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Coordinated State-of-Charge Control Strategy for Microgrid during Islanded Operation

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Abstract – In this paper, a coordinated state-of-charge (SOC) control strategy for the energy storage system (ESS) operating under microgrid islanded mode to stabilize the frequency and voltage was proposed. The proposed SOC control loop is made up of PI controller, which uses a SOC state of the energy storage system as an input and an auxiliary reference value of secondary control as an output. The SOC controller changes the auxiliary reference value of secondary control to charge or discharge the ESS. To verify the proposed control strategy, PSCAD/EMTDC simulation study was performed. The simulation results show that the SOC of the ESS can be regulated at the desired operating range without degrading the stabilizing control performance by proposed coordinated SOC control method.

Keywords: Microgrid, Islanded operation, Coordinated control, Energy storage system (ESS), State-of-charge (SOC)

1. Introduction

Though the penetration of distributed generation (DG) into the electric power system is limited due to insufficient economic benefit, it will be accelerated for various reasons. The increase in DG penetration depth and the presence of multiple DG units in electrical have introduced the concept of the microgrid [1-3], which is a cluster of interconnected DG units, loads and intermediate energy storage systems. This system is interconnected to the distribution network of the utility, but they can also be operated in isolated from the main grid in the case of faults in the upstream network [4]. In grid-connected mode, the frequency and voltage of the microgrid is maintained within a tight range by the main grid. However, in an islanded operation, the frequency and voltage should be controlled by only existing DG units in the microgrid. Moreover, in islanded mode, with relatively few DG units, the frequency and voltage control of the microgrid is not straightforward.

In particular, the frequency of the microgrid will fluctuate rapidly due to intrinsic characteristics of the RES and DG units. The RESs have an intermittent nature since their power outputs depend on the availability of the primary source, i.e. wind and sun, and thus they cannot ensure the power supply required by loads. Furthermore, the DG units with relatively slow response primary energy source have insufficient dynamic performance in terms of load tracking [5, 6]. Therefore, stabilizing the frequency and voltage is one of the main issues in islanded operation [7]. To overcome these limitations, the introduction of an ESS is considered to be an effective solution. The ESS is based on a power electronics device and has a very fast response time. Therefore, a properly designed ESS can allow a system to stabilize by absorbing and injecting instantaneous power. Studies have been reported on the use of ESSs to stabilize power systems and RESs [8-10]. In [8] and [9], a control scheme for reducing a power fluctuation of wind generation system is presented. This scheme utilizes the stored energy of the ESS to smooth the power output of wind generation system. In addition, the ESS can contribute to stabilize the frequency of isolated power system [10]. Discussions on the use of an ESS in a microgrid are presented in [11-14]. In [11-13], the ESS is installed in a common dc link to complement the slower power output of the primary energy source, particularly fuel cell. Through installing the ESS into a DG system with a relatively slow response primary energy source, a microgrid can be stabilized during islanded mode even though the load changes quickly. The application of an electric double layer capacitor (EDLC) as a power system stabilizer is presented in [14]. In this work, a control method for the EDLC is proposed to maintain the power quality of the microgrid in islanded operation. These previous works indicate that control capability of the ESS is limited by energy capacity of the storage device. If only the ESS is involved in stabilizing the microgrid, it may be result in operation failure of the ESS. To prevent the ESS from operation failure, the power outputs of the dispatchable DG units should be coordinated to share the load following burden of the ESS. In [15], the local secondary control method, by using a PI controller at each dispatchable DG unit, is proposed to return the power output of the ESS to zero. This local secondary control is activated only using local information which is measured at each DG unit, therefore this method is difficult to achieve efficient coordinated operation of DG units in the microgrid. In [16], it proposes a coordinated control

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strategy of ESS and DG in microgrid for islanded operation. The proposed coordinated control strategy is based on the hierarchical structure with a central control level and a local control level. This control strategy consists of a primary control action of the ESS and a secondary control action of the MMS. During islanded operation, the frequency and voltage are regulated by fast-acting primary control of the ESS. The secondary control of the MMS detects the change of the power output of the ESS and tries to return the power output of the ESS to reference value by dispatching the power output set points of dispatchable DG units. However, the energy capacities of these ESSs are finite, and unlimited charge/discharge for compensation can cause overcharge or over discharge of ESS. This overcharge or over discharge can eventually result in the operation failure of the ESS. In fact, the most significant issue to operate the ESS stably during islanded mode is that SOC should always to be maintained in its proper range. To regulate the SOC of the ESS continuously in islanded mode, the control of the energy storage system's SOC is required. Moreover, this SOC control should not affect control performance of the ESS. Therefore, an advanced coordinated control scheme of the MMS considering the SOC of ESS should be studied. One method to control ESS's SOC is autonomous SOC control [8, 17, 18]. In these papers, the control scheme uses the SOC as an auxiliary signal, which is fed back to the ESS itself via controller. As a result, wind farm can be dispatched from power system operator without over-charging or over discharging of the ESS. However, these SOC control method adds bias on the ESS's output. Thus, it would cause unnecessary fluctuations in power output of DG unit and deteriorate the control performance in microgrid applications. This paper proposes a coordinated SOC control strategy for the energy storage system operating under microgrid islanded mode to stabilize the frequency and voltage. This SOC control loop makes up of PI controller, which uses a SOC state of the ESS as an input and an auxiliary reference value of secondary control as an output. The SOC controller changes the auxiliary reference value of secondary control to charge or discharge the ESS. This means that this method uses DGs for regulating the SOC, not add bias on the power output of the ESS. To verify the proposed control strategy, PSCAD/EMTDC simulation study was performed. The simulation results show that the SOC of the ESS can be regulated at desired operating range without degrading of stabilizing control performance by proposed coordinated SOC control method.

