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Low Voltage Ride Through Characterization of Wind Energy Conversion Systems

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Abstract. Low Voltage Ride Through (LVRT) has emerged as an essential requirement that system operators demand to wind energy conversion systems (WECS). LVRT characterization is to get the minimum grid voltage profile under which the transient stability of WECS is not possible. This paper will determine the LVRT capability of existing Egyptian WECS. The methodology for analyzing wind power systems will require the modeling of three different wind turbine generator technologies. These are the fixed speed induction generator (SCIG), variable slip IG with variable rotor resistance, and doubly-fed IG with rotor-side converter. The methodology also requires the modeling of wind power plant, and the equivalent representation of power system.

Simulation results are obtained for different IG technologies. They will provide a good understanding of the dynamic behavior of existing wind farms, and how to improve the stability and LVRT capability. Moreover, the results will form a template for the requirements by wind farm developers and power utilities in Egypt when developing new wind farms.

Key words

Fixed speed SCIG, variable slip IG, doubly-fed IG, low voltage ride through, grid code

1. Introduction

The main objective of electric power utilities is to operate their electric systems in a safe, secure, efficient and economical manner. An important challenge for the safe operation of the Egyptian electric grid is the increasing penetration of renewable energy generation, enforced through the 2007 resolution of the Supreme Council of Energy which states that Egypt should have 12% of its generation capacity supplied by wind power by the year 2020. The transmission system operators are reluctant to integrate such amount of wind power unless they are ensured that this step will not disrupt the stability of the whole power network. The development of the wind power generation could face the risk of being stopped if measures are not taken to ensure that there will be means to support stability and reliability of the power system.

Today more than ever, utilities need electrical models of wind farms and methods of analysis that will help them to identify and cope with potential problems of grid stability. The methodology for analyzing wind systems will require:

1. Description and modeling of wind turbine generator technologies/ wind power plant aggregated models.
2. Wind power plant / power system representation.
3. Simulation performed with a system model implemented in a simulation software.
4. Analysis of the impact of wind energy.

This paper determines the dynamic behavior of existing Egyptian wind energy conversión systems in Zafarana. The methodology for analyzing wind power systems will require the modeling of three different wind turbine generator technologies. These are the fixed speed induction generator (SCIG), variable slip IG with variable rotor resistance, and doubly-fed IG with rotor-side converter. The methodology also requires the modeling of wind power plant, and the equivalent representation of power system. Simulations are performed with the system model implemented in the PSCAD/EMTDC simulation software [1]. Simulation results are presented for different IG technologies. The results are compared to the German LVRT grid code [2] which is receiving a wide acceptance and being used as a template for similar requirements from many countries with wind generation. The results of the paper can easily and reliably be implemented by wind farm developers and power utilities in Egypt when developing new wind power plants and/or modifying the Egyptian grid.

2. Methodology for analysis of Wind Turbine (WT) systems

1. Description and Modeling of Wind Turbine Generator Technologies

Wind turbine generators (WTGs) in the market are classified in one of four basic types [3], based on the generator topology and grid interface. These types are:

- Fixed-speed IG: Nordex N43/600 WT is used in Zafarana farms 1 and 2.
- Variable slip IG with variable rotor resistance: Vestas V47/660 WT is used in Zafarana farms 3 and 4.
- Variable speed, doubly-fed IG with rotor-side converter Gamesa G52/850 WT is used in Zafarana farms 5-8.
- Variable speed generators with full converter interface: This type is not yet used in Egypt.

The detailed modeling of types 1- 4 wind turbine units is given in References [4 and 5].

2. *Wind Power Plant Aggregated Models*

A typical modern wind power plant (WPP) consists of tens or hundreds of turbines of the same types. A wind turbine generator (WTG) at Zafarana farms is usually rated at low three phase voltage output (690V). A pad mounted transformer (1.05MVA) at each turbine generator steps up the voltage to the medium voltage collector system (22 kV). Several turbines that are physically close together are connected to laterally to form a group (or a circuit). Several of these groups are connected to a larger main feeder. Several of these feeders are connected to the substation where the substation transformer (26.4 MVA) steps up the voltage to a desired transmission level (220 kV). A very large WPP can have several substation transformers.

