The impacts of distributed generation using high speed wind turbines on power system transient stability

Annastacia Maina, Michael J. Saulo

Department of Electrical and Electronics Engineering, Technical University of Mombasa, Mombasa, Kenya

Email address:

Annastaciam2000@gmail.com (A. Maina), michaelsaulo@yahoo.com (M. J. Saulo)

Abstract: Wind power generation source differs in several respects from conventional sources of energy like hydro and thermal. Furthermore, wind generators are usually based on different generator technologies other than the conventional synchronous generators. The stochastic nature of wind, makes it very difficult to control the generator power output. Most wind turbines are based on induction generators which consume reactive power just like induction motors during system contingency, which in turn deteriorates the local grid stability. This paper proposes to study and analyze the impact of distributed generation using high speed wind turbines on power systems transient stability. This is achieved using a simplified model of the IEEE 30 bus system which replicates the Kenyan grid system. The base line case simulations were carried out using Dig SILENT Power factory version 14.0 software and results recorded. Thereafter, a Double Fed Induction Generator (DFIG) model was integrated to the system and various faults introduced in the system. The results showed that, the addition of the DFIGs to a power system network, does not negatively affect the stability of the system. It was evident that even with increased penetration of wind power up to 10.2%, the system showed a high degree of transient stability. Consequently, from the simulation results, as the system approaches stability, the swings are more or less of equal magnitude. As the penetration level of DFIGs increased from 0% to 10.2%, the critical clearing time also increased. This clearly shows that the transient stability of the power system is improved by DFIG penetration in the power network.

Keywords: DFIG Model, Dig SILENT, Stability, Synchronous Generator

1. Overview of Wind Resources in Kenya

Of all renewable energy sources, wind power is the most mature in terms of commercial development in the world. The development costs of wind power have decreased dramatically in recent years. Potential for development is huge, and the world's capacity is far larger than the world's total energy consumption. Worldwide, total capacities of about 60,000MW have been installed, with a yearly production of about 100 TWh [1]. There is still little experience in using wind for power generation in Kenya, however, awareness and interest is steadily growing. The most recent investment in wind energy in Kenya is Ken Gen's 5.1MW farm in Ngong comprising six 850kW turbines installed in August 2009. A further 610MW are to be developed by Independent Power Producer's comprising; 300MW by Lake Turkana Wind, 60MW Aeolus Kinangop wind, 100MW Aeolus Ngong' wind, 60MW Osiwo Ngong' wind, 60MW Aperture Green Ngong'

and 30MW Daewoo Ngong' wind. The Best wind sites in Kenya are Marsabit district, Samburu, parts of Laikipia, Meru north, Nyeri, Nyandarua and Ngong hills. On average the country has an area of close to 90,000 square kilometers with very excellent wind speeds of 6m/s and above [1].

Researchers on non-grid-connected wind power/water electrolytic hydrogen production system showed that wind power grid connection is the only application of large-scale renewable sources in the world [2].

The random effects of wind affect the quality of wind power and the contribution rate of wind power on the grid is hardly beyond 10%. The wind powered generator needs to meet the requirements of power grid such as stabilization of frequency, voltage and phase, which increases complexity. As a result, the "Non-grid-connected wind power was invented. Research showed that hybrid systems e.g. wind and solar complement

each other effectively that is saying, "either the sun is shining or the wind is blowing, so there is always something producing power" [4].

1.1. Introduction

Global warming is occasioned by burning of fossil fuels such as oil, coal etc. These has resulted to the production of greenhouse gases. Consequently, affecting the environment and people's health. The advent of renewable energy resources is a promising mitigation to the problems. The call for increased application of renewable energy technologies is growing due to the global warming. Global warming refers to an unequivocal and continuing rise in the average temperatures of earth climate system. There are several renewable energy resources for the electrical power system. Among those, wind energy is one of the fastest growing renewable energy resources [1, 3, 4]. This paper proposes to study and analyze the impact of distributed generation using high speed wind turbines on power systems transient stability.

Generating realistic wind speeds is an important task when the effects of the wind productions in an electricity system have to be analyzed. The fluctuating wind speed is the origin of the temporal variation of the power injected by this production type and thus has direct effect on the grid stability. One of the challenges of wind speed simulators is mainly to reproduce the different scale fluctuations, as described in [4]. In this regard, different models have been developed during the past decades. The model considered here is built up in two stages, comprising two components, a slow and fast, the same as in [5]. With some minor modification, more accurate wind models (that take into consideration e.g. long-term [6] or cross–correlations [7] are of this nature. An overview of some more approaches can be found in [8]. It is important to add that. However, to get a realistic simulation of a specific site, records of historical data are needed to obtain the parameters of the model, because even the best model is useless if not accurately fitted.

