Transients of a Micro-Grid System with Multiple Distributed Energy Resources

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***Abstract*— This paper investigates dynamic behavior and transients of a distribution subsystem with multiple distributed energy resources to pre-planned and/or accidental switching events. The switching events may lead to islanding of the subsystem and formation of an autonomous micro-grid. The micro-grid includes three distributed generation (DG) units. One unit is a conventional rotating machine interfaced through a synchronous generator. The second unit is an electronically-interfaced unit equipped with independent control on real and reactive power outputs. The third unit is a fixed-speed wind-turbine based power generation unit connected through an induction generator. The micro-grid operation and power management of the system are studied during the grid-connected mode, the autonomous operation and ride-through between the grid-connected and the autonomous modes. The studies are performed based on a digital computer simulation approach using the PSCAD/EMTDC software package. The studies show that (i) an appropriate control strategy for the electronically-interfaced DG unit can ensure stability of the micro-grid and improve voltage quality at designated buses, even during islanding transients, and (ii) the dynamic power management strategy can assist with minimizing the negative impact of power variations of the wind turbine and control corresponding frequency fluctuations of the micro-grid in the islanding operation.**

***Index Terms*— Micro-grid, distributed generation, fixed-speed wind turbine, islanding, electromagnetic transient, power management.**

I. Introduction

Distributed power generation system is emerging as a complementary infrastructure to the traditional central power plants. This infrastructure is constructed on the basis of decentralized generation of electricity close to consumption sites using Distributed Generation (DG) sources [1].The increase in DG penetration depth and the presence of multiple DG units in electrical proximity to one another have brought about the concept of the micro-grid [2],[3]. A micro-grid is a portion of a power system which includes one or more DG units capable of operating either in parallel with or independent from a large utility grid, while providing continuous power to multiple loads and end-users. The idea supporting the formation of the micro-grid is that a paradigm consisting of multiple generators and aggregated loads is far more reliable and economical than a single generator serving a single load.

An autonomous micro-grid is formed when an electrical region capable of autonomous operation is islanded from the remainder of the grid; e.g. a distribution substation along with its feeders that service both DG units and local loads. Formation of an autonomous micro-grid, due to an islanding process, can be caused by disturbances, such as a fault, or as a result of pre-planned switching events. After disconnection from the main grid, micro-grid experiences transients. The severity of the transients is highly dependent on (i) the pre-islanding operating conditions, (ii) the type of the event that initiates islanding, and (iii) 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.

From the power generation and control perspective, DG units are divided into two main categories of dispatchable and non-dispatchable sources. A dispatchable DG source is defined as a fast-response energy source which has adequate capacity to meet the real and reactive power commands, within specified limits. Such a source may interface through a power converter and include storage devices on its DC side, e.g. a variable-speed wind-turbine based power generation unit connected through a back to back converter to utility systems, or a fuel-cell powered converter [4], [5], [6]. A non-dispatchable source is either a slow-response source in terms of its response time to variations in real and reactive power references during transients or acts as an uncontrollable source which is highly dependent on the power provided by its prime source. An example for the former case is a gas-turbine generator with the response time in the order of 50 ms to a few seconds. The latter source can be named as a photovoltaic source or a fix-speed wind-turbine based power generation source that relies only on solar radiations or wind resources with unpredicted, time-varying nature, as the input energy [7].

The wind-turbine based DG unit is one of the fastest growing source of power generation in the world mainly due to (i) strong world wide available wind resources, (ii) environmentally-friendly power generation source specially suitable for remote areas, and (iii) rapid technological development [8]. The continuous trend of increase in the rate of DG connection and penetration depth of wind-turbine based DG units can provoke several technical concerns and adverse impact on the operation of distribution systems [9]. Control and protection, stability issues and power quality of the supply are the main concerns [10], [11]. However, the presence of an electronically-interfaced DG unit in a multiple-DG micro-grid environment can ensure stability of the micro-grid and maintain voltage quality of the system [12], [13].

