Analyzing the DFIG Inclusion in an Electrical Grid

Rubén Tapia-Olvera, *Member, IAENG,* Agustina Hernandez-Tolentino, Omar Aguilar-Mejia and Antonio Valderrabano-Gonzalez

Abstract—**With the increasing penetration of wind energy conversion system in distribution grids, utilities are requiring these renewable resources to provide reactive power supports during steady state and transient operating conditions. Wind energy conversion systems with doubly fed induction generators are able to independently control active and reactive power. This paper examines the reactive power control capability of doubly fed induction generator connecting to distribution grid with and without the inclusion of capacitors banks. The dynamic response characteristics of the wind power generator in the case of fault in the network to assure the secure and reliable operation of wind farm is presented. The stator-flux-oriented vector control principle is applied to build a model of the doubly fed induction generator en dq synchronous coordination system and the PSCAD/EMTDC simulation software is employed to investigate its performance into distribution grid of eleven nodes.**

Index Terms—**DFIG, distribution grid, reactive power.**

I. Introduction

WIND power may be considered as one of the most promising renewable energy sources after its progress during the last three decades. However, its integration into power systems has a number of technical challenges concerning security of supply, in terms of reliability, availability and power quality [1-3].

Since the penetration of wind power generation is growing, system operators have an increasing interest in analyzing the impact of wind power on the connected power system. For this reason, grid connection requirements are established. In the last few years, the connection requirements have incorporated in addition to steady state problems, dynamic requirements, like voltage dip ride-through capability [4-5]. The most common requirements under these disturbances are low voltage ride through (LVRT) which usually implies: voltage profile immunity, reactive current injection, active and reactive power limitation under fault and recovery and limitation in reactive energy consumption [5-6]. Therefore, in electrical grids where plans include wind generation systems a detailed analysis is required, it must be contain relevant technical aspects of the operation in steady state and transient conditions. However, the model has an important role to ensure correct results.

In the past, when a serious failure in the electrical grid was presented wind energy conversion systems (WECS) were disconnected. However, due its penetration has been increased it is necessary that all time must remain connected, because they provide a large amount of power, therefore, it can cause major problems to the grid [7]. The continuous operation under different perturbations is not easy to get, the control structure must ensure proper dynamic response. The major literature includes control structure to doubly fed induction generator (DFIG) connected to an infinite bus but not contain all structure electrical grid [1, 8-9]. Analyzing a control structure with a suitable model system largely ensure proper operation in actual conditions. Therefore, a comprehensive study of electrical grid including WECS with detail control structure considering the effect of major disturbances and the behavior of voltage and power flows is required.

II. DFIG-based Wind Turbines

Fig. 1 shows the schematic diagram of DFIG-based wind generators. The DFIG is an induction machine with a wound rotor where the rotor and stator are both connected to electrical sources, hence the term “doubly- fed”. The rotor has three phase windings that are energized with three-phase currents. These rotor currents establish the rotor magnetic field. The rotor magnitude field interacts with the stator magnetic field to developed torque. The magnitude of the torque depends on the strength of the two fields. The system ensures efficient power conversion due to variable rotor speed, which adjusts itself automatically in accordance with prevailing wind speeds. Speed variability is made possible by the directionally dependent transfer of slip power via the frequency converter, which changes as follows [10]: a) In the sub-synchronous operating mode (partial load range), the stator of the DFIG supplies power to the grid and also the slip power to the rotor via slip rings and the frequency converter; b) In the super-synchronous operating mode (nominal load range), both the stator output power and the rotor slip power are fed into the grid.

The stator is connected to the network by a transformer, while the rotor connection to the network is performed through a bidirectional frequency converter (formed by two power electronic converters AC/DC, reversible) and a

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Rubén Tapia-Olvera, Agustina Hernández-Tolentino and Omar Aguilar-Mejia are with the Engineering Department at Polytechnic University of Tulancingo, Tulancingo, Hidalgo, CO 43629, Mexico (corresponding authors to provide phone: 775-755-8319; fax: 775-755-8321; e-mail: ruben.tapia, [agustina.hernandez], [omar.aguilar]@upt.edu.mx).

