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Special Issue on Emerging and Renewable Energy: Generation and Automation

Effect of Doubly Fed Induction Generator on Transient Stability

Analysis under Fault Conditions

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Abstract

Wind is one of the most widely used non-conventional sources of energy. The majority of wind farms use a variable speed Wind Turbines Generator (WTGs) equipped with Doubly-Fed Induction Generator (DFIG) due to their advantages over other WTGs. The analysis of Wind Energy (WE) dynamics with the DFIG – Wind Turbines (WTs) has become an interesting research issue during transient faults. This paper investigates the effects of the different faults on transient stability. The analysis is performed on a 6-bus test system during transient faults and loss of excitation in synchronous generators. The stator-flux oriented vector control approach used for both stator and Rotor Side Converter (RSC) is proposed to mitigate DFIGs impacts on the system stability. The dynamic performance of DFIG variable speed WT under faults conditions are simulated using Neplan® program, considering different disturbance natures.

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Keywords: Keywords: Doubly-fed induction generator; Fault types; Transient stability; Wind Energy

1. Introduction

Due to the high depletion rate of conventional energy sources and increasing environmental concern, more efforts are done in electricity generation from Renewable Energy Sources (RES). Among various RES, Wind Energy (WE) is the most rapidly growing one. Australia will be a 20% Renewable Energy by 2020 [1].

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The largest producer of renewable energy within the EU-28 in 2013 was Germany, with a 17.5 % share of the total; Italy (12.2 %) and France (12.0 %), followed by Spain (9.1 %) and Sweden (8.7 %) [1-3]. The impact of WE on dynamic behavior of power system during different operations conditions with larger penetration on the grid will be analyzed. Recently, the study of the influence of WE on power system transient stability has become a very important issue. In Doubly-Fed Induction Generators (DFIGs), the induction generator is grid-connected at the stator terminals while the rotor mains via a partially rated AC/DC/AC Variable Frequency Converter (VFC). The VFC consists of a Rotor-Side Converter (RSC) and a Grid-Side Converter (GSC) connected back-to-back by the DC-link capacitor. The VFC controls the active and reactive power of the generator and achieving faster dynamic response with low harmonic distortion, etc., handling only a very small fraction (25-30%) of the total power [2]. When connected to the grid, the RSC of the DFIG may be blocked during a grid fault to protect it from over-current in the motor circuit [1, 4]. Accordingly, the WT trips shortly. Few seconds after the fault clearance, it is automatically re-connected to the power network. The author in [5] has proposed a feature of uninterrupted operation of a DFIG WT during grid faults. The rotor circuit is first short-circuited by a Crowbar circuit (an external resistor), then; the generator starts to absorb reactive power as it acts as a conventional induction generator, the operation of the WT in producing active power continues. To have a control over the reactive power and voltage, the GSC can be set. In order to prevent the WT from fatal over-speed, the pitch angle controller has to be activated. The RSC will re-start and the WT will return to normal operation. Once the fault has been cleared, the voltage and frequency will recover in the power network. However, for weak power networks with small power capacity, the GSC cannot provide sufficient reactive power during a grid fault, the RSC will not restart, and the WT will be disconnected from the power network. However, it is important to maintain the voltage stability and to preserve uninterrupted operation of the DFIG WTs.

Transient stability deals with the ability of a power system to maintain synchronism when subjected to a large or severe disturbance such as loss of generation, loss of large loads, or a transmission line fault [6]. Synchronous generator rotor angle, speed and bus voltages are some of the system variables typically affected by transient disturbances. Steady state stability studies are concerned with the small and gradual changes in the system operating conditions. The bus voltages must always be close to their nominal values. The phase angles between two bus voltages should be significantly small. Reddy and Kumar [7] have presented the analysis of the variable speed Wind Energy Conversion System (WECS) employing DFIG with Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) type converters. Bouzekri and Allaoui [8] have designed a control strategy for enhancing the quality of energy of a grid-connected variable speed DFIG base WECS. Three different controls for active stator power, reactive stator power control and harmonic rotor current have been applied to manage the priority control using the active filter with Synchronous Reference Frame (SRF) method harmonic compensation. Babu and Mohanty [9] have presented the modeling and simulation of WT driven DFIG which feeds power to the utility grid. The proposed DFIG, based on the vectorized dynamic approach, has been applied to all types of induction generator configurations for steady state and transient analysis. The power flow control has been obtained by connecting two back to back PWM converters between the rotor and utility grid. Kouzi and Filah [10] have proposed the Genetic Algorithm (GA) for the adaptive neural-fuzzy controller applied to the indirect vector control of DFIG for wind power generation. Choudhury et al. [11] have simulated DFIG system with a back-to-back converter at the rotor end using PI controllers. The system performance under steady state has been analyzed for sudden changes in the grid voltage. The generated stator voltages and currents, active power supplied to grid, VAR requirement for the DFIG have been observed.