2. Stochastic Wind Speed Simulation

2.1. The Slow Component

The first part, which was already used by author [9] is a generator of hourly mean wind speeds. This time series model is based on an ARMA (Automatic Regressive Moving-Average) model that is given by

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + ... + \phi_n y_{t-n} + \alpha_t + \theta \alpha_{t-1} + \theta_2 \alpha_{t-2} + .. \theta_m \alpha_{t-m} \quad (1)$$

The data series y_t is used to build the model, that is to calculate the auto–regressive $\emptyset_i$, $i = 1, 2…, n$ and the moving average parameters $\emptyset_i$, $j = 1, 2…, m\{\alpha_t\}$is a Gaussian white noise process with zero mean and standard deviation of σ_a which is part of the moving average (MA) part of the model. Considering the orders, the process is referred to as ARMA (n, m). The parameter used in this study were chosen from an ARMA (3,2) approach, but the model was developed up to

(4,3) and can be easily adapted to other orders. For example, a pure AR(2) model [8] which was implemented before can also be seen as an ARMA model with $n = 2$ and m = 0.The order of the model depend on the quantity of historical data available, since if there is only a little data, an accurate model cannot be reached even with higher orders. There is a range of literature available regarding parameter estimation. Fitting models are normally based on least square regression methods that try to minimise the error value. For AR parameter estimation, the Yule-Wallker equations are widely used. The simulated hourly mean wind speed [6] can be obtained by

$$\overline{v_1}(t) = \mu + y_t \quad (2)$$

Where μ is the mean wind speed of all the observed data. If observed hourly mean speeds μ_h and standard deviation σ_h are available, a more realistic simulated wind speed can be calculated as

$$\overline{v_2}(t) = \mu_h + \sigma_h . y_t \quad (3)$$

This method is explained in detail in [6].

2.2. The Fast Component

Being able to compute hourly mean wind speeds might be enough for several application of the energy systems model, but as temporal scalability was a requirement for the latter, a more detailed model was needed. The ability to reproduce realistic wind speeds in real time can be gained by adding the so called fast component to the previously described slowly varying signal. For this purpose turbulent phenomena are modelled by a highly fluctuating signal given in [5] by the following differential equation.

$$\frac{d\omega}{dt} = -\frac{\omega(t)}{T} + kv_h(t)\sqrt{\frac{2}{T}}\xi(t) \quad (4)$$

Where $T = L/\overline{v}$, L being the turbulence length scale, v is the velocity of wind, k a factor that depends on the geographical location of the wind turbine site [9], $\xi(t)$ a Gaussian white noise and $v_h(t)$ the hourly mean wind speed. The equation describes a stationary Gaussian process. This component allows us to generate a time continuous signal that represents area time wind speed.

3. System Modelling

The power extraction from wind turbine is a function of three main factors: the wind power available, the power curve of the machine and the ability of the machine to respond to wind fluctuation. The expression for power produced by the wind is given by [12, 13]:

$$P_m(v) = \frac{1}{2} C_P(\lambda, \beta) \rho \pi R^2 v^3 \quad (5)$$

Where ρ is the air density is radius of turbine rotor is wind speed, C_p is power coefficient of wind turbine, λ is the tip

speed ratio and β represents pitch angle. The tip-speed ratio is defined as:

$$\lambda = \frac{R\omega}{v} \qquad (6)$$

Where w is the turbine rotor speed. Therefore, if the rotor speed is kept constant, then any change in the wind speed will change the tip speed ratio, leading to change of power coefficient C_p, as well as the generated power output of the wind turbine. However, if the rotor speed is adjusted according to the wind speed variation, then the tip-speed ratio can be maintained at an optimal point, thereby yielding maximum power output from the system.

For a typical wind power generation system, the following simplified elements are used to illustrate the fundamental working principle. The system primarily consists of an aero turbine, which converts wind energy into mechanical energy, a gearbox, which serves to increase the speed and decrease the torque and a generator that convert the mechanical energy into electrical energy.

The mechanical equation is characterized by [14]:

$$J_m\omega + B_m\omega = T_m + T \qquad (7)$$

$$J_e\omega_e + B_e\omega_e = T_t + T_e \qquad (8)$$

$$T_t\omega_e = -T\omega \qquad (9)$$

Where J_m and J_e are the moment of inertia of the turbine and the generator respectively, B_m and B_e are the viscous friction coefficient of the turbine and the generator, T_m is the wind generated torque in the turbine, T is the torque in the transmission shaft before gear box, T_e is the generator torque, ω is the angular velocity of the turbine shaft and ω_e is the angular velocity of the generator rotor.

The relationship between the angular velocity of the turbine ω and the angular velocity of the generator ω_e is given by the gear ratio:

$$Y = \frac{\omega_e}{\omega} \qquad (10)$$

Then, using equation 7, 8, 9 and 10 we obtain

$$J_\omega + B_\omega = T_m - YT_e \qquad (11)$$

With

$$J = J_m + Y^2 J_e \qquad (12)$$

$$B = B_m + Y^2 B_e \qquad (13)$$

From equation 5 and 6 we deduce that the input wind torque is:

$$T_m(v) = \frac{P_m(v)}{\omega} = \frac{P_m(v)}{\frac{\lambda v}{R}} = k_v v^2 \qquad (14)$$

Where

$$k_v = \frac{1}{2}C_P\rho\pi\frac{R^3}{\lambda} \qquad (15)$$

Now let us consider the systems electrical equations. In this study we used a double feed induction generator (DFIG) whose characteristic matches the metrological conditions in Ngong. The induction machine is feed from both stator and rotor. The stator is directly connected to the grid or a standalone MV line. While the rotor is fed through a variable frequency converter (VFC).

In order to inject electrical power at constant voltage and frequency to the utility grid, over a wide range (from sub-synchronous to super synchronous speed), the active power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction. Therefore, the VFC consist of two four-quadrant IGBT PWM converters (Rotor side converter (RSC) and grid side converters (GSC) connected back to back by a dc link capacitor [15, 16].