Although it is important to model a WPP to be as close as possible to the actual implementation, It is not practical to model in detail all individual turbines and the collector system for simulations typically conducted by power system engineers. To simplify, it is a common practice to represent the entire WPP with a small group of equivalent turbine generators or a single turbine generator (aggregated model). This representation is more practical for bulk system simulations.

A method to derive and validate equivalent aggregated models for a large WPP was described in References [4, 6 and 7]. The method is applicable to any large WPP. It illustrates how to derive a simplified single-machine equivalent aggregated model of a large WPP (that includes an equivalent collector system model), preserving the net steady state and dynamic behavior of the actual installation. Hence, a WPP with many wind turbines can be simplified into the aggregated single turbine representation (STR), Figure 1.

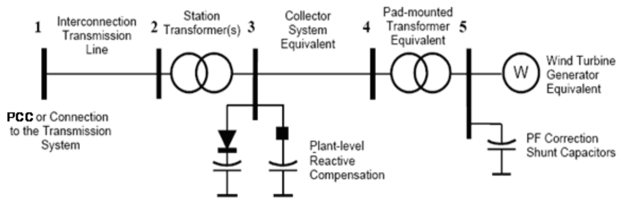

Figure 1 – Single turbine representation for a WPP

3. *Wind Power Plant / Power System Representation*

3.1. Wind power plant representation

In Figure 2, the dashed line circumscribes the power system elements that may require dynamic models. The solid line circumscribes the power system network of a WPP representation. The behavior of a very detailed model can be closest to the real wind turbine performance, but the computational cost may be excessive. When the response to grid disturbances is of interest, it is mainly the description of the generator and control schemes that affects the response of the turbine. However, simulation models must incorporate the description of the

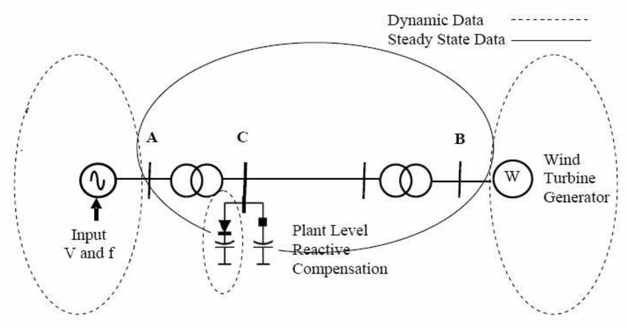

Figure 2 – Steady state and dynamic data groupings.response

aerodynamics and drive train in order to predict their impact.

3.2. Power system representation

In this study, the Egyptian power network is represented as an infinite-bus connected to the point of common coupling through an equivalent impedance. This technique has limitations, including unbalanced situations and lack of complete knowledge of network conditions. The PSS/E software program is used to determine the Thevenin's equivalents of the Egyptian networks of 2012, 2013, and 2017 as viewed from several WPP buses. The results of these calculations show that an average value of (0.002 + j0.016 p.u) can be considered for the Thevenin's equivalent impedance as seen from Zafarana buses.

4. Simulation Results

4. 1 Fixed speed wind turbines

Fig. 3 shows the PSCAD representation of the Nordex WT (fixed-speed IG). The figure gives the parameters of the LV/MV transformer, connection cable, MV/HV transformer, and the Thevenin equivalent of the grid impedance at the connection bus.