The main objective of this paper is to investigate dynamic behavior and transients of a micro-grid with multiple DG units

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Presented at the International Conference on Power Systems Transients (IPST'05) in Montreal, Canada on June 19-23, 2005
Paper No. IPST05-080

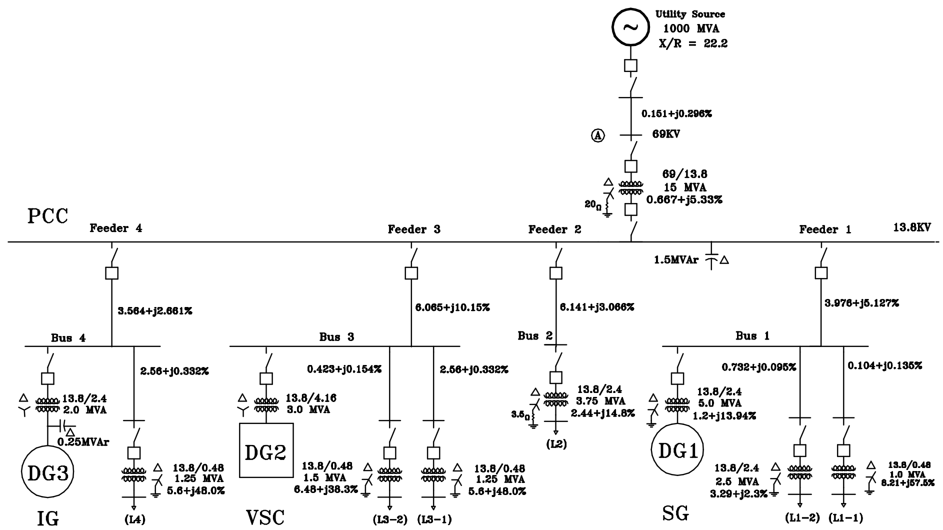

Fig. 1. Single-line diagram of the study system

TABLE I
WIND TURBINE AND INDUCTION GENERATOR PARAMETERS

Wind Turbine		Induction Generator	
Rotor Diameter	76 m	**Rated Voltage**	2400 volt
Hub Height	50 m	**Rated Power**	1255.3 kVA
Gear Box	1: 57.7	**Gen. Speed**	910 rpm
Startup Wind Speed	3.1 m/s	**Inertia Constant (H)**	0.176 s
Rated Wind Speed	11 m/s	**Startup speed**	85% of ω_s

to pre-planned and/or unplanned switching events which may lead to islanding of the micro-grid. Section II and III of the paper introduce the micro-grid study system and the specifics of its PSCAD/EMTDC model, respectively. Section IV briefly describes the dynamic power management strategy adopted for the micro-grid system to meet real and reactive power requirements of the system in all operating modes. Section V reports the conducted studies and discuses the obtained results. Conclusion are stated in Section VI.

II. STUDY SYSTEM

Fig. 1 shows a single-line diagram of a 13.8-kV distribution system connected to the utility main grid through a 69-kV radial line which forms a micro-grid. The utility system is represented as a 69-kV, 1000-MVA short-circuit capacity bus. The micro-grid includes three DG units. $DG1$ is a 1.8-MVA conventional diesel-generator or a gas-turbine generator equipped with excitation and governor control systems. $DG2$ is a 2.5-MVA electronically-interfaced unit using a voltage-sourced converter (VSC) as its interface medium. $DG3$ represents a fixed-speed wind-turbine set with rated capacity of 1.25-MVA which is interfaced through an induction generator (IG). A combination of linear and nonlinear loads are supplied through four radial feeders of the subsystem. The load on feeder 3 is assumed to be a sensitive industrial load. The system parameters are given in Fig. 1 and Table I.

III. SYSTEM MODEL

The PSCAD/EMTDC software package is used to develop a time-domain simulation model of the micro-grid study system of Fig. 1. The component models used for the simulation are as follows. The main grid is represented by an equivalent model of a 69-kV three-phase voltage source with the short-circuit capacity of 1000-MVA and X/R ratio of 22.2. The distribution lines and constant impedance loads of the system are modelled as lumped series R and L elements. $DG1$ is modelled as a single-mass synchronous machine. The machine electrical system is represented in the d-q-0 frame with two rotor windings on each axis. The excitation and governor systems of the machine are also included in the model. During startup procedure, the synchronous generator is treated as a source where the rotor speed is constant. After 0.3 s the machine model is activated and at 0.45 s the rotor speed is released to be adjusted by the governor. The synchronous machine parameters are given in [14].

