Contribution of an Energy Storage System for Stabilizing a Microgrid during Islanded Operation

Jong-Yul Kim*, Seul-Ki Kim* and June-Ho Park*

Abstract – In this paper, the cooperative control scheme of micro sources and an ESS (Energy Storage System) during islanded operation is presented and evaluated by a simulation study. The ESS handles the frequency and voltage as a primary control. Then, the secondary regulation control returns the current power output of ESS into a pre-planned value. The simulation's results show that the proposed cooperative control scheme can regulate the frequency and voltage and reduce the consumption of the stored energy of ESS.

Keywords: Microgrid, Islanded operation, Cooperative control, Energy storage system

1. Introduction

Though the penetration of distributed generations to the electric power system is limited due to a lack of economical benefits, it will be accelerated for various reasons. The increase in the penetration depth of DGs (Distributed Generators) and the presence of multiple DGs in electrical proximity to one another have brought about the concept of the microgrid [1-3], which is a cluster of interconnected DGs, loads and intermediate energy storage systems. As usual, the microgrid operates in grid-connect mode, but, when a fault occurs in the upstream grid, it should disconnect and shift into islanded operation mode. In grid-connect mode, the frequency of the microgrid is maintained within a tight range by the main grid. In an islanded operation, however, which has relatively few microsources, the local frequency control of the microgrid is not straightforward. The frequency of the power system has a strong coupling with the active power in the network. If demand increases, the frequency will fall unless there is a matching increase in generation and vice versa. The rate of change of frequency depends on the inertia of the systems (i.e., the larger the inertia, the smaller the rate of change). During a disturbance, the frequency of the microgrid may change rapidly due to the low inertia present in the microgrid. Therefore, local frequency control is one of the main issues in islanded operation [4]. To overcome this challenge, the cooperative control of the microsources and the energy storage system is very important in maintaining the frequency of the microgrid during islanded operation. In this paper, the cooperative control strategy of micro sources and the energy storage system is presented and evaluated by a computer simulation study.

2. Microgrid Configuration

A microgrid is a cluster of interconnected micro sources that are referred to as distributed generators, loads and intermediate energy storage systems that co-operate with each other to be collectively treated by the grid as a controlled load or generator [5]. Fig. 1 shows a typical configuration of a microgrid. It comprises, in addition to loads, RES (Renewable Energy Sources) as well as a diesel engine, gas engine, micro turbine and an energy storage system as support systems to fulfill the stable operation of a facility. This microgrid is connected to the grid at the PCC (Point of Common Coupling), and operates in parallel with a utility grid under normal situations. The microgrid disconnects from the utility grid, however, and transfers into islanded operation mode when a fault occurs in the upstream grid. The conventional micro sources existing in the distribution network mainly use rotating machines. They are directly connected to the grid to supply electric power, but new technologies, such as the micro turbine, PV, Wind, and Fuel Cells, that are proposed for use in the microgrid are not suitable for supplying energy directly to the grid, and have to be interfaced with the grid through an inverter stage. In terms of controllability of power output, there are two types of micro sources in the network: controllable and non-controllable sources. Controllable sources mean that the power output of each micro source can be controlled by the command signal arbitrarily. On the contrary, non-controllable sources, such as RES, do not have this manageable nature since their output power depends on the availability of the primary source. The loads are either critical or non-critical. Critical loads require a high reliability and quality of power without any short-term interruptions in both normal and emergency situations. Non-critical loads may be shed during emergency situations. The intermediate ESS (Energy Storage System) is an inverter-interfaced battery bank (BESS), SMES, super-capacitor or flywheel. The storage device in the microgrid is analogous to the spinning reserve of large generators in the conventional grid. They ensure the balance between energy gen-

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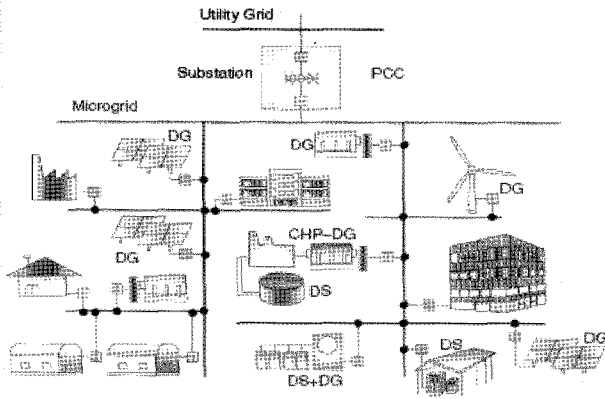eration and consumption especially during islanded operation [6].

