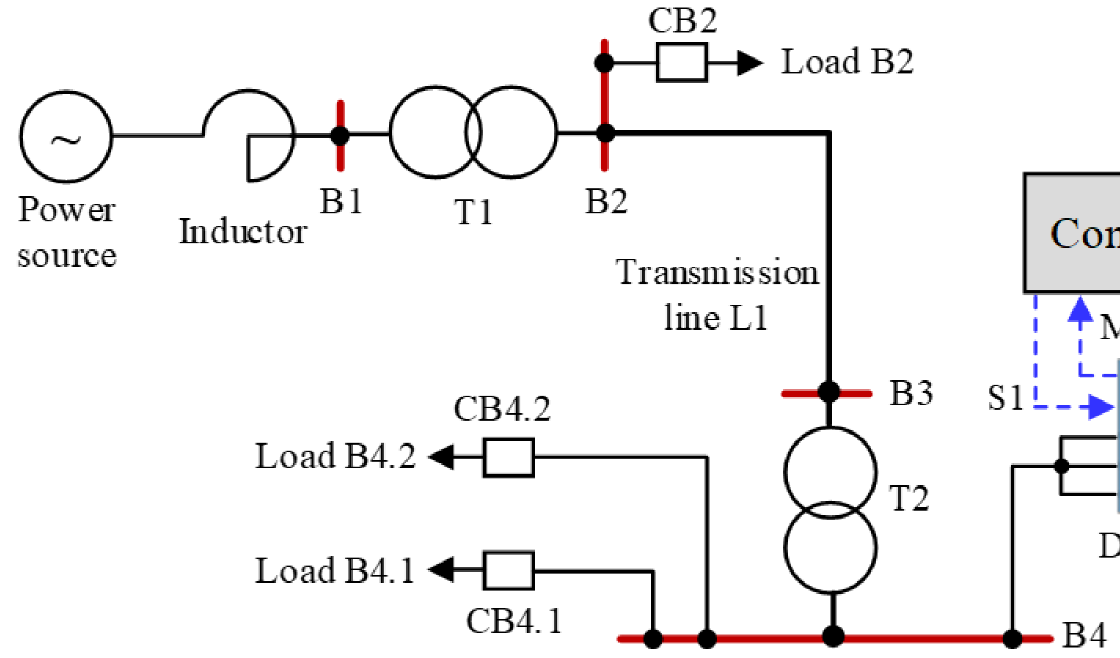

Fig.7 A System with the participation of DFIG base WTS

The system described in Fig.7 has different power distribution depending on total power generating from DFIG based WTS and requirements of electric loads. So, power generating to power source or absorbing from power source can be determine by analyzing some operating scenarios as following.

If power generating from DFIG based WTS is smaller than total power of electric load at B4 Bus (the 1st operating scenario), power flows in whole considered system are represented in Fig.8.

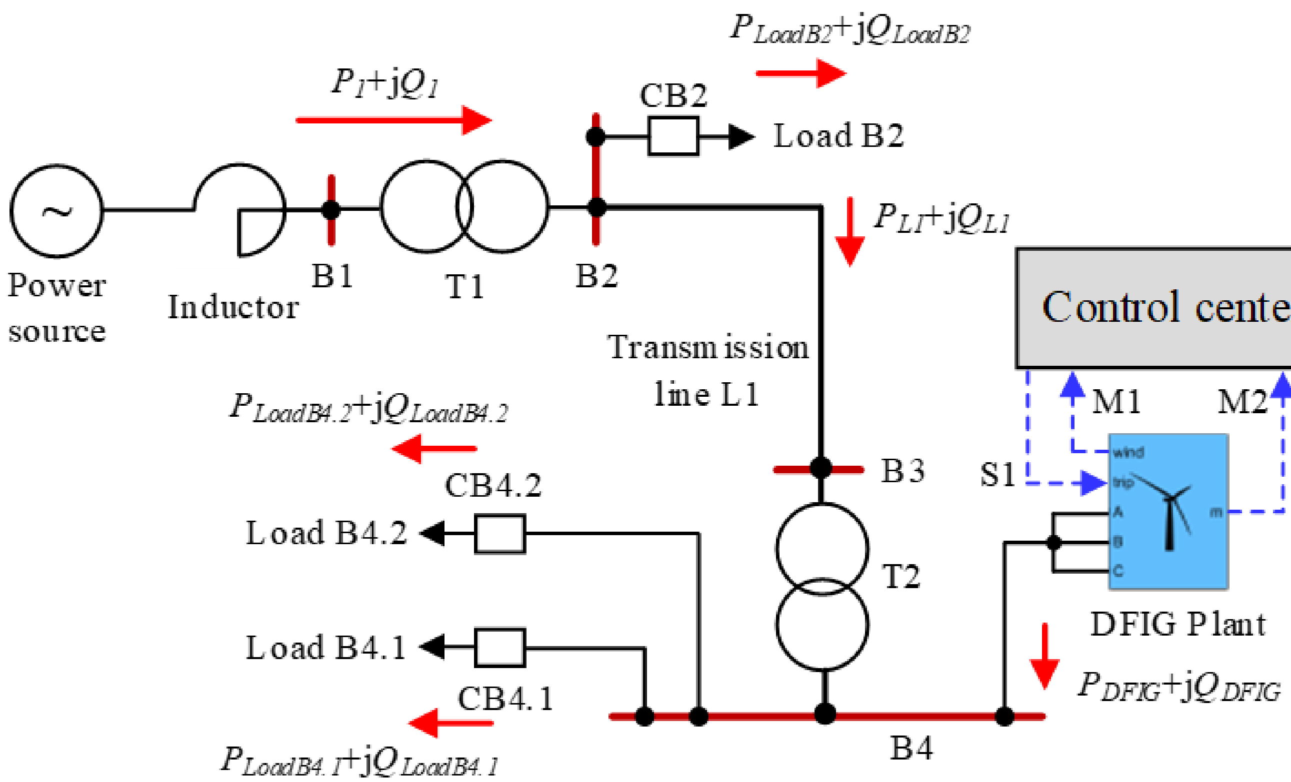

Fig.8 The 1st operating scenario

If power generating from DFIG based WTS is higher than total power of electric load at B4 Bus (the 2nd operating scenario), power flows in whole considered system are represented in Fig.9.