2. Microgrid Configuration

A microgrid consists of low voltage (LV) distribution systems with DG units, e.g. CHP units, microturbines, fuel cells, PV systems, and wind turbines (WT), together with ESS and loads. A microgrid is coupled with the main utility grid through interconnection switch at the PCC as per standard interface regulations. The interconnection switch at the PCC is operated to connect and disconnect the entire microgrid from the main utility grid as per the selected mode of operation [1, 2]. The microgrid operates in parallel with a utility grid under normal situations. The microgrid disconnects from the utility grid, and transfers into islanded operation mode when a fault occurs in the upstream grid. The storage device in the microgrid is analogous to the spinning reserve of large generators in a conventional grid; they ensure balance between energy generation and consumption, especially during islanded operation [19]. The microgrid has a hierarchical control structure as shown in Fig. 1. It has two control levels: central control level and local control level.

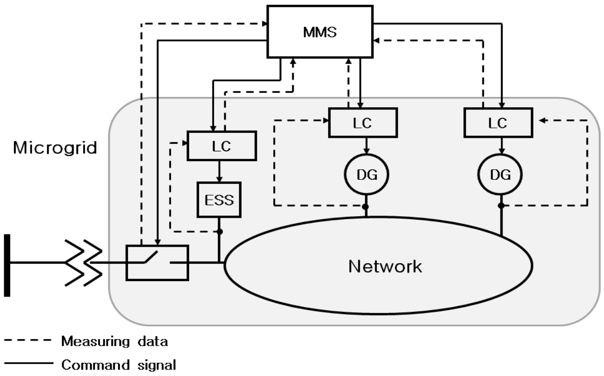


Fig. 1. The hierarchical control structure of microgrid

The management of microgrid in two operation modes is performed through a local controller at DG units and ESS, and a central controller [16]. In many applications of the microgrid, this central controller is called as various names, such as MMS, μ-EMS, microgrid energy manager, and power gate controller. In this paper, we call it MMS. The MMS is a supervisory centralized controller that includes several key functions (such as economic managing functions and control functionalities). It can exchange information with the DG units and dispatch the power output set points to the LC of the DG units. The LC that is located at each DG unit controls the power output to be in accordance with the power output set point from the central controller.

3. Coordinated Control Strategy for Microgrid Islanded Operation

3.1 Main concept for islanded operation [16]

The main concept for islanded operation involves the coordinated control of ESS and other dispatchable DG units.

In primary control, the ESS tries to stabilize the frequency and voltage locally with the fast-acting response. As a result, the frequency and the voltage of the microgrid can be regulated at the normal values [14-16]. However, the power balancing control capability of the ESS is limited by its available system capacity. Therefore, the power output of the ESS should be brought back to zero as soon as possible by the secondary control in the MMS in order to secure the maximum spinning reserve and reduce the stored energy consumption [20]. The secondary control of the MMS ensures the required power for returning the power output of the ESS to zero by sending out active and reactive power output set points to the dispatchable DG units.

3.2 Primary control of energy storage system

The ESS consists of an energy storage device and a grid-interfacing power conditioning system (PCS).

A supercapacitor and lead-acid battery bank can be considered as an energy storage device to be used for stabilizing the microgrid during islanded operation. Fig. 2 shows the configuration of a three-phase grid-interfacing PCS with battery bank [21, 22].

The controller consists of an upper grid controller and a d-q frame-based lower current controller [23]. In grid-connected operation, all of the DG units and the ESS are in PQ control mode, where the power output set point is provided by the MMS. In this mode, the upper grid controller regulates the active and the reactive power injected into the grid and outputs the d- and q- axis current commands, I_{d_ref} and I_{q_ref}. Otherwise, in islanded operation, the upper grid controller regulates the frequency and voltage of the microgrid, and also outputs the d- and q-axis current commands as shown in Fig. 3.

