Impacts of wind and solar integrations on the dynamic operations of distribution systems

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***Abstract*— The integration of large-scale distributed generation (DG) and energy storage significantly affect the dynamic behaviors of distribution systems. Distributed systems are facing new challenges in terms of their dynamic behaviors due to the addition of large-scale DG into low-voltage distribution systems. This paper analyses the important effects of the penetration of large-scale wind, solar and energy storage on the dynamic operation of distribution systems during transient conditions. The impact of keeping DG units connected to a distribution grid during and after a grid disturbance is investigated. The behaviors of energy storage devices under fault conditions during a distributed system's islanding are also studied. The impact of the penetration of renewable energy resources on a system is demonstrated through nonlinear simulations using the IEEE benchmark sixteen bus distribution system. The results show that solar, wind and energy storage dynamics have significant impacts on dynamic behaviors and voltage stability of distribution systems.**

I. Introduction

Next two decades will see an increasing penetration of DG at the distribution level of the grid. Among different sources of DG, renewable energy have taken center stage in providing clean generation and replace some of the country's baseline generation. As a result the operation and structure of distribution system is changing with the integration of distributed generation. However, most utility electric power systems are not designed to accommodate active generation and energy storage at the distribution level. Among the new issues, there is the question of transient voltage variation and dynamic voltage stability of distribution systems during low-voltages in the presence of a large penetration of DG [1].

Nowadays, it is more common for DG to be considered in the context of the wider concept of distributed energy resources (DER) which include not only DG but also energy storage and responsive loads [2]. The power system architecture of the future, incorporating DER, will look very different from that of today. This changing nature of a power system has considerable effects on its dynamic behaviors and result in power swings, dynamic interactions between different power system devices and less synchronized coupling. A high penetration of DG will affect the steady-state and dynamics of this distribution system.

Traditionally, distribution network design did not need to consider issues of stability as the network was passive and remained stable under most circumstances provided its transmission network was stable [3]. Even now, stability is hardly considered when assessing renewable DG schemes. However, this is likely to change as the penetration of these schemes increases and their contributions to network security become greater. The areas that need to be considered include transient, as well as, long term dynamic stability and voltage collapse.

In the future, a large-scale implementation of renewable energy sources for power generation can be expected. However, the uncontrollable nature of generators, especially when renewable energy sources such as wind, wave and sun are exploited, makes their output powers difficult to predict. Moreover, as high power fluctuations from these generators can be expected, energy storage systems/devices may be needed to cover the resulting imbalances between the power generation and energy consumptions. Energy storage devices are one of the most critical components for the successful operation of a distributed system in which their main function is to be able to balance the power and energy demand with the generation.

With a rapid increase in a DG's penetration levels, its power system stability can vary due to the presence of the new power generation at the distribution level. The effect of synchronous machine-based DG's excitation system's control modes is discussed in [4]. It is shown that, when the synchronous machine based DG is equipped with a voltage regulator, the voltage stability is improved compared with a DG with constant lagging, constant unitary and, finally, constant leading power factor [4]. The impact of induction machine-based DG units on long-term voltage stability is investigated in [5] and [6] in which it is shown that, compared with the base case, the voltage stability margin is worse with induction generator-based DG units operating at their nominal power.

The dynamic behavior of a synchronous DG connected to a distribution system during fault conditions is studied in [7]. In [8], the impact of DG units on the transient stability of a distribution network is investigated and it is shown that not all should be tripped according to the IEEE Std. 1547 because some DG technologies can surpass the critical clearing time (CCT) given by that standard. It is shown in [9] that induction generators do not have a noticeable impact on transient stability, unlike synchronous generator-based DG units, which decrease the maximum rotor speed deviations but increases the oscillation durations due to inter-area oscillations. Synchronous and induction machine-based DG units are compared in [5] in terms of transient stability and short-term voltage stability. It is shown that voltage sags caused by a phase-to-ground fault are made worse in almost all cases except when the DG is equipped with a voltage

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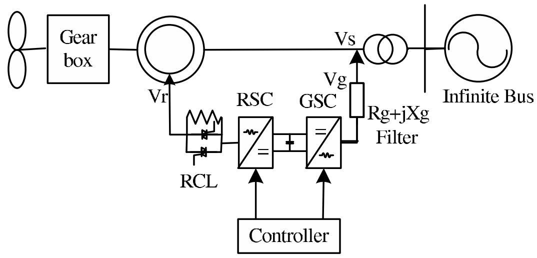

Fig. 1. Schematic diagram of DFIG.

controller and is located far from the fault.

