Master's Thesis
석사 학위논문

A Smart Grid Control Strategy for Improved Power Efficiency

Keunhye Choi (최 근 혜 崔 根 惠)

Department of Information and Communication Engineering

정보통신융합공학전공

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By

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

11. 15. 2013

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[1] Declaration of Ethical Conduct in Research**:** I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

A Smart Grid Control Strategy for Improved Power Efficiency

Keunhye Choi

Accepted in partial fulfillment of the requirements for the degree of Master of Science

11. 15. 2013

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ABSTRACT

Korea has been experiencing power demand supply problems during summer and winter. We aim to solve these problems by mitigating the difference of supply and demand power amount. This thesis presents a smart grid control strategy for improved power efficiency using energy storage devices of a microgrid system. The microgrid system is the combination of a photovoltaic (PV) array, loads, and a battery energy storage system (ESS) via a DC bus. The control strategies were defined as multi-modes of operation, including a rest operation without use of battery, power charging, and power discharging, which enables either a grid connected mode or an islanded mode. A supervisory control regulates power generation of the individual components so as to enable the microgrid system to operate in the proposed modes of operation. The concept and principle of the microgrid system and its control were described. In the battery converter, state-feedback control is used to discharge power as user wants. Modeling and simulation were based on MATLAB/Simulink. A 100-kW microgrid inverter and its control system were developed. The simulation results were presented to evaluate the dynamic performance of the microgrid system under the proposed modes of operation.

Keywords: microgrid, battery energy storage system, state-feedback control.

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Ⅰ. INTRODUCTION

Korea has been experiencing power demand supply problems during summer and winter. If the power demand sharply increases in these particular time of the seasons, frequency of a power system is exceeds the standard range (60Hz±0.2) and the power grid is shut off by the negative sequence relay, resulting in a blackout. In general, electric power supply of plants such as fossil fuel power generation or nuclear power generation is controlled by amount of electric power demand and plants adjust power demand supply imbalance. However, power demand supply imbalance caused by a radical increase of power demand cannot prevent the frequency dropping in the power system, because production rate of power in plants does not follow increased rate of load in the power system. The loads in the power system don’t use good power quality and appropriate quantity. In addition, the stability of the power system decreases when load changes are impossible to predict and a variation in frequency is very large compared to the fundamental frequency. Furthermore, power imbalance, due to the failure to prevent the grid frequency fluctuations, can cause accidents.

Actually this situation happened on September 15th, 2010 in Korea. By the late summer heat, the power demand suddenly surged and backup power of Korea Electric Power Corporation (KEPCO) fell less than a 100kW power. KEPCO carried out rotation outage of major city in Korea and each cities are damaged, resulting in estimated damage of 30,191 billion won [1]. The major problem was inability to deal with a dangerous situation with agility. For stability of the power system, unexpected situation should be solved by quickly. Comprehensively response time reduction of unexpected events and increment of elements that threaten the stability in the power system (e.g. increasing distributed generations) make it difficult to stabilize the power system.

As the electric power system evolves into Smart Grid, the centralized energy management by a utility grid (e.g. KEPCO managing the entire power system in Korea) is no longer adequate to the new operational environment with new system components such as renewable energy sources, distributed generators, electric vehicles, and so on [2]. In addition, the existing system management has difficulty in regulating the entire power system. In this connection, a concept of microgrid plays a key role to transform the existing power system management organization into Smart Grid and requiring the distributed control scheme on the power system operation.

Previous studies have focused on decentralized or hierarchical control architectures for intelligent microgrids. Many people have been making every effort possible to establish a specific control plan of microgrids [3]. However, it does not guarantee enough time securement to be possible to cope with power system problems that overloads, failure in the power system, weighted risk of the power plants, and so on. There are also recent studies being done on a cooperative control strategy of energy storage system for stabilizing the microgrid [4]. These control schemes can resolve stabilization for microgrids in an islanded mode, but they require a complex control scheme with operations in a grid-connected mode. Additionally, very few attempts have been made at multi-objective intelligent microgrids management using the energy storage system connected to a central Smart Grid management system.