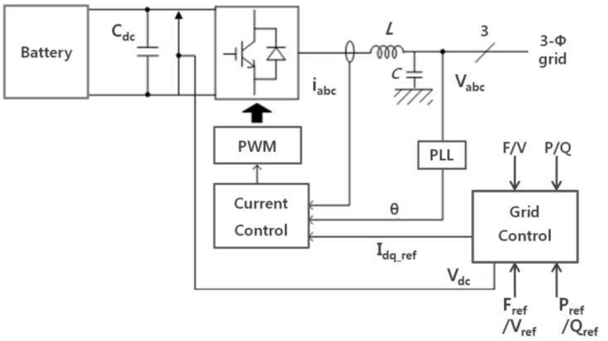


Fig. 2. Configuration of ESS

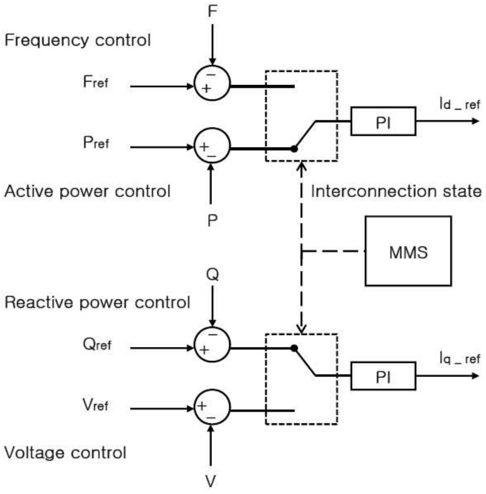


Fig. 3. Block diagram of grid controller

The transition from fixed power control to frequency and voltage is activated by information received from the MMS. The MMS receives the state of connection from the STS, and then the received information is passed to the ESS through a serial communication link. The lower current control scheme is presented in Fig. 4. Once the current reference(I_{d_ref} and I_{q_ref}) is determined, d-q transformation control is applied to enable the active and reactive components of ac output power to be mutually independently controlled. In the current controller, d- and q-axis reference voltage(V_{d_ref} and V_{q_ref}) is generated using errors between dq current reference and measured d-q current(I_d and I_q). The generated d-q reference voltage is transformed into the a-, b-, and c- axis reference voltage V_{a_ref}, V_{b_ref}, and V_{c_ref} by the d-q to abc transformation block. In the PWM block, the desired voltage waves V_{abc_ref} and the triangular carrier signal are compared at cross-over points and create turn-on and turn-off switching signals for the six insulated gate bipolar transistors(IGBTs).

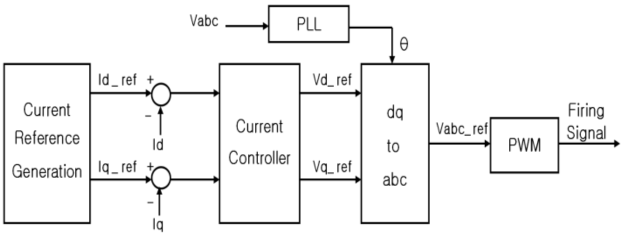


Fig. 4. Current control scheme of ESS

3.3 Secondary control of MMS

The goal of the secondary control of the MMS is to return the power output of the ESS to zero quickly without degradation of power quality. The MMS receives the information about system states as an input, e.g. power outputs of the ESS and DG units, frequency and voltage, and the closed loop control issues the power output set points for the dispatchable DG units. The LCs are responsible for regulating the power output locally in each component. Fig. 5 shows the coordinated control strategy in islanded mode. In the secondary control of the MMS, there are two separated control loops : one for the active power control and the other for the reactive power control. Each closed control loop has an integral controller. The closed control loops compare the measured power output of the ESS (P_{ess} and Q_{ess}) and the reference value (P_{ess_ref} and Q_{ess_ref}) to obtain the error. This error is compensated

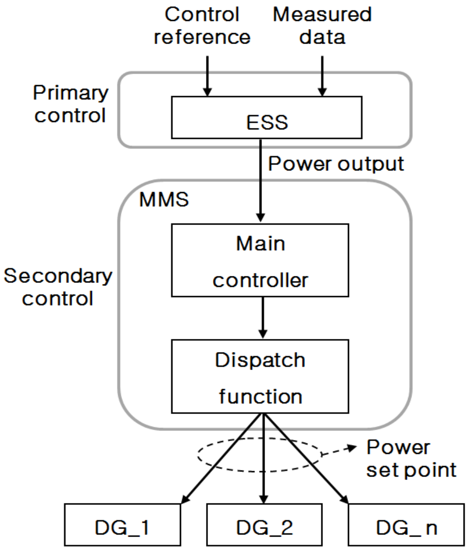
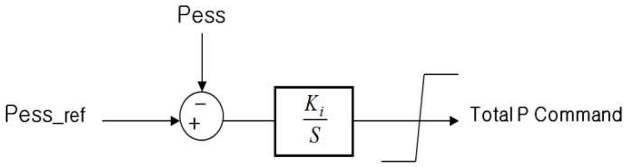
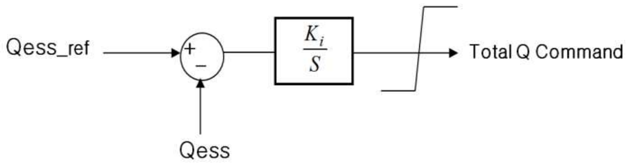


Fig. 5. Structure of secondary control



(a) Active power control loop



(b) Reactive power control loop

Fig. 6. Block diagram of secondary control

by a controller to produce a total power command (Total P Command and Total Q Command) as shown in Fig. 6.