Fig. 1. Typical configuration of a microgrid

The microgrid has a hierarchical control structure as shown in Fig. 2. It has two control layers: MMS (Microgrid Management System) and LC (Local Controller). The MMS is a centralized controller that deals with management functions such as disconnection and re-synchronization of the microgrid and the load shedding process. In addition to this function, the MMS is responsible for the supervisory control of micro sources and the energy storage system. Using collected local information, the MMS generates a power output set point and provides it to the LCs. An LC is a local controller located at each micro source and controls the power output according to the power output set from the MMS [7].
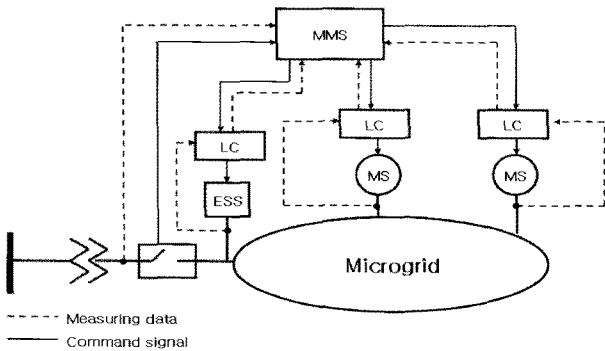

Fig. 2. The hierarchical control structure of a microgrid

3. Control of an Inverter Based Micro Source System

3.1 Control Characteristics of an Inverter Based Micro Source

For the VSC (Voltage Source Converter) shown in Fig. 3, assume that the fundamental phasor of the voltage on the AC bus is Vac and that the fundamental phasor of the voltage on the converter side of the VSC is Vvsc. The angle between Vac and Vvsc is δ. The reactance of the transformer is X. Ignoring the resistance of the transformer, the magnitude of the real and reactive power flowing over the VSC are:

$$P = \frac{|V_{vsc}||V_{ac}|}{X} \times \sin \delta \qquad (1)$$

$$Q = \frac{|V_{vsc}| \cos \delta - |V_{ac}|}{X} \times |V_{ac}| \qquad (2)$$

From Eq. (1), the magnitude of real power flowing over the VSC is primarily determined by δ. The direction is determined by the relative position between Vac and Vvsc. When Vvsc lags behind Vac, the VSC functions as a rectifier and absorbs real power from the AC system. When Vvsc takes the leading position, the VSC works as an inverter and dispatches real power to the AC system. Thus, by adjusting δ, control over the amount of real power delivered via the VSC can be achieved.
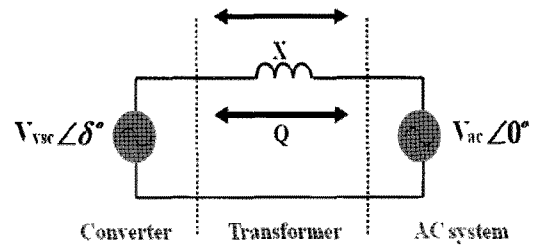

Fig. 3. Equivalent circuit between AC system and converter

Normally, the per unit value of X is in the range of 0.1pu to 0.3pu, and δ is relatively small. Hence, from Eq. (2), it is desirable to control Q by Vvsc. The direction is decided by the relative magnitude between Vvsc and Vac as shown in Fig. 4 [8].
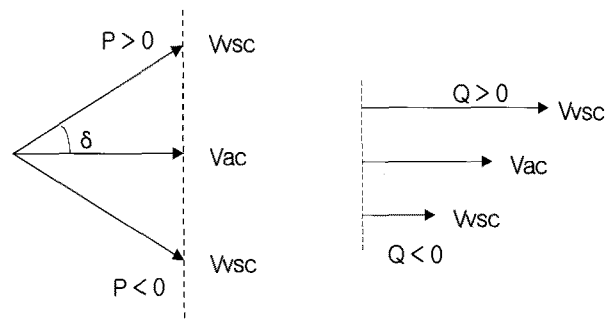

