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Dynamic Behavior Improvement in a Microgrid with Multiple DG Units Using a Power Sharing Approach

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***Abstract*--This paper investigates dynamic behavior of a distribution subsystem (microgrid) with three distributed generation (DG) units to planned and accidental switching event. Three DG units are one gas-turbine synchronous generator and a variable-speed wind turbine with doubly fed induction generator (DFIG) and a converter based DG. A power control approach is proposed for DG units to provide both voltage and frequency regulation capability and hence an improvement on transients and dynamic behavior of a microgrid system. Two distinct operation modes, i.e. grid-connected and islanding mode are used in the proposed approach for proper transfer from normal to islanding operation. Case studies are simulated based on both planned and unplanned islanding scenarios to evaluate the performance of the control approach. The study results show that the proposed power sharing approach for DGs in the microgrid may contribute to mitigate microgrid system transients, improving dynamic performance, and reducing frequency changes following disturbances that subsequent to islanding**.

***Index Terms*-- Distributed Generation, DFIG, islanding, microgrid, power sharing.**

I. INTRODUCTION

THE growing diffusion of Distributed Generation (DG) in the MV networks is the result of several concurrent factors. Firstly, the deregulation of energy markets, with separation of generation, transmission, distribution and supply of energy. Secondly, the availability of new, cheaper and efficient small size generators based on new technologies. Thirdly, the ever growing difficulties in expanding transmission & distribution networks and large generation plants due to environmental concerns [1]. One of the new technical issues created by distributed generation interconnection is inadvertent islanding. Islanding occurs when a portion of the distribution system becomes electrically isolated from the remainder of the power system, yet continues to be energized by DG connected to the isolated subsystem. This is also about the concept of the micro-grid.

It can be desirable to permit such islanded operation to increase customer reliability, and this is often done where the DG provides backup power to the facility where it is installed [2],[3].However, to realize the full benefit of high DG penetration depth, the islanded operation of micro-grids needs to be considered. After disconnection from the main grid, micro-grid experiences frequency and voltage deviations. The amount of these deviations is highly dependent on 1) the pre-islanding operating conditions, 2) the type of the event that initiates islanding, and 3) the type of the DG units within the micro-grid. The micro-grid is expected to remain operational after islanding, and meet the corresponding load requirements during the autonomous operation [4],[5]. A power sharing strategy is required for sound operation of a microgrid with multiple (more than two) DG units, particularly during the autonomous mode of operation.

Fast response of power sharing strategy is more critical for a microgrid as compared with a large interconnected grid. The reasons are 1) presence of multiple small-DG units with significantly different power capacities and generation characteristics, 2) presence of no dominant source of energy generation during autonomous mode of operation, and 3) fast response of converter based DG units, which can adversely affect voltage/angle stability if appropriate provisions are not in place. The microgrid power sharing approach assigns real and reactive power references for the DG units to 1) efficiently share real-/reactive power requirements of loads among the DG units, 2) quickly respond to disturbances and transients due to the changes in the system operating mode, 3) determine the final power generation set-points of the DG units to balance power and restore frequency of the system, and 4) provide a means for re-synchronization of the autonomous microgrid with the main grid for reconnection[6],[7].

The wind-turbine based DG unit is one of the fastest growing sources of power generation in the world mainly due to (i) strong world wide available wind resources, (ii) environmentally-friendly power generation source especially suitable for remote areas, and (iii) rapid technological development [8],[9]. Among the different wind energy conversion systems, double fed induction generators (DFIG) are capable of providing the required capabilities without the need of large costs on the power electronics hardware, provided that adequate control strategies are added [10]. The