Antonio Valderrabano-Gonzalez is with Mechatronics Department at Universidad Panamericana Campus Guadalajara, Zapopan, Jalisco, CO 45010, Mexico (e-mail: avalder@up.edu.mx).

transformer. The grid side converter always runs at mains frequency, the vector control can independently absorb or inject active power through the machine rotor and can control the reactive power exchanged between the machine and the electrical grid. The rotor side converter instead, works at variable frequency depending on the operating point. This topology is named back-to-back (BTB) converter. The control structure is the main part to regulate de DFIG performance.

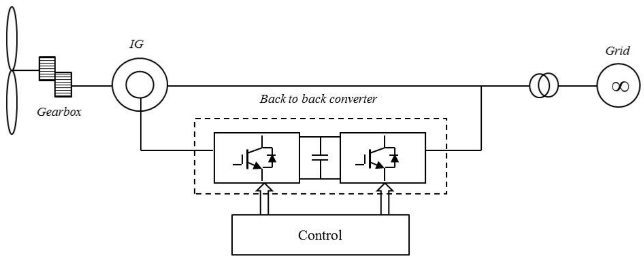

Fig. 1. Schematic diagram of DFIG-based wind generators.

III. Control Scheme

The BTB converter is formed by two voltage source converters (VSC) sharing a DC bus that allow independent control, Fig. 1. To achieve control in power conversion with minimal impact on the conventional grid a BTB converter switched by pulse width modulation (PWM) techniques is used.

A. Source side converter control

The objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The vector-control method is used as well, with a reference frame oriented along the stator voltage vector position, enabling independent control of the active and reactive power flowing between the grid and converter. The converter is current regulated, with the d-axis current used to regulate the dc-link voltage and q-axis current component to regulate the reactive power. Fig. 2 shows the schematic control structure of the grid-side converter [11].

The voltage equations in synchronously rotating *dq*-axis reference frame are [12]:

$$v_{cd} = Ri_{cd} + L_r \frac{di_{cd}}{dt} - \omega_e L_r i_{cq} + v_{cd1} \quad (1)$$

$$v_{cq} = Ri_{cq} + L_r \frac{di_{cq}}{dt} + \omega_e L_r i_{cd} + v_{cq1} \quad (2)$$

The angular position of the grid voltage is calculated as

$$\theta_e = \int \omega_e dt = \tan^{-1} \frac{v_{c\beta}}{v_{c\alpha}} \quad (3)$$

where $v_{c\alpha}$ y $v_{c\beta}$ are the converter grid-side voltage stationary frame components. The *d*-axis of the reference frame is aligned with the grid voltage angular position θ_e. Considering that the voltage grid amplitude is constant, v_{cq} is zero and v_{cd} is constant. The active and reactive power will be proportional to i_{cd} and i_{cq} respectively. Assume the grid side transformer connection is start; the converter active and reactive power flow are,

$$P_c = 3(v_{cd} i_{cd} + v_{cq} i_{cq}) = 3v_{cd} i_{cd} \quad (4)$$

$$Q_c = 3(v_{cd} i_{cq} + v_{cq} i_{cd}) = 3v_{cd} i_{cq} \quad (5)$$

The control scheme uses a current decoupling for i_{cd} and i_{cq}, to determine the component i_{cd}, the voltage difference in DC bus is used. While, the value for i_{cq} is calculated by the displacement factor in grid side inductor.

For the internal control loop it is necessary to design the proportional integral (PI) controller's parameters, which are obtained by application of the Laplace transform to (1) and (2) that represent the grid-side converter voltages in its *dq*-components. The reference for the voltages values v^*_{cd} and v^*_{cq} can be obtained by [11]:

$$v^*_{cd} = -v'_{cd} + (\omega_e L_r i_{cq} + v_{cd}) \quad (6)$$

$$v^*_{cq} = -v'_{cq} - (\omega_e L_r i_{cd}) \quad (7)$$

These reference values are the inputs used in the PWM technique in order to guarantee the DC voltage level and the required power factor.