Figure 4 shows the dynamic performance of the fixed-speed wind turbine following the occurrence of a rigid short circuit fault at the 22 kV bus.. The wind speed is assumed equal to 13m/s. The fault occurs at t= 6 sec, and lasts for 0.1 s. The terminal voltage of the 22 kV bus falls to zero, while the voltage of the induction machine falls to a very low value. The electromagnetic torque and generated power are equal to zero during the fault time. The shaft starts to accelerate and the machine speed increases, Fig.4(b). When the fault is cleared at t=6.1 s, the induction machine draws a large amount of reactive power (4 to 6 times the rated power) from the grid, which is required for the excitation of the induction generator, Fig. 4(e). The inrush current drawn by the induction generator is displayed in Fig. 4(j). The terminal voltage of the induction generator builds up as shown in Figs. 4(g) and (h), and the induction generator is successfully recovered. As a result, the induction machine supplies active power, and the generator speed is reduced to its pre-fault value.
More dynamic behavior of the fixed-speed wind turbine is obtained at wind speed of 13m/s for a rigid short circuit

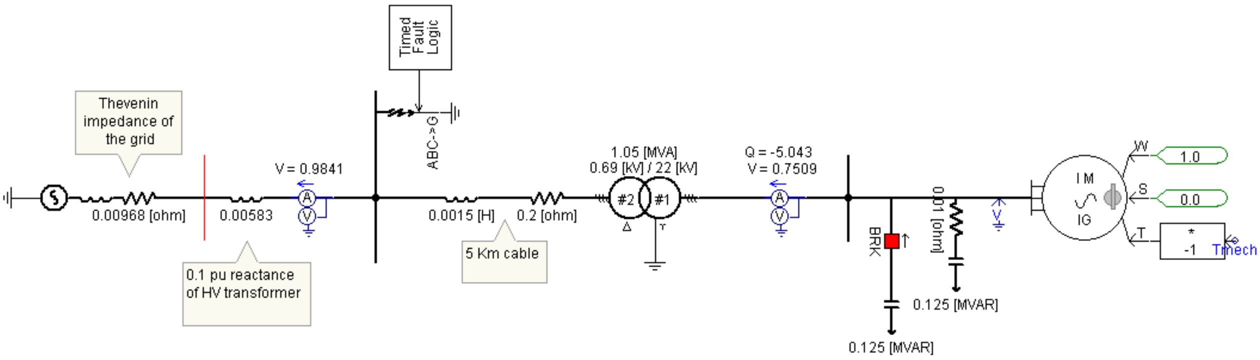

Figure 3 PSCAD representation of the fixed-speed wind turbine connected to the grid.

fault with variable duration. If the fault duration is increased to 0.645 s, the induction generator fails to recover when the fault is cleared. In this case, the stator winding draws a very high current. As a result, the voltage drop due to the transformers and the cable impedances is high. This drop reduces the voltage at the generator terminals. At the same time, the shaft speed is continuously increasing (run away). In this case, the time-inverse over-current protection relaying system will disconnect the generator from the grid when the maximum allowable time for this high current is reached. In addition, the mechanical brake will lock the shaft.

More results are obtained for the dynamic behavior of the fixed-speed WT for different wind speeds and different fault durations. Table 1 summarizes the LVRT capability of the fixed-speed WT under study at wind velocity of 13 m/s. In conclusion, the LVRT capability of the fixed-speed wind turbine is governed by the stability limit and/or the current-time characteristics of the induction machine. As expected, the maximum time before losing the stability of the induction generator due to a fault is reduced for higher voltage dips. It is also noted that as the cable length increases, there is a slight reduction in the time before losing the stability. This can be attributed to the fact that the feeder impedance is not the dominant impedance between the generator and the fault if compared to the impedance of the LV/MV and MV/HV transformers.

Similar results are obtained for the dynamic behavior of the fixed-speed WT for different wind speeds and different fault durations. Table 2 summarizes the LVRT capability of the fixed-speed wind turbine at wind velocity of 10 m/s. Compared to Table 1, the time that the machine can maintain its stability increases with reduced wind speeds, i.e., the LVRT capability is better for reduced wind speeds. The reason is that for a reduced wind speed, the induction generator feeds less active power and hence requires less reactive power. This in turn reduces the recovery time of the induction generator after fault clearance.