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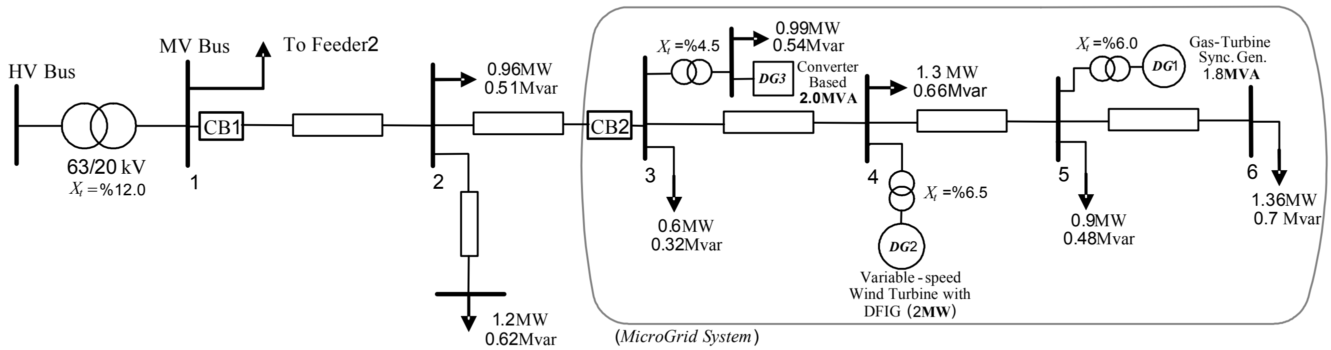

Fig. 1. Schematic diagram of the study system

control flexibility provided by the DFIG electronic converter makes it possible to define various control strategies for participation in primary frequency control and voltage regulating support.

In this paper a power sharing and control approach based on locally measured signals without communications is proposed to provide real and reactive power balancing. This can cause an improvement on dynamic behavior of a microgrid in autonomous mode, during and subsequent to islanding process.

To investigate dynamic behavior and to evaluate the performance of the proposed power sharing and control approach, some case studies are simulated based on both planned and unplanned (e.g., a short-circuit event on upstream section of the feeder) islanding scenarios. The study system is designed and the corresponding PSCAD/EMTDC based digital computer simulation model is developed.

II. System Description

Single-line diagram of a medium voltage local distribution feeder is shown in the Fig. 1. In this system, the microgrid system is assumed to be a portion of distribution feeder and is supplied by three distributed generation (DG) units. DG1 is a 1.8 MVA conventional gas-turbine synchronous generator equipped with excitation and governor control systems, a full description of such a gas-turbine generator can be found in [11]. DG2 represents a variable-speed wind turbine set with rated capacity of 2 MW which is interfaced through a doubly fed induction generator (DFIG) with rated capacity of 2.5 MVA. DG3 is a 2 MVA electronically-interfaced unit using a voltage source converter (VSC) as its interface medium. The DG1, DG2 and DG3 parameters are given in Table I. The microgrid system is separated from the rest of MV feeder by a circuit breaker.

III. Islanding Practice and Operation Strategy

Under the regulation governing distribution system operation, an islanding scenario is only permitted for loads with dedicated generation units. As a result, DG units must be equipped with specific islanding detection and prevention schemes to disconnect the unit within 2 seconds of an islanding event [12]. In the case of future microgrid applications, with the potential of islanding operation, a fast

TABLE I
Distributed Generations Parameters

DG1 (gas-turbine synchronous generator) parameters		
Synchronous machine characteristics S_n=1.8MVA , V_n=11kV		
X_d=1.56p.u.	X_q=1.07p.u.	T'_d=3.5s
X'_d=0.29p.u.	X'_q=0.35p.u.	T''_d=0.035s
X''_d=0.17p.u.	X''_q=0.17p.u.	T''_q=0.037s
X_l=0.055p.u.	R_s=0.0036p.u.	H=1.04s
AVR parameters: K_A=400, T_A=0.02s. Turbine-Governor total time constant: about 500ms		
DG2 (Variable-speed Wind Turbine with DFIG) parameters		
DFIG parameters S_n=2.5MVA , V_n=0.69kV , ω_s=1500 r.p.m.		
R_s=0.01p.u.	X_s=0.1p.u.	X_m=3.0p.u.
R_r=0.01p.u.	X_r=0.08p.u.	No. of poles=4
Wind Turbine characteristics P_n=2MW		
No. of blades=3	Rotor diameter=80m	Air density = 1.255kg/m^3
Gear box ratio=1:85	Inertia constant=3.5s	Nominal wind speed=12m/s
cut-in wind speed=4.5m/s	cut-off wind speed=25m/s	K_{opt}=0.63
DG3 (Converter Based DG) parameters		
Voltage Source Converter parameters S_n=2.0MVA , V_n=4.16kV		
Output Impedance (R_f+jX_f)	0.007+j0.07 p.u.	

and reliable detection algorithm is required to effectively distinguish between an islanding condition and other types of disturbances.