Total power command is further used by a dispatch function block to generate a power output set point for each dispatchable DG unit, as shown in Fig. 5. In dispatch function block, total power command is converted into power output set point for each individual DG unit by using (1) and (2).

$$P_{ref\_i} = pf\_P_i \times \text{Total P Command} \quad (1)$$

$$Q_{ref\_i} = pf\_Q_i \times \text{Total Q Command} \quad (2)$$

where P_{ref_i} and Q_{ref_i} are the active and reactive power output set point for the ith DG unit, and pf_P_i and pf_Q_i are the participation factors for the ith DG unit, which is determined by (3).

$$pf\_P_i = \frac{P_{av\_i}}{P_{t\_av}}, \quad pf\_Q_i = \frac{Q_{av\_i}}{Q_{t\_av}} \quad (3)$$

$$P_{t\_av} = \sum_i^n P_{av\_i}, \quad Q_{t\_av} = \sum_i^n Q_{av\_i} \quad (4)$$

In (3) and (4), P_{av_i} and Q_{av_i} are the available active and reactive power of ith DG unit, P_{t_av} and Q_{t_av} are the total available active and reactive power of the DG units in the microgrid. The available reactive power of ith DG unit, Q_{av_i}, is computed based on the rated apparent power for each DG unit in (5).

$$Q_{av\_i} = \sqrt{S_i^2 - P_{ref\_i}^2} \quad (5)$$

4. Coordinated SOC Control Strategy for Energy Storage System during Islanded Operation

4.1 Main concept

In many cases, the ESSs are used to compensate fluctuations in RES system, and stabilize the power system.

However, the energy capacities of these ESSs are finite, and unlimited charge/discharge for compensation can cause overcharge or over discharge of ESS. This overcharge or over discharge can eventually result in the operation failure of the ESS [8, 17, 18]. The status of the ESS is indicated as a SOC, which expresses dischargeable energy in percentage of a ESS's rated capacity. The SOC is obtained by the integral of the ESS output. Here, the SOC can be characterized by its charging efficiency and discharging efficiency as follows [24] :

$$SOC = \int (\eta_{sto} \times \eta_{inv} \times P_{ess})dt \times K_{kWh \to \%} + SOC_o \quad (6)$$

$$\eta_{sto} = \begin{cases} \eta_{sto\_charge} & (P \geq 0) \\ \dfrac{1}{\eta_{sto\_discharge}} & (P < 0) \end{cases}, \quad \eta_{inv} = \begin{cases} \eta_{inv} & (P \geq 0) \\ \dfrac{1}{\eta_{inv}} & (P < 0) \end{cases} \quad (7)$$

where η_{sto_charge} and $\eta_{sto\_discharge}$ are the charging and discharging efficiency of energy storage, respectively, η_{inv} is efficiency of grid-interfacing inverter, P_{ess} is power output of the ESS, $K_{kWh \to \%}$ is converting constant from kWh to percentage, and SOC_o is an initial SOC value.

In the case of charging and discharging system with 100% of efficiency, the stored energy will be equivalent to the summation of charged and discharged energy, and the dischargeable energy will be the same as the stored energy. However, the charging and discharging efficiencies are not 100%. In practice, these values are less than 90%. Thus SOC of the ESS will be decreased as time goes on. To operate an ESS continuously in islanded mode, the control of the energy storage system's SOC is required. This SOC control should not affect control performance of the ESS. Therefore, an advanced coordinated control scheme of the MMS considering the SOC of ESS should be studied. One method to control ESS's SOC is autonomous SOC control [8, 17]. This method can be used to control the SOC in cases of wind power smoothing application. In this method, the state of the ESS's SOC is fed back to the ESS itself via controller such as a PI controller. This is a conventional method to control the SOC and its scheme is relatively simple. However, this method adds a bias on the ESS's output. When the ESS acts as primary control unit that has the fastest response time, this bias caused by the SOC control would not be compensated. This would result in unstable operation of the microgrid.

4.2 Design of SOC controller

To avoid reduction of compensation ability, a coordinated SOC control method is proposed. In this method, the state of the ESS's SOC is given to the MMS. Since the ESS's output power is dependent on the other dispatchable DG units output, the ESS itself compensates the bias and this compensation is the process of SOC control. In other words, the control of the ESS's SOC is achieved by compensation of artificial biases made by the other dispatchable DG units. Thus, the frequency is not affected by SOC control. Fig. 7 presents detailed block diagram of SOC control method. The SOC controller is a simple PI controller that is relatively slow in order not to degrade the effectiveness of the secondary control but fast enough to prevent full energy storage charge or discharge during islanded operation. The measured SOC is compared with the reference SOC value. If SOC deviates from the reference value, an error between the reference and measured SOC is amplified by the gain K_p and integrated with the gain K_i. The output signal of PI controller is added to the original active power reference of secondary control loop as an auxiliary reference signal. If PI controller has the larger proportional gain and the integral gain, the deviation of SOC will be decreased, however, auxiliary reference signal will be larger. Too large biased auxiliary reference signal may not only cause the unstable operation of the microgrid, but also reduce the controlling reserve of the ESS. Therefore, gains of PI controller should be selected considering this constraint.