As there are many concerns regarding power system stability with a large penetration of DG units, a number of issues should be investigated before connecting large-scale DG units into existing systems. This paper compares the performances of doubly-fed induction generators (DFIGs), direct drive wind generators (DDWGs) and PV (photovoltaic) generators during low-voltages. In addition, during low-voltages, the penetration level with LVRT capability are determined. The impact of energy storage devices on the dynamic performances of DG units during islanding is investigated. Finally, the minimum fault ride-through criteria needed to prevent disconnection of different types of DG units during transmission grid faults are compared.

The organization of this paper is as follows: Section II describes the models used to represent the main network components and electrical system; Section III provides a short description of the test system; in Section IV, a number of case studies are outlined and discussed. The conclusions are summarized in Section V.

II. Modeling

Dynamic models of the devices considered in this paper are presented in this section. For stability analyses we include the transformer and transmission line in the reduced admittance matrix. The DFIG schematic, in which the stator winding is connected directly to the network while the rotor winding is connected to the network through two back-to-back voltage source converters (VSCs), is shown in Fig. 1. Variable speed operation is obtained by injecting a variable voltage into the rotor at a slip frequency. This voltage is obtained using two AC/DC insulated gate bipolar transistor-based VSC linked by a DC bus.

The function of the rotor-side converter (GSC) control is to limit the rotor fault current and to increase the damping of stator flux, and consequently, to enhance the ride-through capability. In normal conditions, rotor current limiter also known as crowbar protection (Fig. 1) is inactive. Once a voltage dip is detected, the crowbar is activated, the rotor-side converter (RSC) operates to control both the active and reactive powers. Once the fault is cleared, the crowbar remains in service for 150 ms to limit the DFIG transients generated by the voltage increase at the time of clearing the fault. The nonlinear model of the wind turbines, as shown in Fig. 2, is based on a static model of the aerodynamics, a two mass model of the drive train, a third-order model of the generator, a GSC with DC-link capacitor, the pitch controller and a RSC.

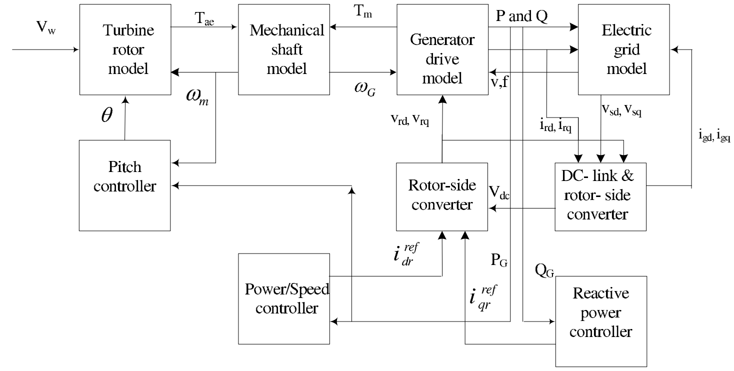

Fig. 2. Block diagram of DFIG wind turbine system.

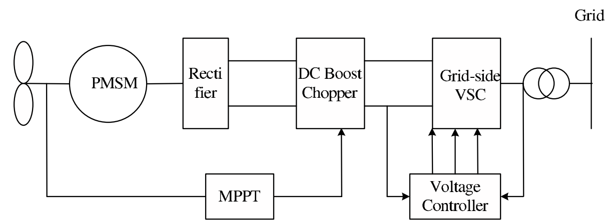

Fig. 3. Schematic diagram of DDWG.