Moreover, Masaud and Sen [12] have proposed a detailed DFIG model in MatlabTM/Simulink using vector control strategy based in stator flux-oriented frames with satisfactorily results has been presented. A new vector control strategy based on the rotor flux-oriented reference frame and compared with the stator flux-oriented vector control. Sediki et al. [13] have established the steady state characteristics of the DFIM under unity power factor operation. Based on the forth synchronized mathematical model, analytic determination of the control laws has been illustrated to show the effect of the applied rotor voltage on the speed and the active power. The stator resistance has been considered. The simple analytical expressions lead to interesting and reliable easy open loop control of the DFIM without any sensors. Alkandari et al. [14] have studied the steady state analysis of the DFIG. It is assumed that the machine is excited on the rotor side by a slip-frequency current injected from an exciter mounted on the same shaft of the machine. The resulting magnetic field rotates at the synchronous speed. Effects of the excitation voltage magnitude and angle on both the active and reactive power when the machine runs at constant speed have been investigated. The control of the excitation

voltage magnitude and phase angle has resulted in governing the mode of the operation of the machine. Islam et al. [15] have demonstrated the steady state characteristics of the DFIG in WE generation system using MatlabTM. Stator and rotor real and reactive powers as well as electromagnetic torque have been analyzed as a function of the slip, the rotor injected voltage and the angle α . From the simulation results, the DFIG characteristics have been affected by its injected rotor voltage. Zhang et al. [16] have discussed the steady-state operation characteristics and power relations in detail on the basis of the equivalent circuit of DFIG. Ren et al. [17] have studied the evolution mechanism and typical models of stability problems. Three-stage evolution mechanism have been proposed to illustrate the evolution process of multiple stability problems of AC/DC power system with large-scale High Voltage (HV) DC and wind power. The rationality and effectiveness of the proposed mechanism and strategies have been verified.

Based on the power characteristic equation, Wang et al. [18] have introduced an analysis method of eliminating equivalent mutual impedance to research the influence mechanism of different wind power penetration rate. In [18] the system power angle characteristics have been improved with the increase of the wind power scale.

In addition, Dimitrios and Athanasios [19] have studied the operational behavior of the DFIG based WECS under power electronic converter and rotor terminals faulty conditions. More specifically, the effect of the short-circuit fault on the back-to-back power electronic converter and in rotor phases has been investigated via simulation using a system of 2 MW. Finally, the consequences of these faults have been evaluated. Edrah et al. [20] have studied the effects of DFIG based wind farms and their controllers on small signal stability. Since wind turbines have to contribute to power system oscillation damping. Damping controller within DFIG rotor side converter has been developed in this study. Edrah et al. [21] have investigated the impact of DFIG control and operation on the rotor angle stability. A control strategy for both the RSC and GSC of the DFIG has been proposed to mitigate the DFIGs impacts on the system stability. The Static Synchronous Compensator (STATCOM) has been utilized to control GSC and provide reactive power support during grid faults. In addition, a Power System Stabilizer (PSS) is implemented to control the reactive power control of the RSC. Bu et al. [22] have studied the small signal stability analysis of DFIGs to assess their modeling adequacy. By evaluating the damping torque contribution to stability margin from different DFIG dynamic model components, the proposed method has provided a quantitative index to show the participation level of each DFIG model component in affecting power system damping performance.