3.1. DFIG Control Scheme

In order to extract the maximum active power from the wind, the shaft speed of the Wind Turbine Generator (WTG) must be adjusted to achieve an optimal tip-speed ratio λ_{opt}, which yields the maximum power coefficient Cpmax, and therefore maximum power (17). In other words, given a particular wind speed, there is a unique wind turbine speed required to achieve the goal of maximum wind power extraction. The value of λ_{opt} can be determined from the maximum of the power coefficient curves versus tip speed ratio, which depends on the turbine modeling characteristics. The power coefficient C_p, is approximated by Equation (16) based on the modeling turbine characteristics (18).

$$C_P(\lambda, \beta) = C_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \qquad (16)$$

Where the coefficients C_1 to C_6 depends on the wind turbine design characteristics and λ_i is defined as

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (17)$$

The value of λ_{opt} can be calculated from the roots of the derivatives of equation (16). Then, based on the wind speed, the corresponding optimal wind turbine speed reference ω^* for maximum wind power tracking is determined by:

$$\omega^* = \frac{\lambda_{opt}.v}{R} \qquad (18)$$

The DFIG wind turbine control system generally consist of two parts: the electrical control on the DFIG and the mechanical control on the wind turbine blade pitch angle.

Control of DFIG is achieved by controlling the variable frequency converter (VFC) that includes control of the rotor-side converter (RSC) and control of the grid side converter (GSC) [19]. The objective of the RSC is to govern both the stator side active and reactive power independently. Whereas the objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude of the direction of the rotor power. The GSC control scheme can also be designed to regulate the reactive power or the stator terminal voltage of the DFIG. A typical scheme of a DFIG equipped wind turbine is shown in Figure 1 [10].
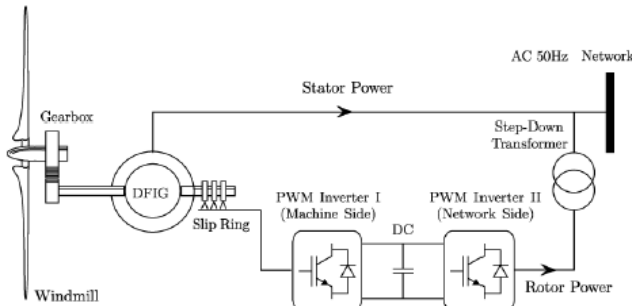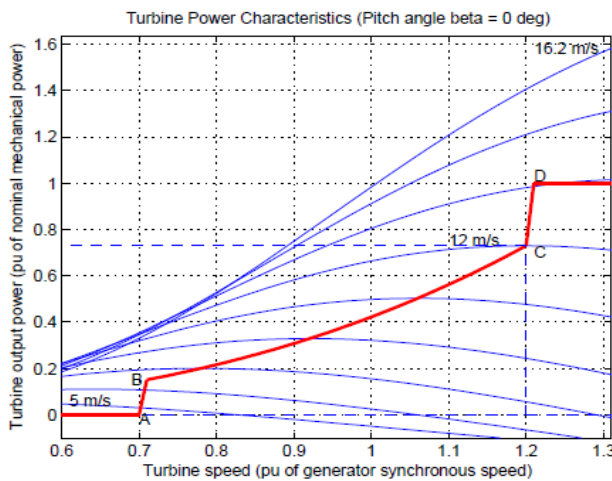

Figure 1. DFIG equipped wind turbine scheme

Figure 2. Turbine power Characteristics

The RSC control scheme is designed in order to regulate the wind turbine speed for maximum wind power capture. Therefore, a suitably designed speed controller is essential to track the optimal wind turbine speed reference ω* for maximum wind power extraction. The drawback to using wind turbines is that they rely on a variable and somewhat unpredictable source. If the wind speed is not sufficient to turn the shaft in the generator, electricity will not be produced. However, systems are now being developed that will lower the minimum wind speed threshold [4]. To compensate for the unpredictable nature of wind conditions, battery storage systems are being integrated to provide electricity when the turbine is not turning. Voltage regulators have been developed and are being improved so that the turbine can recharge the batteries while simultaneously producing electricity. These should ultimately make wind turbines more affordable [5].

Wind turbines provide a relatively inexpensive way to produce electricity compared with (photovoltaic) PV, the only other truly green technology. Wind turbines are expected to keep this cost advantage in the future **[10].** One of the major costs associated with a wind turbine system is the tower that the turbine must be placed on. A rule of thumb is to raise the turbine 30 feet above any obstruction within a 300 feet radius [5].

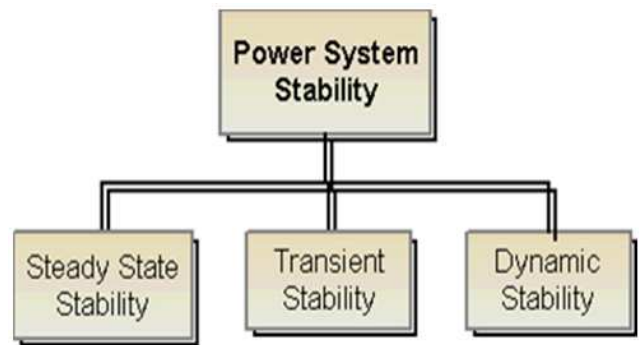# 4. Classification of Power Systems Stability

Figure 3. Classification of Power system Stability

Power system stability can be divided into three main categories as shown in Figure 3 below;

The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence.

4.1. Steady State Stability

These studies are restricted to small and gradual changes in the system operating conditions. In this we basically concentrate on restricting the bus voltages close to their nominal values. We also ensure that phase angles between two buses are not too large and check for the overloading of the power equipment and transmission lines [4]. These checks are usually done using power flow studies.