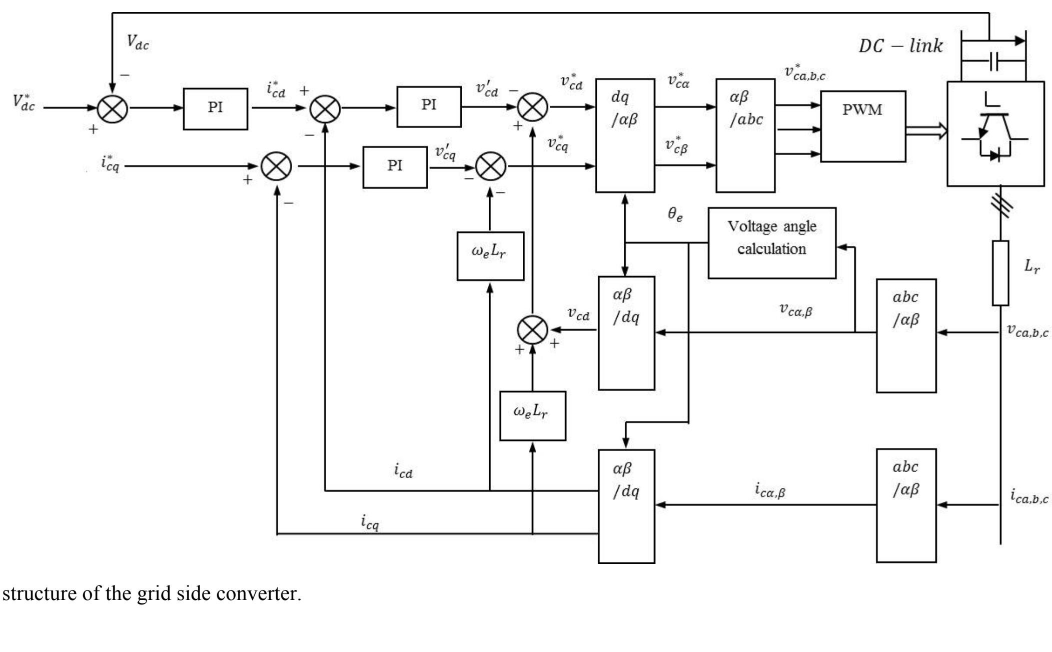

Fig. 2. Control structure of the grid side converter.

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B. Rotor side converter control

The rotor side converter provides the excitation of the induction machine. So, it is possible to control the torque, therefore, the speed of the induction generator and the power factor of the stator terminals. The rotor side converter supplies a variable excitation frequency depending on the conditions of the wind speed.

The first step for the rotor side converter control is to determine the instantaneous stator rotating flux vector location θ_s.

$$\begin{cases}\psi_{s\alpha} = \int\left(v_{s\alpha} - R_s i_{s\alpha}\right)dt \\ \psi_{s\beta} = \int\left(v_{s\beta} - R_s i_{s\beta}\right)dt\end{cases} \quad , \quad \theta_s = \tan^{-1}\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right) \qquad (8)$$

The next step is to generate the rotor current references. For this purpose two PI regulators with the inputs of Q_{ref} and ω_r are used, Fig. 3.

IV. Simulation Results

The test utility network configuration used in this paper is shown in Fig. 4 as a single line diagram. It consists in a grid of 11 buses with voltage at 13.8 kV. There are 9 loads in the system with total active and reactive ratings of 1.1475 MW and 0.7101 MVARs, respectively. There are two wind farms connected in 7 and 10 buses through back to back converter with a control structure shown in section III. In order to verify the control scheme of the DFIG inside an electrical grid, we study the demand of active, reactive power and its capability to remain connected to the distribution grid with security. Two cases are analyzed in the PSCAD software.