The originality of this paper is height the impact of DFIG grid connected on power system stability considering different disturbance natures such as transient faults. The rest of the paper is organized as following: In Section 2, the problem statement is exhibited. The modeling and control of the DFIG is described in Section 3. Then the system under study is described in Section 4. The results and the discussion of several cases are outlined in Section 5. Finally, the paper conclusions and perspectives are summarized in Section 6.

Nomenclature

D, Q	Direct, Quadrature axes	I_{dqs}, V_{dqs}	Stator current, voltage in d-q references
M	Mutual inductance (H)	R_{sr}	Stator and Rotor resistance (Ω)
I_{dqr}, V_{dqr}	Rotor Current, Voltage in d-q references.	P_s, Q_s	Stator active, reactive powers
VFC	Variable Frequency Converter	RSC	Rotor-Side Converter
GSC	Grid-Side Converter	PWM	Pulse Width Modulation

2. Problem Statement

This paper aims at studying the dynamic performance of the multi- machine the DFIG under various types of faults (i.e, three phases to ground, phase to phase fault, and single line to ground and generator G1 loss of excitation) for transient stability analysis. The reason behind this problem is related to the fact that the DFIG stator is directly connected to the grid, as shown in Fig.1.

During grid faults, one or more of the phase voltages at the Point of Common Coupling (PCC) may suddenly drop to zero. This results in large stator current transients, leading to high currents flowing through the converters due to the magnetic coupling between stator and rotor windings [23]. As the converter ratings are defined according

to the desired variable speed range under normal grid voltage conditions, it may not be possible to control the rotor currents during transients. Indeed, when the rotor-side voltage or current reaches the power converter limit, DFIG control is lost and protected against the converter thermal breakdown. Even if the DFIG is subjected to small stator voltage imbalance, with the converter operating inside its limits, the stator current may be highly unbalanced, leading to torque pulsations that result in acoustic noise and, at high levels, may destroy the rotor shaft, gearbox, and blade assembly [25]. Dedicated countermeasures, in terms of protection and control, are therefore required.

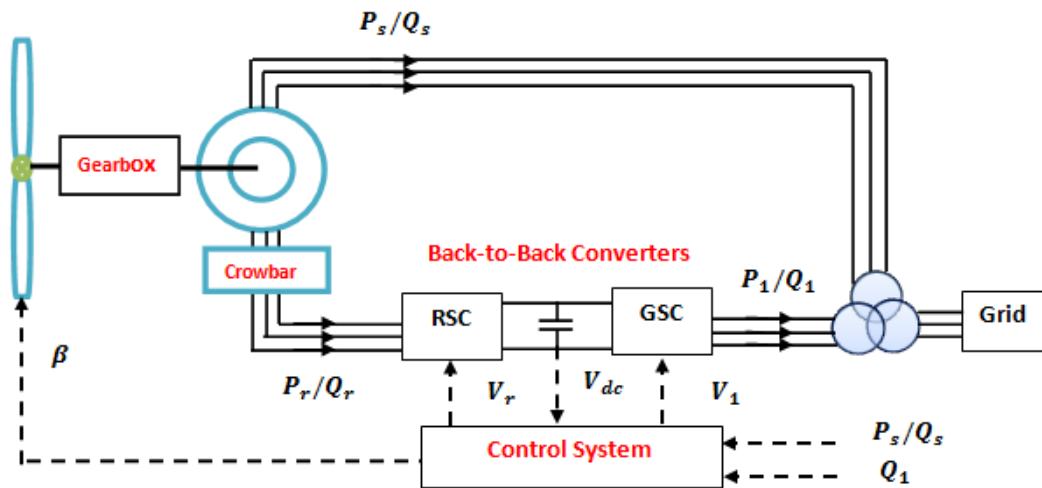


Fig. 1: Configuration of a DFIG Wind Turbine.

3. DFIG Modelling

The general structure of DFIG based WT is shown in Fig. 1. The DFIG consists of WT, gear box, a wound rotor induction generator, back-to-back converter and their controllers. The induction generator stator is directly connected to the grid whereas the rotor is fed through the back-to-back voltage source converter. The Crowbar is used during grid faults to protect the RSC from over current in the rotor circuit.