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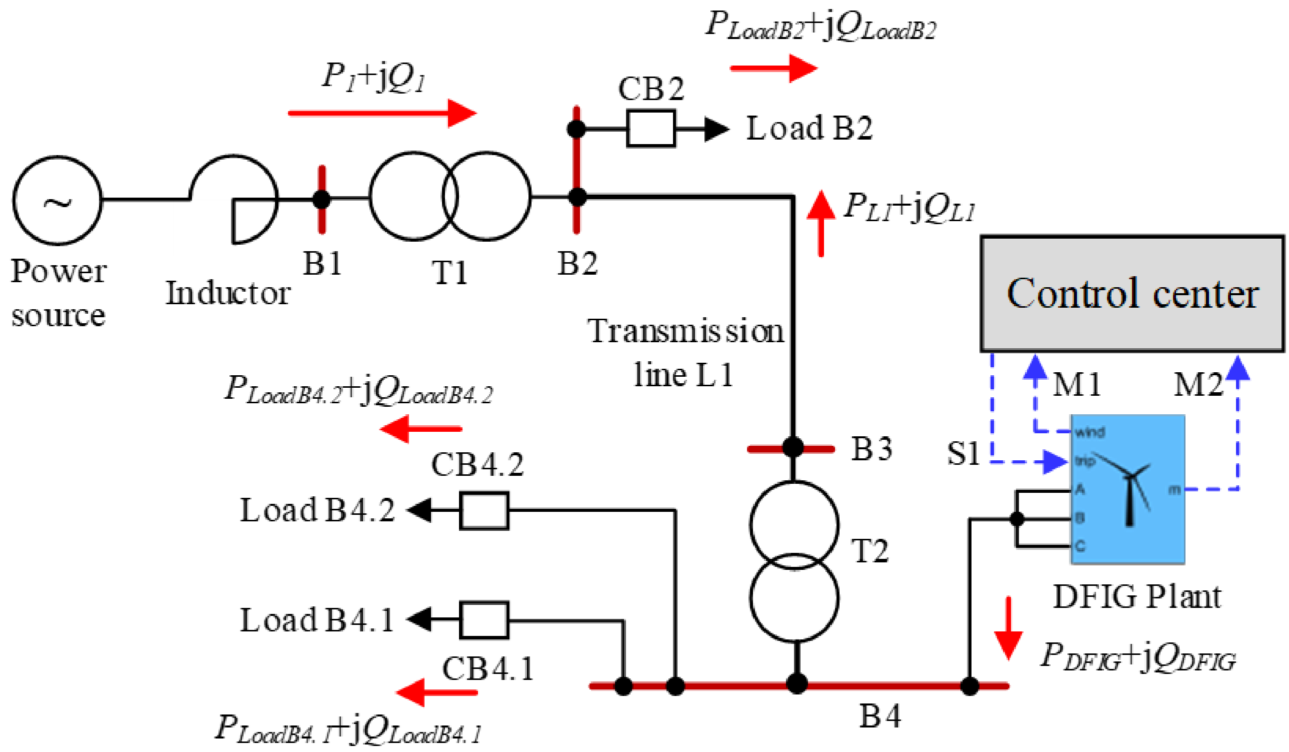

Fig.9 The 2nd operating scenario

If power generating from DFIG based WTS is higher than total power of electric load at B4 Bus (the 3rd operating scenario) and power of electric load at B2 Bus is smaller than power generating from DFIG side of the transmission line, power flows in whole considered system are represented in Fig.10.

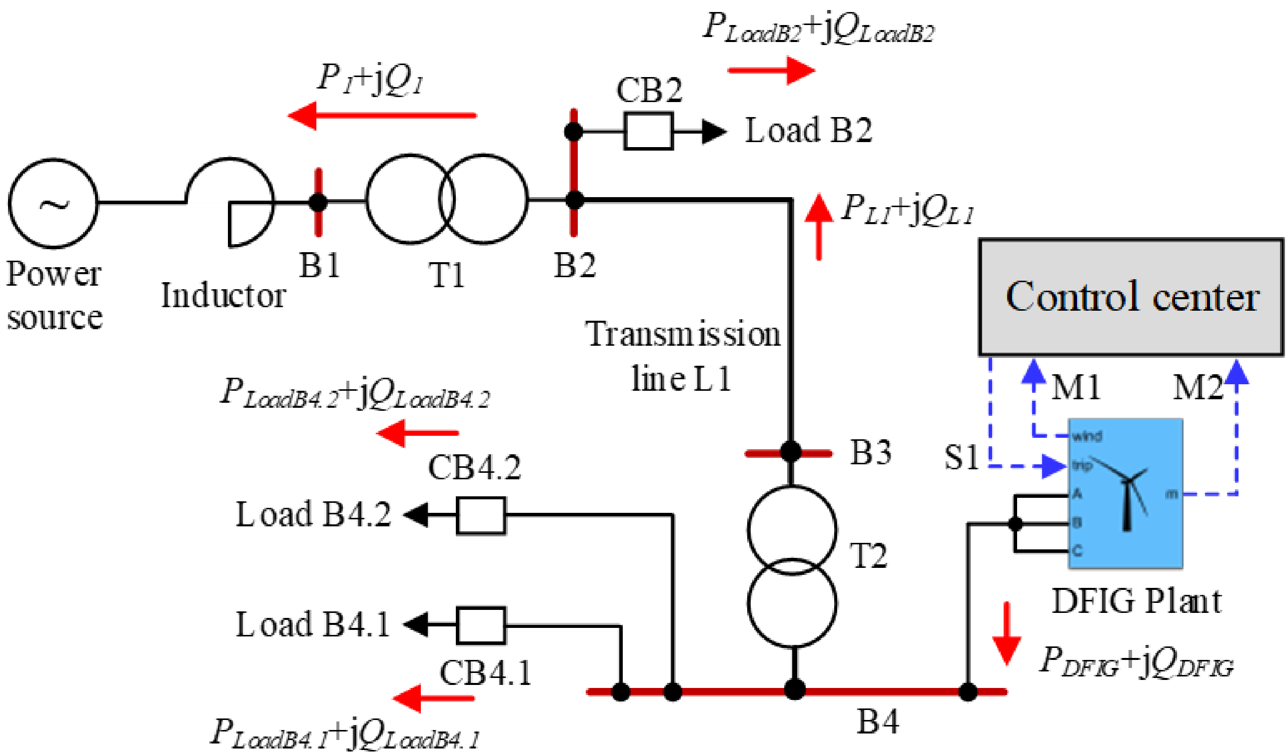

Fig.10 The 3rd operating scenario

If power generating from DFIG based WTS is zero (the 4th operating scenario), power flows in whole considered system are represented in Fig.11. This scenario can happen in case of too small or too high wind speed or having faults in DFIG. So, power source must be met all power requirements for all electric loads.