A. Case 1

This case presents the power flow analysis of electrical grid with wind turbines. Initially the system is inactive; all variables have values equal to zero, after a transient period are stabilized around of a constant value at steady state. The 9 loads are of 150 kVA each one that is the nominal capacity of the transformer with a power factor of 0.85. Table I shows the measurements for different wind speeds from 6 to 15 m/s. The generation units should remain around unity power factor at the connection point due to the control scheme. The level of reactive power is controlled by the conversion system by assigning a reference value equal to zero. It can be seen that turbines are operating with a factor close to unity. Furthermore, we can see that the DFIG has the ability to regulate the reactive power flow exchanged with the grid in steady state at different wind speeds. The control structure guaranties such behavior.

TABLE I
MEASUREMENT OF POWER FLOW IN EACH GENERATION UNIT

Wind Speed m/s	DFIG 1			DFIG 2		
	P1 *MW*	Q1 *MVArs*	FP1	P2 *MW*	Q2 *MVArs*	FP2
6	0.169	-0.017	0.99	0.173	0.003	0.99
8	0.209	-0.001	0.99	0.201	-0.009	0.99
9	0.276	0.010	0.99	0.287	0.012	0.99
12	0.568	0.0005	0.99	0.570	0.001	0.99
15	1.205	-0.079	0.99	1.253	-0.054	0.99

It can be seen that system's control has a good response. However, the control system operates with unity power factor, there is no reactive power exchange with the distribution network. Therefore, it is examines the inclusion of a capacitor bank in the common connection point in order to cover the supply of reactive power demanded by the loads, transformers and transmission line to avoid problems of stability and improve voltage profile.

The comparison results with and without inclusion of capacitors banks are presented in Table II. It is convenient to analyze how are the adjusted and modified the line losses; the total demand of active and reactive power is 1.1475 MW and 0.7101 MVARs, respectively. The total active power generated without the inclusion of the capacitor bank is 1.173 MW and the reactive power is equal to 0.7785 MVARs.

Table II shows that without capacitors banks the active power demand is supplied by 98.99% by wind turbines, while that 1.01% is cover by the AC grid. For the case of reactive power the results are different, the 100% reactive power demanded by the system is taken from the conventional AC network, hence the importance to include the capacitors banks to compensate reactive demand.

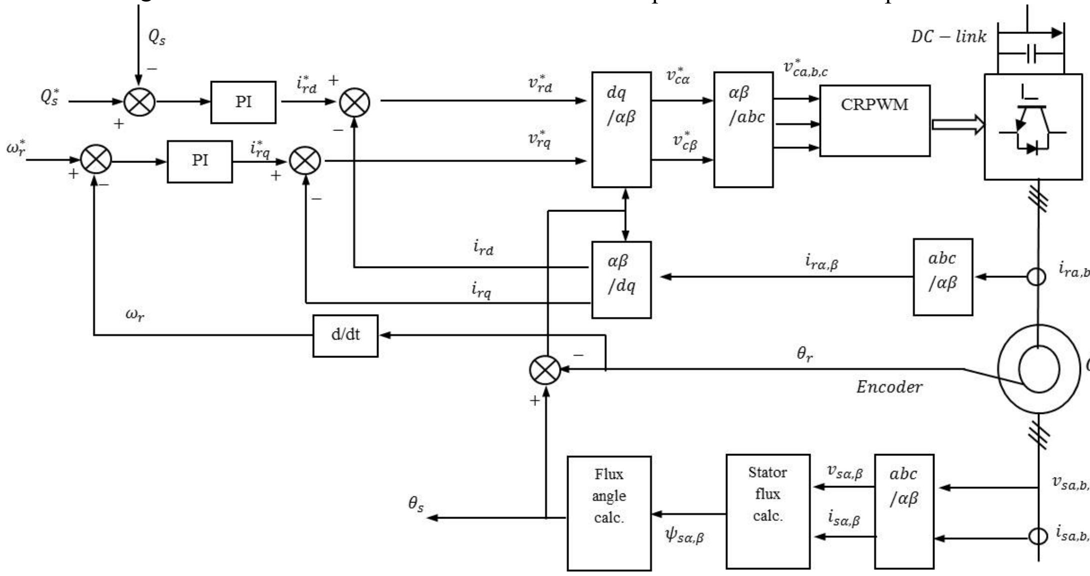

Fig. 3. Control structure for rotor side converter.