The DFIG based wind farm is modelled in detail in the simulation tool. Although, as the main purpose of this study is to examine the impact of DFIG on power system transient stability and to analyze the capability of DFIG based wind farm to damp power systems oscillations, only the modelling of the induction generator and DFIG-RSC are presented in [20-23]. Fig. 2 shows the overall vector control scheme of the DFIG-RSC. The reference signals i_{dr} and i_{qr} the outer control loops are generated by controlling the stator reactive and active power respectively. Then, the error signal is generated by deducting the current signals i_{dr} and i_{qr} from reference signal i_{dr}^* and i_{qr}^* respectively. The generated error signals are formed into two voltage signals v_{dr1} and v_{qr1} by the inner control loops using two PI controllers. Finally, the output of the inner current loops (v_{dr1} and v_{qr1}) are compensated by the corresponding cross coupling terms (v_{dr2} and v_{qr2}) to form the rotor d-q voltage signals (v_{dr} and v_{qr}) respectively. These signals are then connected to the PWM to create signal for the IGBT control [24, 25].

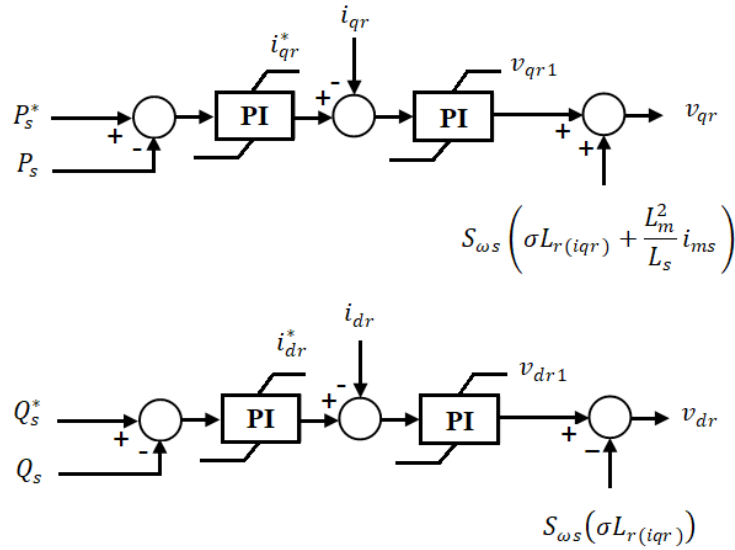


Fig. 2: Overall vector control of the DFIG rotor side converter, voltage control strategy [18].

4. System under study

In order to study the effect of DFIG wind turbines of 5 MW on power system transient stability for the system presented in Fig. 3. The system total load is 50 MW and 25 MVar, the two synchronous generators are equipped with the Automatic Voltage Regulator (AVR) of IEEE type 1. However, the static and dynamic data of the system under study can be found in [20-21].

The time domain simulation with a detailed model of synchronous generators and DFIG based wind farm is used in this study. The system under study and the DFIG wind turbine are modelled and simulated by using NEPLAN® software [26].

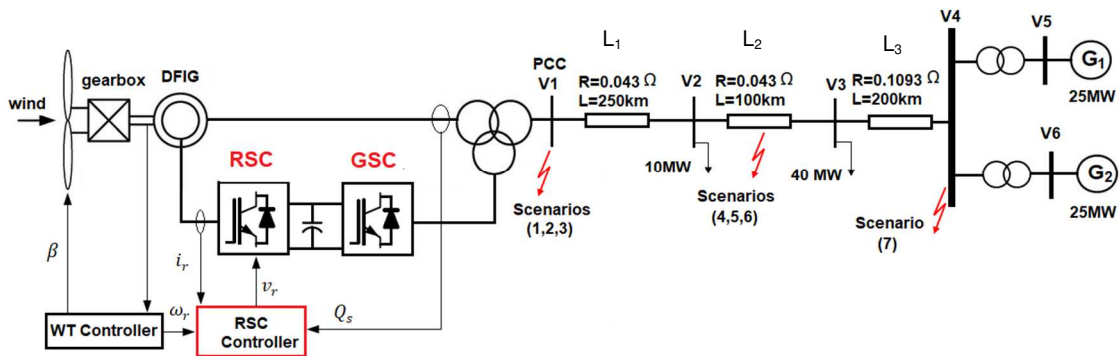


Fig. 3: Single line diagram of the system under study.