$DG2$ 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-0 frame and utilizes the concept of instantaneous power to control real/reactive power exchange with the system by specifying d and q components of converter currents, [15]. The converter dc side is represented as a constant dc voltage source.

$DG3$ is modelled as a combination of a 2.4-kV squirrel-cage induction generator with a two-mass representation of the mechanical part connected to the utility grid through a step-up transformer with the leakage inductance of 8%. The induction machine parameters are given in [14].

A. Wind Turbine Model

The electrical part of $DG3$ is represented by a squirrel-cage induction generator connected to the utility grid. The mechanical part of the $DG3$, including wind turbine, gearbox, generator rotor and low-speed/high-speed shaft, is represented by an equivalent of a two-mass dynamic system. The moment of inertia of the wind turbine and low-speed shaft masses, also stiffness of the low-speed shaft are transferred to the generator (high-speed) side [9].

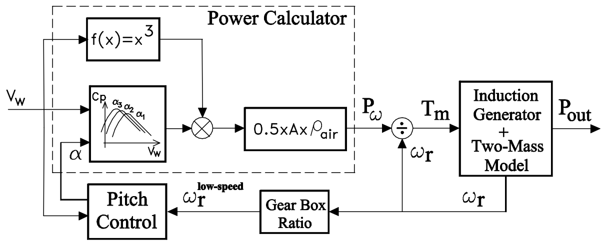

Fig. 2. Wind speed simulator

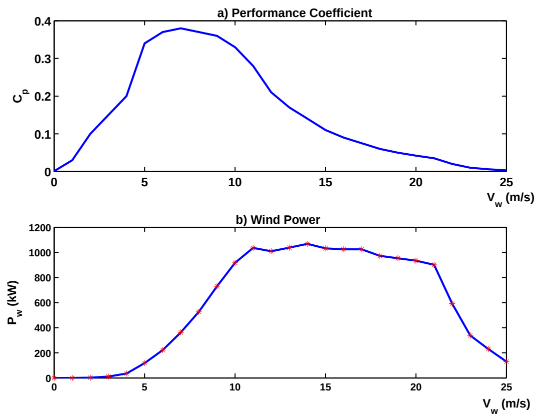

Fig. 3. Wind power characteristics a) Performance curves ($C_p - V_w$) b) Turbine power curve ($P_w - V_w$)

The variable nature of the wind speed and its reflection on the input mechanical torque of the induction generator are also modelled by a wind-speed simulator. The wind-speed simulator is shown in Fig. 2 which is composed of a power calculator block and a pitch control block. The power calculator block uses a set of performance curves for the turbine, "$c_p - \lambda_w$" characteristic where c_p is the performance coefficient and λ_w is the tip speed ratio of the turbine, to determine the power extracted from the wind. The output power, P_w, is a nonlinear function of the wind speed (V_w) and the pitch angle (α) determined by the pitch control block. The pitch angle is adjusted based on variations in the wind speed to control the revolution of the low-speed shaft in an acceptable range. Hence, the power generated by the wind turbine is approximately limited to the rated value for the wind speed above the rated speed of the turbine. The resulted "$c_p - V_w$" curve of the proposed wind turbine, assuming 1-2% changes in the speed of the induction generator, and the related power curve for a wide range of wind variations are shown in Fig. 3. The input torque (T_m) of the induction generator is calculated from the estimated wind power divided by the revolution of the high-speed shaft, Fig. 2.

IV. Power Management of the Micro-Grid

A multiple DG micro-grid is a distribution system which includes more than two DG units. The DGs supply the local loads, with the capability of the grid-connected and the autonomous (islanding) operation. Regardless of the micro-grid mode of operation, real and reactive power managements of the DG units have direct impact on the system operational behavior in terms of voltage/angle stability, power quality, and availability of the service to consumers. In a micro-grid system none of the DG units acts as a spinning reserve or as a back-up generation. This is in contrast to interconnected power systems where large plants are assigned as spinning reserves.

In the proposed micro-grid system, Fig. 1, $DG1$ is a conventional source with relatively slower response in real and reactive power control with respect to the electronically-interfaced DG unit ($DG2$). The wind turbine unit ($DG3$) is also restricted to the limitation applied by the wind source. Thus, $DG1$ and $DG3$ are both non-dispatchable sources which cannot quickly respond to power management of the system during transients and large disturbances. Only $DG2$ is assumed as a dispatchable source with adequate capacity to provide independent control on its real/reactive power generation. During the steady-state operation, the overall power management strategy of the system is designed based on an optimum power balance among all DG units.