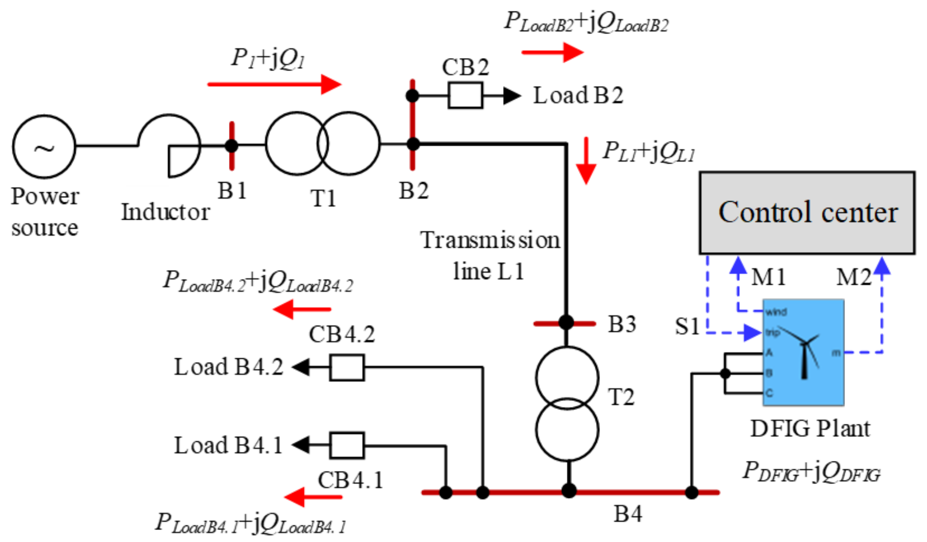

Fig.11 The 4th operating scenario

B. Simulation results

To evaluate power distribution in whole system as introduced in Fig.7, paramerters to simulate in MATLAB software is represented as following tables. These parameters can be charaterized for power source, inductor, T1 and T2 transformers, electric loads, DFIG base WTS and L1 transmission line.

Table I Parameters of power source and inductor [11]

Number	Name of parameter	Symbol	Value
1	Voltage amplitude	$U_{ph\text{-}ph}$	120 kV
2	Frequency	f	60 Hz
3	Positive-sequence resistance of inductor	R_1	0.1 W
4	Positive-sequence capacitance of inductor	L_1	3×10^4 H
5	Zero-sequence resistance of inductor	R_0	0.3 W
6	Zero-sequence capacitance of inductor	L_0	9×10^4 H

Table II Parameters of T1 transformer [11]

Number	Name of parameter	Symbol	Value
1	Rated power	S_{rated}	47 MVA
2	Voltage ratio	$U_{primary}/U_{secondary}$	120kV/25kV
3	Primary and secondary winding resistance	R	2.67×10^{-3} *(pu)*
4	Primary and secondary winding capacitance	L	0.08 *(p.u)*

Table III Parameters of T2 transformer [11]

Number	Name of parameter	Symbol	Value
1	Rated power	S_{rated}	10.5 MVA
2	Voltage ratio	$U_{primary}/U_{secondary}$	25kV/575V
3	Primary winding resistance	R	8.3×10^{-4} *(p.u)*
4	Primary winding capacitance	L	0.025 *(p.u)*

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Table IV Parameters of maximum electric loads

Number	Name of parameter	Symbol	Value
1	Load B2	$P_{LoadB2}+jQ_{LoadB2}$	4+j0 MVA
2	Load B4.1	$P_{LoadB4.1}+jQ_{LoadB4.1}$	6+j0 MVA
3	Load B4.2	$P_{LoadB4.2}+jQ_{LoadB4.2}$	1+j0 MVA

Table V Parameters of DFIG [11]

Number	Name of parameter	Symbol	Value
1	Number of generator	n	06
2	Rated power	P_{rated}	1.5×10^{-6} MVA
3	Rated voltage	U_{ph-ph}	575 V
4	Power factor	cosj	0.9
5	Rated frequency	f	60 Hz
6	Rated wind speed	v_{rated}	12 m/s
7	Cut-in wind speed	v_{cut-in}	3 m/s
8	Cut-out wind speed	v_{cut-in}	60 m/s

Table VI Parameters of transmission line [11]

Number	Name of parameter	Symbol	Value
1	Length	L	30 km
2	Positive resistance	R_1	0.1153 W/km
3	Zero resistance	R_0	0.413 W/km
4	Positive Inductance	X_1	1.05×10^{-3} H/km
5	Zero Inductance	X_0	3.32×10^{-3} H/km
6	Positive Capacitance	C_1	11.33×10^{-9} F/km
7	Zero Capacitance	C_0	5.01×10^{-9} F/km

The scenario for the variation of electric loads at B2 and Buses is represented in Fig.12.

