Dynamic Response of Doubly Fed Induction Generator Wind Turbines with Transmission Grid Connection in Northeastern

P. Poochonk and S. Sirisumrannukul

***Abstract*— *Wind power plants have been playing an important role for electricity production around the world. In Thailand, connecting wind farms to the grid needs to comply with the established grid code to make sure that any possible negative impacts will not harm the system technically. The transmission system operator and the power system planning division of Electricity Generating Authority of Thailand (EGAT) are responsible for investigating such impacts from wind farm connection under both normal operating and disturbance conditions. This paper presents a stability study of the dynamic responses of a large-scaled doubly fed induction generator (DFIG) wind power plant when connected to transmission grids. The DIgSILENT Power Factory software package, of which wind turbine built-in modules are well developed, is served as the main tool in the stability simulation. The fundamental operation of DFIG, model components, model development and control systems are explained in detail. A case study is performed with a stability-prone system of 11 buses in a Northeastern area of Thailand. The study results indicate that under wind fluctuation, capacitor switching and fault conditions, the wind farm equipped with the developed control models for a DFIG wind farm has a capability to maintain the voltages at the local station bus and also the point of common coupling within allowable limits.*

***Keywords*— Dynamic response, DFIG, Wind turbine, Transmission grid connection.**

1. INTRODUCTION

Currently, the energy crisis is the key issue for every country to pay attention. Especially in industrialized countries, electricity generation relies mainly on fossil fuel of which the reserved quantities are limited, and the pollutions from the fossil fuel combustion process contribute to the global warming phenomena. As a result, to retain the growth in their domestic demands for electricity continuously, a new alternative power development (e.g., wind power, solar power) is one solution to reduce the fossil fuel consumption and to alleviate the global warming problems.

Electricity generation from wind energy is one of the considerable alternatives due to clean energy, land uses for agriculture in the wind farm areas, and the significant reason, infinitely available resource. Accordingly, in several countries not only the development of wind power generation has still increased, but also the improvement of its technology has been carried out continuously.

In Thailand, the viable power generation from the large scale wind farm is still in early stage of development due to a number of constraints on potential areas that possess desirable quantities of wind energy, land availability, accessibility to the utility grid, transportation and capital cost. In general, wind speed in the northeast of Thailand is moderately high in mountainous areas. However, the grid systems in these areas are relatively weak due to low electricity consumption, and as wind energy is also intermittent, electricity generated cannot be reliable all the time. Hence, the system planners have to conduct a technical feasibility study of the interconnection of wind power plants to the grid so as to investigate the static and dynamic responses of the plants to ensure that their static and dynamic capabilities can meet grid system planning criteria.

Many large wind farms employ doubly fed induction generator (DFIG) with variable speed wind turbines. More than 60% of the yearly installations of new wind farms employ DFIG. The configuration of a DFIG wind turbine consists of an induction generator, the rotor circuit of which is connected with the stator circuit via a partial scale power converter. The converter rating is typically 25% of the rating of total system and the operating speed range of the DFIG is ±33% around the synchronous speed. The wind turbine requires a control system that control both machine-side and grid side converters under normal operating and disturbance conditions.

This paper presents a stability study of the dynamic responses of a large scaled DFIG wind power plant when connected to transmission grids in a northeastern area of Thailand. The configuration of this type of a DFIG wind turbine consists of a DFIG, a turbine, a rotor shaft, machine and grid-side converters, and control systems. Aggregated models for the whole wind power plant can be applied so that the study can be performed to capture the dynamic characteristics of the plant adequately.

A power system simulation tool, DIgSILENT Power Factory, is employed as the main tool to analyze wind turbine-grid interaction. In this software package, both an

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extensive library for grid components and a dynamic simulation language (DSL) [1] for modeling wind turbine component are provided. Nevertheless, the wind turbine models of the software package are composed of only basic functions or generic models for control of pitch angle, power, current, and turbine and rotor-shaft. Specific details of control systems for these components will not be considered since the wind turbine technology of each manufacturer is different.

In the simulation, the dynamic responses of DFIG wind turbines to normal, reactive power variation and grid fault are investigated based on the power system data of Electricity Generating Authority of Thailand (EGAT). The results from the investigation are then be evaluated as discussed.

2. DFIG WIND TURBINE MODEL

Wind turbines operate in a wide range of wind speeds. Due to the requirement in speed control, three wind velocities separate the operation into the four operating regions as shown in Figure 1, which represents a typical power versus wind speed curve of a wind turbine. The cut-in velocity (v_{cut-in}) is defined as the wind speed at which the turbine starts to generate the power. Below this wind speed, it is not efficient to turn on the turbine. The rated velocity (v_{rated}) is the wind speed at which the turbine reaches its rated turbine power. The cut-out velocity $(v_{cut-out})$ is the maximum wind speed at which the wind turbine can still operate. Beyond this wind speed, the rotor has to be shut down to keep the blades, the electrical generator and other components from reaching damaging level [2].