Fig. 4. Active and reactive power flow in according to magnitude and phase of converter output voltage

3.2 Control of an Inverter Based Micro Source

Inverter-based micro sources are controlled in either PQ control mode or VSI (Voltage Source Inverter) control mode. In the PQ control mode, the micro sources act as a current source and regulate the active and the reactive power injected into the grid. The control scheme of the micro source is presented in Fig. 5. Once the power reference (Pref and Qref) is determined, dq transformation control is applied to enable the real and reactive components

of AC output power to be mutually independently controlled. Through the PI control in the current reference generation block, errors between power reference (Pref and Qref) and measured power output (P and Q) are processed into the q- and d-axis reference current Id_ref and Iq_ref, respectively. In a current controller, d- and q-axis reference voltage Vd_ref and Vq_ref are generated using errors between dq current reference (Id_ref and Iq_ref) and measured dq current (Id and Iq). The generated dq reference voltage is transformed into the a-, b-, and c- axis reference voltage Va_ref, Vb_ref, and Vc_ref by the dq to abc transformation block [9]. The phase-lock-loop (PLL) block generates a signal synchronized in phase to the converter input voltage Vabc to provide the reference phase angle for the rotational inverse d-q transformation. When the desired voltages on the a-b-c frame are set, a pulse width modulation (PWM) technique is applied because of its simplicity and excellent performance. In the PWM block, the desired voltage waves Vabc_ref and the triangular carrier signal are compared at cross-over points and create turn-on and turn-off switching signals for the six IGBTs. In the VSI control mode, the micro sources emulate the behavior of a synchronous machine, thus regulating the voltage and frequency of the system. The VSI acts as a voltage source, with the magnitude and frequency of the output voltage. The voltage and frequency references are the pre established nominal values of the microgrid [7]. In grid-connect operations, all of the micro sources and energy storage systems are in PQ control mode, where the power output set point is provided by the MMS.
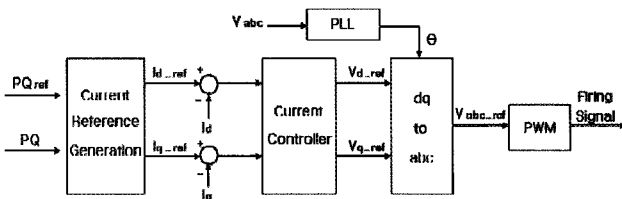

Fig. 5. PQ inverter control structure

4. Cooperative Control Strategy for Islanded Operation

4.1 ESS Control Scheme

In Islanded operation can take place by unplanned faults at an upstream grid. When the fault occurs, MMS should detect the event as soon as possible and disconnect the microgrid from the upstream grid. In grid-connect mode, the frequency of the microgrid is maintained within a tight range by the main grid, but, in islanded mode, which has relatively few micro sources, the local frequency control of the microgrid is not straightforward. During islanding, the power balance between supply and demand does not match at the moment. As a result, the frequency of the microgrid will fluctuate, and the system can experience a blackout unless there is an adequate power balance

matching process. The rate of change of frequency depends on the inertia of the systems. During a disturbance, the frequency of the microgrid may change rapidly due to the low inertia present in the microgrid. The controller of the energy storage system inverter responds in milliseconds. Otherwise, because of the nature of the control of some micro sources such as a diesel generator, gas engine, and fuel cell, these micro sources have a relatively slow response time. Obviously, the ESS should play an important role in maintaining the frequency and voltage of the microgrid during islanded operation.
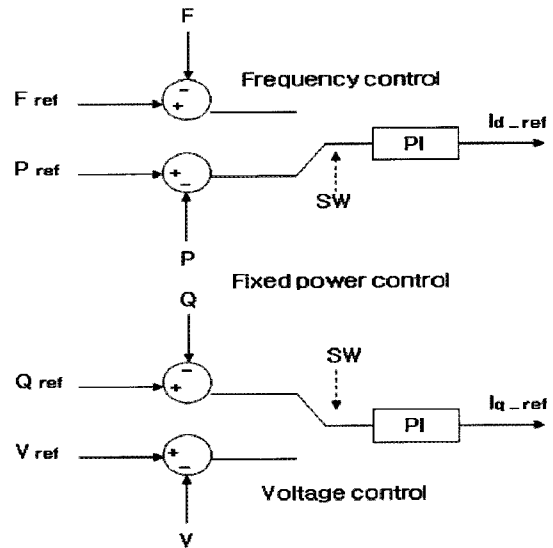