4. 2 Wound rotor IG based WECS (variable slip IG)

Fig. 5 presents the Vestas (wound rotor induction generator) WT unit with its electronic rotor resistance controller. A 3-phase external resistance of 1 ohm is connected to the rotor winding. It is modulated by a single IGBT switch through a 3-phase bridge rectifier. The wound rotor induction machine with a controlled external rotor resistance is called OptiSlip induction generator

Table1: LVRT capability of fixed-speed wind turbine at wind speed of 13 m/s

22KV bus Voltage level (Fault level)	Duration in seconds that fixed-speed wind-turbine can withstand the fault level	
	Cable length 5 km	20 km
Zero(100% dip)	0.645 s	0.6177 s
25% (75% dip)	0.795 s	0.7677 s
35% (65% dip)	0.943 s	0.9073 s
50% (50% dip)	Stable/depend on the machine current-time c/cs	

Table 2: LVRT capability of fixed-speed wind turbine at wind speed of 10 m/s

22KV bus Voltage level (Fault level)	Duration in seconds that fixed-speed wind-turbine can withstand the fault level
Zero (100% dip)	2.48 s
25% (75% dip)	2.94 s
35% (65% dip)	3.715 s
50% (50% dip)	Stable/depend on the machine current-time characteristics

(OSIG) [8 and 9]. The slip of the generator is dynamically varied by changing the rotor circuit resistance.

The dynamic behavior of the Vestas OSIG is studied when a rigid short circuit fault on the 22 kV side of the MV/HV transformer occurs, and under different wind speeds. Fig. 6 shows the LVRT performance of the OSIG at wind speed of 10 m/s. When the fault occurs at t = 9 s, the shaft starts to accelerate and the speed of the machine increases, Fig.6(b). When the fault is cleared at t = 9.3 s, the induction machine draws a large amount of reactive power from the grid (4 times the rated power), which is required for the excitation of the induction generator, Fig. 6(e). The induction machine gets excited and supplies active power. The rotor speed is reduced to its pre-fault value. The terminal generator builds up, and the induction generator is successfully recovered. A similar behavior is obtained when the wind speeds is 16 m/s. Since the 16m/s is higher than the rated wind speed, the rotor resistance controller is activated to limit the generated power to its rated value. When the fault occurs at t = 9 s, the rotor controller increases the rotor resistance to regulate the generated power at its rated value. It is worth mentioning that the rotor resistance controller works as an active crowbar.

For wind speeds lower than the rated value, the dynamic performance of the OSIG is similar to the fixed-speed units (the rotor resistance controller is deactivated).