In this research, the islanding and formation of a microgrid is assumed to be detected within 100ms (5 cycle in 50Hz). After detection, islanding mode operation of microgrid by changing the DGs control mode is activated.

In the proposed microgrid system, fig. 1, the islanding incident that results in the islanding operation can be due to either planned (intentional) or unplanned (unintentional) switching event. In the case of planned islanding operation, appropriate microgrid load sharing among the DG units and main grid may be scheduled prior to islanding. Thus, the islanding process results in minimal transients and the microgrid continues operation. An unplanned islanding and microgrid formation is due to either a fault and its subsequent switching events or some other unexpected switching process. Prior to islanding, the operating conditions of microgrid could be widely varied, e.g., the DG units can share load in various manners. In the proposed system, planned islanding and unplanned islanding due to a fault in upstream of microgrid will be investigated.

In the grid-connected mode, DG units are expected to supply their local demand or operate in its optimal efficiency operating point. This can be due to the economics aspects.

Also to avoid interference with the voltage regulator devices in the network, DGs normally operate at constant power factor (close to unity) and do not control the grid voltage actively. In the study system of fig. 1, DG1 generates constant real power output (close to unity power factor), DG2 delivers maximum power extracted from the wind with unity power factor (DFIG capability), and DG3 generate constant real and reactive power output to supply the local load . In this mode, the grid acts as a slack bus which dominantly supports the real/reactive power requirements during transients or due to the power fluctuations caused by DG2, and also stabilizes the frequency.

In the islanding mode operation, fast and flexible real/reactive power control strategies are required to minimize dynamics of the system and damp out transient power oscillations where no infinite source of power is available. In the proposed approach the real power of each DG unit is controlled based on a frequency-droop characteristic and a complimentary frequency restoration strategy. Also reactive power control strategy of the microgrid is based on voltage regulating approach. The developed dynamic model of a variable-speed wind-turbine with doubly fed induction generator is employed to provide additional support to primary frequency control and voltage regulating of the microgrid.

In the proposed system, DG1 is equipped with excitation and governor systems. After islanding detection, DG1 switches to islanding mode by regulating its terminal voltage at reference value, e.g., 1pu, through excitation system (using Automatic Voltage Regulator) and by controlling deviations in generator speed through governor system that is implemented based on a frequency-active power relation (droop characteristic) and frequency restoration loop (using an integrator).

DG2 switches to islanding mode by contributing to primary frequency control and regulating its terminal voltage through both q and d-axis of rotor currents. Also DG3 activate the islanding mode by fast response to real and reactive power command through control of both d and q-axis of converter currents. The reference commands for real and reactive power of DG3 are locally implemented based on f-P droop characteristic and terminal voltage regulating, respectively.

IV. System Model

Time domain simulation model of the study system (Fig. 1) is developed using PSCAD/EMTDC software package.

In the study system, the main grid (63kV side of the distribution substation) is represented by a 63kV three-phase voltage source with the short-circuit capacity of 1100MVA and *X/R* ratio of 15.5. Each feeder is represented as a three-phase overhead line with lumped *RL* elements per phase or cable with pi equivalent circuit (*R*, *L* and *C* elements) per phase. DG1 is modeled as a synchronous machine. The machine electrical system is represented in the d-q-o frame with two rotor winding on each axis. The excitation and governor systems of the machine are also included in the model. DG2 is modeled as a variable-speed wind turbine with DFIG. The mechanical power generated by the rotor is converted into electrical power using a DFIG. In the doubly fed (wound rotor) induction generator, the stator winding is coupled directly to the grid. The rotor winding is connected to a back to back voltage source converter. Speed controller, primary frequency controller, and terminal voltage regulator are included in the model.