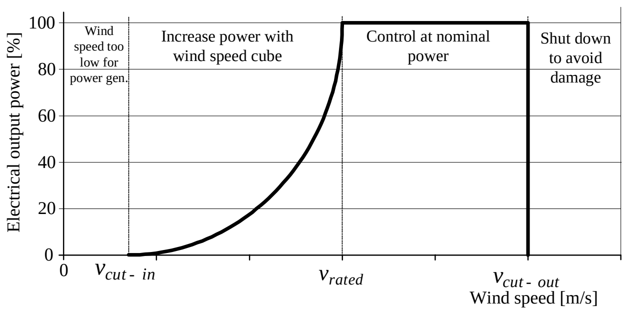


Fig. 1. Operating Region of Wind Turbine

For normal operation, the rotor side converter (RSC), as shown in Figure 2, has a function of controlling active and reactive power outputs to the grid using a vector control method, where active and reactive power can be independently controlled. Such a control technique is known as a decoupling method. Active and reactive powers are measured from the grid and compared with references. An active power reference is determined from the wind turbine power curve. A reactive power reference is determined from a grid voltage controller. In other words, reactive power is not directly controlled, but the voltage is controlled instead.

When wind speed increases, kinetic energy and therefore mechanical torque also increases. At this point, the pitch control plays is essential for wind turbine control. During a short circuit, the bus voltage will drop while the stator and rotor currents increase. These high current can damage the RSC and hence requiring a protection system. A protection system is activated when the rotor current, the grid voltage and the rotor speed exceed their setting limits. For this reason, the rotor circuit is to be shorted via a crowbar resistance whereas the RSC will be blocked indicating that the wind turbine is temporarily out of control for active and reactive powers.

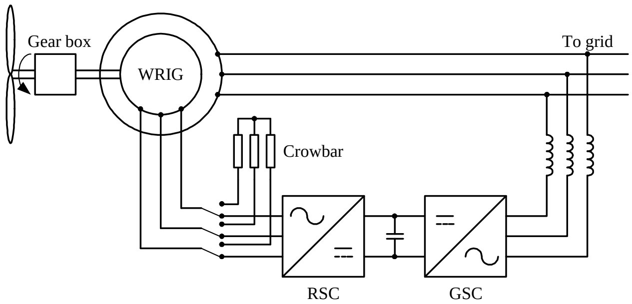


Fig. 2. DFIG with Crowbar Resistance Scheme

The operation of the control system will function properly when the voltage at the DC bus is constant. Therefore, a grid side converter (GSC) has to keep the DC voltage constant under normal operating condition.

A. Doubly Fed Induction Generator Model

The DFIG model consists of two parts: wound rotor induction generator and PWM converter. The model equations for stator and rotor voltages are given by Eqs. (1) to (4).

$$u_{sd} = R_s i_{sd} + j\omega_{syn}\psi_{sd} + \frac{d\psi_{sd}}{dt} \quad (1)$$

$$u_{sq} = R_s i_{sq} + j\omega_{syn}\psi_{sq} + \frac{d\psi_{sq}}{dt} \quad (2)$$

$$u_{rd} = R_r i_{rd} + j(\omega_{syn} - \omega_r)\psi_{rd} + \frac{d\psi_{rd}}{dt} \quad (3)$$

$$u_{rq} = R_r i_{rq} + j(\omega_{syn} - \omega_r)\psi_{rq} + \frac{d\psi_{rq}}{dt} \quad (4)$$

The swing equation for stability study is expressed by

$$J_r \frac{d\omega_r}{dt} = T_e - T_m \quad (5)$$

The above equations are the fifth-order model (including the movement equation of the generator rotor) with representation of the fundamental-frequency transients of the stator current [3]. In voltage stability investigation, the common third-order model of induction generators is often applied by neglecting the stator transient in Eqs. (1) and (2).

A PWM converter is connected in the rotor circuit. This converter is controlled by a PWM factor defined by the ratio between DC and AC voltages at the slip rings. In addition, the output voltage of the converter is assumed ideal sinusoidal, and switching loss is neglect.