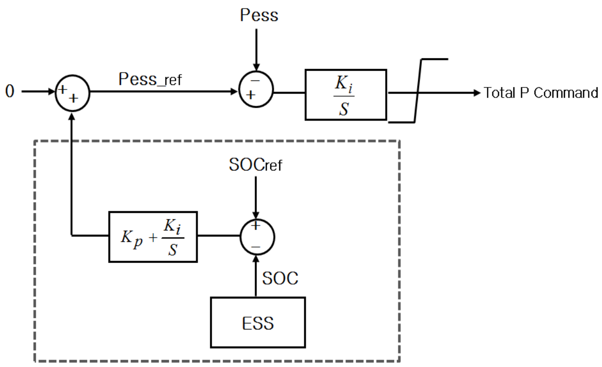


Fig. 7. Block diagram of coordinated SOC control

5. Simulation Study

5.1 Configuration of Test System

Fig. 8 and Table I show the configuration and details of the studied microgrid system. The test system consists of DG units, ESS, STS with IED, a distribution line, and loads. The DG units include a PV system, a PV and WT hybrid system, and diesel generators. A simulation platform under the PSCAD/EMTDC environment was developed to evaluate the dynamic behavior of the microgrid. In the PSCAD/EMTD model, the RES and the ESS were modeled as an equivalent voltage source model for convenience. A typical synchronous generator model in the library was used to represent the diesel generators. The upstream grid was modeled as an equivalent voltage source with the Thevenin impedance, and the load and distribution line were represented by constant impedance model, i.e. R and X.

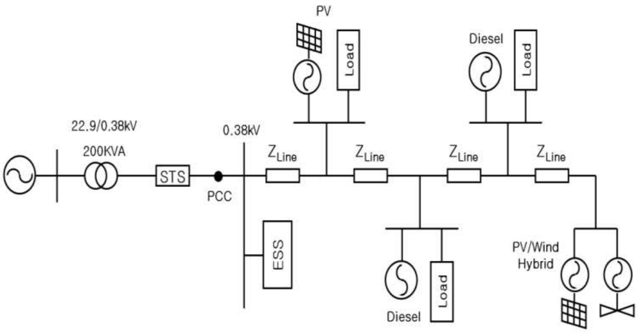


Fig. 8. Configuration of test system

Table 1. Details of test system

Item	Description and Parameters
System Configuration	- DG unit : Diesel generators - RES : PV, PV and WT hybrid - ESS : Battery energy storage system - Loads : Constant impedance load - Interconnection switch : STS
Generation Capacity	- PV 10kW - Hybrid 20kW(PV 10kW, WT 10kW) - Diesel generator 20kW and 50kW - BESS 20kW
Load	- Load 1 : 50kW - Load 2 : 50kW+j50kVar - Load 3 : 10kW+j10kVar
Transformer	3- phase 22.9/0.38kV 200kVA Leakage impedance %Z = 6%
Line Impedance	R= 0.1878Ω/km, X=0.0968Ω/km

5.2 Simulation results

In this section, numerical simulations show effectiveness of the SOC control for keeping the SOC of ESS within its proper range while the stabilizing performance of the ESS maintains. In this simulation, we assumed that the efficiencies of the PCS and charging/discharging phase are 90% and 90%, respectively. The initial SOC of the ESS is 65% and the proper SOC range is assumed from 30% to 100%. Thus SOC of the ESS can be calculated by (6) and (7). Figs. 9 and 10 present the active load and power outputs of RES used in this simulation cases.