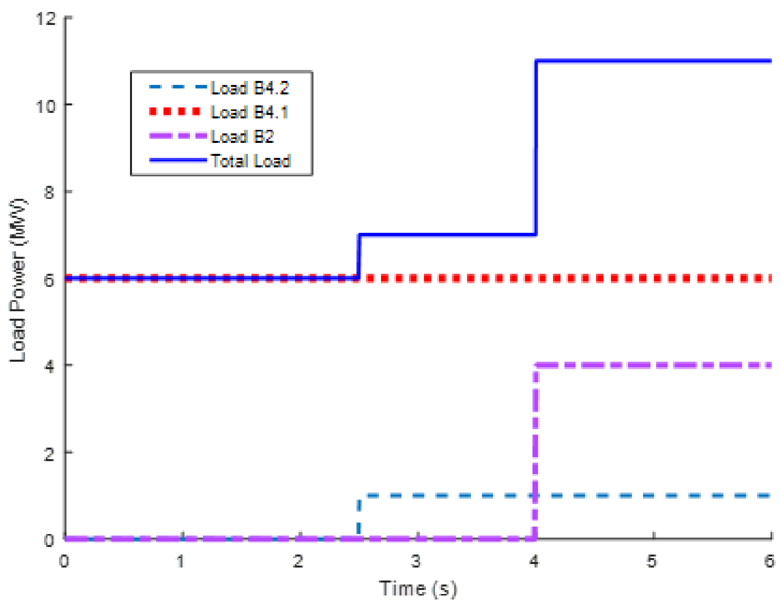

Fig.12 Scenario for the variation of electric loads

Simulation result about load requirements at B4 Bus is shown in Fig.13. At this bus, power of loads increases from 6 MW to 7 MW (due to adding Load B4.2) at the 2.5th second. Because voltage source is fixed, the value of current module also increases corresponding to variation of load power.

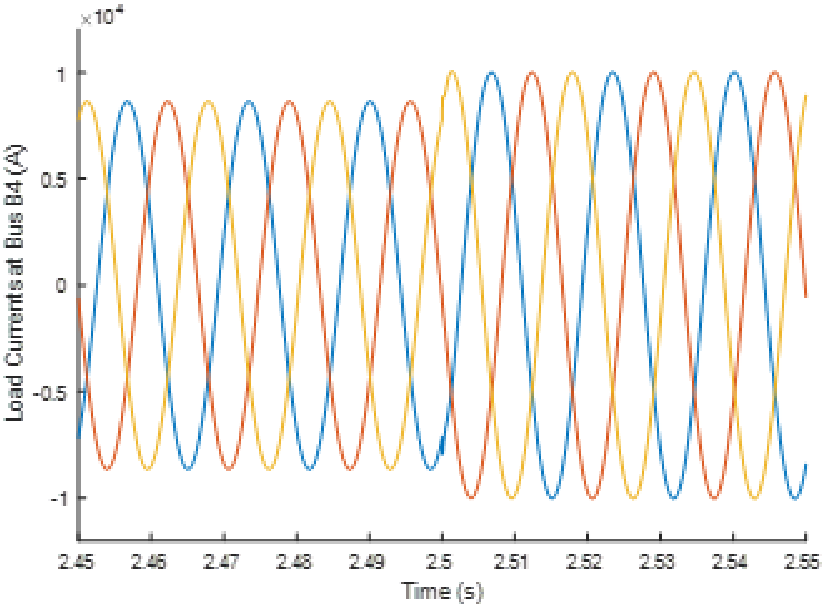

Fig.13 Load currents at Bus B4 from the 2.45th second to the 2.55th second

Simulation results about load requirements at B2 Bus is shown in Fig.14. At this bus, a 4-MW power is switched on at the 4th second which caused suddenly variation of current module from zero value. So, it causes a large excitation that affects much to the system.

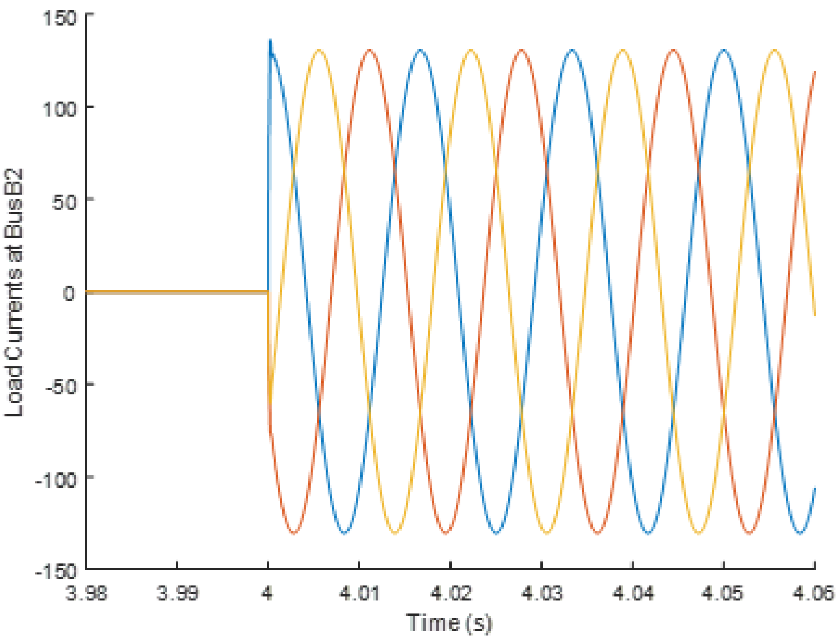

Fig.14 Load currents at Bus B2 from the 3.98th second to 4.06th second

Simulation result about output current from DFIG based WTS in case of 15 m/s wind speed in whole considered time is shown in Fig.15 and from the 2.45th second to 2.55th second is shown in Fig.16. It is easy to realize that three-phase currents wave at output terminals of DFIG based WTG have pure sinusoidal wave and their module only fluctuates very small at the 2.5th second (Load B4.2 is added at this time) or the 4h second (Load B2 is added at this time). After half cycle time from having variation loads, their module comes back to rated value (1 p.u). It means that controllers work very well to maintain stably for operating states of DFIG based WTS corresponding to large excitations in the system.