The rotor of the wind turbine, with radius R_i, converts energy from the wind to the rotor shaft, rotating at speed, ω_{m_i}. The power from the wind depends on the wind speed, V_{w_i}, the air density, ρ_i, and the swept area, A_{wt_i}. From the available power in the swept area, the power on the rotor is based on the power coefficient $c_{p_i}(\lambda_i, \theta_i)$, which depends on the pitch angle of the blade, θ_i, and the ratio between the speed of the blade tip and the wind speed, denoted as the tip-speed ratio, $\lambda_i = \frac{\omega_{m_i} R_i}{V_{w_i}}$. The aerodynamic torque applied to the rotor for the i^{th} turbine by the effective wind speed passing through the rotor is given as [10]:

$$T_{ae_i} = \frac{\rho_i}{2\omega_{m_i}} A_{wt_i} c_{p_i}(\lambda_i, \theta_i) V_{w_i}^3, \tag{1}$$

where c_{p_i} is approximated by the following relation [11]:

$$c_{p_i} = (0.44 - 0.0167\theta_i)\sin\left[\frac{\pi(\lambda_i - 3)}{15 - 0.3\theta_i}\right] - 0.00184(\lambda_i - 3)\theta_i,$$

where $i = 1, \cdots, n$, and n is the number of wind turbines. The complete nonlinear model of DFIGs is given in [12].

Fig. 3 is the simple diagram of a DDWG. The AC power output from the generator is converted into DC power through diode rectifier circuits. The grid-side connection is realized by a self-commutated pulse-width modulated (PWM) converter that imposes a PWM voltage to the AC terminal. A complete description of a DDWG model is given in [13].

A PV system can be modeled at several different levels of complexity depending on its intended application. Fig. 4 shows a PV system connected to the grid through a DC-AC inverter, a DC-DC converter and a DC-AC inverter. As

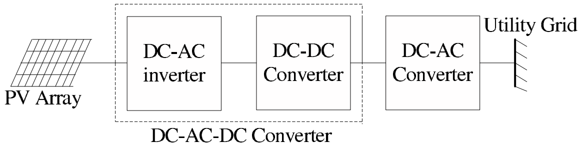

Fig. 4. PV System Connected to Grid

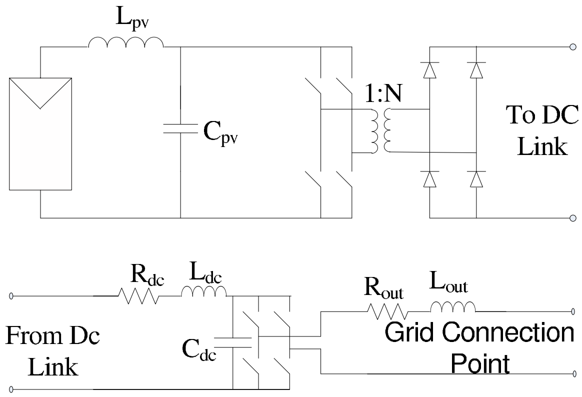

Fig. 5. Equivalent Model of Grid Connected PV System

generally the output voltage of a PV module is low, at first a DC-AC converter is used to convert the output of PV array into AC which is then stepped up through a transformer. Again, AC is converted into DC and transmitted through the DC link to reduce its loss. Therefore, it can be said that a DC-AC-DC converter operated at 50 Hz is used to increase the voltage level as per the grid's requirement. Finally, DC is converted into AC through the inverter.

The equivalent model of the grid connected PV model [14], which consists of several switching elements, is shown in Fig. 5. As it is very difficult to fully model the PV system to analyze the stability due to the nonlinear nature of the switching schemes, the switching devices are considered as being ideal, as mentioned in [14]. A step-up transformer with a turns ratio, N, is connected to increase the voltage level of the PV array. Although the output of the inverter is not purely sinusoidal, it is considered to be in [14].