The behavior of this converter are described by [4]

$$P_{AC} = \mathrm{Re}(U_{AC} \times I_{AC}) = U_{DC} \times I_{DC} = P_{DC} \tag{6}$$

$$u_{rd} = \frac{\sqrt{3}}{2\sqrt{2}} \times PWM_d \times U_{DC} \tag{7}$$

$$u_{rq} = \frac{\sqrt{3}}{2\sqrt{2}} \times PWM_q \times U_{DC} \tag{8}$$

B. Aerodynamic Model

The power conversion from the wind is derived by the following equation [5].

$$P_{wind} = \frac{1}{2}\rho\pi R^2 u_w^3 C_p(\lambda, \beta) \tag{9}$$

The efficiency of the conversion is expressed by the power-coefficient (C_p), which is a function of angle of rotor blades and tip speed ratio (ratio between blade tip speed and wind speed) [5], [6].

$$C_p(\lambda, \beta) = 0.22 \cdot \left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) \cdot e^{-\frac{12.5}{\lambda_i}} \tag{10}$$

and

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{11}$$

C. Pitch System

The pitch system model consists of two main components [4], [7]: a PI controller and a blade servo motor. To make the model more realistic, the rate limit of the blades is also taken into consideration. The pitch model is shown in Figure 3.

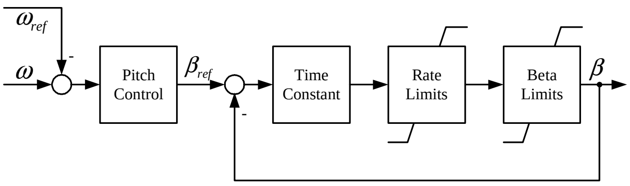


Fig. 3. Pitch Systems Model

D. Drive-train Model

The conventional lumped mass model may not be sufficient for stability study of DFIG wind turbine behavior because during disturbance, dynamic response of DFIG is the function of kinetic energy of the shaft. For this reason, a two-mass model is used to represent the drive train model [3].

The two-mass model, shown in Figure 4, comprises a large mass and a small mass [4]. The large mass represents the turbine inertia at low speed shaft whereas a small one represents the generator inertia at high speed shaft. The two masses are connected via a shaft having stiffness and damping coefficients and a gear box having a ratio of $1:\eta_{gear}$. The equations that represent the two-mass model [4], [6] are

$$J_t \frac{d\omega_t}{dt} = (T_t - T_{shaft}) \tag{12}$$

$$T_{shaft} = k_g\theta_{tg} + D_g\left(\omega_t - \frac{\omega_g}{\eta_{gear}}\right) \tag{13}$$

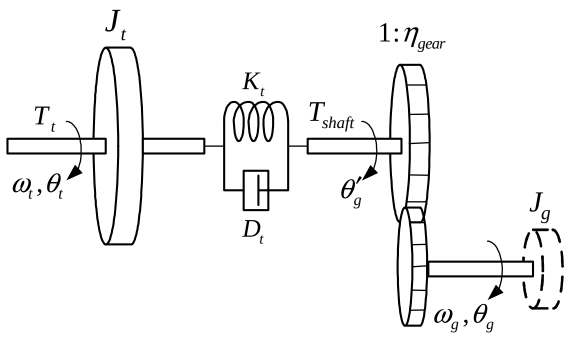


Fig. 4. Two-mass Model

The variable θ_{tg} is the electrical twist angle of the shaft, given by

$$\frac{d\theta_{tg}}{dt} = \omega_t - \frac{\omega_g}{\eta_{gear}} \tag{14}$$

E. RSC Model

As previously described, the RSC can control active and reactive powers independently by vector control techniques. There are two loops in the cascade control configuration of the RSC shown in Figure 5. The current reference of fast (or inner) loop is obtained from the slow (or outer) loop (a PI controller for active and reactive power control) [4], [7].

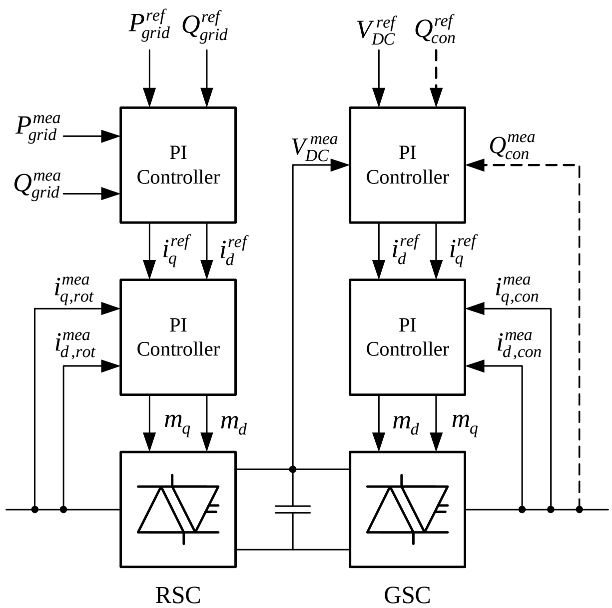


Fig. 5. Control Scheme of DFIG

For normal operation, P_{grid}^{ref} in Figure 5 is determined from a maximum power point tracking (MPPT) function. For a given wind speed, the MPPT determines the designed maximum by the $P-\omega$ curve [4], [8] as shown in Figure 6. This scheme is called active power control.