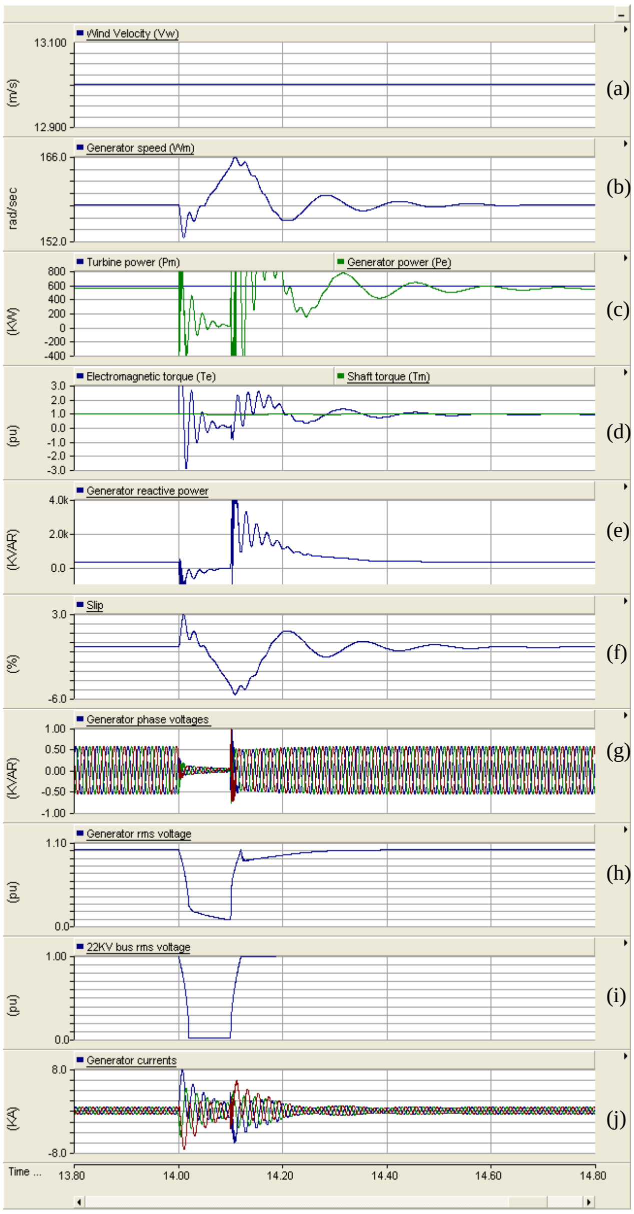

Figure 4: Dynamic performance of fixed-speed wind turbine during a rigid short circuit fault for 0.1 sec at wind speed of 13m/s.

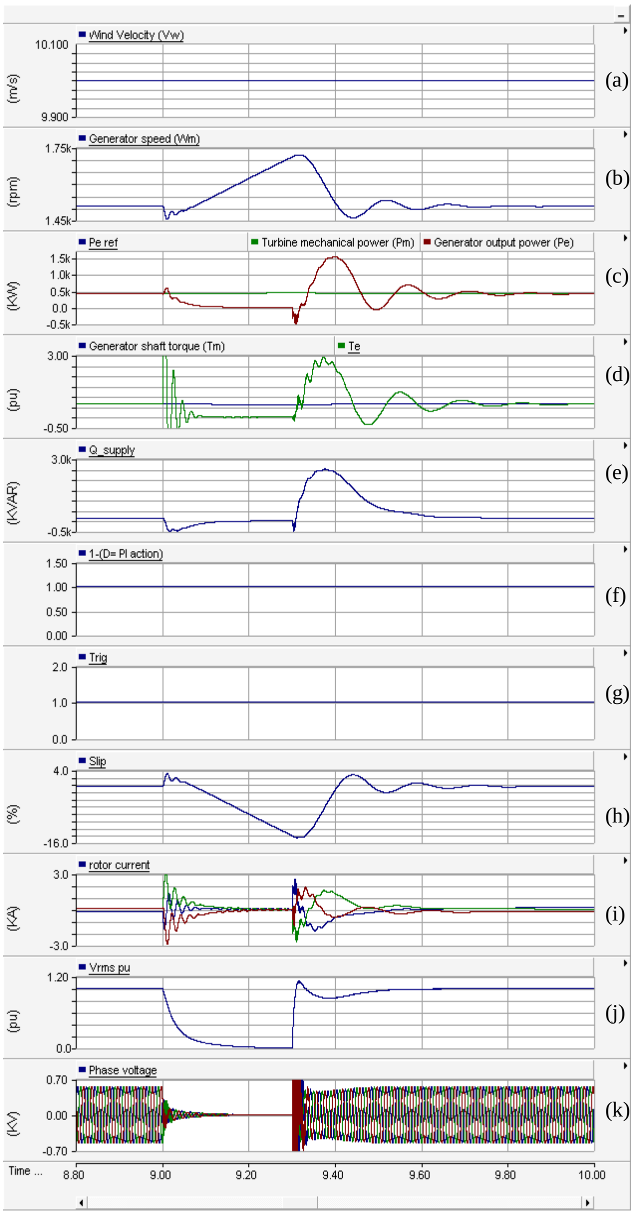

Figure 6: Dynamic performance of Vestas OSIG wind turbine during a rigid short circuit fault for 0.3 sec at wind speed of 10m/s