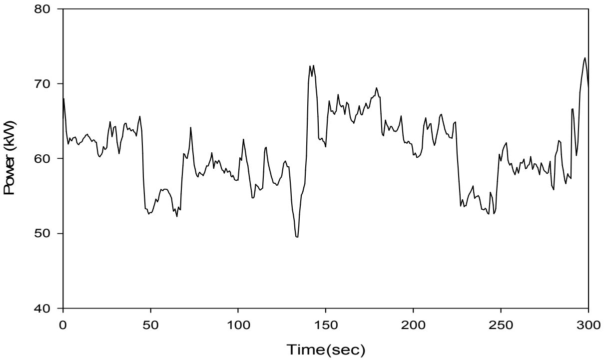


Fig. 9. Active load

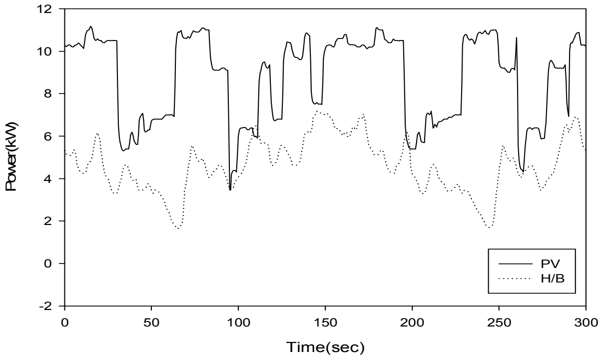
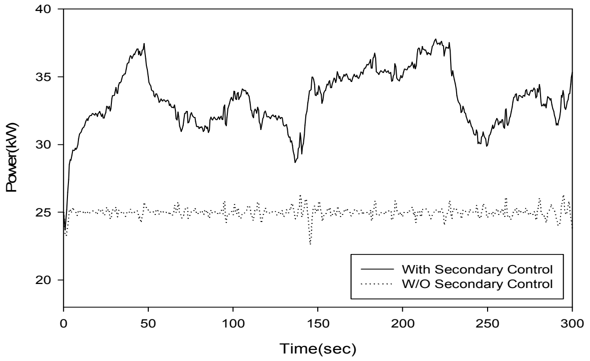


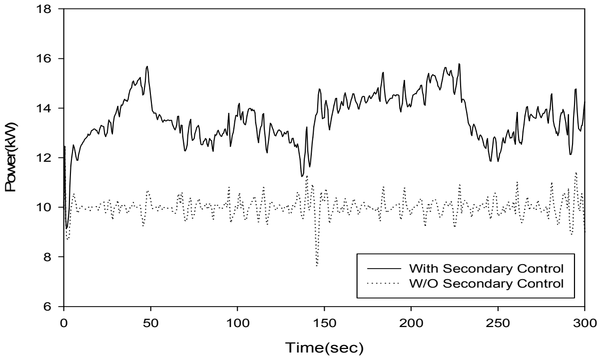
Fig. 10. Power outputs of RES

Case A) Effect of secondary control on SOC of the ESS

In this case, the effectiveness of secondary control was evaluated in terms of SOC of the ESS. Figs. 11 and 12 compare the active power outputs of diesel generators and the ESS in cases with and without secondary control. In Fig. 11, the power outputs of diesel generators were changed to regulate the power output of the ESS at zero. As a result, power output of the ESS in case with secondary control considerably reduced compared to the case without secondary control. This means that the power losses in the charging and discharging phase of the ESS are reduced. In Fig. 13, this effect can be seen in terms of SOC of the ESS. In case with secondary control, the SOC also decreased with time. However, the rate of decrease was much slower than in case without secondary control. Fig. 14 presents the frequency deviations in cases with and without secondary control. There was no degradation by introducing the secondary control.