If the generator speed exceeds its limit, the pitch control decreases the angle of attack at a rate limit of ±7 deg/s for overspeed protection. This control scheme is called speed controller.

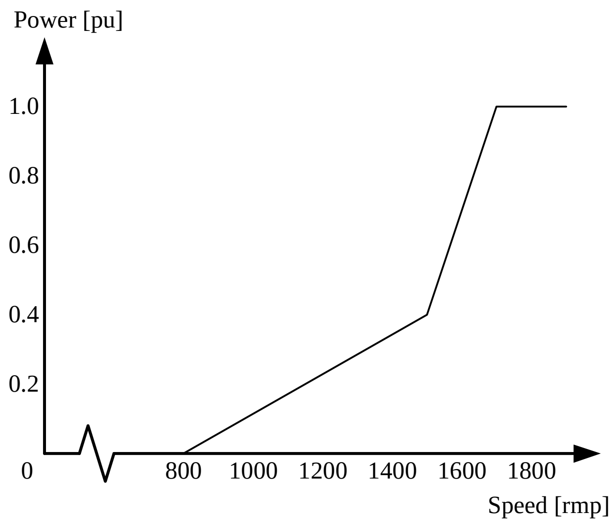


Fig. 6. Power versus Speed Curve

The reactive power reference, Q_{grid}^{ref} , in Figure 5 is obtained from a grid voltage controller (see Figure 7). This reference value depends on the difference between V_{grid}^{ref} and V_{grid}^{mea}. The grid voltage controller keeps the voltage constant as long as the RSC is not blocked or the output power does not violate the MVA rating of the generator.

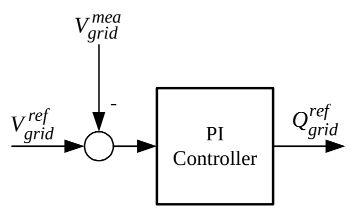


Fig. 7. Grid Voltage Controller

F. Crowbar Protection

During a short circuit, the stator current will increase rapidly. This current will be transferred to an inductance coupled between the stator and the rotor and may damage the RSC. To avoid such damage, the rotor current needs to be compared with a specified current limit. If the short circuit current exceeds the limit, the crowbar resistance will be inserted into the rotor circuit and the RSC is then blocked [3], [4]. This operation makes it possible for the DFIG to continue being connected with the grid and is able to supply power as soon as the fault has been cleared. This mode of operation is known as fault ride trough capability, which has been introduced in the grid code for wind turbine connection [9].

G. GSC Model

A cascade control is implemented in the GSC, as shown in Figure 5. There are two control parameters. The first parameter, DC voltage, is compared with a DC voltage setpoint in the outer loop of the GSC controller. The output of this controller will be the reference for the inner loop. The other parameter, reactive power reference, is set to zero to have a unity power factor at GSC circuit.

During disturbances, although the RSC is blocked by the crowbar protection, the GSC is still strongly connected to the grid. Various design schemes of GSC may be developed such as STATCOM, reactive power boosting, etc [4]. to improve grid voltage profile and also power quality. But in this paper, only DC voltage control is considered.

3. AGGREGATED WIND FARM MODEL

Due to economic reason, wind turbines are located in the same area and operated as a wind farm. The owner of a wind farm with an installed capacity greater than 10 MW is obliged to sell his or her power to EGAT. With the associated network and wind farm technical data, the system operator will analyze possible impacts due to the connection of the wind farm, which needs to comply with the established grid code.

If detailed models, although yielding exact results, are taken in to account in the study, it would be time consuming and complicated to arrive at a solution in the calculation. For this reason, an aggregated model to represent a large wind farm by one lumped wind turbine would be more appropriate while introducing minor discrepancy in the final results. An aggregated model can be achieved by rescaling the rating of all elements in the system. The aggregation model represents the system as if all parameters of the individual wind turbines, such as wind speed, mechanical speed and generator speed were identical. However, as far as individual wind turbines are concerned, their parameters are different due to location and operating conditions. Hence, the aggregation assumption is useful in some situations for example, initial planning studies or worst-case scenario analysis. In addition, since the goal of this paper is to study the impact of wind farm to transmission system, not to the wind farm itself, an aggregation model could be adequate in the investigation [4], [10]. To have more accurate results, a semi-aggregated model should be included [7].

4. CASE STUD

The test system shown in Figure 8 is located in a northeastern area of Thailand. This area is subject to the risk of voltage stability problems due to the fact that there are not as many power plants in the area as in central and eastern areas. Furthermore, loads are scattered in the area.