4.2. Transient Stability

It involves the study of the power system following a major disturbance. Following a large disturbance the machine power (load) angle changes due to sudden acceleration of the rotor shaft. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance [18].

4.3. Transient Stability Indicators

The transient stability of a system can be assessed by means of certain indicators. In this project, four different indicators have been chosen to analyze the stability of the test system [18].

The four transient stability indicators chosen are:

i) Rotor Speed deviation-is the maximum amount of deviation in the rotor speed during fault.

ii) Oscillation duration -is the time taken by the oscillations to reach a new equilibrium after the clearance of the fault.

iii) Rotor angle–The response of the rotor angle of the generator to different types of faults is considered.

iv) Terminal voltage–The variation in the terminal voltage of the DG due to different fault conditions is monitored. The voltage stability is analyzed by taking into consideration the drop in voltage level during fault and the time taken by it to settle down after the clearance of the fault.

4.4. Dynamic Stability

This is the ability of a power system to maintain stability under continuous small disturbances. (Also known as small-signal stability) These small disturbances occur due random fluctuations in loads and generation levels. In an interconnected power system, these random variations can lead catastrophic failure as this may force the rotor angle to increase steadily [4, 18].

4.5. What is Distributed Generation

Distributed generation (or DG) in this papers context, generally refers to small-scale (typically 1 kW – 50 MW) electric power generators that produce electricity at a site close to customers or that are tied to an electric distribution system. Distributed generators include, but are not limited to synchronous generators, induction generators, reciprocating engines, micro-turbines (combustion turbines that run on high-energy fossil fuels such as oil, propane, natural gas, gasoline or diesel), combustion gas turbines, fuel cells, solar photo voltaic, and wind turbines. Distributed generation is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than can traditional power generators.

4.6. Benefits of Distributed Generating Systems

i) Flexibility - DG resources can be located at numerous locations within a utility's service area. This aspect of DG equipment provides a utility tremendous flexibility to match generation resources to system needs.

ii) Improved Security - The utility can be served by a local delivery point. This significantly decreases the vulnerability to interrupted service from imported electricity supplies due to natural disasters, supplier

5. Methodology

Figure 4, shows simplified model of an IEEE 30 bus power system used as the base case in this paper. The reason is that the entire Kenyan Grid system replicates a 30 bus power system. The model was developed using Dig-SILENT Power factory version 14.0 using available load data. After which load flow studies were carried out on the system, which incorporates the DFIG turbines.
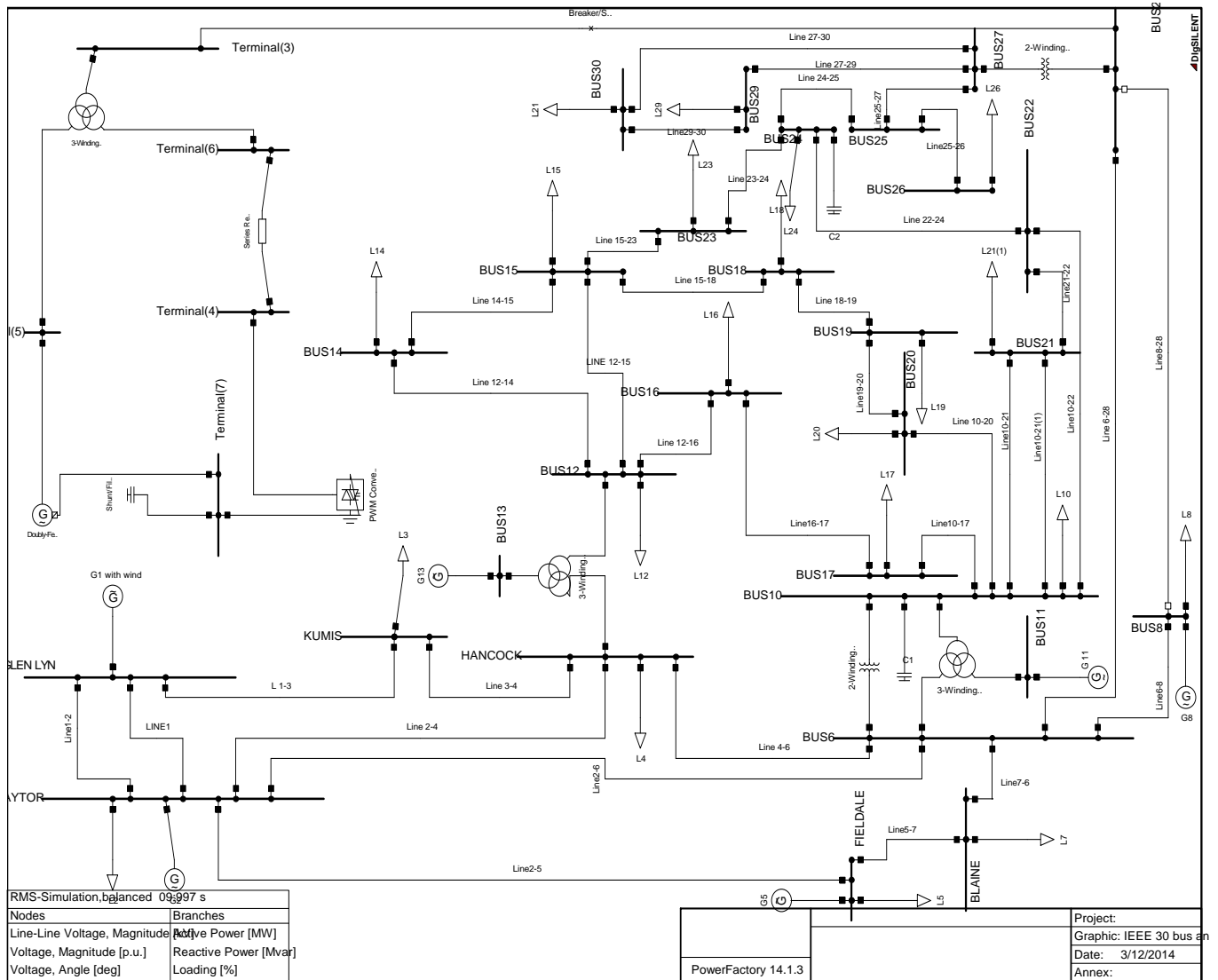
Figure 4. *IEEE model with DFIG*