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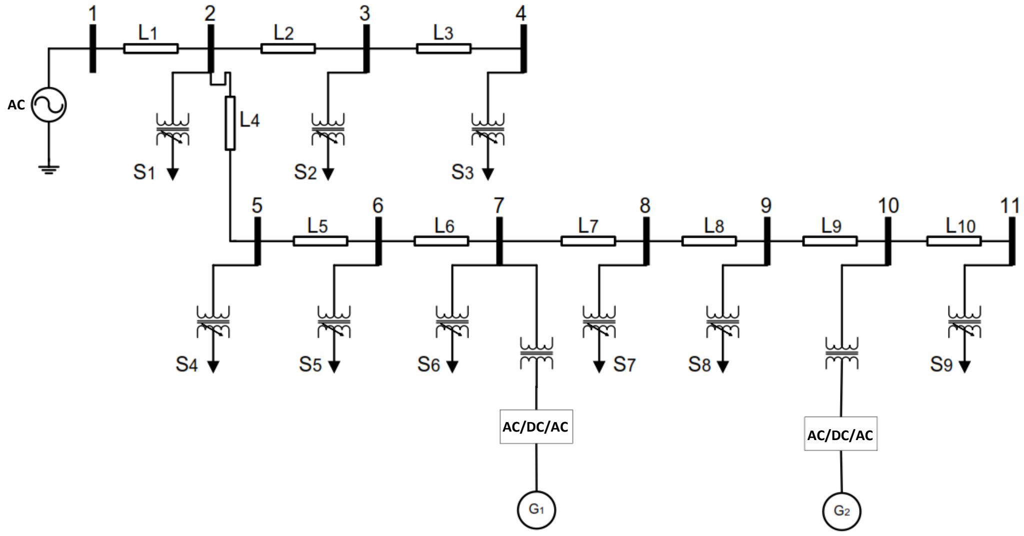


Fig. 4. Single line diagram of test electrical grid.

The total active power generated is very similar for both cases. On the other hand, the capacitors banks cover 100% of the reactive power demand for both loads and losses. It can be seen that the losses in the network decreases with integration of the capacitor banks from 68.4 KVARs to 57.9 KVARs and 10.2KVARs supplied to AC system. Similarly, the connection of distributed generation systems close of the loads exhibits two main advantages: a) the loads are powered by generating systems from alternative energy sources rather than conventional sources, b) improving the voltage profile making the system more robust. The voltage profile is better with capacitors banks inclusion all magnitudes are close to 1.0 pu, nodes 8-11 have similar performance, Table III. The phase angles maintain their values more close to each other respect the systems without capacitors, Table III.

TABLE II

COMPARISON RESULTS WITH AND WITHOUT INCLUSION OF CAPACITORS BANKS.