A. Variable-speed Wind Turbine with DFIG

The equations describing a doubly fed induction machine can be found in [14]. When modeling the DFIG, the generator convention will be used, which means that the current direction is toward output instead of inputs. The generator equations in d-q reference frame used in this research is given in [15]. Note that the d-q reference frame is rotating at synchronous speed with the q-axis 90^o ahead of the d-axis. The position of the d-axis coincides with the maximum of the stator flux, which means that V_{qs} equals the terminal voltage e_t and V_{ds} equals zero [15]. For simplicity, dynamic phenomena and switching transients in back to back voltage source converter are neglected. Instead, the rotor-side converter is modeled as a controllable voltage source and the grid-side converter is modeled as a controllable current source.

The rotor-side converter is used to control speed and both active and reactive power outputs through V_{qr} and V_{dr} components obtained from two separate sets of PI controllers.

To consider the rated capacity of the back to back converter, the limits are imposed on both rotor d and q-axis currents. The grid-side converter is used to take into account the balance of the active power between the rotor and the grid.

1) Maximum Power Extraction and Speed Controller

The maximum (optimal) power obtained from a given wind speed is commonly expressed by the following equation:

$$P_{opt} = 0.5\rho Cp_{opt}(\lambda_{opt},\theta)A_r v_w^3 \quad (1)$$

Being Cp_{opt} the optimal power coefficient of the wind turbine for a given wind speed, A_r (m^2) the effective area covered by the turbine blades, v_w (m/s) the wind speed and ρ (kg/m^3) is air density. The calculation of the optimal power coefficient, Cp_{opt}, can be obtained from the following function [15]:

$$Cp_{opt}(\lambda_{opt},\theta) = 0.22(116/\lambda_i - 0.4\theta - 5)e^{-12.5/\lambda_i} \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda_{opt} + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \quad (3)$$

The optimal tip speed ratio is defined as $\lambda_{opt} = \frac{\omega_{topt} r}{v_w}$ (4)

where r (m) is the blade radius and ω_{topt} is the optimal wind turbine rotor speed (rad_mech/s) for a given wind speed. From (1) and (4) an optimum (maximum) power value -P_{opt}- can be obtained as a function of the shaft speed, referred to the generator side of the gearbox, as follows:

$$P_{opt} = K_{opt}\omega_r^3 \quad (5)$$

where $K_{opt} = (\rho/2)(Cp_{opt}/\lambda_{opt}^3)\pi r^5$, ω_r=(P/2)Gω_t, being P number of poles and G the gear ratio. From (5) the wind turbine pre-defined optimal extraction power curve can be established for a given K_{opt} associated to a fixed blade angle.

In this research, K_{opt} is defined for a fixed blade angle equal to zero degree. The adopted value for K_{opt} is given in Table I. In Fig. 2 the maximum power extraction curve adopted for variable-speed wind turbine is shown.

The speed controller is controlling the electro mechanical torque (T_e). The reason for such control is that the torque is directly dependent on the quadrature component of the rotor current (i_{qr}), when stator resistant is neglected [16].

The following relation between torque and i_{qr} holds, in which e_t is the terminal voltage.

$$T_e = -\frac{L_m e_t}{L_s + L_m} i_{qr} \quad (6)$$

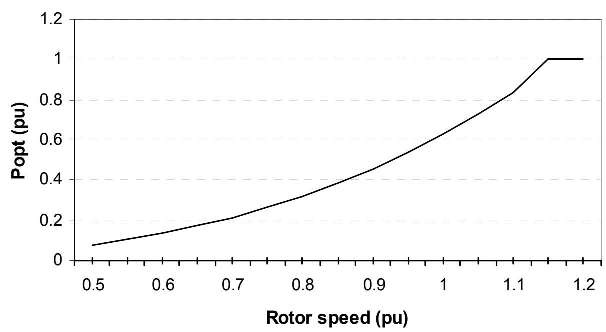

Fig. 2. Optimal power extraction curve

From (5), it can be derived the relation between electro mechanical torque and rotor speed as follows:

$$T_{e\,opt} = K_{opt}\omega_r^2 \quad (7)$$

From (6) and (7), the rotor speed controller is implemented by measuring the actual rotor speed and then calculate the value of i_{qr} needed to realize the desired electro mechanical torque. The resulting i_{qr} ($i_{qr\,ref}$) is fed into the DFIG through V_{qr} component using a PI controller, see Fig. 3. This control algorithm is applied up to maximum mechanical power of the turbine.