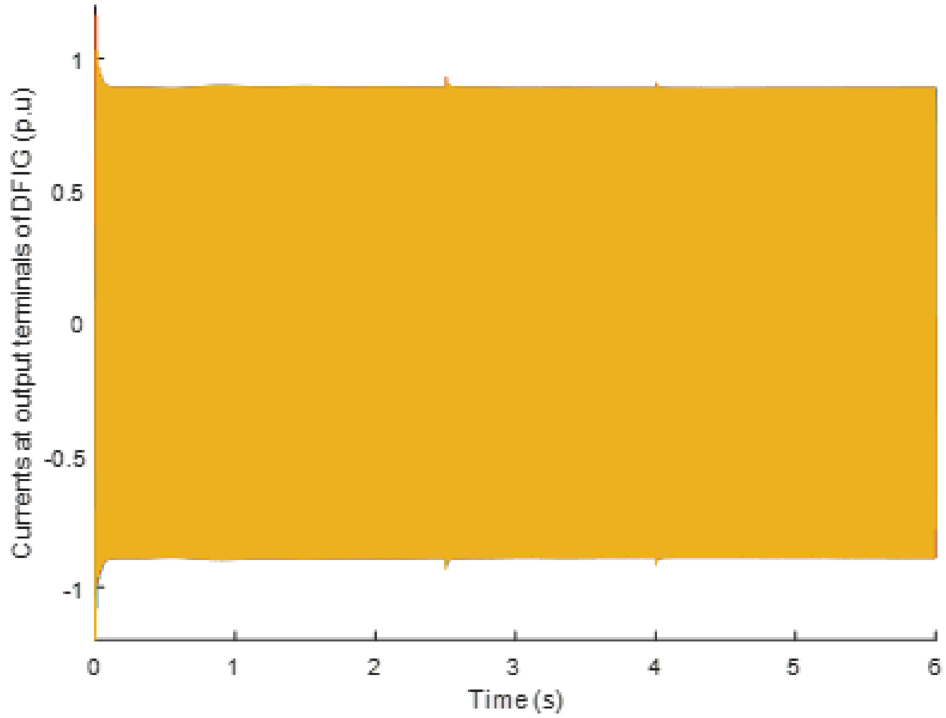

Fig.15 Currents at DFIG output terminals in whole time range

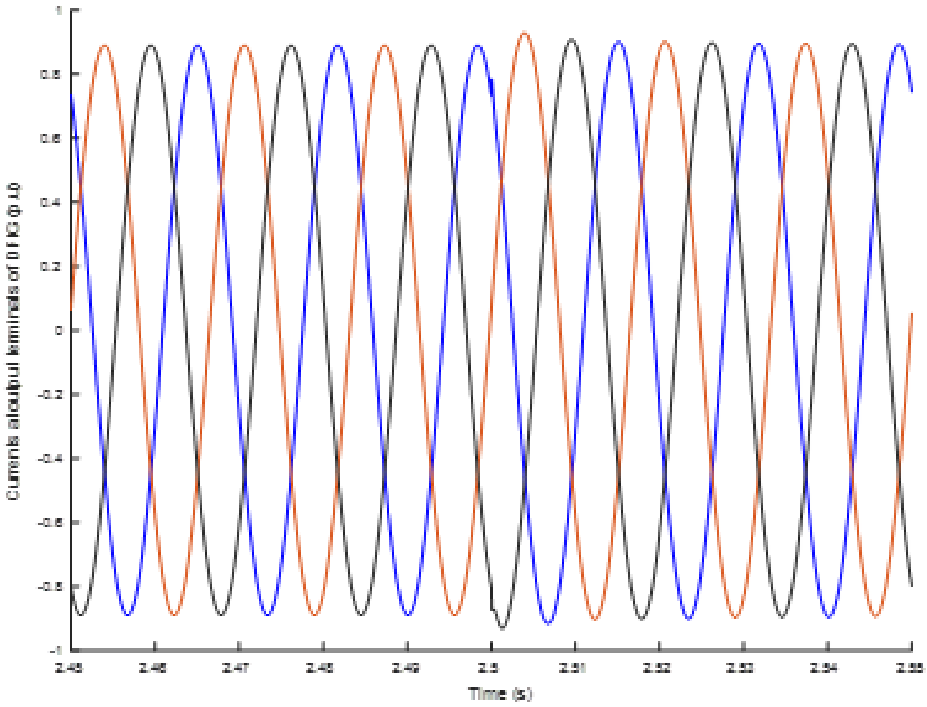

Fig.16 Currents at DFIG output terminals from the 2.45th second to the 2.55th second

Simulation results about current from power grid from the 2.45th second to the 2.55th second (Load B4 is added at this time) and from the 3.95th second to the 4.05th second (Load B2 is added at this time) are shown in Fig.17 and Fig.18. It's easy to realize that current module at the time after the 2.5th second is smaller than at the time before the 2.5th second but they have in-phase currents. Moreover, current module at the time after the 4th second is smaller than at the time before the 4th second but they have reserve-phase currents.

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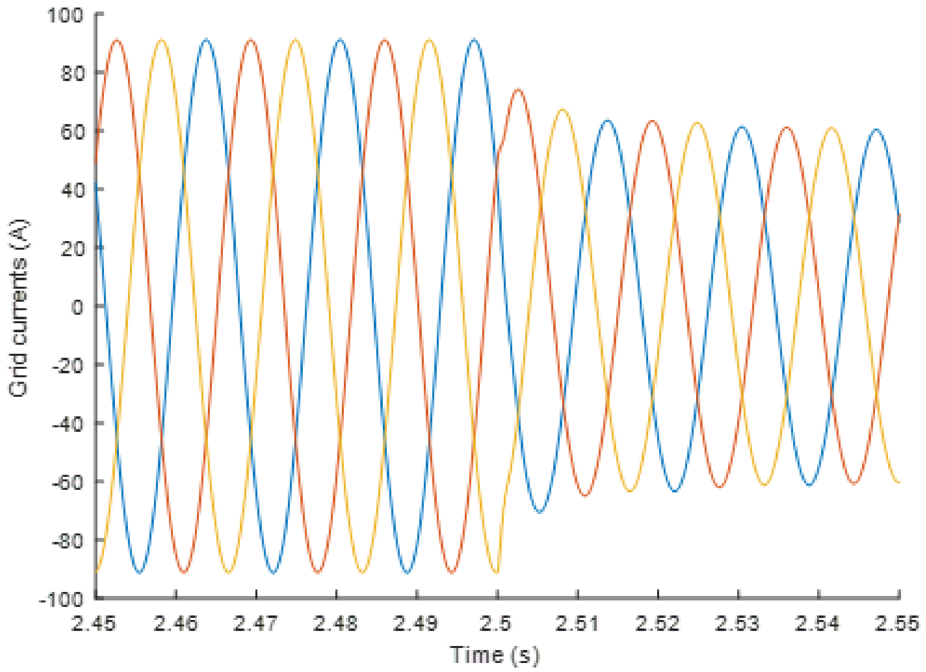