Line		Without capacitors banks			With capacitors banks		
from	to	P *MW*	Q *MVArs*	S *MVA*	P *MW*	Q *MVArs*	S *MVA*
1	2	0.037	0.779	0.779	0.0134	-0.0102	0.016
2	3	0.254	0.161	0.300	0.256	0.162	0.302
2	5	-0.357	0.516	0.627	-0.371	-0.254	0.449
3	4	0.127	0.080	0.150	0.128	0.080	0.151
5	6	-0.489	0.429	0.650	-0.500	-0.339	0.604
6	7	-0.618	0.344	0.707	-0.632	-0.423	0.760
G1	7	0.566	0.0002	0.566	0.574	0.377	0.686
7	8	-0.183	0.256	0.314	-0.190	-0.134	0.232
8	9	-0.310	0.177	0.356	-0.319	-0.217	0.385
9	10	-0.438	0.094	0.447	-0.450	-0.302	0.541
G2	10	0.570	-0.0007	0.570	0.583	0.391	0.701
10	11	0.126	0.079	0.148	0.128	0.081	0.151
2	1	-0.016	-0.753	0.753	-0.013	0.0107	0.017
3	2	-0.254	-0.160	0.300	-0.255	-0.161	0.301
5	2	0.370	-0.504	0.625	0.373	0.258	0.453
4	3	-0.127	-0.080	0.150	-0.127	-0.080	0.150
6	5	0.500	-0.419	0.652	0.503	0.342	0.608
7	6	0.631	-0.333	0.713	0.631	0.425	0.760
8	7	0.185	-0.248	0.309	0.191	0.135	0.233
9	8	0.314	-0.165	0.354	0.322	0.221	0.390
10	9	0.443	-0.080	0.450	0.454	0.31	0.549
11	10	-0.126	-0.079	0.148	-0.128	-0.08	0.150

B. Case 2

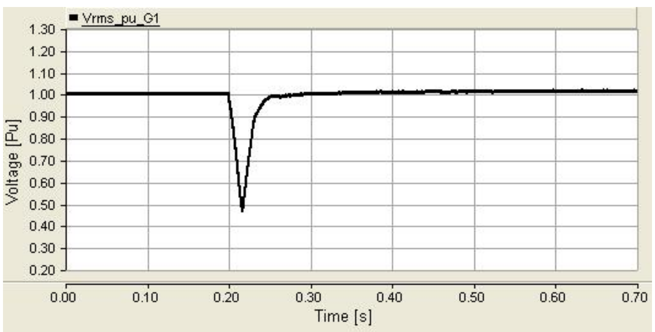
The second case analyzes the behavior of DFIG in face to voltage drop across the network considering a wind speed of 12 m/s, the reactive power control is regulate by side source converter. When the voltage exceeds a critical limits turbine the reactive power controller supplied or absorbed to prevent over voltage or under voltage, which could result in the disconnection.

TABLE III

MAGNITUDE AND PHASE ANGLE OF NODAL VOLTAGES.

Node	Without capacitors banks		With capacitors banks	
	Voltage (pu)	Phase (degrees)	Voltage (pu)	Phase (degrees)
1	1.0	0.0	1.0	0.0
2	0.97	0.9799	0.99	-0.08
3	0.97	0.892	0.99	-0.168
4	0.97	0.87	0.99	-0.190
5	0.97	1.71	1.0	0.107
6	0.97	2.18	1.01	0.266
7	0.97	2.81	1.02	0.507

The system is subjected to a three-phase short-circuit fault at bus 9 after 10 ms is delivered. At t = 0.2 s the voltage at terminals G1 has decreased about 50% of its nominal value, while the active and reactive powers present a transient period and reach steady state values, Fig. 5. In the case of the generator 2, Fig. 6, the reduction in voltage has a level of approximately 65% of the nominal value; the powers after 0.08 milliseconds return to its steady-state value. The results exhibit good control structure performance when a DFIG is included in a typical electrical grid.