A model of NGONG wind farm was also developed. The types of wind turbines used in the study are variable speed (DFIGs). The DFIG model was constructed from the built-in components of power system simulation software. All the 6 wind turbines of power approximately 5.1MW. Resulting to a total power of 36MW were aggregated into one equivalent DFIG machine.

An IEEE 30 bus system is used for this study to represent the Kenyan power system. This is a test system widely used in power system research and education. The reasons for using test system rather than using a model of practical system are as follows:

- Practical power systems data are partially confidential.

- Dynamic and static data of the systems are not well documented.
- Calculations of numerous scenarios are difficult due to large set of data.
- Lack of software capabilities for handling large set of data.
- Less generic results from practical power system.

The size and type of the test system play a very vital role in the analysis of the transient stability. A large system may increase the time and complexity of the analysis whereas a small system may lead to neglecting necessary factors. Therefore, a medium sized representative IEEE 30-bus system has been chosen for the study.
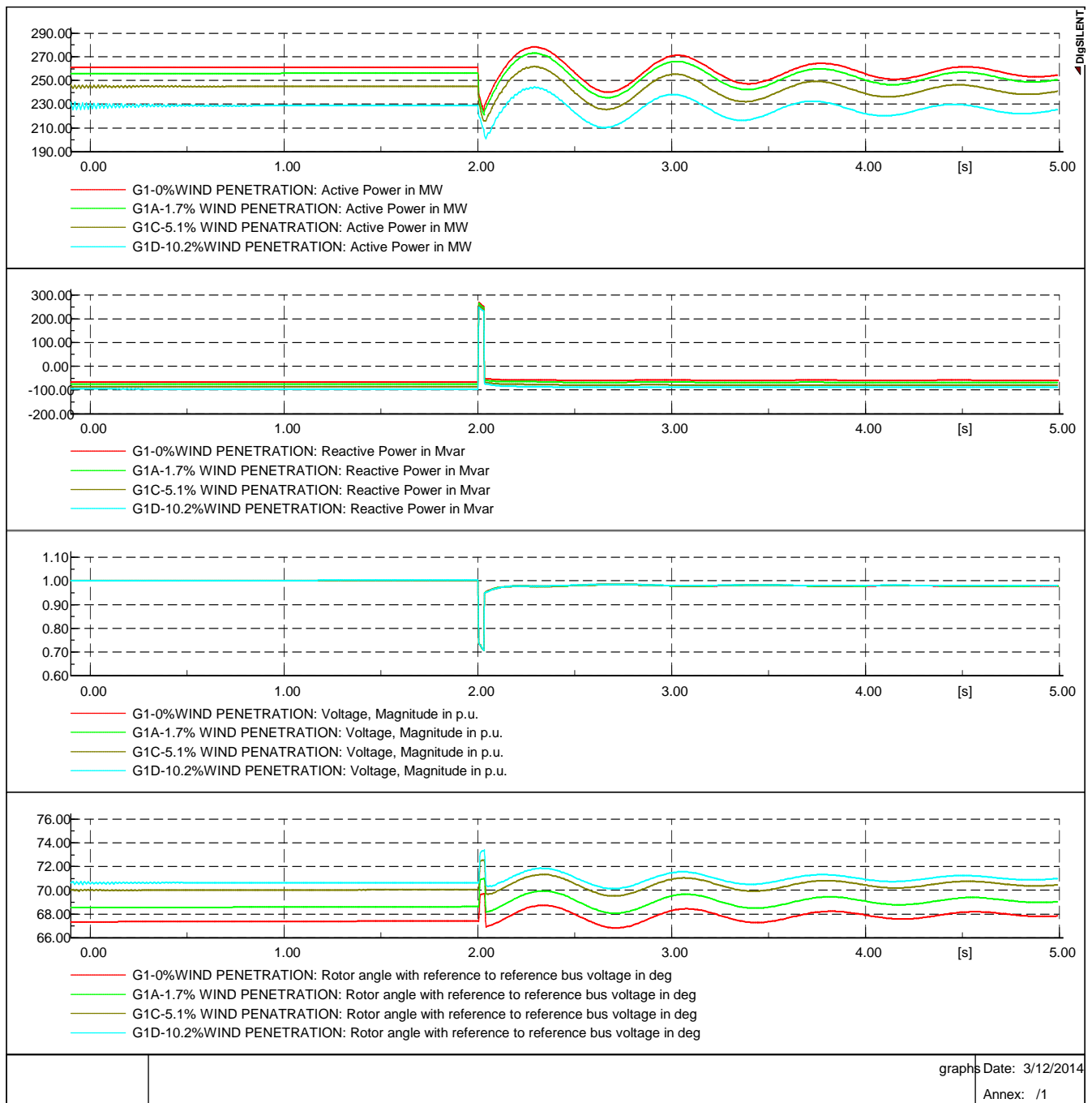
6. Result and Discussion