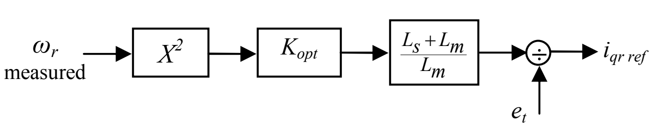

Fig. 3. Rotor speed controller (maximum power extraction)

2) Primary Frequency Support

Variable-speed wind turbines are controlled to capture as much power as possible from the wind. The large blades of the turbine give this type of DG unit a significant inertia however. The kinetic energy stored in their inertia give the turbine the possibility however to support primary frequency control for a short period. One particular advantage of variable speed wind turbine is that, unlike thermal or gas turbine power plants, they can increase their output power almost instantaneously [17]. This is an important feature, especially for a microgrid system when it goes to islanding mode operation.

The primary frequency control integrated into the rotor-side speed (active power) control loop is similar to the one usually used in synchronous generator. In this case, the droop (characterized by a regulation R, expressed in p.u. in the system base) is used to produce a change in the active power injected by the DFIG when a system frequency variation occurs. The active power increment is therefore proportional to the system frequency variation and is defined as follows:

$$P_{injected} = P_{ref} - (1/R)(\omega_{sys} - \omega_{sys\text{-}ref}) \quad (8)$$

This generated active power requires a new operating point of the DFIG. The primary frequency control that integrated into the rotor-side speed control loop is implemented by converting the required active power to equivalent electro mechanical torque, see Fig. 4. Note that this feature (primary frequency control) is activated when an islanding condition occur. ω_{sys} is obtained from grid connection bus voltage of the DFIG using a PLL (phase lock loop).

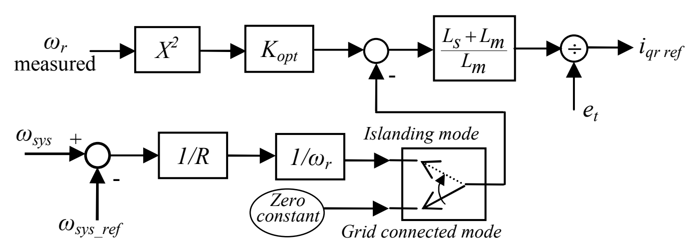

Fig. 4. Integrated active power and primary frequency control of the DFIG

For wind speeds below maximum rated speed (according to the operational optimal power curve) the input reference electro mechanical torque to the active power (rotor speed) control loop in DFIG follows the equations (6) and (7) as discussed in this section. However, for wind speed larger than maximum rated speed, the blade pitch regulation dominates the control and limits the energy captured from the turbine.

3) Reactive Power Control & Terminal Voltage Regulator

Variable-speed wind turbine with DFIG has a capability to control its terminal voltage. It is an important feature, especially for a microgrid islanding operation. By this feature, DFIG can contribute the reactive power management and voltage regulation of the microgrid. A terminal voltage controller is being developed here. It can be applied in two operation mode of microgrid (grid connected mode and islanding operation mode). When stator resistance is neglected, the reactive power generated by the wind turbine is directly dependent on i_{dr} [16]. It can be shown the relation between reactive power generated and i_{dr} is as follows:

$$Q_{grid} = -\left(\frac{L_m}{L_s + L_m}\right)(i_{dr,magn} + i_{dr,gen})e_t - \frac{e_t^2}{\omega_s(L_s + L_m)} \qquad (9)$$

In (9), the direct component of the rotor current has been split into a part that magnetizes the generator, $i_{dr,magn}$, and a part that determines the net reactive power exchange with the grid, $i_{dr,gen}$. The direct component of the rotor current necessary to magnetize the generator itself has the following value:

$$i_{dr,magn} = -e_t/(\omega_s L_m) \qquad (10)$$

The value of $i_{dr,gen}$ determines whether net reactive power is generated or consumed. The terminal voltage will increase when more reactive power is delivered to the grid. The voltage controller should have the following features:

- In grid-connected mode operation of the microgrid, DFIG should be operated at unity power factor.
- Terminal voltage of DFIG should be adjusted appropriately when microgrid goes to islanding mode.