Fig. 6. Control scheme of the ESS

In grid-connect operations, all of the micro sources and ESS adopt the fixed power control mode, which means that the micro sources and ESS generate constant active and reactive power. Usually, power output of the ESS may be fixed at zero when the microgrid is operated in grid connect mode, but, since the fixed power control of ESS supplies constant power, it cannot provide proper frequency and voltage controlling ability in islanded operation. Therefore, the control scheme of the ESS has to be switched from fixed power control to frequency/voltage control during islanded operation. Otherwise, other controllable micro sources are still fixed power control. By proper control action of the ESS, the frequency and voltage of the microgrid can be brought back to normal values after a disturbance. Fig. 6 shows the detailed control block of an ESS, as previously mentioned.

4.2 Secondary Regulation Control

Though the frequency and voltage of a microgrid in islanded operation can be effectively controlled by applying an F/V control scheme in the ESS, the control capability of the ESS may be limited by its available energy storage capacity. Therefore, the power output of the ESS should be brought back to zero as soon as possible. The secondary regulation control is in charge of returning the

current power output of the ESS to the pre-planned value, which is usually set at zero. This secondary regulation control is performed by using the cooperative control scheme of micro sources and ESS in MMS. When operating in islanded mode, the ESS regulates the frequency and voltage in local control actions, and then the MMS calculates the proper power outputs of each micro source to make the power output of the ESS equal zero, as shown in Fig. 7. The calculation procedure of MMS is as follows:

a) Calculate the power deviation of ESS:

$$\Delta P_{ESS} = P_{ESS}^{mea} - P_{ESS}^{sch} \qquad (3)$$

where ΔP_{ESS} is the power deviation, P_{ESS}^{mea} is the measured active power output, and P_{ESS}^{sch} is the pre-planned power output.

b) Calculate the power output of each micro source:

$$\Delta P_{ref\,,i} = pf_{\_}P_i \times \Delta P_{ESS} \qquad (4)$$

where $\Delta P_{ref,i}$ is the change of power output at i*th* micro source, and $pf_{\_}P_i$ is the participant factor of i*th* microsource.

Therefore, the final active power output set point of the micro source is determined by the summation of current generation power (Pbase,Qbase) and change of power output (ΔP_{ref}, ΔQ_{ref}) as shown in Fig. 8. The change of power output value and the final set point are calculated every second by MMS. The final reactive power output set point produced can also be calculated in the same way as active power.
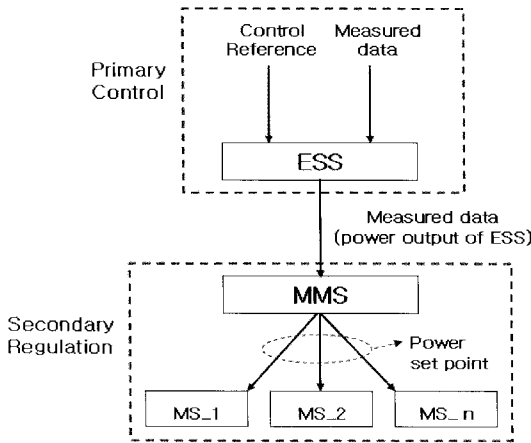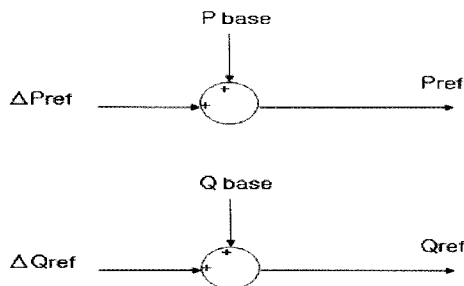
5. Simulation Study