In the grid-connected mode, DG units are expected to supply their local load demand to minimize the power flow throughout the system. This is either due to the economics of generation or transmission of power in the deregulated environment. Considering the similarity of the micro-grid to conventional utility systems, $DG1$ and $DG2$ generate constant real power outputs and regulate their terminal voltages (PV-Buses), and $DG3$ delivers maximum power extracted from the wind (variable PQ-source with negative Q). 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 $DG3$, and also stabilizes the frequency [12].

In the autonomous mode of operation, the available power of the DG units must meet the total load demand of the micro-grid; otherwise system must undergo load shedding to match generation and demand. In addition, 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. Generally, $DG1$ contributes to supplying the load demand based on the steady-state power balance of the micro-grid and responds to small-signal disturbances due to its slow response in real/reactive power control. $DG2$ is designed to (i) mainly respond to transient power variations and sudden changes in the reactive power of the micro-grid, and (ii) supply the difference between the load demand and the total power generated by $DG1$ and $DG3$ to meet the instantaneous load sharing of the system. Although the steady-state power management of the system can be achieved through communication among DG units to specify their operating points, power management strategies established on the basis of locally measured parameters are needed to improve system response time, reliability and to minimize cost.

A. *Power Management of* $DG1$

$DG1$ is equipped with excitation and governor systems. Variations in the terminal voltage of $DG1$, from the pre-set reference value, is compensated by the excitation system through controlling field voltage which is applied to the

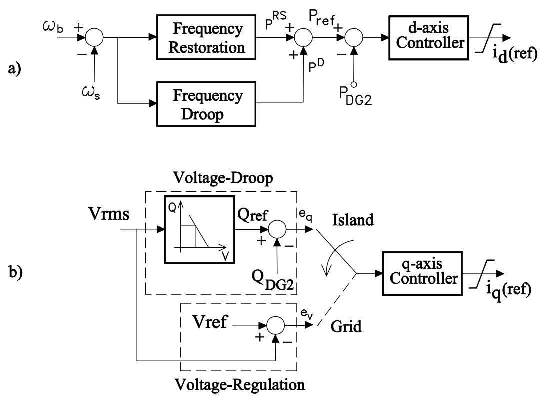

Fig. 4. Power management block for $DG2$ a) Real power controller b) Reactive power controller

generator field winding. The governor system is implemented based on a frequency-power relation to regulate deviations in the generator speed due to transient disturbances. Through the governor, $DG1$ can share a common active load with other DG units in a micro-grid.

B. Power Management of $DG2$

The power management block for electronically-interfaced $DG2$ is shown in Fig. 4. The real power generation of $DG2$ is controlled based on a frequency-droop characteristic [16] to dynamically adjust the real power output of the unit, and a frequency restoration algorithm [17] to adjust the system frequency after transients. Input to the block is the locally measured frequency of the micro-grid (ω_s) which is compared with the base system frequency (ω_b), Fig. 4a. The output from the real power generation controller is the reference signal for the d-axis current controller ($i_d(ref)$) corresponding to the difference between the real power output of $DG2$ (P_{DG2}) and the calculated reference power (P_{ref}). The reactive power control strategy of $DG2$ is based on a bus-voltage regulation strategy during the grid-connected mode and then is switched to a voltage-droop characteristic for the islanding operation, Fig. 4b. The reactive power strategy for the islanding mode opposes the deviations in the DG2-bus voltage using a pre-set V-Q curve. The output from the reactive power generation controller is the reference signal for the q-axis current controller ($i_q(ref)$). The d- and q-axis current controllers are used to control the instantaneous values of the converter ac-side current components i_d^{DG2} and i_q^{DG2} respectively [15].

V. Study Cases

Several case studies are conducted to examine the 13.8-kV system operation in the grid-connected mode, during separation and in the islanded mode. Case studies are chosen to illustrate both the steady-state response to the changes in the system operating point, and the dynamic response when the system undergoes a transient.