It is generally known that wind speed in the northeast of Thailand is moderately high but the grid systems in such areas are relatively weak because the power network is not well developed. These areas are therefore subject to voltage stability problem. In the northeast of Thailand, most of the transmission systems are operated at a voltage level of 115 kV. Large power plants that have capability for voltage control are located quite far from the wind farm. These generation units are modeled as synchronous generators with their excitation and governor systems. The consumptions or loads are represented by the ZIP model, which means that the loads depend on their connection voltage. The coefficients of the loads are taken from an EGAT standard.

As illustrated in Figure 8, it is assumed that a 25x2 MW is connected to an EGAT substation through a 25 km, 115 kV, 795 MCM ACSR line. Note that there is currently no wind farm in the studied area. However, it is envisaged that a number of wind farms will be installed in the foreseeable future due to the promotion of wind energy from the government. The system has 11 buses with a total install generation of 730 MW and a total demand of 500 MW. DFIG wind turbines parameters can be found in [3], [6], [10] and [11]. The rated wind speed of each wind turbine in the wind farm is 11.2 m/s.

A. Normal Operation (Wind Speed Fluctuation)

As the output power of the wind farm varies with wind speed, system behavior during wind speed fluctuation should be evaluated. Since the aggregated model is used, each of wind turbines has an identical wind profile.

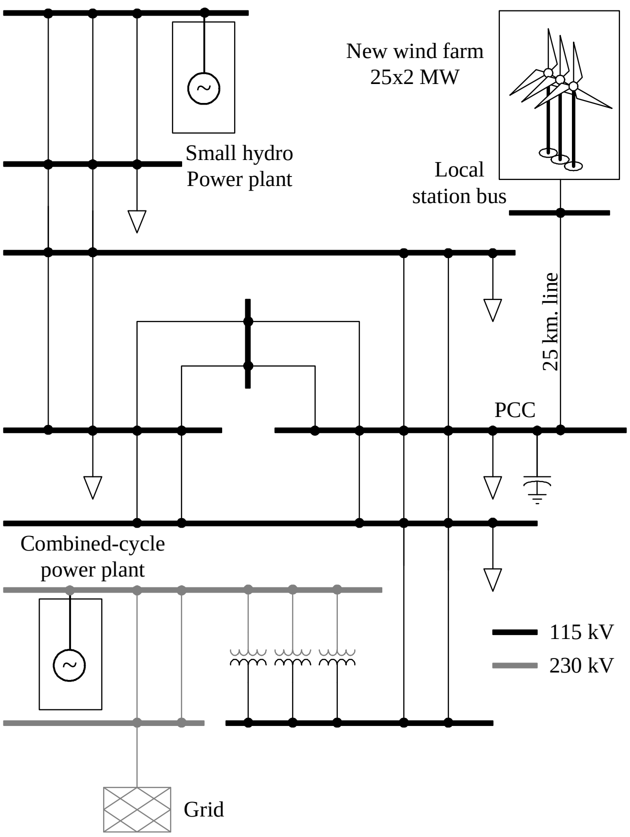


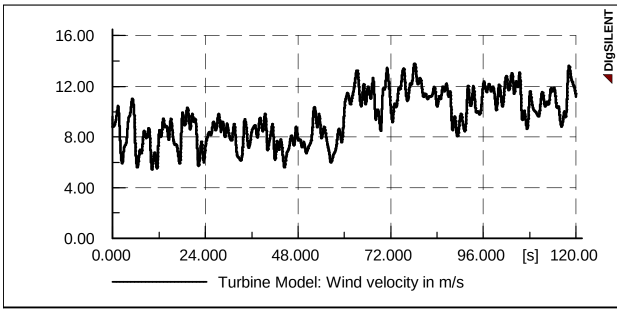
Fig. 8. Single-line Diagram of Test System

The simulation result for normal operating condition is shown in Figure 9. It is observed from Figure 9a that there are two wind speed regions: high wind and low wind. In the low wind region (wind speed less than 11.2 m/s), the wind turbine is operated with maximum peak power tracking. The generated active power and the wind speed profile have a similar trend as shown in Figure 9b becuase the generated power varies with the cube of wind speed. The dash line in Figure 9b represents the reactive power which is kept to zero by the control system of the RSC. In the high wind speed region (wind speed greater than 11.2 m/s), the wind turbine has to keep the generated power below or at its rating of 50 MW. The line in the Figure 9c represents the operation of pitch control. We can see that adjustment of the pitch angle is only needed during the high wind speed region. The effect of the turbine size on the voltage profile at the point of common coupling is shown in Fig. 9d. It is observed that doubling the turbine size can cause the voltage to fluctuate than does the existing size. Therefore, large-sized wind farms would not be allowed in this area.