We propose to develop a dynamic modeling and control scheme of a hybrid system including PV array system, energy storage devices in real-time. The energy storage devices, using existing system in microgrids, consider the stability and dispatch-ability of its power injection into the grid. The system can operate in three different modes, which include charging, discharging, and rest operations in order to transfer electric power, and regulate voltage level in a grid. In order to effectively achieve such modes of operation, a modified technique is applied; a modified hierarchical control strategy for an energy storage charger/discharger using a state-feedback control technique. Additionally, we provide mode operation of microgrids (e.g. grid-connected and islanded modes) when this modified technique operates. Dynamic modeling and simulations were based on Matlab/Simulink SimPowerSystems. A 100kW hybrid inverter and its control system were developed. Descriptions of the system and control, simulation works were focused on the dynamic performance. The simulation results were presented and discussed to evaluate the dynamic performance of the proposed control scheme for stable power transfer and voltage level of grid. This control scheme has several advantages as follows: prevents sudden power accidents (e.g. outage in grid, transmission line faults, and generation problems), meets loads demand of microgrids in real-time, and reduces a loss of supplied (transferring) power because power generates nearby.

This thesis is organized as follows. Section II presents background knowledge and related work. Section III introduces microgrid simulator and its main components. Section IV proposes and discusses two methods to enhance power quality in DC microgrids by reducing circulating current. Sections V and VI present performance evaluations and conclusions

Ⅱ. BACKGROUND – SMART GRID ORGANIZATION

2.1 Smart Grid (Microgrids)

The Smart Grid defines next generation power system to optimize energy efficiency by exchanging real-time electric power information between power providers and consumers that communicate in full-duplex, by integrating existing power grid and ICT (Information Communication Technology). Fig. 1 presents an entire smart grid structure of DOE (Department of Energy in U.S) [25]. The goal of the Smart Grid is to determine the amount of power transmission and distribution by analyzing the amount of electricity through full-duplex communication and to transfer these stabilized electricity until each loads. The Smart Grid has further offered alternatives to participants looking to enhance the reliability, sustainability, and capability for customer choices in energy systems [5].

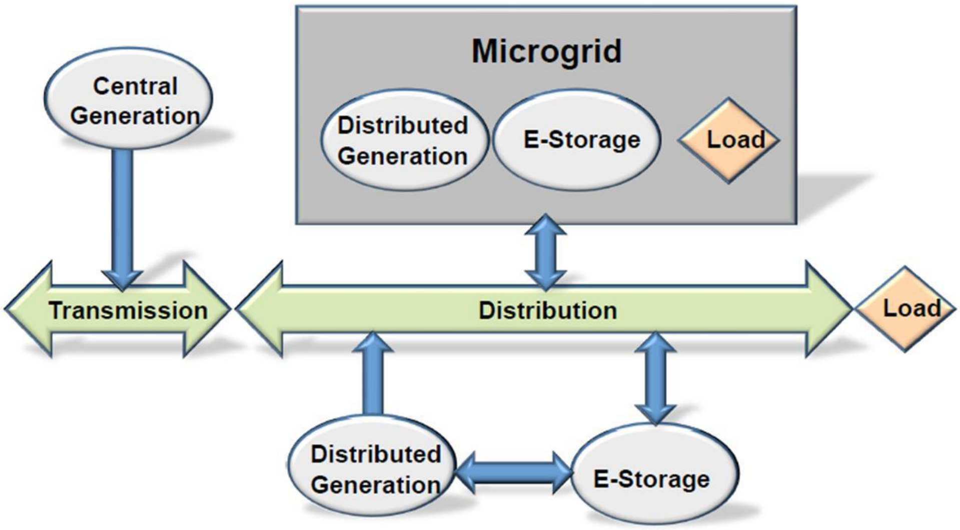


Fig. 1. DOE Smart Grid Structure

Microgrids are modern, small-scale power units of the Smart Grid (centralized energy management system). They consist of renewable energy generations, loads, energy storage devices, and various controllers (e.g. DC-DC converter, DC-AC converter, PWM generator, etc.). Those generate, distribute, and regulate the flow of electricity to consumers, but do so locally. Smart microgrids are an ideal way to integrate renewable resources on the community level and allow for customer participation in the electricity enterprise [6]. Recently, attention on the microgrid has been growing in many countries because it is closely related to environmental friendliness, the diverse needs of the end user for higher power quality and restrictions on the extension of power transmission and distribution facilities [7]. Microgrids are operated in two modes: the grid-connected mode and the islanded mode. In normal environments, the microgrids are linked to a utility grid, operate in parallel with the utility grid, and interchanges power according to a power balance between supply and demand in the microgrids. However, a situation of being disconnected with the utility grid can occur when a fault occurs in the upstream power grid or a power supply/demand problem happens. At the moment, the microgrid operates in the islanded mode and rotates power like an isolated island. The power balance between supply and demand is one of the important management factors in both operation modes. In the grid-connected mode, the microgrid interchanges power to a linked utility grid to meet the balance. On the other hand, in the islanded mode, the microgrid tries to meet the balance internally using the increase in generation or decrease loads [8], [9].