The equivalent circuit, with the approximations mentioned before, is shown in Fig. 6 in which, I_L is the light generated current, I_{ON} the dark diode characteristics of the photocells, L_{pv} and C_{pv} the wiring inductance and capacitance of the PV cells, respectively, $I_s = 9 \times 10^{-11}$ the saturation current, R_s and R_{sh} the series and shunt resistance of the array respectively, δ the firing angle, K the amplitude modulation index of the PWM scheme, i_{pv} the current flowing through the array, v_{pv} the output voltage of the array, R_{dc} the resistance of, L_{dc} the reactance of, C_{dc} the capacitance of, i_{dc} the current flowing through and v_{dc} the output voltage of the DC link, respectively, R_{out} and L_{out} the resistance and reactance of the line connected to the grid, i_{out} the current flowing through the line connected to the grid, and $v_g = Vg\cos(\omega t)$ the AC voltage of the grid where V_g is the magnitude of v_g. The dynamic model of a PV generator is described in [14].

A battery energy storage system (BESS) is connected to

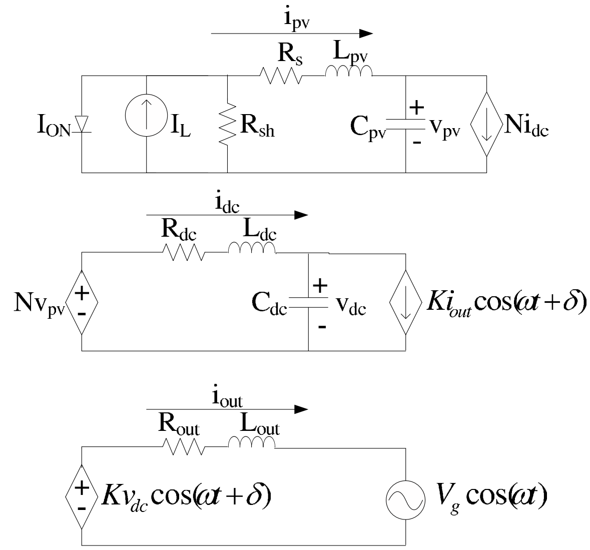

Fig. 6. Equivalent Circuit Diagram of Grid Connected PV System

the grid through power electronic interface and operated as a controllable voltage source in order to mitigate the problems raised during voltage sags and faulted conditions. During islanding of DG units, the BESS provides the required power to balance and stabilize the system. In this paper the BESS is modeled as an nonlinear voltage source and the complete model is given [15].

III. Test System

A 16 bus 3 feeder distribution system is used in this paper. A single-line diagram of the test system is shown in Fig. 7 and the numerical values of the parameters are given in [16]. The test system used is modified by connecting two wind farms at bus 3 (DFIG) and bus 6 (DDWG) and a PV generator at bus 15. The nominal voltage of the feeder is 23 kV. It is a radial distribution system with a total load of 28.7 MW and 9.48 MVAr which is modeled as (i) a 20% large induction motor load [17], (ii) a 25% small induction motor load [17], and (iii) a 45% static load. The active and the reactive components of the static load are represented by constant current and constant impedance models, respectively, as recommended in [18] for dynamic simulations.

IV. Case Study

In order to gain a deeper insight into these complex issues, a number of cases are considered but only a few are presented in this paper due to space limitations. Simulation studies are carried out using nonlinear models of different power system devices and the widely used power system simulator (PSSE) and PSAT. Both static analyses and nonlinear simulations are used to analyze the effects of DG penetration into the existing distribution system considered.