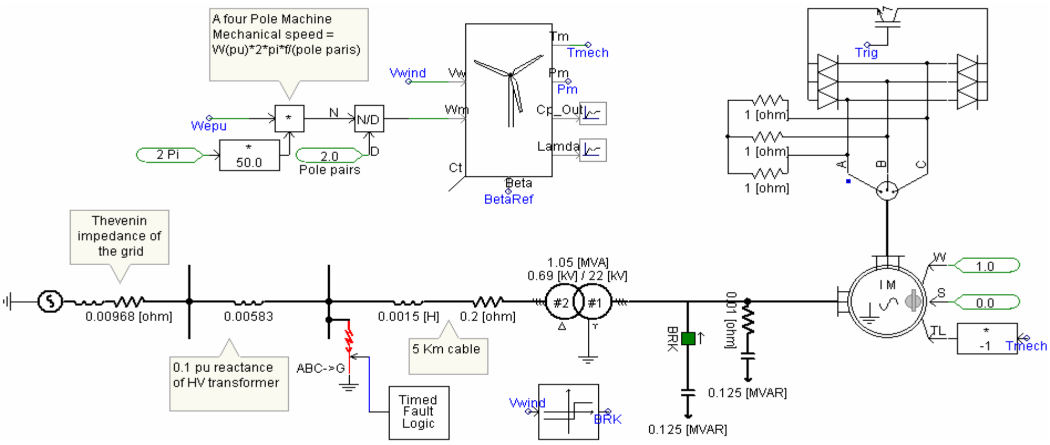

Figure 5: PSCAD representation of Vestas wind turbine unit connected to the grid.

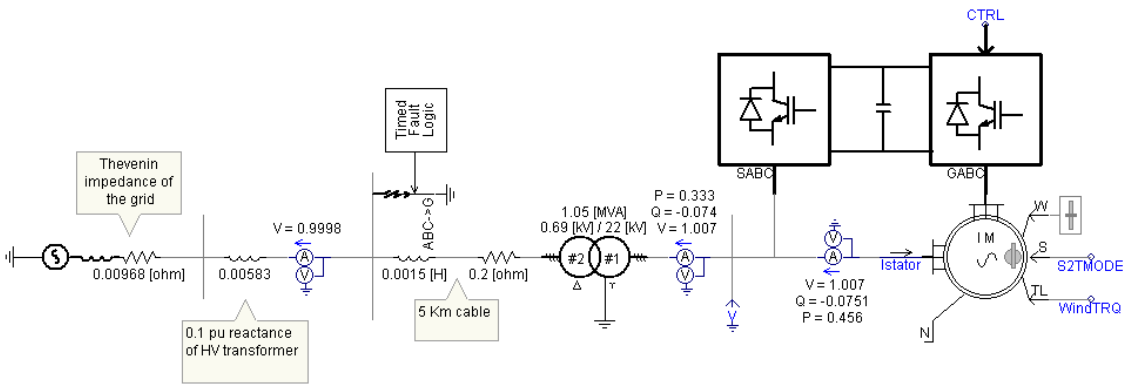

Figure 7: PSCAD representation of Gamesa G52/850 wind turbine unit (DFIG) connected to the grid.

4. 3 DFIG based WECS (variable speed doubly-fed IG)

The PSCAD representation of Gamesa G52 wind turbine unit (DFIG) connected to the grid is shown in Fig. 7. Figure 8 shows the dynamic performance of the DFIG during a voltage dip of 75% for a duration of 350 ms and at a wind speed of 13m/s. At this wind speed, the DFIG works in the super-synchronous mode. The slip is negative and the grid-side converter power is positive (fed to the grid) due to the super-synchronous operation. During the fault and after the crowbar becomes active (t = 6.12 to 6.36 sec.), the DFIG feeds active power from both the stator and rotor to the fault. At the instant of fault clearance, the stator of the induction machine draws heavy currents from the grid. Hence, the crowbar operates to limit the stator current, and the induction machine behaves like the direct connected squirrel cage induction machine. It draws a large amount of reactive power (4 time the rated power), Fig. 8(g), to build up the flux. If the fault duration is increased to 360 ms at the same wind speed of 13 m/s, the DFIG fails to recover as indicated in Fig. 9.