Fig.17 Grid currents from the 2.45th second to the 2.55th second

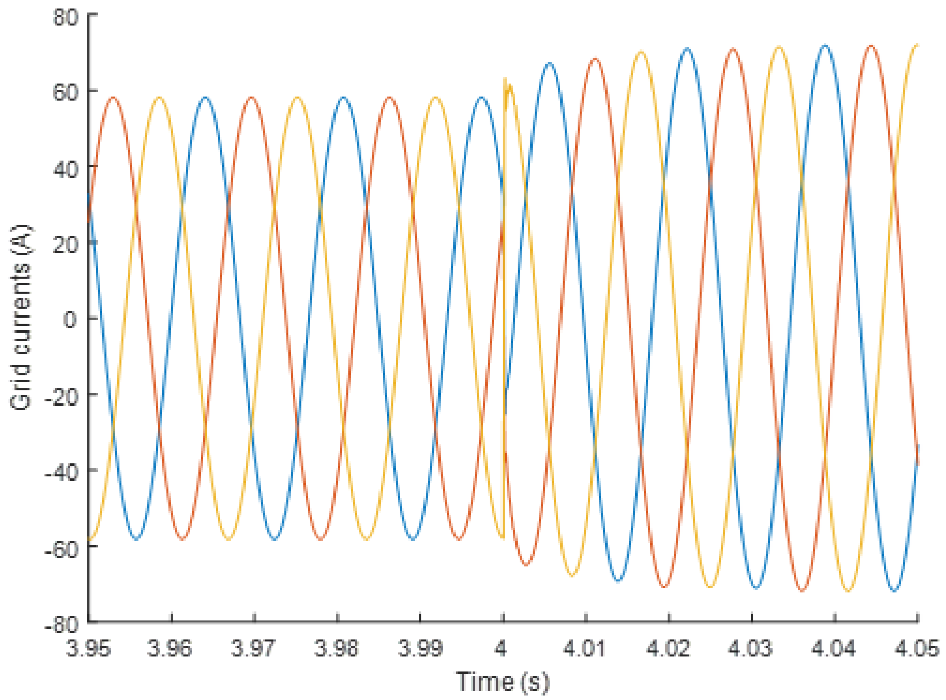

Fig.18 Grid currents from the 3.95th second to the 4.05th second

Simulation result about power generating from DFIG based WTS is shown in Fig.19. Power characteristic of DFIG base WTS becomes stably very fast due to the meaning of controllers. At the times having load excitations, power generating from DFIG based WTS has some small fluctuation in short time corresponding to the small fluctuation of load current after switching a new load on.

Power characteristics met for B4 and B2 Buses are shown in Fig.20 and Fig.21. At the initial stage, power met for loads increases gradually corresponding to the transient response of the current although load requirements are suddenly switched on from 0 MW to 6 MW. When a load is added by a load step (the 2.5th second and the 4th second), power characteristics also fluctuate in very short time.