(a) Diesel generator 1



(b) Diesel generator 2

Fig. 11. Power outputs of the DG units in Case A

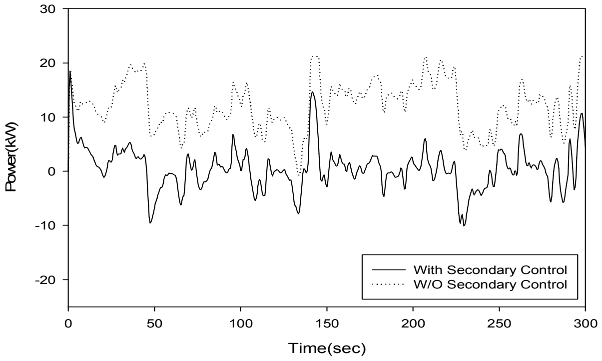


Fig. 12. Power output of the ESS in Case A

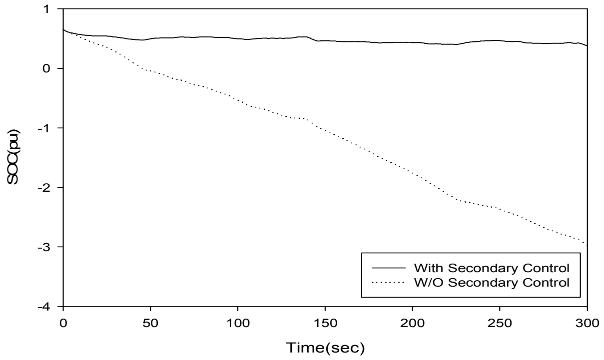


Fig. 13. SOC of the ESS in Case A

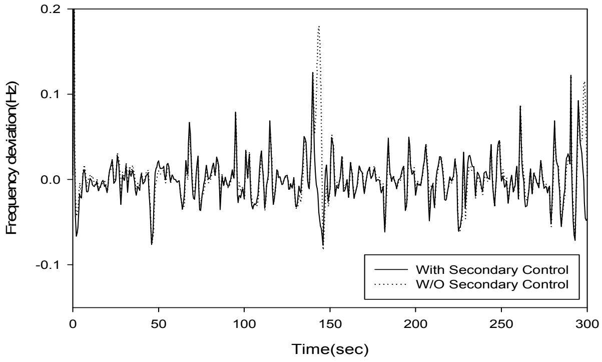


Fig. 14. Frequency deviation in Case A

Case B) Comparison of SOC of the ESS for different storage capacities

Fig. 15 shows power output of the ESS in case with only secondary control applied. The power output of the ESS injected or absorbed active power to stabilize the frequency during islanded operation. Fig. 16 presents SOC of the ESS for various energy storage capacities. In all cases, the SOC got decreased with time because of power losses in the PCS and the battery bank. In case with relatively larger capacity, i.e. 4,800kWsec, 2,400kWsec, and 1,200kWsec, the SOC maintained within proper range. On the other hand, in case with small capacity, i.e. 600kWsec, the SOC decreased to below minimum range. This situation results in failure of the ESS operation. Thus, the proper SOC control method is needed to reduce the capacity of energy storage.

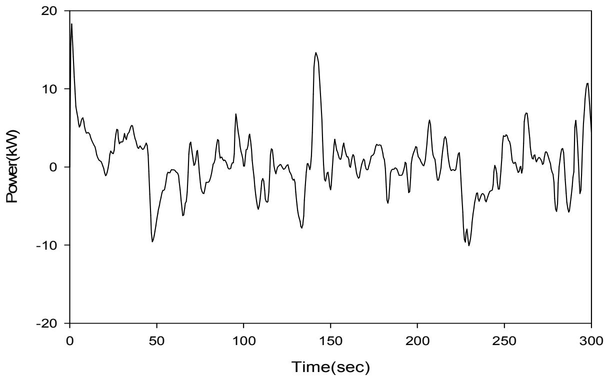


Fig. 15. Power output of the ESS in Case B

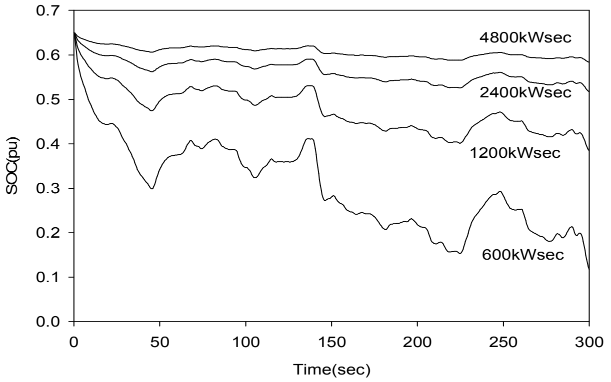
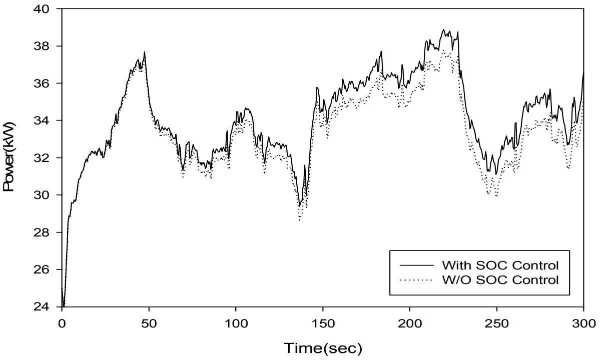


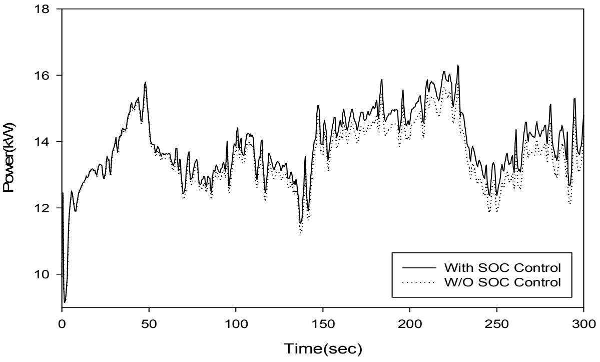
Fig. 16. SOC of the ESS for various capacities in Case B

Case C) Effect of SOC control on SOC of the ESS

In this case, effectiveness of coordinated SOC control was evaluated when the storage capacity and initial SOC were 1,200kWsec and 65%, respectively. Figs. 17 and 18 compare the active power outputs of diesel generators and the ESS in cases with and without SOC control. In Fig. 17, the power outputs of diesel generators in case with SOC control were a little larger than in case without SOC control. This difference results from the SOC control function. To regulate the SOC of the ESS at a desired value, i.e. 65%, the diesel generators output more active power to charge the ESS. When only secondary control without SOC regulating action was applied, the SOC got decreased and closed to minimum range. This means that the storage capacity should be increased to operate stably. On the other hand, applying SOC control algorithm, the SOC maintained with the range of 48% to 67% as shown in Fig. 19. Fig. 20 presents SOC of the ESS for different energy storage capacities. When the SOC control is applied, the capacity of energy storage can be reduced to 600kWsec. From these results, we can find that the energy storage capacity of ESS can be reduced more by applying SOC