A simulation platform under the PSCAD/EMTDC environment was developed to evaluate the dynamic behavior of the microgrid. Fig. 9 shows the studied microgrid single line diagram. The PV, wind and diesel generation system has been connected to 380V low voltage lines, which connects to a 22.9kV distribution feeder through a pole transformer. The BESS is connected to a 380V busbar, which is near the PCC. The 380V line is connected to micro sources and two loads through the overhead line. The short circuit capacity of the 22.9kV bus is 68.4MVA. The X/R ratio of the bus impedance is 52. The test system is built up under the PSCAD/EMTDC environment. In the PSCAD/EMTDC model, RES sources and BESS are modeled as an equivalent current source model for analysis convenience. A typical synchronous generator model in the PSCAD/EMTDC library is used to represent the diesel generator. The upstream grid is modeled by an equivalent voltage source with thevenin impedance, and the load and line impedance are represented by constant impedance models, R and X.
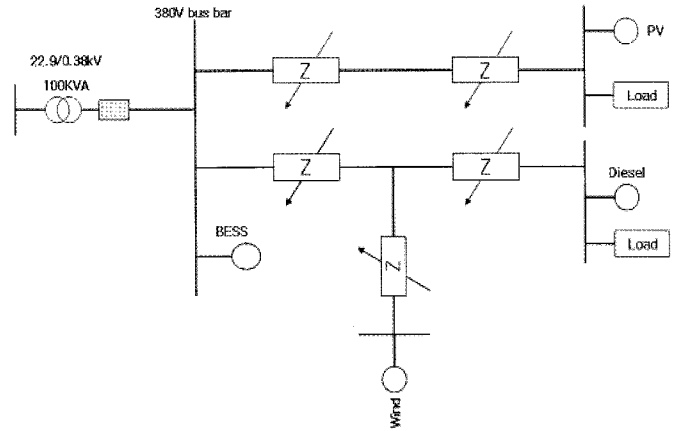

Fig. 9. Configuration of the test microgrid system

The detailed aspects of the test system are as follows:

a) Test System Configuration
 - No. of Sources: 4 (PV, Wind, Diesel generator, BESS)
 - No. of Loads: 2
 - No. of lines: 2 (25kW/line)
b) Generation Capacity of Microsources
 - PV 11kVA and Wind 11kVA
 - Diesel generator 25kVA
c) Capacity of Energy Storage System
 - BESS (Battery Energy Storage System) 10kWh
 - PCS of BESS system 25kVA
d) Load
 - Peak Load 40kW+j19kVar
 - Constant impedance model (R/X)
e) Transformer
 - 3phase 22.9/0.38kV 100kVA
 - Leakage impedance %Z = 6%
f) Line impedance
 - R= 0.1878ohm/km, X=0.0968ohm/km

Fig. 7. Cooperative control structure

Fig. 8. Micro source power output set point calculation

6. Study Results

Case A) Islanded Operation without Switching of ESS Control Mode

Fig. 10 shows the dynamic performance of the microgrid when the BESS uses fixed power control during islanded operation. The control schemes of the micro sources and the BESS have fixed power control in the grid-connect mode. The scenario is characterized by a total load of 20kW+j9.6kVar and a local generation of PV 2kW, Wind 3kW, and diesel generator 5kW+j5kVar. The initial power set point of BESS in the grid-connect mode is set at zero.

A fault in the upstream grid occurs at t=1s. After islanding, the control scheme of the BESS is still a fixed power control. As shown in the simulation results, the BESS does not contribute to the frequency and voltage of the microgrid, resulting in the initiation of unstable operation of the system.