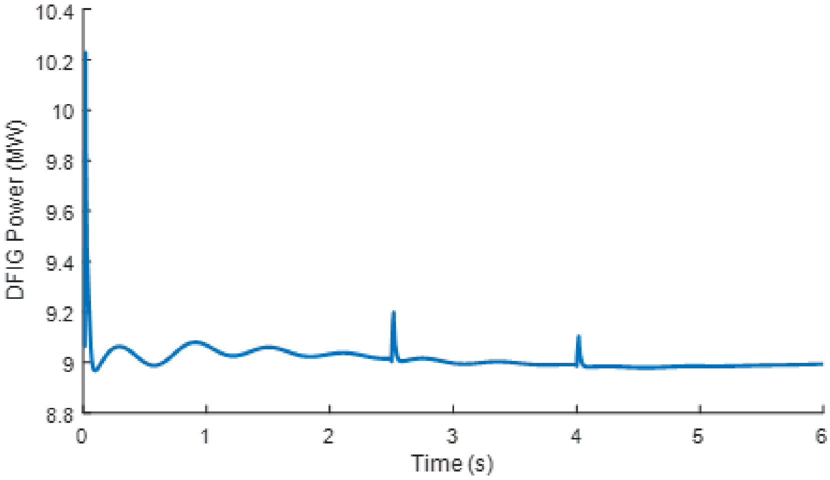

Fig.19 DFIG power in case of fixed wind speed

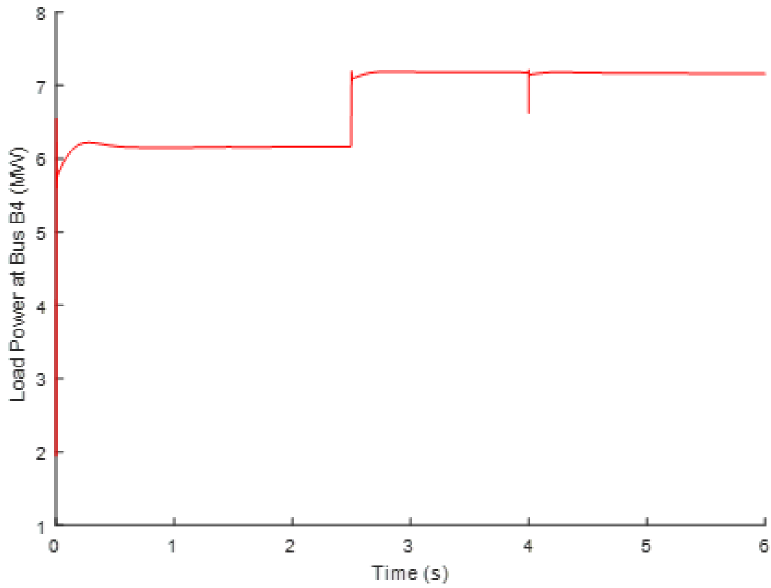

Fig.20 Load power at bus B4

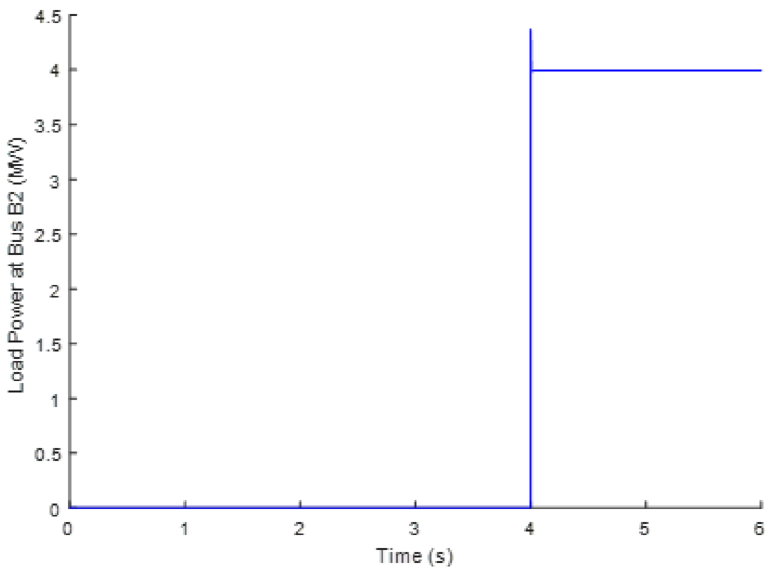

Fig.21 Load power at bus B2

Simulation result about exchange power between power source and considered system at B2 Bus is represented in Fig.22. It has positive sign at the time before the 4^{th} second because load power total in this range time is smaller than power generating from DFIG based WTS. It has negative sign at the time after the 4^{th} second load power total in this range time is higher than power generating from DFIG based WTS. It can be observed by the phase transition at the 4^{th} second of current as simulation result in Fig.18.

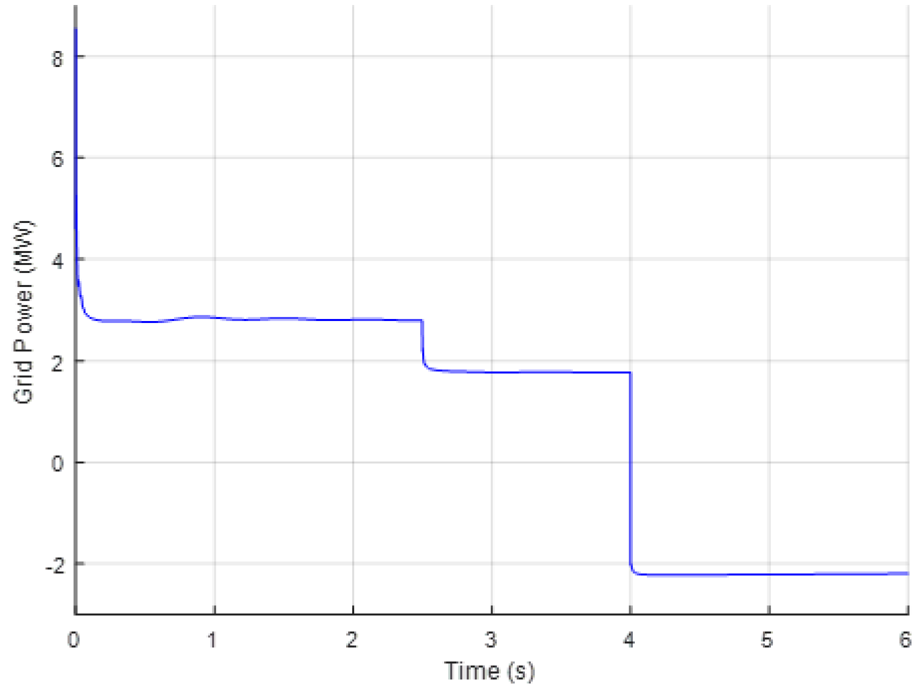

Fig.22 Grid power at fixed wind speed

In case of considering the variation of wind speed, simulation about power generating from DFIG based WTS is shown in Fig.23. Exchange power between power source and considered system is depicted in Fig.24.