Figure 5. *Generator 1-fault on line 2-6*

The disturbance investigated is a three-phase short-circuit on different lines close and far away from the main Generators. This three-phase fault represents the most severe disturbance for transient stability problems between the wind farm and the IEEE 30 bus system. The parameters analyzed include voltage, active power, reactive power, rotor angle with reference to reference bus voltage. These were chosen for study since they are the most common transient stability indicators. The base case was first simulated to determine the initial conditions then followed by a load flow calculation. The results are shown in Figure 5 below. In the next scenario, the DFIG

model was connected to the IEEE 30 bus system and load flow calculations were also performed. The results are shown in Figure 6 below. Transient stability was then performed on the base case scenario with and without wind power to determine the critical clearing time with and without wind power.

In evaluating transient stability, the critical clearing time (CCT) is calculated for all cases i.e. with and without wind power. The base case represents the normal operation of the system without any wind power connected to the system. Thus the network is characterized by synchronous generators. The generators are dispatched in away, that most areas are having a

balanced power flow. After performing transient Stability simulations, the critical clearing time (CCT) for the base case was found to be 20ms.
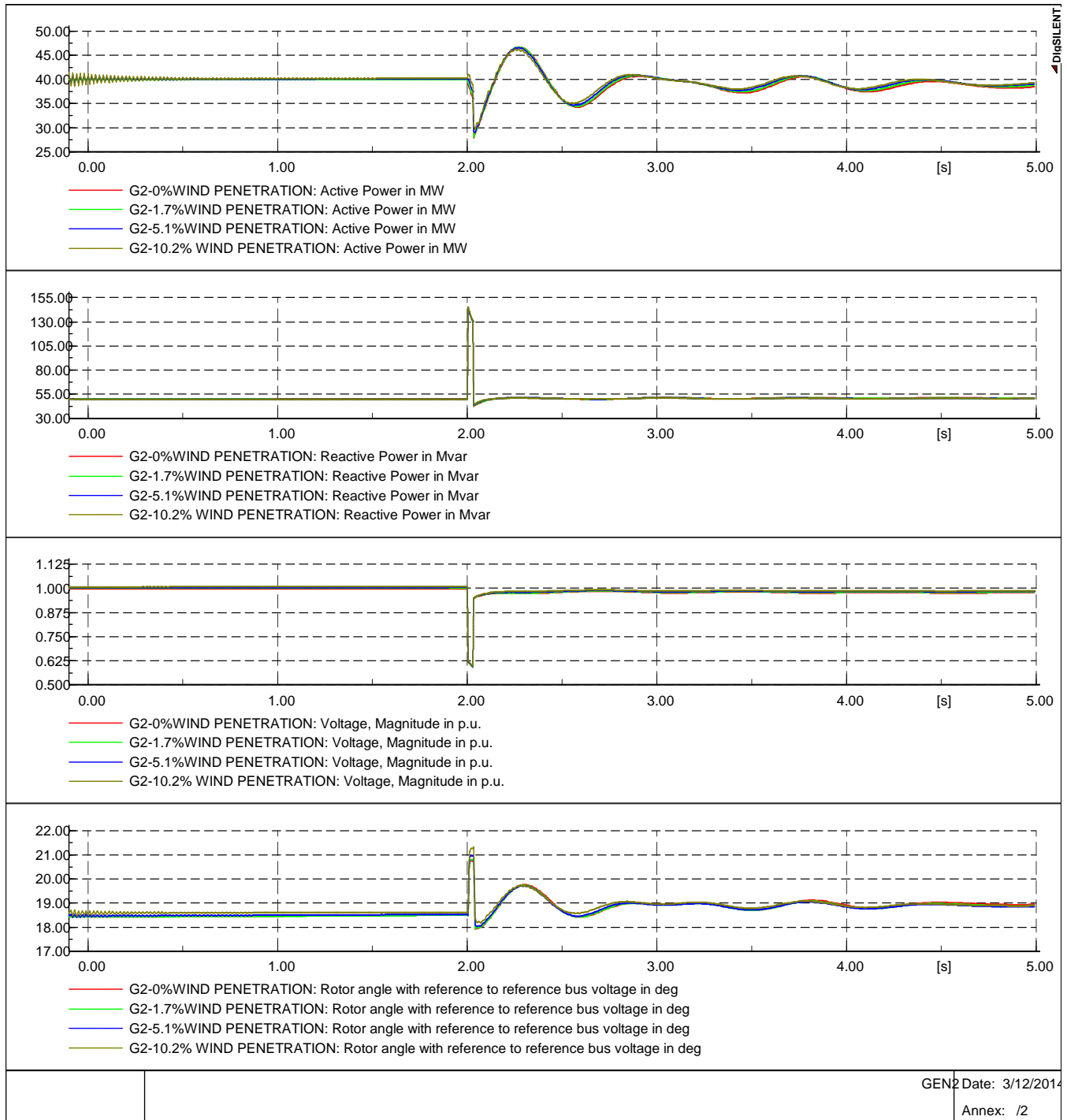

Figure 6. Generator2-fault on line 4.1

In the next scenario the IEEE 30 bus used as the base case was integrated with wind turbines and run for transient simulation. Active and reactive power flows were almost equal to those of the base load-flow. The analysis of the CCT resulted in an increased stability limit compared to the Base Case which had only synchronous generators in service. The corresponding increases depending on penetration level is as shown in the Table 1 below.