Case B) Islanded Operation with V/F Control of the ESS and without Secondary Regulation Control

In this case, the control mode of BESS switches from fixed power control to V/F control during islanded operation. The scenario is characterized by a total load of 20kW+j9.6kVar and the generation of PV 5kW+j1kVar, Wind 5kW+j1kVar, and diesel generator 5kW+j3kVar. The two consecutive events are applied. A fault in the upstream grid occurs at t=1s, and total load increases from 20k+j9.6kVar to 25kW+j12kVar at t=16s. After islanding, the control scheme of BESS shifts to V/F control. Otherwise, during islanded operation, the power output of micro sources is maintained at a constant value (PV 5kW+j1kVar, Wind 5kW+j1kVar, and diesel generator 5kW+j3kVar). The power output of BESS, however, increases from zero to 6.2kW+j5.3kVar very quickly. After a short transient period, the frequency and voltage of the microgrid can maintain pre-defined normal values (60Hz and 1.0pu) due to the fast response of the BESS. In the event of load change followed by islanding, the frequency and the voltage can be brought back to normal values as shown in Fig. 11. The power output of BESS in the steady state maintains a constant value after the event. The control capability of the BESS may be limited by its available energy storage capacity. Therefore, the power output of BESS should be brought back to zero after the disturbance, requiring the
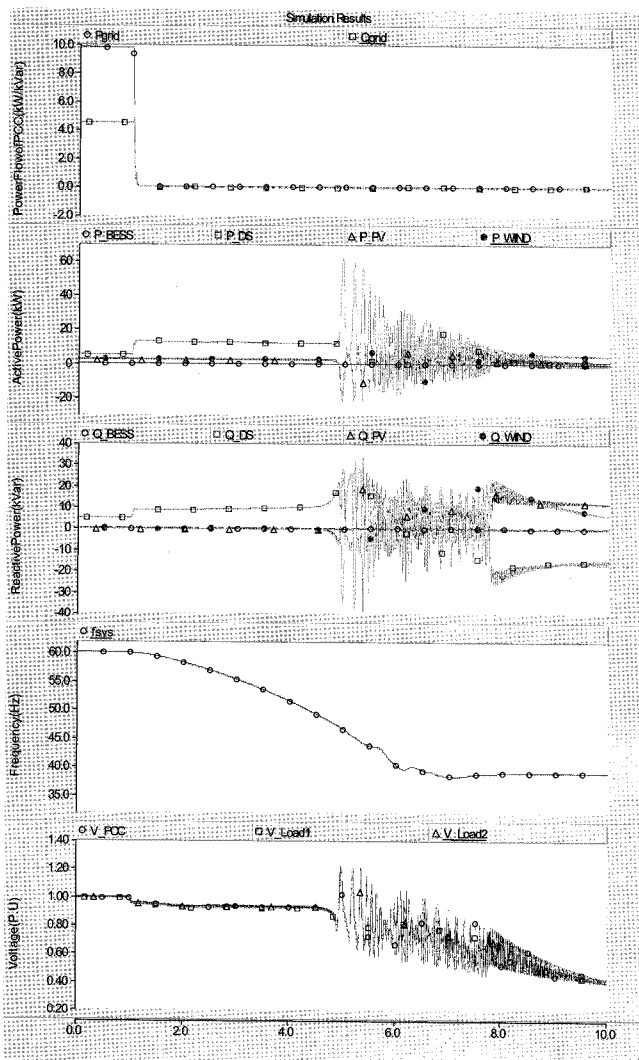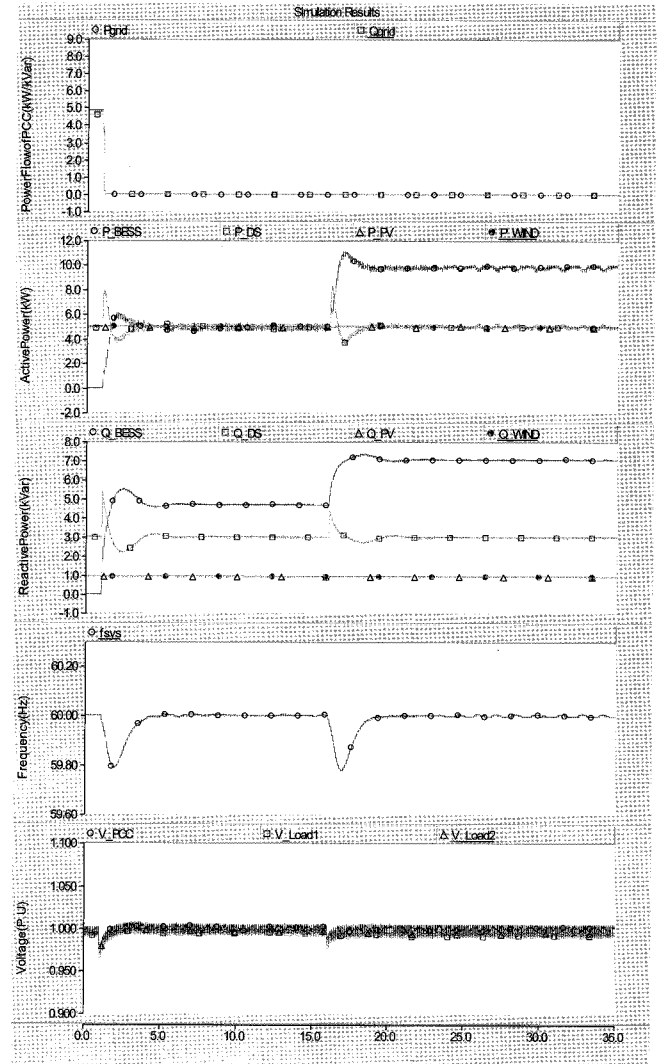