(a) Diesel generator 1



(b) Diesel generator 2

Fig. 17. Power outputs of the DG units in Case C

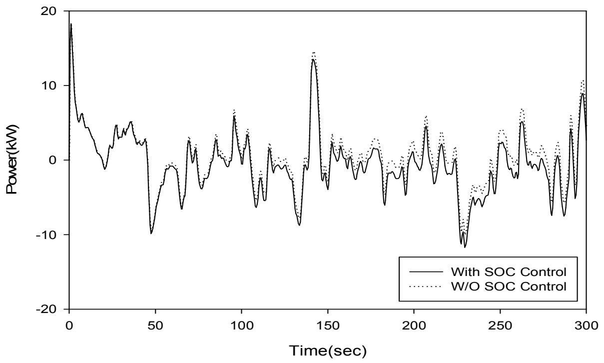


Fig. 18. Power output of the ESS in Case C

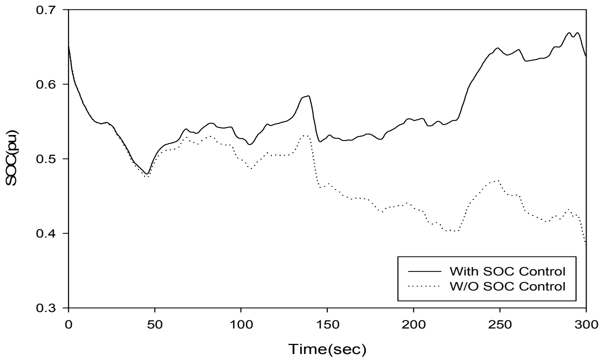


Fig. 19. SOC of the ESS in Case C

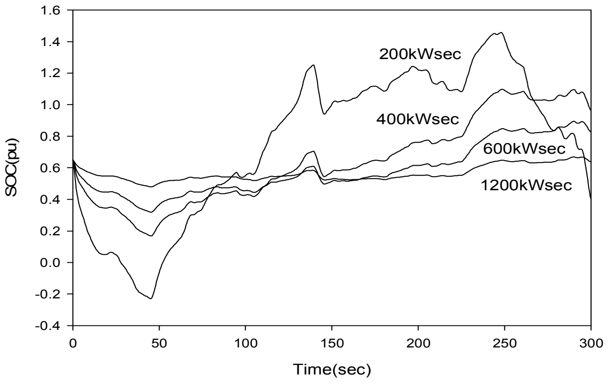


Fig. 20. SOC of the ESS for various capacities in Case C

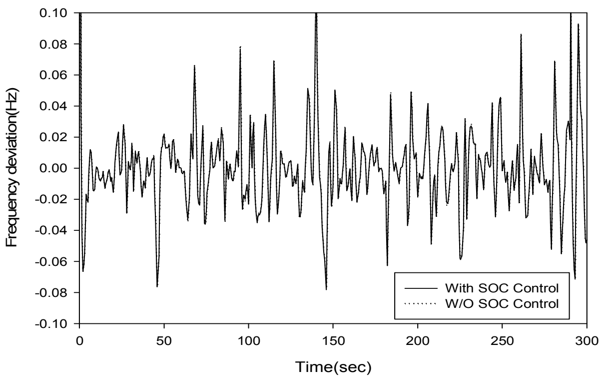


Fig. 21. Frequency deviation in Case C

control. Fig. 21 presents the frequency deviations in cases with and without SOC control. There was no degradation of the frequency control performance by introducing the SOC control.

6. Conclusion

During islanded operation, the frequency and voltage of the microgrid may change rapidly due to power unbalance between supply and demand. The DG units existing in the microgrid don't have enough fast response characteristics to stabilize the frequency effectively. To overcome this technical issue, the introduction of the ESS is considered. However, the control capability of the ESS for stabilizing the microgrid is limited to energy capacity of the storage device. Therefore, the secondary back-up control action is necessary to return the power output of the ESS to zero quickly. Furthermore, SOC control action should regulate SOC of the ESS within proper range in order to secure continuous stable operation of the ESS. To achieve these goals, a coordinated SCO control strategy for the microgrid was proposed. By introducing the SOC control loop into secondary control, the SOC regulated within the proper range. The SOC control loop consisted of PI controller, which had state of the SOC as an input and auxiliary reference of the secondary control as an output. Since the control of the ESS's SOC is achieved by compensation of artificial biases made by the other dispatchable DG units, the frequency was not affected by SOC control. From simulation results, we can find that the required capacity of energy storage can be reduced by coordinated SOC control strategy.

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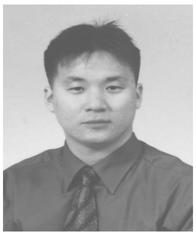

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