A voltage controller that satisfies the above features is proposed and depicted in Fig. 5.

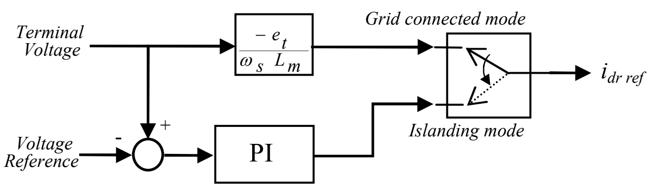

Fig. 5. Terminal voltage controller of the DFIG

B. Converter Based Distributed Generation

DG3 is represented by a three-phase equivalent of a VSC system. Each terminal of the converter is connected to the system through a lumped series *RL* branch. The control system of the converter is represented in the d-q frame and utilized the concept of instantaneous power to control real/reactive power exchange with the system by specifying d and q components of converter currents, [17]. The converter dc side is represented as a constant dc voltage source.

The power control strategy for converter based DG3 is shown in Fig. 6. The set-points P_{ref} and Q_{ref} can be chosen by the operator. In order to achieve full decoupling of the active and reactive power control loops, the converter is current controlled. In the reference frame synchronized with the grid voltages, it is $v_{gq}(t)=0$ and as a consequence:

$$P_g = v_{gd}\, i_{gd} \qquad (11)$$
$$Q_g = -\, v_{gd}\, i_{gq}$$

Thus, from the active and reactive power reference values and the measured grid voltages, it is possible to calculate the dq current reference values, as:

$$i_{gd,ref} = P_{g,ref}/v_{gd} \qquad (12)$$
$$i_{gq,ref} = -Q_{g,ref}/v_{gd}$$

For the current controller, two PI regulators have been chosen in order to meet the requirements of stability of the system and to make the steady state error be zero.

In the islanding mode operation, the real power generation of DG3 is controlled based on a frequency-droop characteristic to dynamically adjust the real power output of the unit, and a frequency restoration loop to contribute for adjusting the system frequency after transients, see Fig. 6a. The output from the real power generation controller is the reference signal for the d-axis current controller ($i_{gd,ref}$).

The reactive power control strategy of DG3 is based on a reactive power injection corresponding to constant power factor during the grid-connected mode and then is switched to a bus-voltage regulation for the islanding operation, Fig. 6b. The output from the reactive power generation controller is the reference signal for the q-axis current controller ($i_{gq,ref}$).

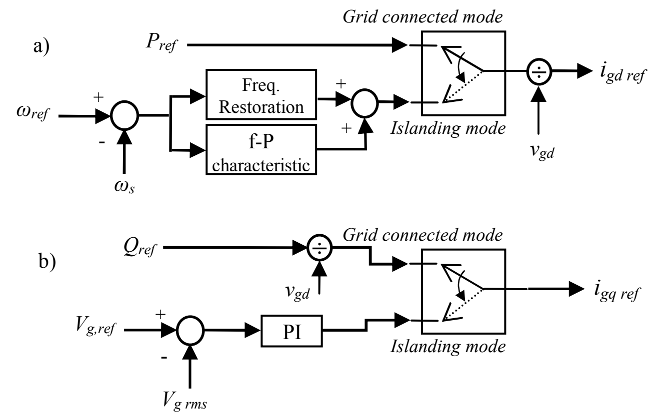

Fig. 6. Power Control for DG3 a) Real power controller b) Reactive power controller

V. Study Cases and Simulation Results

Some case studies have been demonstrated to show the ability of DG controllers and power sharing approach to continue the mirogrid operation during separation and in the islanded mode. Case studies are chosen to illustrate both the steady-state and dynamic response to the changes in the system operating point.