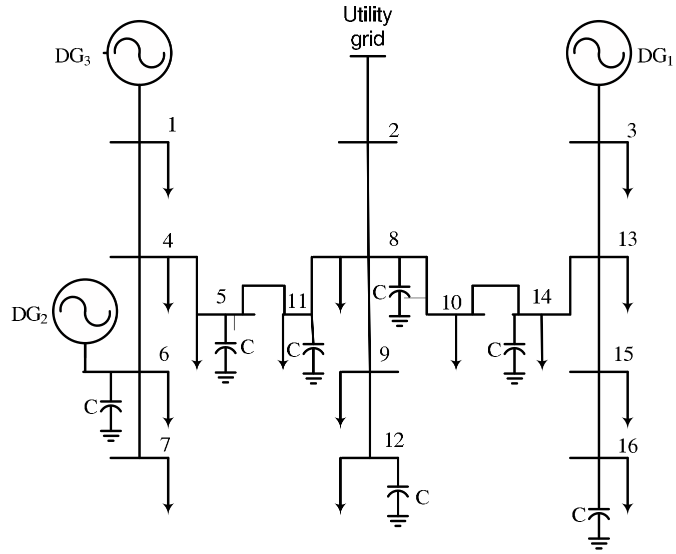

Fig. 7. 16 bus distribution system

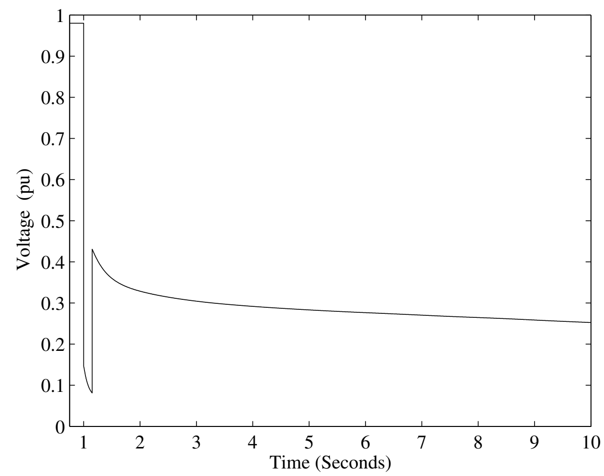

Fig. 8. Terminal voltage of DG_2 for three-phase fault at bus 7

TABLE I
PENETRATION LEVEL AT DIFFERENT OPERATING MODES

Control modes	Bus 1 (MW)	Bus 3 (MW)	Bus 6 (MW)
no control (unity pf)	9.15	7.75	12
power factor	12.5	11.5	18.5
voltage	15.75	13.5	20

A. Integration level with steady-state voltage control capability of DG units

It is well known that IEEE Std 1547-2003 does not allow DG units to actively regulate voltage at the point of common coupling. This is true in Australia for a DG with a capacity of less than 30MW for which power factor must lie between unity and 0.95 (leading) for both 100% and 50% real power injections. However, a DG embedded with a voltage control capability can significantly enhance the penetration level.

In this analysis we consider three cases: (i) DG units without a voltage control capability (operated at a unity power factor, as suggested by IEEE 1547); (ii) DG units with power factor control mode; and (iii) DG units with a voltage control capability. We allow a maximum $\pm 10\%$ voltage variation at the DG buses. The maximum penetration levels for the DG units in three different buses are given in Table I in which penetration is limited due to the voltage rise problem. The penetration level can be increased by 54.16% and 66.67% at bus 6 if the DG units are operated at the power factor and voltage control modes, respectively. From Table I, it is clear that more DG units can be accommodated if they are installed with voltage control operating modes.

B. Transient voltage instability

Although, generally, DG integration is only limited due to voltage rise, the transient and voltage stabilities can also limit large-scale DG integration under very stressed operating conditions. To study this the test system is congested by increasing the load demand and transmission line length by twice those given in [16]. Under this stressed condition, a wind farm of capacity 30 MW and comprised of DFIGs can be accommodated at bus 6 without violating the voltage constraint. Fig. 8 shows the terminal voltage of DG_2 for a three-phase fault at bus 6 which is subsequently cleared after 0.24 s. It is clear that, although it satisfies a steady state voltage variation, the system becomes unstable due to its nonlinear interactions and dynamic instability. From modal analysis it was found that the critical mode is related to voltage states and instability occurs due to reactive power mismatch.

C. Comparisons of DFIGs, DDWGs and PV generators

The stator winding of a DFIG is directly connected to the network while the rotor winding is connected to the network through two back-to-back VSCs. On the contrary, as the full power converters of a DDWG totally decouple the generator from the grid, grid disturbances have no direct effect on the generator. The dynamic of PV generation is considerably different to that of conventional generation involving rotating machines.

In this paper a 30 MW DG is considered at bus 6. This DG is represented by DDFIs, DDWGS and PV generators sequentially for the dynamic analysis. We have considered voltage control mode for this analysis as it provides better performance. To compare performances during low voltages, detailed simulations are performed for a symmetrical 3-phase fault at bus 7 which is subsequently cleared after 150 ms. Fig. 9 shows the terminal voltages of considered DG units from which it is clear that the DDWG provides better performances in terms of overshoot and settling time than do the DFIG and PV generator. During the post-fault phase, the DDWG takes 0.02 s to recover the voltage to the nominal value whereas the DFIG and PV generator take 0.10 s and 0.18 s, respectively.