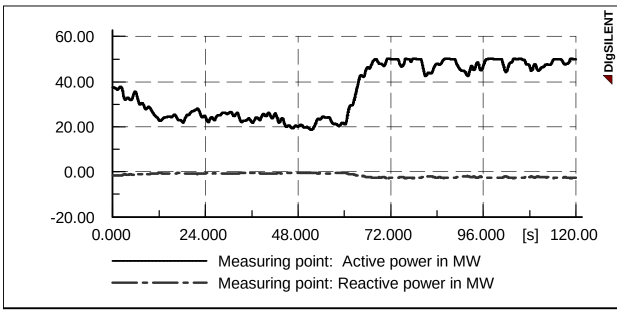
B. Reactive Power Variation

Reactive power variation and therefore voltage fluctuation frequently happen in a weak grid. They can be caused by sudden load change, loss of voltage control generator, short circuits (long distance from wind farm), switching and also from wind turbine itselfs (i.e., wind speed variation).

In order to investigate an effect of reactive power, a 2x24 MVAr capacitor bank at the PCC of Figure 8 is suddenly tripped to see the response of the wind farm under undervoltage condition and is suddenly connected to the system to see the response under overvoltage condition.



(a)



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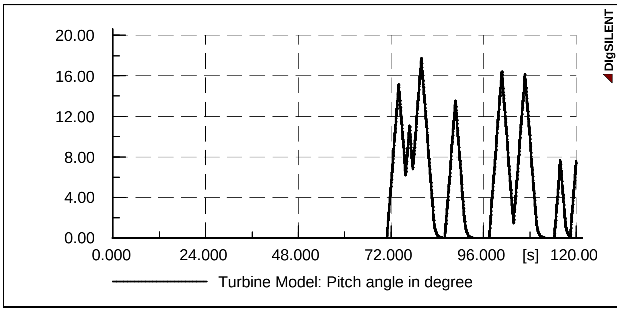

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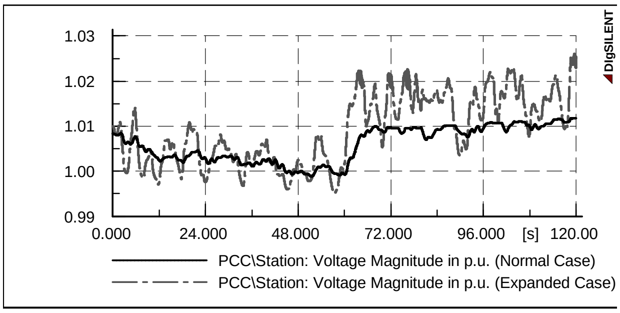


(d)

Fig. 9. Simulation Results, (a) Wind speed, (b) Active and reactive power at PCC , (c) Blade pitch angle of wind farm and (d) Voltage magnitude at PCC

As shown in Figure 10, when the capacitor is switched off from the system at $t = 1$, the voltages at the PCC and the wind farm station rapidly drop without any reactive power supplied from the wind farm. After that the voltage climbs up slowly because of no voltage control devices installed at the wind farm. Although there are remote generators (i.e., hydro and combined cycle power plants) that can cover the loss of reactive power, these generators contributes only a small reactive compensation because of their distant locations. The voltage at the PPC suddenly increases at $t = 3$ due to a switching of the first half (24 MVAr) of the capacitor. After the other 24 MVAr of the capacitor being switched on (48 MVAr in total) at $t = 5$, the wind turbine sees a voltage rise again before entering steady state. It is very interesting to note that the final voltage level will never be the same as that of $t = 0$ because the wind farm has no voltage control devices.

With control devices, the wind farm has an ability to compensate reactive power under reactive power variation as shown in Figure 11. The voltage level at the local station bus can be maintained to its initial value within a fraction of second. The voltage profile at the PCC can also be improved.

C. Grid Fault Operation

Many grid codes in several countries require wind turbines to remain connected to support the power system under fault conditions in order to restore the system to its prefault state as soon as possible [9]. Such requirements are known as fault ride through (FRT) or low voltage ride through (LVRT) capability of wind turbines.