Fig. 10. Simulation results of case A

Fig. 11. Simulation results of case B

secondary regulation control to make the power output of BESS equal zero.

Case C) Islanded Operation with V/F Control of ESS and Secondary Regulation Control

The dynamic behavior of the microgrid with V/F control of BESS and the secondary regulation during islanded operation is evaluated. The control schemes of the micro sources and the BESS are also fixed power control in the grid-connect mode. The operating scenario is the same as the previous simulation case B. The islanding, due to a fault in the upstream grid, occurs at t=1s, and total load increases at t=16s. After islanding, the control scheme of BESS shifts to V/F control. As a result of the fast control acting of BESS, the frequency and voltage of the microgrid maintain normal values during two consequent disturbances as shown in the previous simulation Case A. The power output of the BESS changes from zero to a certain value to control the frequency and the voltage as soon as the disturbance occurs, and it is returned to zero due to secondary regulation control, which is performed in the MMS. During islanded operation, the power output of mi-

cro sources are also changed from an initial constant value to a new set point calculated by Eq. (3)-(4). This secondary regulation control can reduce the consumption of the stored energy of BESS without lowering the control performance as shown in Fig. 12. Finally, we evaluate the islanded operation performance of the microgrid with the continuously varying load as shown in Fig. 13. The islanding occurs at t=1s and load changes as shown in Fig. 13. According to the load change, the BESS injects or absorbs the power from the microgrid to regulate the frequency and voltage. Then, the secondary regulation control detects the change in the power output of the BESS and assigns the difference to the diesel generator.