5. Simulation Results

In this study, different faults are applied to the transmission network to analyze their effect on the transient stability. The simulation results show the dynamic behavior of the (bus voltages, stator voltage, stator active power and reactive power) before, during and after faults. It is observed that the active and reactive power supplied by the utility grid are decoupled and DC- link voltage is maintained constant due to the control strategy of the GSC. The different scenarios are simulated to assess the impact of DFIG integration on the power grid. The fault duration is considered 500 ms, impedance fault is zero. The description of the different faults is:

A.1. Case A. Different faults on transient stability

- | | |
|---|---|
| Scenario 1. Three phase to ground fault at bus 1. | Scenario 2. Phase to phase fault at bus 1. |
| Scenario 3. Single phase to ground fault at bus 1. | Scenario 4. Three phase to ground fault at the middle of L_2 . |
| Scenario 5. Phase to phase fault at the middle of L_2 . | Scenario 6. Single phase to ground fault at the middle of L_2 . |
| Scenario 7. Three phase to ground fault at bus 4. | |

In Case A, the system is subjected to different faults considering the Scenarios (1-7) in order to analyze the voltage dynamic behavior at all buses. Fig. 4 depicts the dynamic performance of the system terminal voltages. It shows that the voltages on the buses are affected when three-phase fault is applied according to Scenarios (1, 4 and 7). The terminal voltage on buses (1, 2 and 3) according to Scenario 1 are respectively (0.0, 0.3 and 0.5) p.u and the terminal voltage at the same buses for Scenario 4 are (0.1, 0.0 and 0.2) p.u. The terminal voltage on all buses is dropped sharply in presence of three-phase fault near to generators side as in the Scenario 7 shown in Fig.3.

The voltage dynamic behavior at stator-DFIG-WT is similar to that of grid buses (1, 2 and 3) due to the stator connect directly with the grid. During the fault period, the DFIG-RSC voltage behavior is decreased to zero when the DFIG crowbar is still active (at 4 s). Although the fault is cleared at 3.5 s, the voltage cannot be completely recovered immediately because the RSC cannot provide the necessary reactive power to the generator for its magnetization process as long as it is blocked due to triggering of crowbar as shown in Fig. 4.

From Fig. 5 the synchronous generators can inject reactive power during the whole fault period, this action enables higher voltage levels at all buses.

For Case A, the response of the synchronous generator speed relation with the mechanical torque T_m is evaluated for different faults. In steady-state, the power system generators operate at balance where the mechanical power input P_m is equal to the electrical power output P_e . When the faults considering the Scenarios (1-7) occur in the system, its initial configuration will be lost, where P_m is constant for a while, then may be greater than P_e . The excess of the mechanical torque T_m over the electrical torque T_e accelerates the rotor. Thereby, the power angle increases. With the power angle rise, the electrical power P_e will begin to increase until it matches the mechanical power input P_m .

At the fault clearance point, the rotor is still running above synchronous speed. Hence, the power angle and the electrical power will continue to increase until the P_m becomes less than P_e then, the rotor will decelerate toward synchronous speed until the power angle reaches its critical value, the rotor angle for G_1 and G_2 will continue to oscillate.

A.2. Case B: Loss of excitation at synchronous generator G_1

In Case B, the impact the Loss of Excitation (LOE) in synchronous generator G_1 on the system transient stability is investigated as shown in Fig. 3 the generators behavior in such situation is simulated. Both generators are connected to the power system, the LOE fault happens in G_1 at $t=3$ s. The results show, when the LOE occurs, the voltage drops at generators terminals, the generator reactive power output falls down and the generator starts to import reactive power from the system. That is because the G_1 absorbs reactive power from the grid when the LOE occurs in G_1 . The dynamic behaviour of terminal bus voltage and active, reactive power of G_1 and G_2 as shown in Fig. 6, 7 respectively.