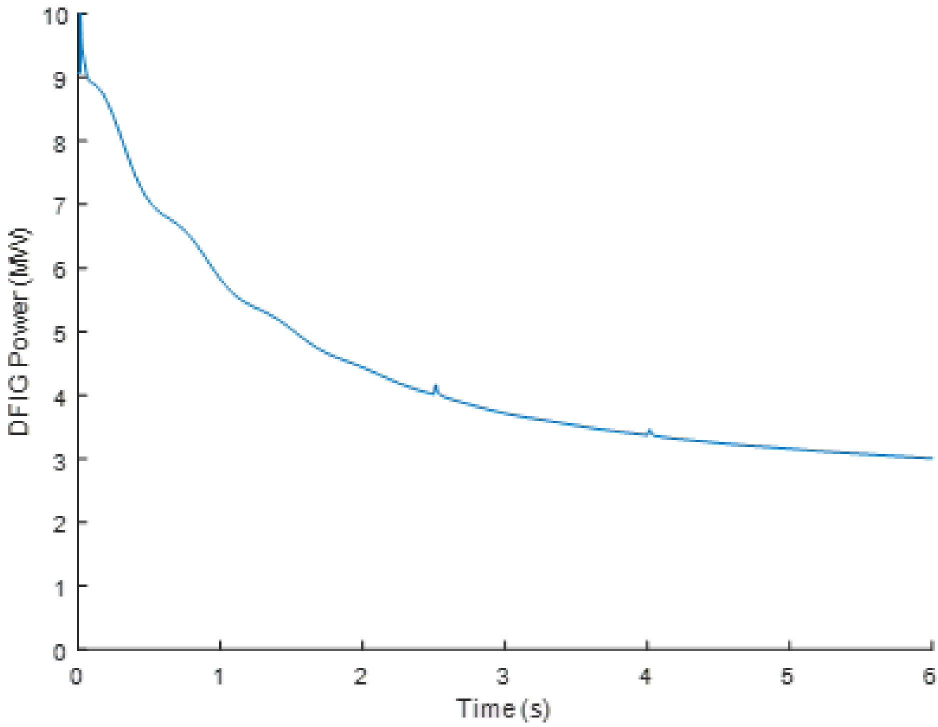

Fig.23 DFIG power in case of variable wind speed

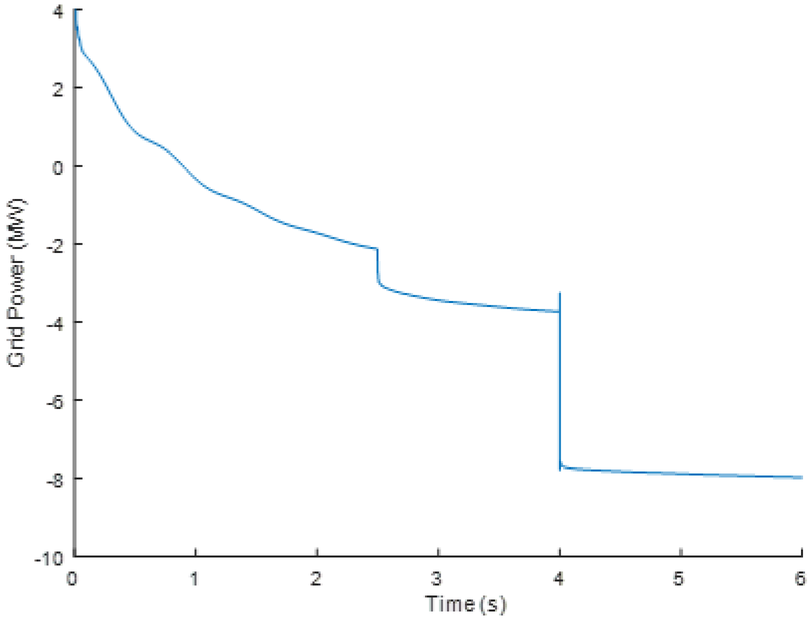

Fig.24 Grid power in case of variable wind speed

Above simulation results demonstrated the power distribution in whole system as described from Fig.8 to Fig.10. The direction of exchange power between power source and considered system changes its sign (from positive to negative). It means that it must be surveyed completely in all operating scenarios to have information about current and power going through main units. It will help to determine maximum value and evaluate the ability to work stably in long time, even if wind speed is variable.

CONCLUSIONS

Successful simulations for the operation of a system with the participation of a DFIG plant based WTS is the main science contribution of this paper. System and control structure for a DFIG based WTS was introduced very detailed, including the participation of power converters to regulate power flows from rotor side and grid side. Operating scenarios happening in a system with the participation of a DFIG plant based WTS at the end of transmission line were considered. These scenarios evaluated the variation of power loads and wind speed and helped operators have complete overviews about this system. It also helped to operate this system stably.

Simulation results showed the capability to harness power from 6 DFIGs in both fixed and variable wind speed scenarios. Controllers in DFIGs helped to regulate power flow, generate it to the grid at any operating time and meet load power requirements. In time range that has small load power (before the 4th second with fixed wind speed), DFIGs provided power for load requirement at B2 Bus and B4 Bus and generated redundant power to power source. In time range that has high load power (after the 4th second with fixed wind speed and before the 2.5th second with variable wind speed), DFIGs didn't provide enough power for load requirement at B2 Bus and B4 Bus. So, load power must be met by absorbing from power source. Simulation results about module and phase of currents at buses demonstrated completely the variation of load power and the variation of power generating DFIGs. It means that simulation process will provide some evaluations about power flows in whole system and determine maximum power value going through each unit if all operating scenarios are considered.

Contributions of this paper will help operators have complete evaluations about instantaneous system values to have suitable solutions such as mobilizing other generations or cut loads off if load requirements is higher than reserved power of power source. This system can continue to be considered some hard faults such as having short circuits at some buses in the system or in itself of DFIG. These scenarios can affect much to the system stability and will be concerned with in next studies.

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REFERENCES

1. Nguyen Phung Quang (2007), *Studying, Designing and Manufacturing a Generator with (10-30) kW rated power suitable for conditions in Vietnam,* A scientific project code KC.06.20CN.
2. Le Tien Phong, Duong Hoa An, Ngo Duc Minh, Vu Xuan Tung, *Design and Integration of Renewable Energy Systems,* A Book published in Publisher of Thai Nguyen University, 2021.
3. Teresa Orłowska-Kowalska, Frede Blaabjerg, José Rodríguez (2014), "Advanced and Intelligent Control in Power Electronics and Drives", *Springer Publisher*, Volume 531, ISBN 978-3-319-03401-0.
4. Ingy Abouzeid, Mohamed Abdellatif Badr, Rania Sweif, Dalal Helmy (2018), *Interpretation of the Operation Modes of the Doubly Fed Induction Machine in Wind Energy Systems,* OSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 13, Issue 1 Ver. I, pp 30-36.
5. Khan, N. Abas, T. Bukhari (2015), *Control of DFIG on Variable Wind Speed,* International Journal of Thermal and Environment Engineering, Volume 10, No. 2, pp 143-158.
6. Youcef DJERIRI (2020), *Robust Second Order Sliding Mode Control of Doubly-Fed Induction Generator for Wind Energy Conversion System,* Acta Electrotecnica et Informatica, Vol.20, No.3, pp 30-38.
7. Gasmi, M. Sofiane, H. Benbouhenni, N. Bizon (2023), *Optimal Operation of Doubly-Fed Induction Generator Used in a Grid-Connected Wind Power System*, Iranian Journal of Electrical and Electronic Engineering, Vol. 19. No.2.
8. Manale Bouderbal, Hala Alami Aroussi, Badre Bossoufi, Mohammed Karim (2023), *Real-Time Power Control of Doubly Fed Induction Generator Using Dspace Hardware,* Sustainability, 15(4), 3638.
9. Rafik Dembri, Lazhar Rahmani, Badreddine Babes, Idris Azizi (2024), *Enhanced Control of Doubly Fed Induction Generator Based Wind Turbine System Using Fractional-Order Fuzzy PD+I Regulator,* Journal Européen des Systèmes Automatisés, Vol. 57, No. 1, pp 211-223.
10. Norbert Klaes, Florian Poschke, Horst Schulte (2021), *Grid Forming Stator Flux Control of Doubly-Fed Induction Generator*, Energies, 14(20).
11. Mathworks, Wind Farm - Doubly-Fed Induction Generator (DFIG), *https://www.mathworks.com/help/sps/ug/wind-farm-dfig-detailed-model.html*