Table 1. Penetration Level Vs. CCT

Penetration Level	CCT(Milliseconds)
0%	20
1.7%	30
5.1%	50
10.2%	55

This means, that the transient network stability is enhanced

when DFIG are connected instead of synchronous generators. Figure 5, shows the results for penetration level of the DFIG.

Figure 5, above shows the graphs for active power, reactive power, voltage magnitude and rotor angle of generator 1 when a fault occurs on line 2-6. It also reveals how the system responds at different penetration levels. When no wind power is introduced the power output from the generator is highest since there is no alternative source of power. However, the introduction of wind power reduces the amount of power generation from generator 1. From the graphs, all the systems

return to stability when the fault is cleared. The number of swings in each case is seen to remain constant indicating that introduction of wind power up to penetration level of 10.2% does not affect the system negatively. The magnitude of the swing at penetration level of 10.2% wind power is slightly less than when no wind power is introduced. This is because with the introduction of wind power there is an alternative source of power to the system and hence the shock experienced on the system is reduced.
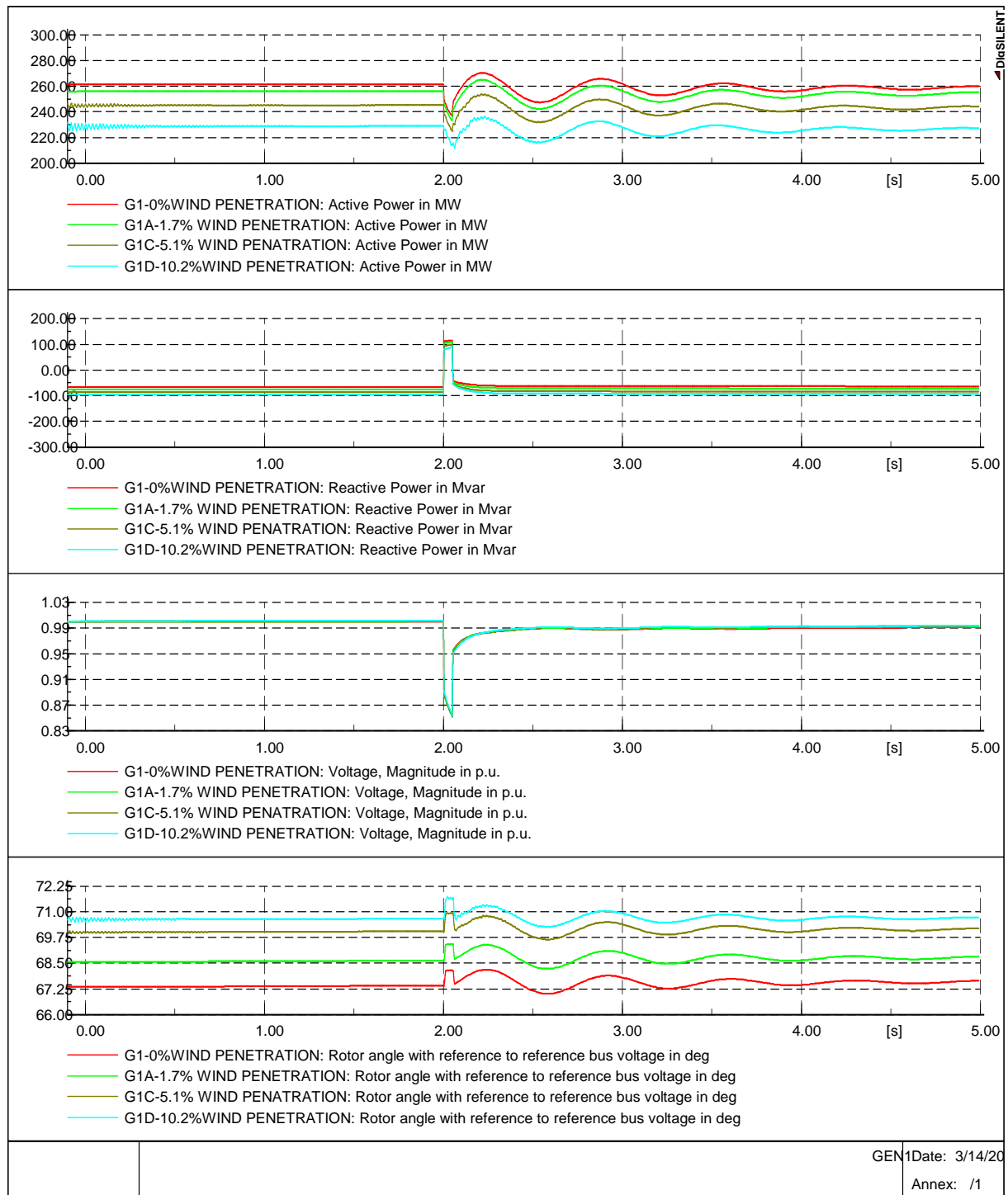