A. Wind Turbine Startup

The objective of this case study is to (i) demonstrate transients involve with startup of a fixed-speed wind turbine, and (ii) investigate impact of wind-turbine based DG unit ($DG3$) on voltage quality and stability of the system. Figs. 5 and 6 show the startup transients. Initially, the micro-grid operates in the grid-connected mode where the load demand is supplied by $DG1$, $DG2$ and the main grid. The total load demand of the micro-grid is 3.35-MW and 1.66-MVAr of which 1.22-MW/0.06-MVAr and 1.68-MW/0.49-MVAr are supplied by $DG1$ and $DG2$ respectively, and the rest by the main grid. The wind turbine startup method is based on no-load acceleration of the turbine-generator system under a rising wind-speed regime which increases the induction generator speed. $DG3$ is connected to the micro-grid at t=2 s when the speed of the induction generator reaches to 85% of the synchronous speed, Fig. 5a. $DG3$ operates in the motoring region for a short period after startup until at t=2.3 s the generator speed passes the synchronous speed and reverses the direction of the real power flow. Fig. 6a shows voltage deviations for the sensitive bus of the system (Bus 3, Fig. 1) and $DG3$-bus (Bus 4). Figs. 5b-d and 6b-d illustrate variations in the real and reactive power of the DG units respectively. In the grid-connected mode, the main grid dominantly responds to power oscillations caused by connection of the wind turbine, Fig. 5d. However, reactive power variations are accommodated with both $DG2$ and the main grid, Figs. 6c and 6d. Thus, the voltage at the sensitive bus of the system (Bus 3) and $DG3$-bus (Bus 4) are maintained within $\pm 1\%$ and $\pm 3\%$ respectively.

Figs. 5 and 6 illustrate that cooperation of $DG2$ with the utility main grid in reactive power compensation of the micro-grid damps out the transients in less than one second and maintains stability of the system. After completion of the startup period the real power generated by $DG3$ is in the range of 0.3-MW to 0.5-MW dependent on the wind-speed fluctuations that changes the power delivered by the utility grid.

B. Pre-Planned Islanding

The objective of this study is to investigate transient behavior of the multiple DG micro-grid due to a pre-planned islanding scenario. Prior to islanding, $DG1$ and $DG2$ supply 1.22-MW and 1.68-MW respectively while the difference between the power generated by $DG3$ and the load demand of 3.35-MW is imported from the grid. At t=1 s the micro-grid is disconnected from the grid by initiating a pre-planned islanding command which opens circuit breakers (CBs) on 69-kV line. Fig. 7 shows the system transients due to planned islanding. Fig. 7a illustrates that the bus voltages are increased mainly due to change in the reactive power control strategy for $DG2$ from the voltage regulation to the voltage-droop characteristic. However, the voltage variations are less than 2%. Figs. 7b and 7c also show power sharing of the DG units after islanding, based on adopted power management strategy for the micro-grid. Hence, the frequency deviations in the islanded system is unnoticeable, Fig. 7d. During the islanding operation, the real power output of $DG1$ varies based on the changes in the output power of $DG3$ due to variations in the wind power that change the speed of synchronous generator, Figs. 7b and 7d.