D. Effect of islanding on dynamic performance

An island with an imbalance between power demand and resources can be expected to have its frequency or voltage go

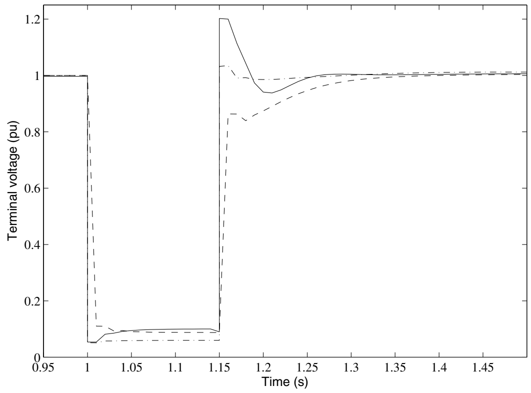

Fig. 9. Terminal voltage for three-phase fault at bus 7 (solid line PV, dashed line DFIG and dash-dotted line DDWG)

quickly outside normal operating bounds. As normally, DG units are operated in a constant power and constant power factor control mode, it is improbable that a precise balance will occur. If a DG uses voltage regulation and governor control characteristics, the island can become more persistent as the DG output may adapt to the islanded system's load demand without reaching the voltage or frequency trip points.

On-grid uses of energy storage (coupled with a DG unit) are generally more beneficial in an isolated environment where the damping effects (voltage and energy supply) of the grid are minimized. Here, the energy storage facilities provide a load following and voltage stability support to the DG unit, thereby allowing the generation component to operate in a more reliable and cost-effective manner. Since storage facilities often have a very quick reaction time and can act as both a dynamic sink and power source, they can behave like a shock absorbers, providing support to existing DG resources and allowing them to operate over a wider range of capabilities.

In this paper, the dynamic performance of this test system is analyzed during islanded, i.e., when it is disconnected from the grid (bus 2). Fig. 10 shows the terminal voltage of DG_2 during the islanded period for three operating conditions: (i) DG units with no control (unity pf); (ii) DG units with voltage control capabilities; and (iii) DG units integrated with a 2 MWh battery energy storage system (BESS) [19]. It is clear that the voltage rises and violates the operating conditions when no control is applied in the DG units. However, when they are embedded with voltage control capabilities, they are capable of meeting operating constraints but show poor damping, oscillations and overshoots. DG units integrated with BESS produce the best performances as they can sink and supply power immediately following a disturbance.

E. FRT scheme comparisons

As disconnection of a large number of wind parks can endanger a system's stability, measures have to be taken to maintain secure system operation. Preventing such a

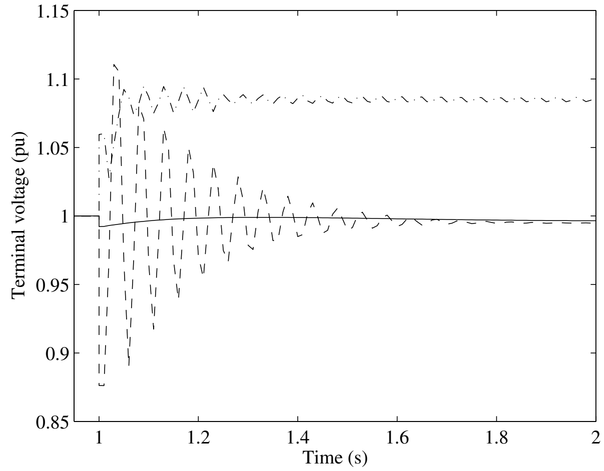

Fig. 10. Terminal voltage of DG_2 during islanding (Solid line battery storage, dashed line voltage control and dash-dotted line without voltage control)

TABLE II
COMPARISONS OF CCT

Index	DFIG	DDWG	PV generators
CCT	3.75 s	4.15 s	3.56 s

disconnection can be achieved by defining fault ride-through (FRT) criteria for the response of a wind park at the point of common coupling (PCC) during and after a disturbance in the transmission grid. To keep DG units connected to the grid without violating stability limits, faults have to be cleared within the CCT required for setting the under-voltage protection.