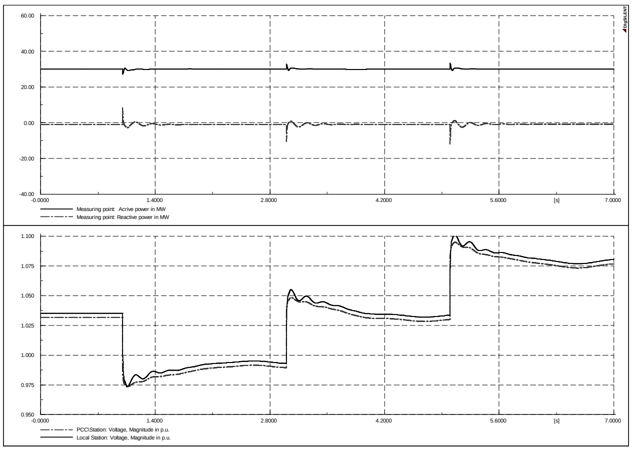


Fig.10. Voltage Fluctuation due to Variation of Reactive Power without Voltage Control Devices

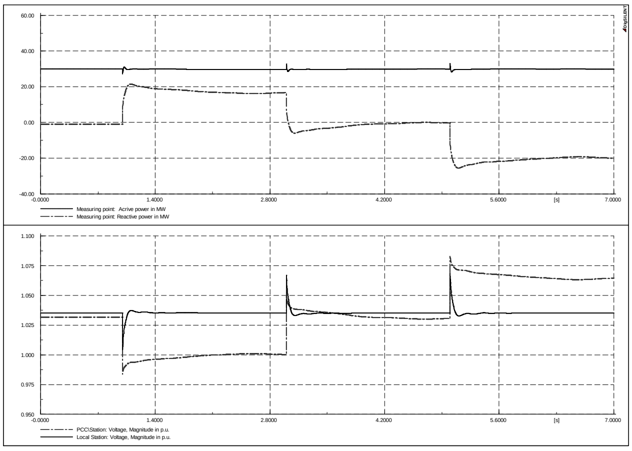
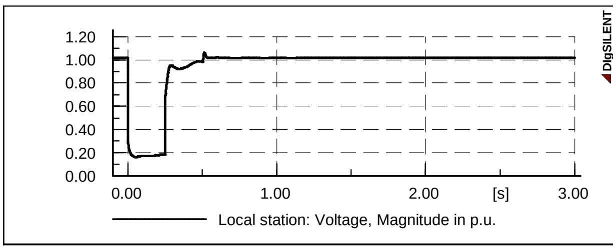


Fig.11. Voltage Fluctuation due to Variation of Reactive Power with Voltage Control Devices

To analyze the impact of grid fault, a three-phase short circuit with duration of 10 cycles is applied at the local station bus. It is assumed that the wind farm has been operated at their rated power before the fault occurs. Dynamic behavior of wind turbines are shown in Figure 12.



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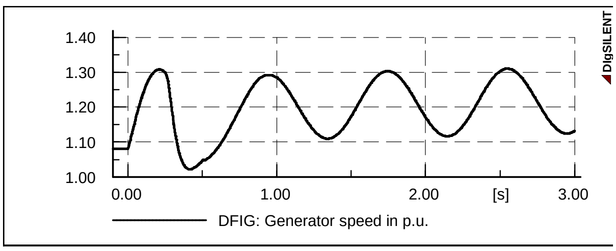

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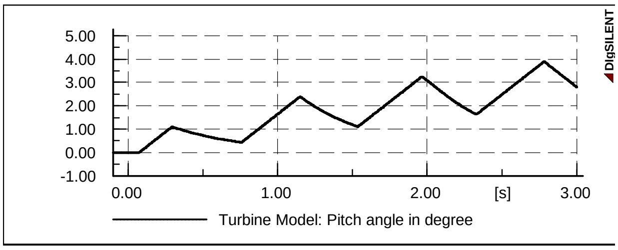

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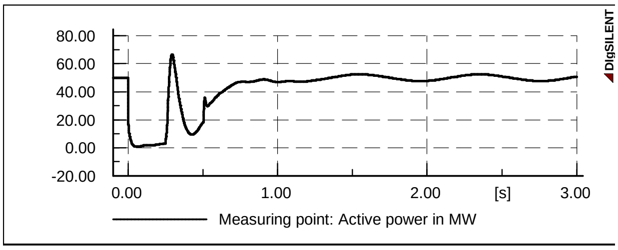

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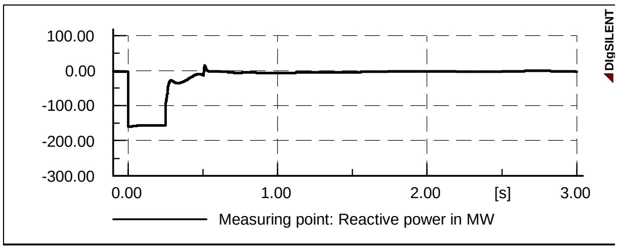

(e)

Fig.12. Dynamic Behavior of DFIG during the fault, (a) Voltage at PCC, (b) Generator Speed, (c) Pitch Angle, (d) Active Power and (e) Reactive Power