A. Planned Islanding

The objective of this study is to investigate transient behavior of the microgrid with DGs due to a planned islanding scenario. Prior to islanding, DG1 supplies 1.21MW/0.06MVAr (close to unity power factor) and DG3 supplies 1.4MW/0.4MVar and the difference between the power generated by DG2 and the load demand of 5.21MW/2.7MVAr is imported from the grid (0.94MW/2.23MVAr). DG2 is operated in unity power factor and a real wind pattern [19] with average wind speed of 10.4 (m/s), as shown in Fig. 7, was used as input to the wind turbine.

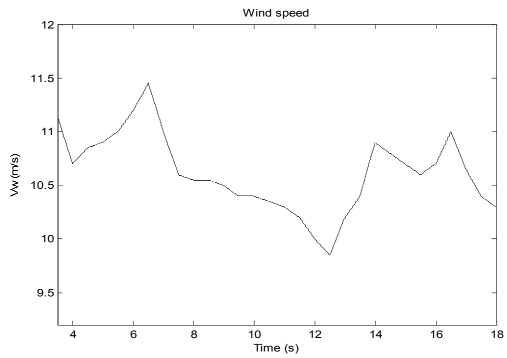

Fig. 7. Real measured wind speed

In this situation, about 82% of the total load active power in microgrid is supplied by DG units and the rest is imported from the main grid. While more than 80% of the total reactive power of the load in microgrid is imported from grid. All DG units use a 5% frequency droop value.

At t=4.0s the microgrid is disconnected from the main grid by initiating an intentional islanding command which opens CB2 in fig. 1. Simulation results for this event are shown in Fig. 8.

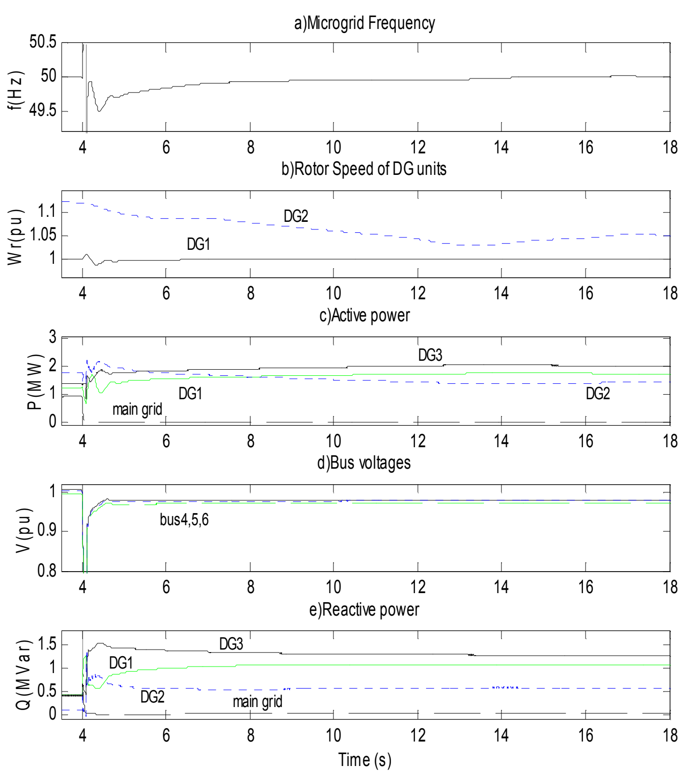

Fig. 8. Planned islanding event

Fig. 8 illustrates that the bus voltages recovered to its normal range in 75ms. It is due to contribution of all DG units in reactive power compensation and voltage regulation of the islanded network (microgrid system).

The above Figure show power sharing of the DG units after islanding based on proposed power control strategy of the DG units in microgrid. DG1 adjusts its real power output, through the action of its governor, according to its dynamic response time. Also, the restoration of microgrid frequency is accomplished by DG1 and DG3, through frequency restoration control loop (integral frequency control) that integrated in control loop.

Fig. 8 clearly shows the DG2 support for the primary frequency control of the islanded system (microgrid), through its proposed controller. During the islanding operation, the real power output of the DG1 and DG3 vary based on the changes in the output power of DG2 due to variation in the wind power corresponding to each response time.