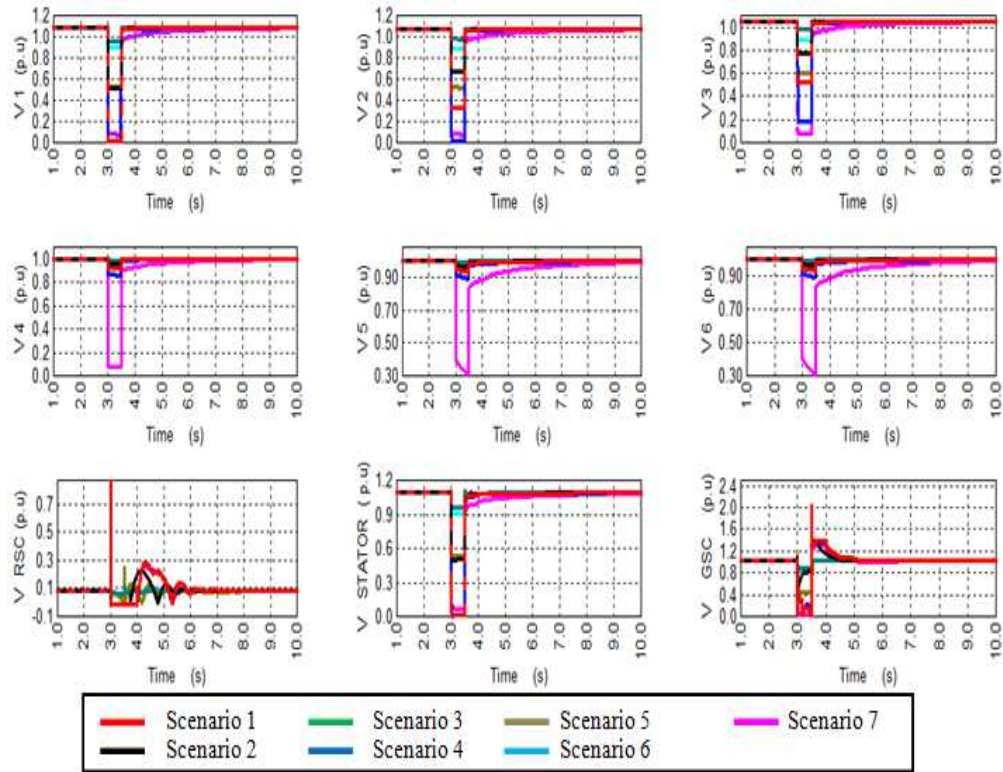


Fig. 4: Voltages dynamic behavior at different buses considering different faults type scenarios.