Different levels of voltage dips are simulated to explore the LVRT capability of the DFIG as done for the fixed-speed wind turbine in the previous subsection. Table 3 summarizes the LVRT capability of the DFIG under study at wind speed of 13 m/s. The LVRT capability of the DFIG based wind turbine is governed by the stability limit and/or the current-time characteristics of the induction machine. As expected, the maximum time before losing the stability of the DFIG due to a fault is reduced for higher voltage dips. It can also be noted that the effect of diversity of cable length is negligible.

Table 3: LVRT capability of DFIG wind turbine at wind speed of 13 m/s

22KV bus Voltage level (Fault level)	Duration in seconds that DFIG wind-turbine can withstand the fault level	
	Cable length 5 k	20 km
Zero (100% dip)	0.139 s	0.139 s
25% (75% dip)	0.350 s	0.354 s
35% (65% dip)	0.450 s	0.454 s
50% (50% dip)	0.663 s	0.656 s
75% (25% dip)	Stable/depend on the machine current-time characteristics	

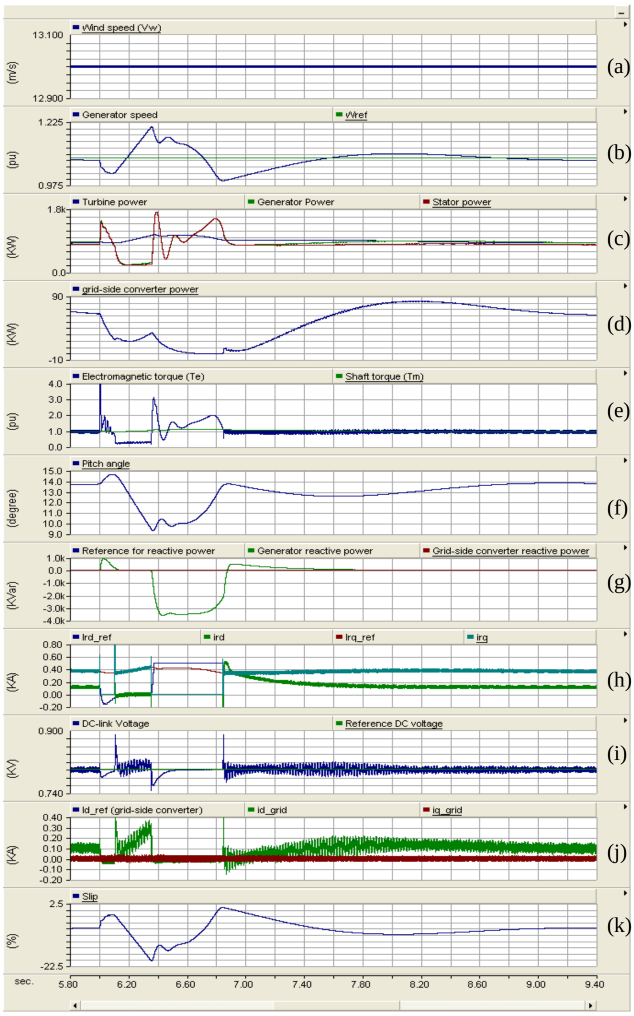

Fig. 8: Dynamic performance of DFIG during a voltage dip to 75% for a duration of 350ms at wind speed of 13m/s.