7. Conclusion

In this paper, the cooperative control scheme of micro sources and energy storage systems during islanded operation is presented and evaluated by a PSCAD/EMTDC simulation study. The ESS, which has a relatively fast response time, plays a primary control role during islanded
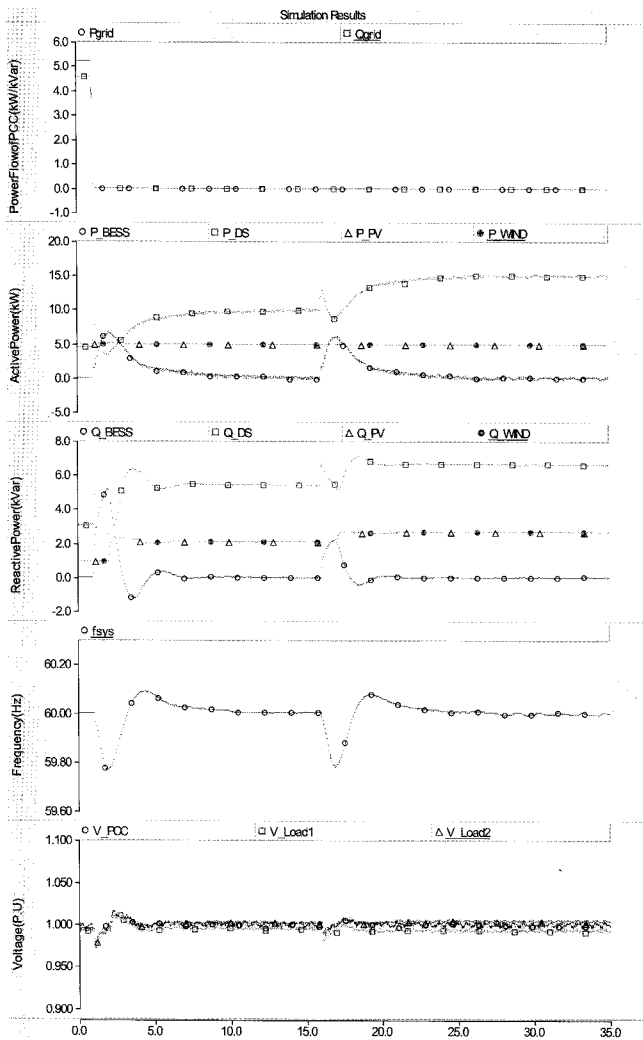
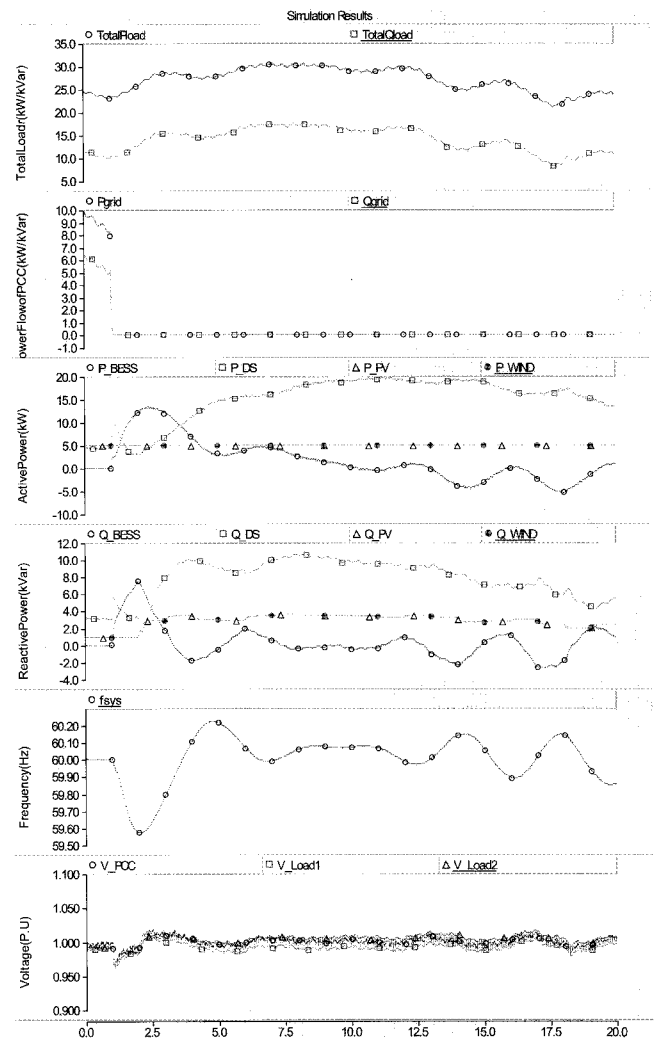**Fig. 12.** Simulation results of case C

Fig. 13. Simulation results with varying load

mode. The simulation's results indicate that the ESS can handle the frequency and the voltage very well. The control capability of the ESS may be limited, however, by its available energy storage capacity. Therefore, power output of ESS should be brought back to zero as soon as possible. The secondary regulation control is in charge of bringing back the current power output of ESS to a pre-planned value, usually zero. The simulation results show that the proposed cooperative control scheme can regulate the frequency and voltage and reduce the consumption of the stored energy of ESS.

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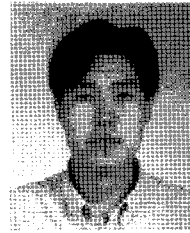
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