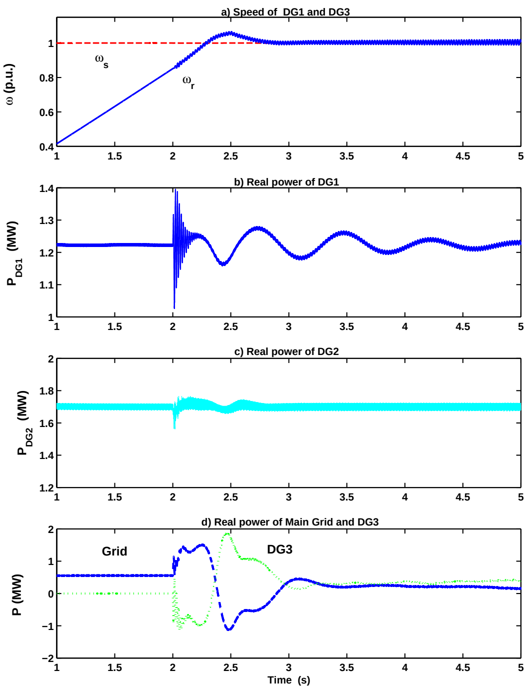

Fig. 5. Case(A)- Real power variations during wind turbine startup at t=2 s

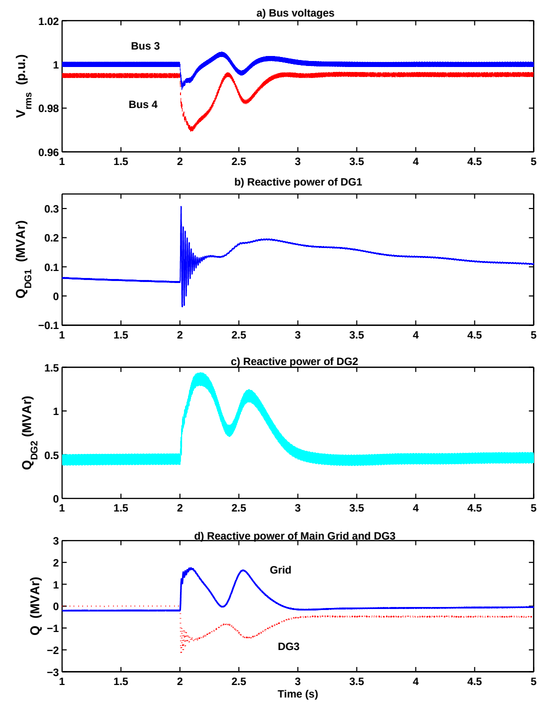

Fig. 6. Case(A)- Reactive power variations during wind turbine startup

C. Three-Phase Line-to-Ground (L-L-L-G) Fault

An unplanned islanding of the micro-grid system due to a fault and its subsequent switching activities in the system is investigated. A general timing sequence for a fault scenario, which complies with protection strategy of distribution systems, is depicted in Fig. 8. It is assumed that a permanent L-L-L-G fault occurs on the 69-kV line at t=0.5 s. The fault is cleared by triple-pole operation of CBs at both ends of the line, 5 cycles after the fault inception, e.g. at t=0.583 s, and a micro-grid is formed due to the accidental islanding, Fig. 8. The islanding phenomena is detected 5 cycles after the CBs open, e.g. at t=0.666s. This changes the power control strategy of the DG units to the islanding mode whereby the reactive power control of $DG2$ is set to voltage-droop characteristic. The CBs of the 69-kV line employ triple-pole auto-reclosure and attempt to re-connect the micro-grid to the main grid 30 cycles after the fault clearing, i.e. t=1.083 s, Fig. 8. Since the fault is permanent, the reclosure is unsuccessful and subjects the micro grid to the second fault which is cleared after 5 cycles, i.e. at t=1.166 s. Here only one reclosure attempt is assumed, however in some cases up to three subsequent unsuccessful reclosure attempts are permitted. The CBs are kept open after final unsuccessful reclosure until the utility system is restored and then manual reconnection permitted.

Fig. 9 shows the system transients during the unplanned islanding scenario. The pre-fault operating conditions of the system are the same as those of the pre-planned islanding case. During the fault, bus-voltages severely drop, Fig. 9a, and the reactive power control of $DG2$ reaches its limit, Fig. 9c. It should be noted that in terms of contribution to the fault current, $DG3$ has no contribution while $DG2$, because of employing a power-electronic interface medium, has a limited contribution maximum 50% above its range, Fig. 9c. However, $DG1$ can basically inject reactive power up to ten times of its rating. Upon clearing the fault, control action of the DG units eventually return the voltages to their normal range. Transiently, due to the fast response of $DG2$ in reactive power support of the micro-grid, the bus-voltage deviations are kept less than 2%. Figs. 9b and 9c also show power sharing among DG units after the fault.

The dynamic real and reactive power management strategies of the system and fast-control action of $DG2$ maintain stability of the micro-grid and regulate bus-voltages even after a severe L-L-L-G fault and its subsequent reclosure attempt.

VI. Conclusion

This paper investigates transients of a 13.8-kV multiple DG micro-grid system and performance of the adopted power management strategies in three operating modes of (i) the grid-connected, (ii) the autonomous operation, and (iii) the ride-through mode. The micro-grid is supplied by three distributed generation (DG) units, i.e. a synchronous machine, a wind turbine and an electronically interfaced DG unit. The latter unit includes fast, independent real and reactive power controls. The simulation studies show that the latter unit: (i) can maintain angle stability of the micro-grid even after most severe islanding transients, primarily through its fast real power control, and (ii) can enhance voltage quality at specific buses, mainly through its fast reactive power control. The dynamic power management strategy of the system also ensures appropriate power sharing among available DG units and responds to power fluctuation of wind-turbine based power generation unit.