B. Unplanned Islanding

In this case study, assumed that an unplanned islanding event of the microgrid system is happened due to a fault occurrence in the upstream section of the MV feeder. Prior to islanding, the microgrid system operates in grid-connected mode where the load demand is supplied by DG1, DG2, DG3 and the main grid. DG1 and DG3 supply 1.21MW/0.06MVAr and 1.4MW/0.4MVar respectively, and the difference between the power generated by DG2 and the load demand is imported from the grid (0.94MW/2.2MVAr).

Note that the DG2 is operated in unity power factor. This condition implies that about 83% of the total active power of the load in microgrid is supplied by DG units and the rest is imported from grid, while less than 19% of the total reactive power of the load in microgrid is supplied by DG units and the rest is imported from grid.

At t=4.0s a three-phase fault occurs on the Bus-2 in upstream section of the supply MV feeder. Considering the proposed system protection scheme, after about 150ms the fault is diagnosed and an opening command is issued for CB2 from DNO (Distribution Network Operator). After opening the CB2, synchronous reclosing operation of the upstream section can be available by CB1, and also islanding operation of the microgrid system will be allowed.

The islanding phenomena is detected 100ms after the CB2 opens, i.e. at t=4.25s. At this moment, operation mode of the DG units in microgrid system switches to the islanding mode. Fig. 9 illustrates the microgrid response to this event.

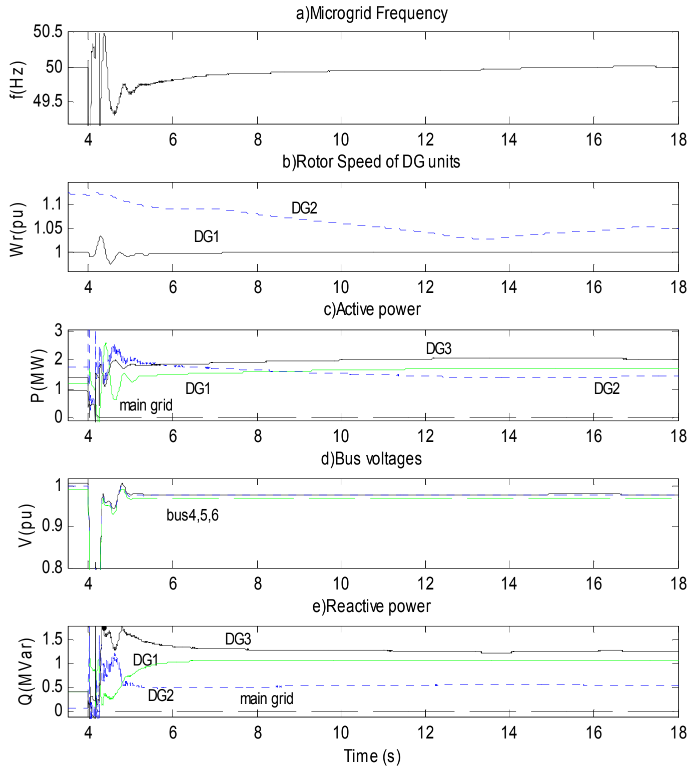

Fig. 9. Unplanned islanding event

From Fig. 9, it is observed that the primary frequency control responds quickly and helps to improve the system frequency response. Also it can be seen that the frequency deviation of the system is limited due to more contribution of the DFIG and converter based DG in frequency control action. This fact makes it possible for the DG1 (synchronous generator unit) to respond by injecting less active power into the microgrid, thereby improving the system frequency smoothly. During the fault, bus-voltages severely drop, Fig. 9. After the islanding detection, fast control actions of the DG units' terminal voltage controllers eventually return the voltages to their normal range.

VI. Conclusions

In this paper, two control modes were adopted for DGs in a microgrid system and examined both planned and unplanned islanding scenarios to evaluate the control approach. The microgrid is supplied by three distributed generation (DG) units, i.e. a synchronous machine, a variable-speed wind turbine with DFIG technology and a voltage-sourced converter based DG unit.

The studies indicate that controls of converter based DG and variable-speed wind turbine with DFIG and the proposed power sharing approach have significant impact on the microgrid dynamic behavior, e.g. reduce frequency changes and improve bus voltages regulation, when islanded from the grid and operates in autonomous mode.

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VIII. Biographies

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