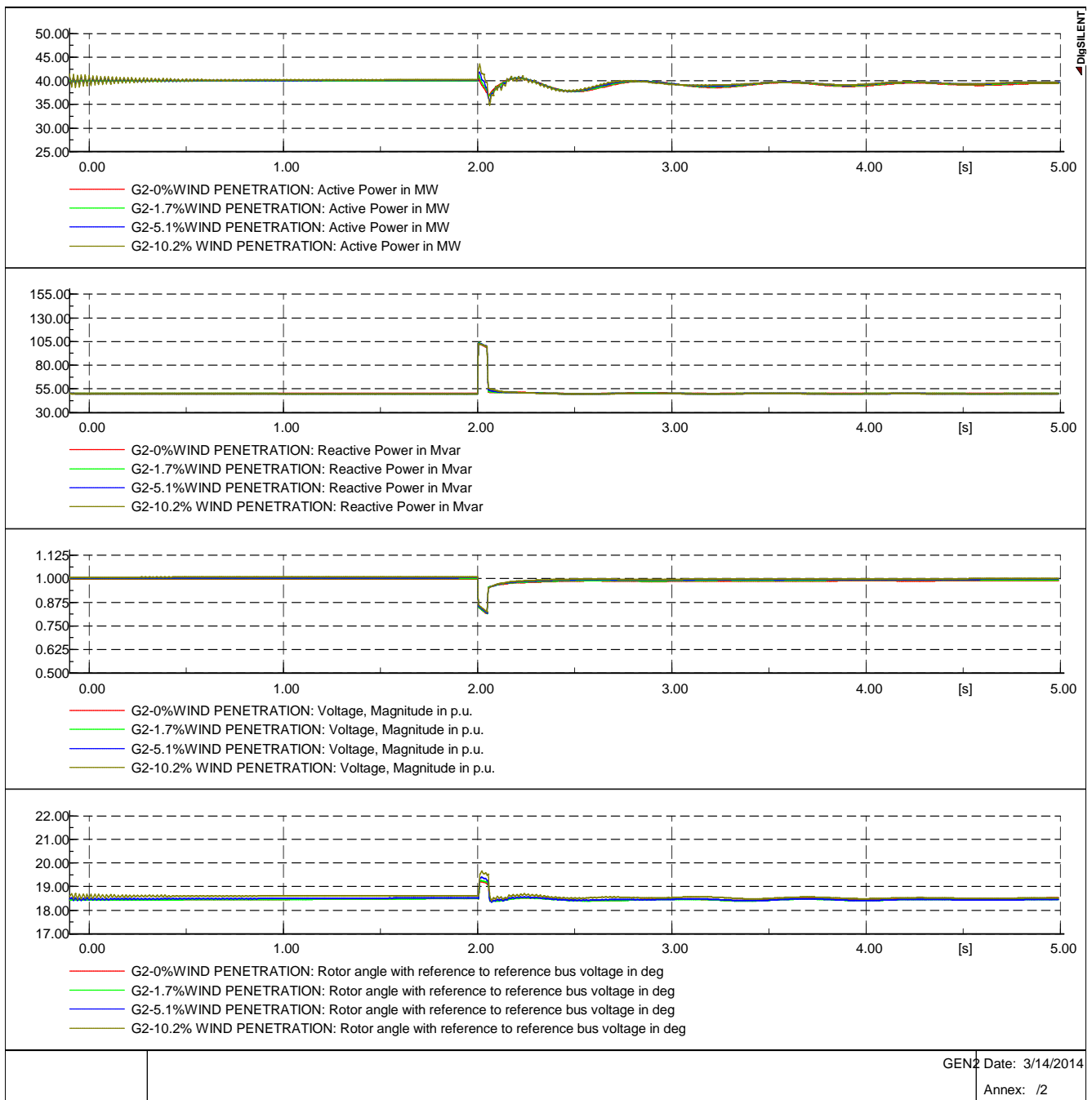*Figure 7. Generator1-fault on line 8-28*

Figure 8. Generator2-fault on line8-28

Figure 6, above are graphs, for monitoring of the parameters in the system by generator 2. This generator has lower rating than generator 1 and the deviation of power from the 0% power generation and 10.2% is insignificant. This is evident from the complete overlapping of all the graphs as shown above. This suggests that if the system has many low rated power generators, the effect of a fault on the system is reduced since there are alternative sources of power.   In this case, again we noted that the magnitude is smaller and the number of the swings before the fault is cleared are reduced. This shows generator 2 does not experience much shock when the fault occurs. This is because the bulk of the generated power is from generator one the graphs are similar with those of fault on line 2-6 on generator 1 only that the swing occurs for a shorter period (about 2 cycles).This is because the fault is triggered on line 8-28 which is far away from generator 1 hence the impact of the fault is less felt (see Figure 7 and 8).

7. Conclusion

In conclusion, the addition of the DFIGs to a power system network, does not negatively affect the stability of the system. From the results and discussion it is evident that even with increased penetration of wind power up to 10.2%, the system showed a high degree of transient stability. It is evident from the simulation results, as the system approaches stability, the

swings are more or less of equal magnitude. As the penetration level of DFIGs increased from 0% to 10.2%, the critical clearing time also increased. This clearly shows that the transient stability of the power system is improved by DFIG penetration. Looking at the results, it shows that DFIG's sudden disconnection could result to pole slip or non-convergence of the system. This is due to loss of equilibrium between the produced power and the consumed power. With an increased number of DFIGs and a three phase fault on line 8-28, the fault temporarily disconnects the DFIGs which were catering for the loads close to it. A larger shock is felt by the synchronous generators since it has to increase its generations to cater for more loads. This could eventually result to pole slip with cyclic fluctuations in voltage subjecting torsion stresses on the shaft of the synchronous generators. A Small disturbance was observed when DFIGs were incorporated in the power system. This was visible from the simulation graphs which were seen to increase with increase in number of DFIGs. This is due to hunting in a synchronous generator as a result of injection of harmonics in the power system by the DFIG.

Acknowledgements

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