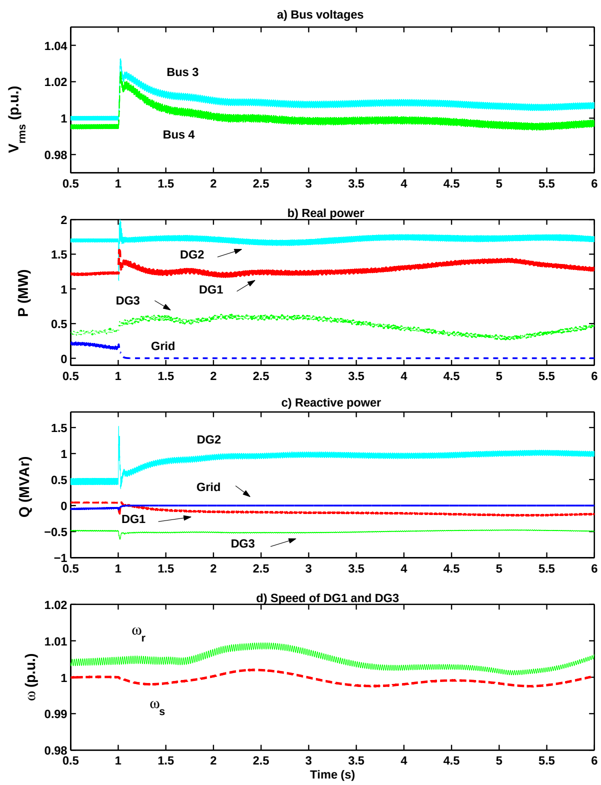

Fig. 7. Case(B)- Pre-planned islanding of the micro-grid at t=0.5 s

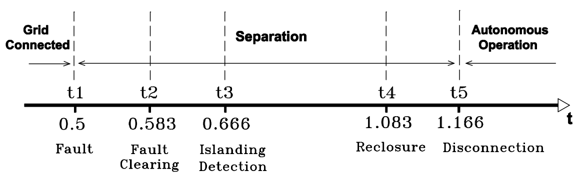

Fig. 8. Fault timing sequence for the unplanned islanding scenario

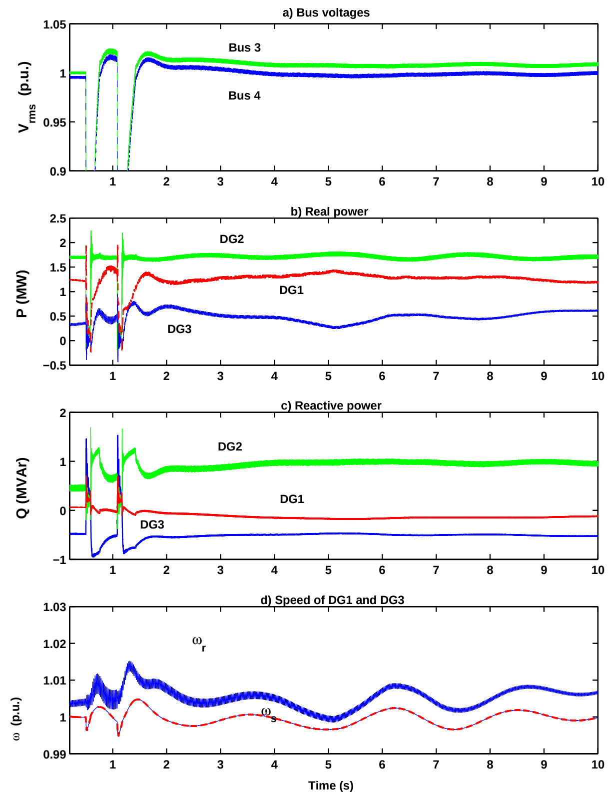

Fig. 9. Case(C)- Three-phase to ground fault at t=0.5 s and islanding of the micro-grid

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