4. 4 LVRT Characterization

In the past connection of wind farms were based on the assumption that in case of a grid disturbance, e.g., severe voltage drop, the wind turbines would disconnect from the system. In a highly penetrated system such a paradigm may result in several thousands Megawatts of wind generation tripping off-line, which is clearly unacceptable. Thus one of the main grid connection regulations as they pertain to wind farms is the requirement of LVRT. The

E.ON [2] requirement is shown in Fig. 10. According to this requirement, tripping of wind turbines/farms is allowed below the red line. Inspection of the results given in Tables 1 and 3 show that they do not comply fully with this code. The fulfilment of the LVRT code would require specific measures such ascontrol strategies for pitching the blades and/or extra support of reactive power [10 and 11].

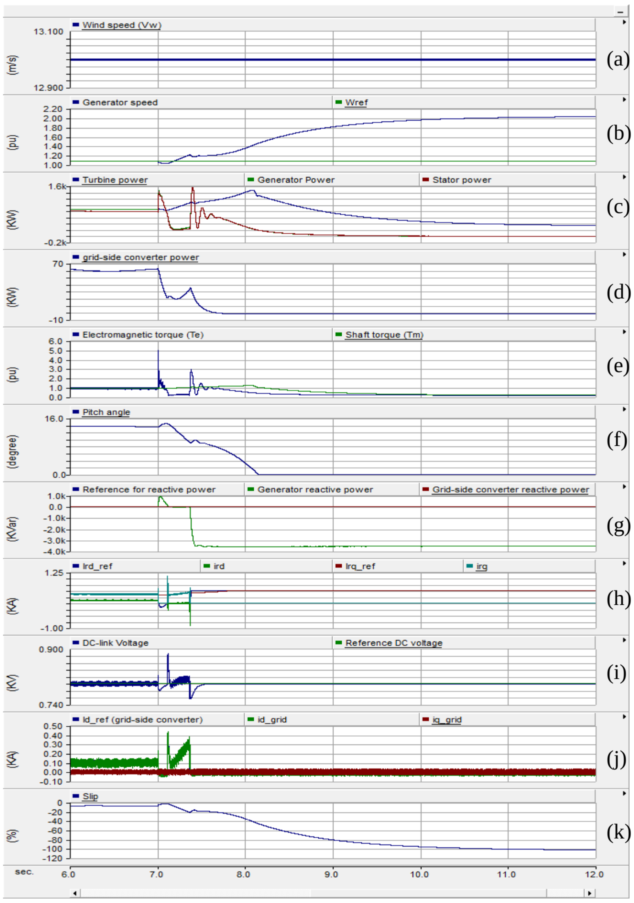

Fig. 9: Dynamic performance of DFIG during a voltage dip to 75% for a duration of 360 m at wind speed of 13m/s.

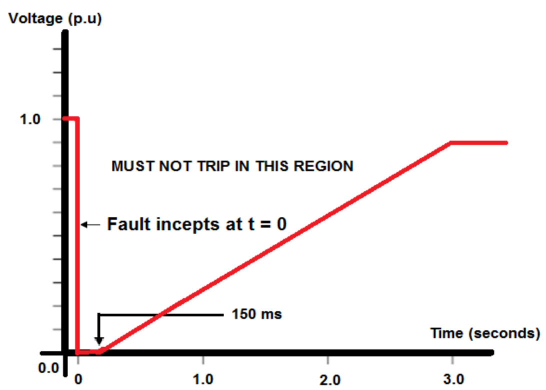

Fig. 10: German (E.ON) standard LVRT Capability equirement.

5. Conclusion

This paper analyzes transient stability issues related to existing wind farms in the gulf of Suez in Egypt. The paper also defines important requirements for the existing wind farms, which are essential for a secure and stable operation of the Egyptian power system. These are mainly related to the reactive power range and the low voltage ride through (LVRT) requirements.

Simulation results are obtained for three different IG technologies. The results of the paper demonstrate that wind farms using squirrel cage induction generators directly connected to the network will most acutely suffer from short circuit faults since they have no direct control of torque or speed, and would usually disconnect from the power system when the voltage drops more than 50% below rated value. In general, fulfillment of the LVRT demand for induction generators will require specific control strategies for pitching the blades and/or extra support by controlled injection of reactive power.

Acknowledgement

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