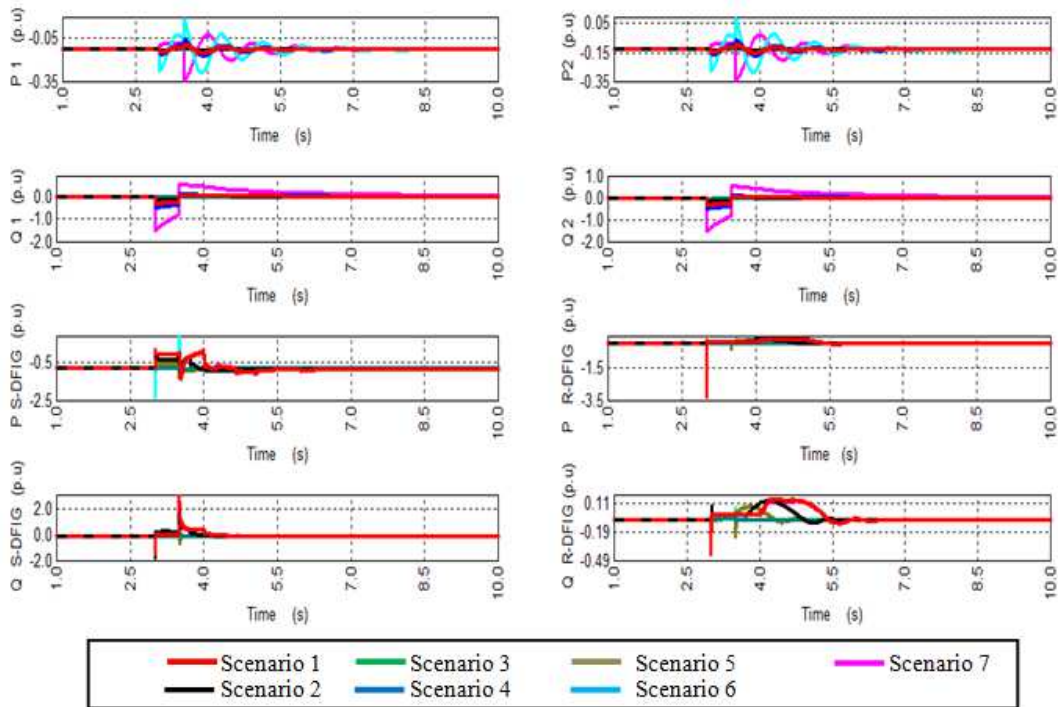


Fig. 5: Active and Reactive power dynamic behavior for Case

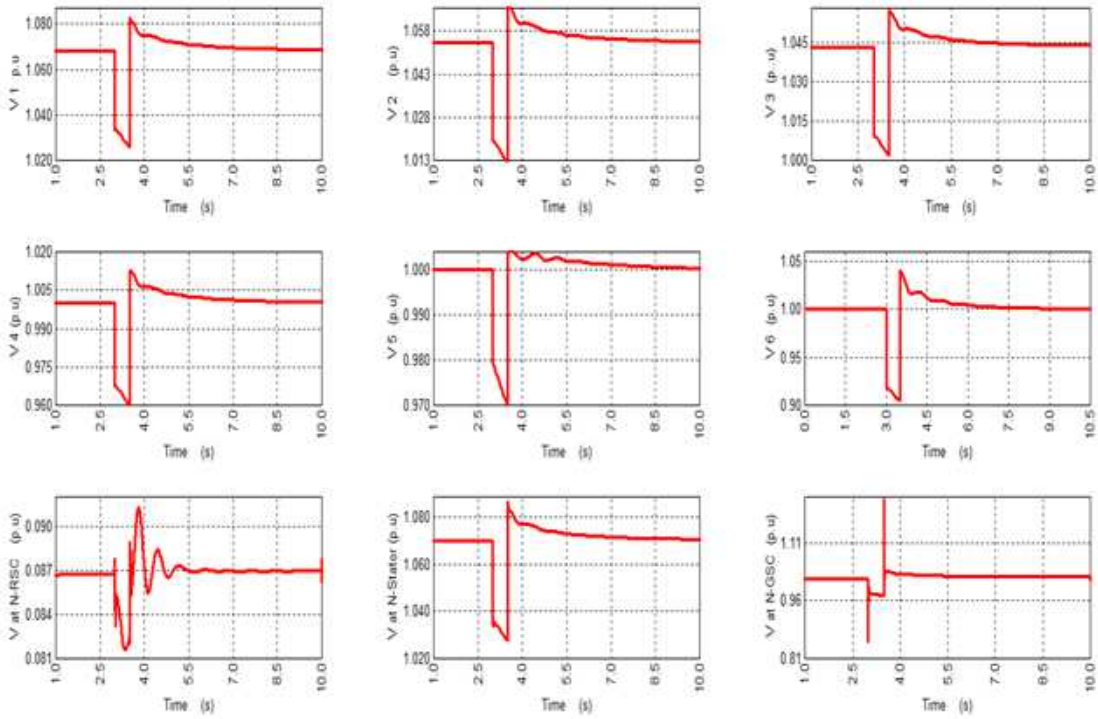


Fig. 6: Voltages dynamic behavior at different buses considering Case B.