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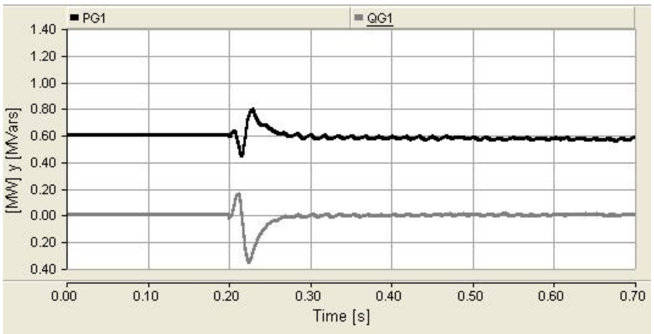
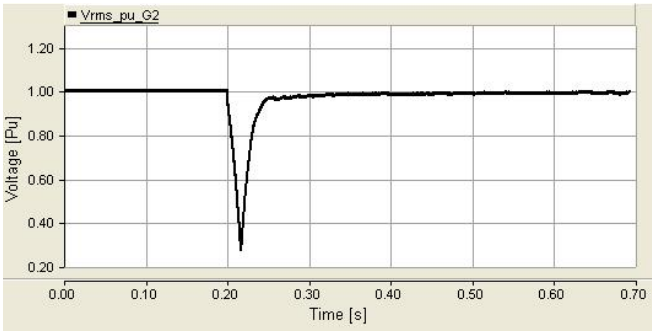


(b)

Fig. 5. Generator 1 when there is a short circuit fault 10 ms at t = 0.2 s: a) terminal voltage; b) active and reactive power.



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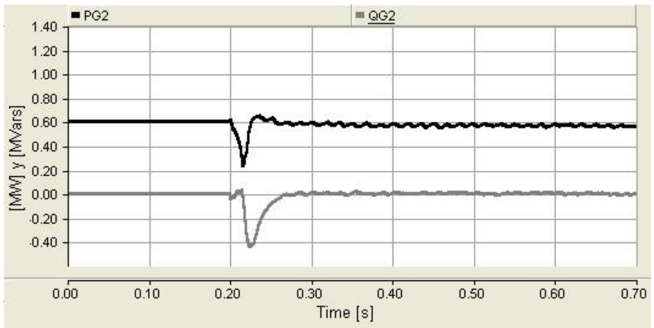
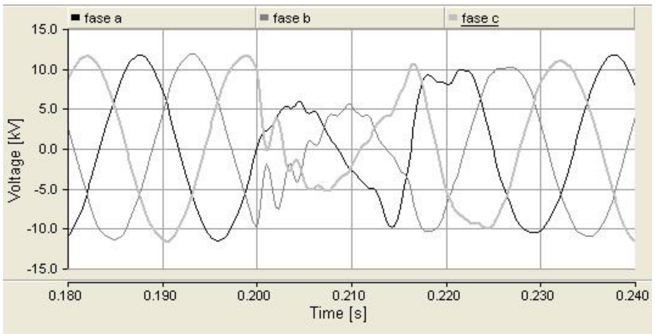


(b)

Fig. 6. Generator 2 when there is a short circuit fault 10 ms at t = 0.2 s: a) terminal voltage; b) active and reactive power.

The impact of the voltage drop in each generation unit depends on the proximity where the fault occurs in the distribution network. For this study the fault is located closer to the generator 2. Fig. 7 presents the voltage behavior in the three phases at connection point of each wind turbine. During fault time the voltage magnitude of terminals G2 is less than G1, at t = 0.210 s the fault is cleared. The units tend to stabilize, and at t=0.220s attain its steady state value, showing a typical waveform at steady state condition for power converters. Control structure adequately fulfilling its task with transient response when hard perturbations in an electrical grid are presented, the results are in accordance with previous case.

The impact of the voltage drop in the grid stability depends on the duration and severity. Fig's. 8 y 9 show when a fault with a duration of 87 ms is applied, the terminal voltage of both units has decreased more than 50% of their nominal value, as a result, the transient period in the active and reactive power of connection point is more prolonged, but the system reach its steady state condition about t = 0.35 s.