In this paper, the CCT is first estimated by using the following equation and then its exact value is determined from simulations in which it is obtained by increasing the fault-time interval until the system loses its stability [20].

$$t_c = \frac{1}{T_m} 2H_m(s_c - s_0), \tag{2}$$

where s_c is the CS of a generator. The CCTs of different types of DG units are shown in Table II from which it is clear that a DDWG can be connected to the grid for a longer time than either the DFIG or PV generator during a fault condition.

F. Interactions among DG units

DG technologies have the potential to significantly affect power system performance. It is important to investigate their impact on the dynamic performances of existing grids and the interactions among different types of DG units. In this paper, all the dynamic responses of controllers are coordinated and simulations are carried out with: (i) DFIGs only; (ii) DFIGs and PV generators; and (iii) DFIGs, PV generators and DDWGs. Figs. 11 and 12 show the terminal voltages and real power outputs of a DFIG with a severe three–phase fault at bus 7 for the above-mentioned cases. It is clear that the interactions among the DG units do not deteriorate the

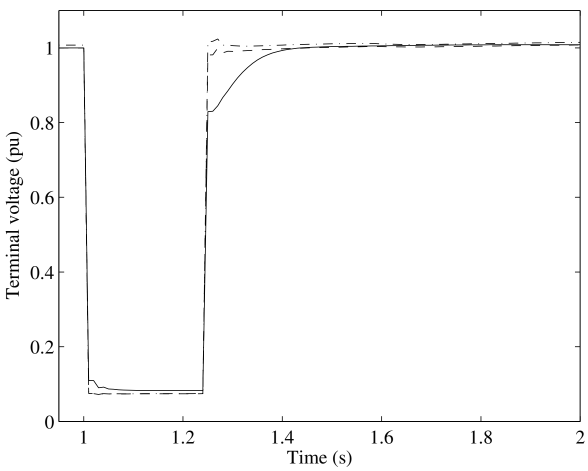

Fig. 11. Terminal voltage of DG2 (solid line DFIG only, dashed line DFIG+PV and dash-dotted line DFIG+PV+DDWG)

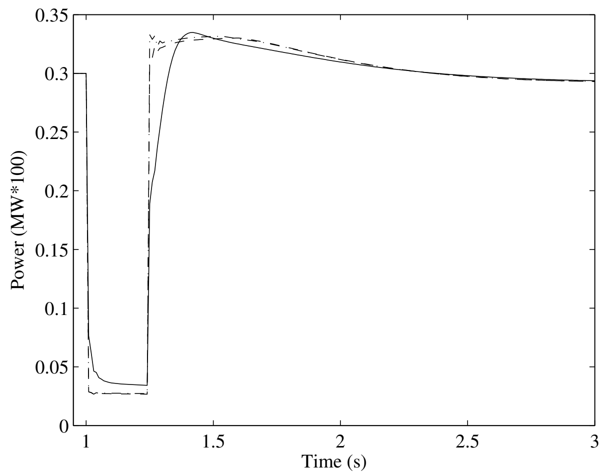

Fig. 12. Real power output of DG2 (solid line DFIG only, dashed line DFIG+PV and dash-dotted line DFIG+PV+DDWG)

dynamic performances provided they are coordinated with each others.

V. Conclusions

In this paper, the impacts of different types of DG units and BESS on the dynamic performances of power systems are investigated. In distribution networks generally DG accommodation is limited by the constraint of voltage rise. In this research it is shown that DG integrated with a voltage control capability can mitigate voltage rise problems and consequently enhance penetration levels. Dynamic voltage instability may also limit DG integration in a stressed system. A DG based on power electronics and equipped with a coordinated control enhances both the damping and voltage stability of a power system. Also, an energy storage device can quickly stabilize a system during the switching period from grid-connected to islanding. In addition, DG units incorporated with the FRT capability can provide additional voltage support for the grid and prevent unnecessary tripping of large numbers of DG units and possible power deficits in the system after fault elimination.

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