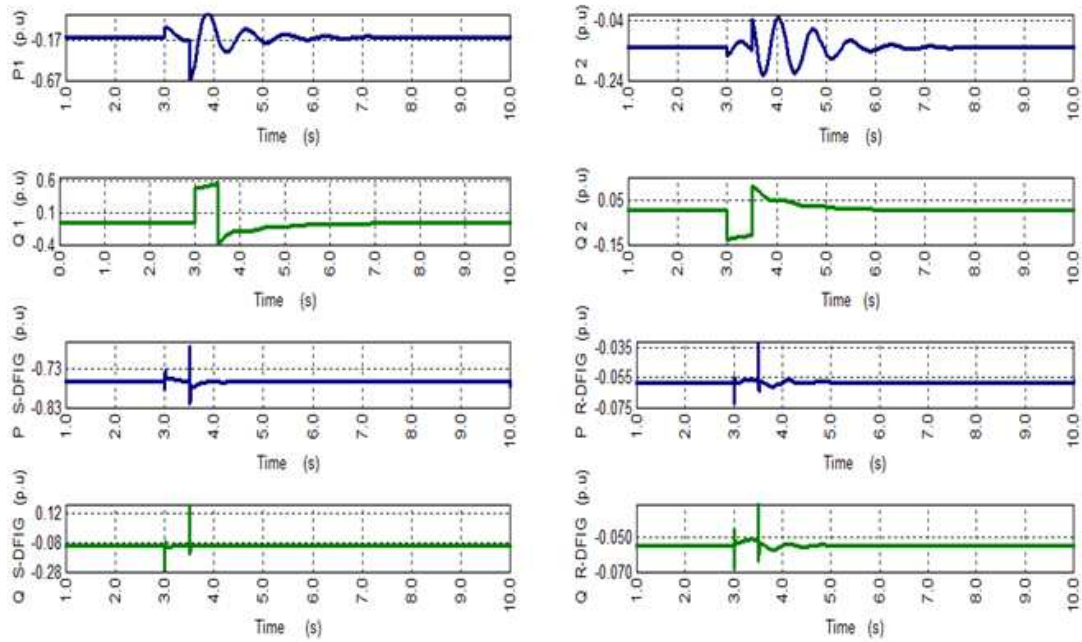


Fig. 7: Active and Reactive power dynamic behavior for Case B.

In order to enhance dynamic behavior for the power system stability, the use of optimization techniques is still a

research challenge in different RE applications [27-35].

6. Conclusions and Perspectives

The transient stability analysis of 6-bus test system using the Neplan[®] software package is illustrated considering different faults Scenarios and Cases operations. During the fault, the voltage at the DFIG generator terminal drops that results in: (i) Generator rotor and stator flux decrease causes generator demagnetizing process. The consequent result is the reduction in the generator electromagnetic torque and active power. Higher mechanical torque results compared to the electromagnetic torque and therefore the generator starts to accelerate. (ii) High current transients appear in the stator and rotor windings. The system protection (Crowbar) is worked to bypass this high current away from the RSC to prevent the converters from any kind of disturbances. (iii) The GSC cannot transfer the whole power from the rotor through the converter to the grid. Consequently, the additional energy charges the DC-bus capacitor rapidly. After the fault clearance, the voltage cannot be completely recovered immediately because the RSC cannot provide the necessary reactive power to the generator for its magnetization process as long as it is blocked due to triggering of Crowbar. Thus, the generator absorbs reactive power from the grid. This action delays the recovering process of the grid voltage. GSC successfully controls the DC-voltage back to its nominal value. When the grid voltage recovers over a certain value, the Crowbar is removed. Accordingly, the generator currents and voltages start to converge to their pre-fault values. From the simulation results, the DFIG wind turbine has no negative impact on power system transient stability upon its iteration into the grid. The damping oscillations can be reduced if the DFIG reactive power is used for controlling the WT's terminal voltage.

According to the results, there are significant differences in the manner of power exchange for maintaining the grid frequency during diverse load conditions. The speed control is performed through a slower electromagnetic torque control in partial load condition. The speed control is considered for reasonable pitch angle control.

In the forthcoming studies, the transient and steady state stability analysis will be comprehensively considered in presence of dynamic loading conditions. Furthermore, to enhance power system stability DFIG systems, different metaheuristic optimization techniques can be used.

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Appendix

Table A1. System parameters.

Parameters	Unit
A. WT parameters:	
Stator voltage	3.3kV
Rotor voltage	3.3kV
Rated power	5MW
Pole Pairs	2
B. Synchronous generator parameter:	
Frequency	50Hz
Rate Power	195MVA
Generator Rated Voltage	13.8 kV
Active power	25 MW

Reactive power

5MVar