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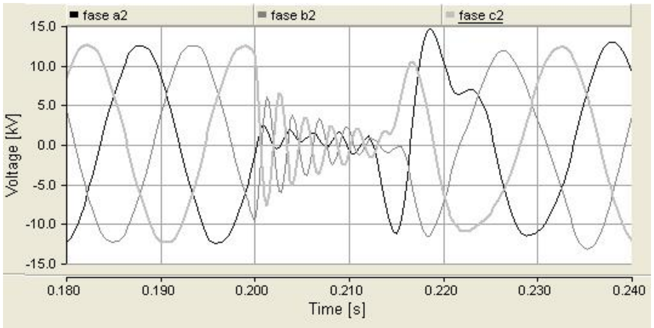
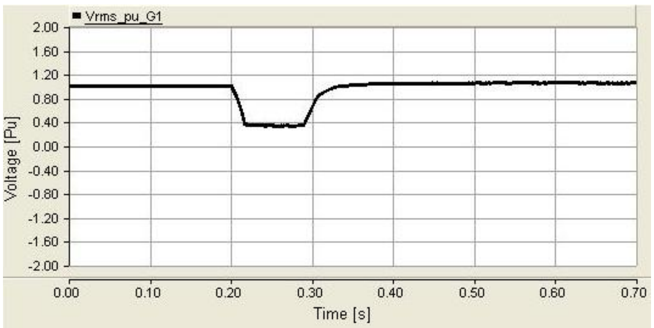


(b)

Fig. 7. Three phase voltage at connection node to the grid when a short-circuit fault is applying at t = 0.2 s: a) G1 unit; b) G2 unit.



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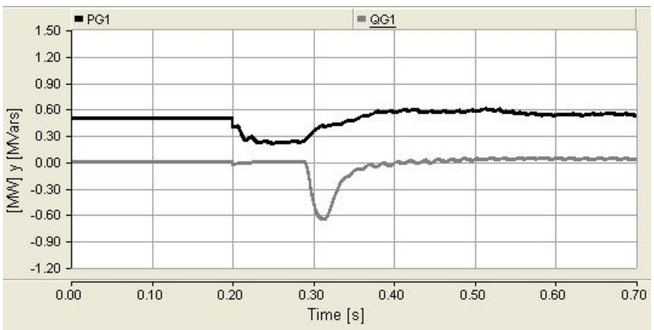

(b)

Fig. 8. Generator 1 when a short circuit fault is applying at t= 0.2 s: a) terminal voltage; b) active and reactive power.

The analysis of two doubly fed induction generators in distribution network has been presented in this paper, each unit represents a wind farm with a detailed control structure. For the analysis and evaluation of the control strategy, a study of power flows and dynamic response were developed. It is concluded that it is necessary to include a capacitor bank in the common point of connection to the network, because the system controller of DFIG operates to a unity power factor. Furthermore, with the inclusion of the capacitor bank is compensated demand for reactive and the voltage profile is improved. The losses present in case 1 are smaller with inclusion of the capacitor bank but the main contribution is observed in balancing the flows of the system under study. Another important aspect is the stability analysis of DFIG connected to network in face to voltage dips.

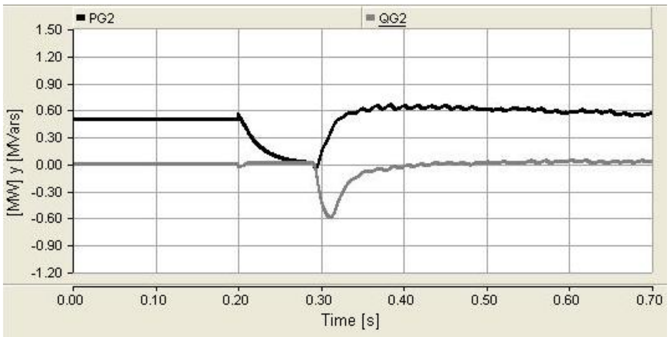

Fig. 9. Active and reactive power of generator 2 when a short circuit fault is applying at t= 0.2 s with a duration of 87ms.

V. Conclusion

The results show that the controller has a fast response and allows wind turbines successfully get over after the fault period and return to their steady state condition. Analysis of detailed control structure when including wind systems in the electrical grid with specialized software presents actual characteristics, which can be used for the planning and operation of electrical networks.

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