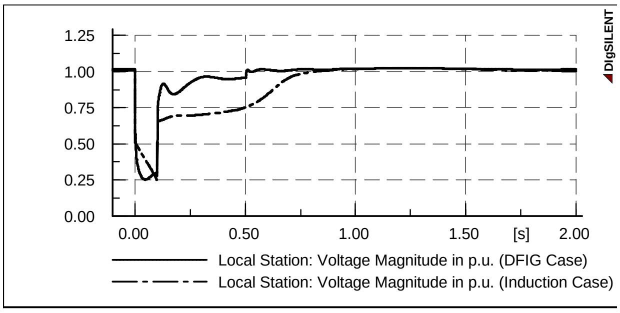

Fig.13. Comparison between DFIG and Conventional Induction Generator

As seen in Figure 12, the voltage at the local station bus drops rapidly owning to the fault at $t = 0$. The stator and also rotor transient currents increase until the rotor current exceeds its rating. The protection system then protects the rotor circuit by inserting the crowbar, resulting in loss of controllability. The generator speed increases due to a decrease in the electrical torque. The pitch control system responses to the overspeeding of the generator by adjusting the pitch angle of the wind turbines. After fault has been cleared, the voltage is not restored immediately because at this moment, the DFIG still acts like a conventional induction generator; namely it absorbs reactive power for its magnetization. Once the crowbar is removed, the voltage gradually reaches its initial value. Active and reactive powers become controllable again.

Figure 13 depicts the voltage response at the local station bus for two types of wind turbine generator, a DFIG and an induction generator. The figure confirms that the DFIG has a better performance on voltage recovery.

5. CONCLUSION

This paper constitues two main parts: DFIG models and a case study on a wind fram connected to a weak system in the Northeast of Thailand. The DFIG is represented by the common 3-order model of an induction generator with a two-mass model for the shaft system. Dynamic response capabilities on the DFIG wind power plants were thoroughly investigated under conditions of normal, reactive power variation and grid fault. Under these operating conditions, the control systems play an important role to maintain the voltage profiles at local station bus and also the point of common coupling within allowable limits. The voltage quality constraint should be met so that the wind farm is able to be connected to the grid.

The aggregated wind turbine model is useful particularly in planning stage, where a number of scenarios need to be completely investigated. The scenarios usually include the worst case analysis where all the wind turbines inside the wind farm operate as if they were a single wind turbine. In other words, for every single moment, all individual wind turbines have the same wind speed and therefore the same torque. It is expected that this research will be a part of the development of a grid connection standard for proper use in Northeastern areas of Thailand.

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NOMENCLATURE

u_{sd}	=	Stator voltage oriented in d-axis
u_{sq}	=	Stator voltage oriented in q-axis
u_{rd}	=	Rotor voltage oriented in d-axis
u_{rq}	=	Rotor voltage oriented in q-axis
i_{sd}	=	Stator current oriented in d-axis
i_{sq}	=	Stator current oriented in q-axis
i_{rd}	=	Rotor current oriented in d-axis
i_{rq}	=	Rotor current oriented in q-axis
ψ_{sd}	=	Stator flux oriented in d-axis
ψ_{sq}	=	Stator flux oriented in q-axis
ψ_{rd}	=	Rotor flux oriented in d-axis
ψ_{rq}	=	Rotor flux oriented in q-axis

ω_{syn} = Synchronous speed
ω_r = Rotor speed
T_e = Electrical torque
T_m = Mechanical torque
PWM_d = D-axis pulse width modulation factor
PWM_q = Q-axis pulse width modulation factor
U_{DC} = DC Voltage at DC bus
ρ = Air density
R = Turbine blade radius
u_w = Wind velocity
β = Pitch angle
λ = Tip speed ratio
J_t = Inertia of the turbine rotor
J_g = Inertia of the generator rotor
T_t = Aerodynamic torque
T_{shaft} = Low speed shaft torque
ω_t = Turbine shaft angular speed
ω_g = Generator shaft angular speed
K_g = Shaft stiffness
D_g = Damping constant
P_{grid}^{ref} = Grid active power reference
P_{grid}^{mea} = Grid measured active power
Q_{grid}^{ref} = Grid reactive power reference
Q_{grid}^{mea} = Grid measured reactive power
V_{DC}^{ref} = DC bus voltage reference
V_{DC}^{mea} = DC bus measured voltage
Q_{con}^{ref} = GSC reactive power reference
Q_{con}^{mea} = GSC measured reactive power
$i_{d,rot}^{mea}$ = Rotor measured current oriented in d-axis
$i_{q,rot}^{mea}$ = Rotor measured current oriented in q-axis
$i_{d,con}^{mea}$ = GSC measured current oriented in d-axis
$i_{q,con}^{mea}$ = GSC measured current oriented in q-axis
V_{grid}^{ref} = Grid voltage reference
V_{grid}^{mea} = Grid measured voltage

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