2.2 Distributed Generation (DG) and Distributed Storage (DS)

Distributed generation plants are mass-produced, small, and less site-specific. DG reduces the amount of energy lost in transmitting power because the power is generated very near where it is used. Additionally, this reduces the size and number of power lines that must be constructed. Distributed energy resource (DER) systems are small-scale power generation and mainly composed of a renewable energy system such as a photovoltaic (PV) array power system, a wind power system, or a fuel-cell system with distributed storage like energy storage device. It is called a Hybrid system that is the integration of renewable energy sources and an energy-storage system. The increasing number of renewable energy sources and distributed generators requires new strategies for their operations in order to maintain the power supply stability and quality [10]. In addition, the operation of hybrid system can affect the entire power system such as voltage level fluctuation, decreasing power quality, unstable frequency level, and so on.

Ⅲ. SYSTEM CONFIGURATION

Fig. 2 presents the configuration of the microgrid power and its control system, and an AC power system. The entire power system consists of AC power system composed of a generator, two transformers, a large-scale load, a grid-interface inverter, an AC grid, and a microgrid system including a PV array, a battery-energy storage, a DC bus, a load, and power electronic converters for regulating the power associated with the energy sources of components in microgrid. The generator has a stator speed at 1800 rpm for producing 60 Hz in the AC grid. The two transformers transfer the power 315kV to 25kV, 25kV to 380V.

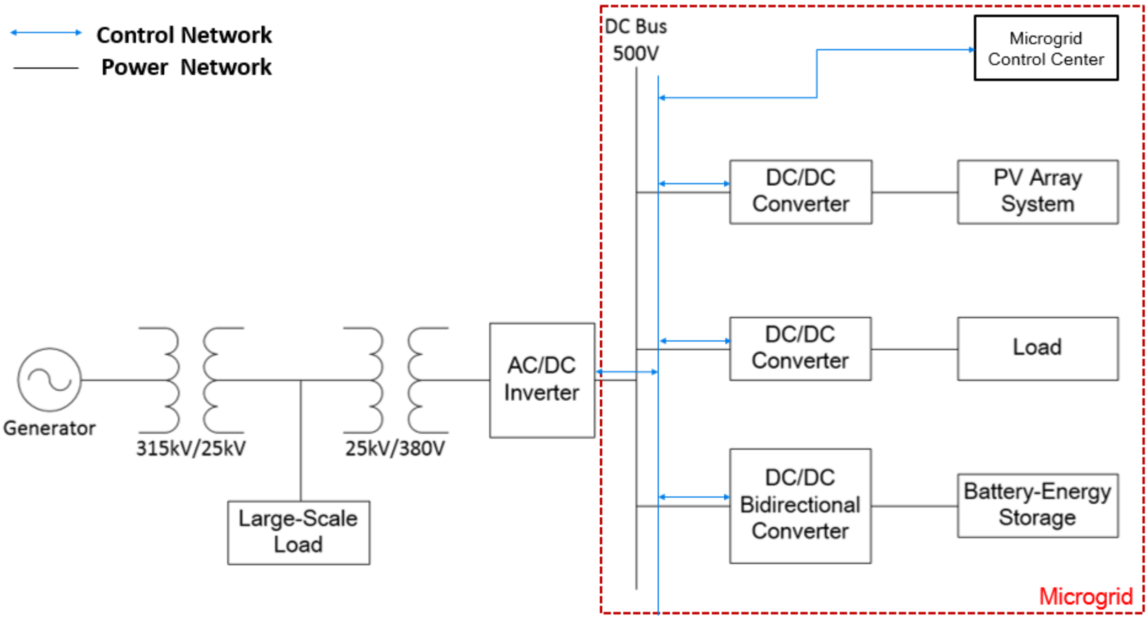


Fig. 2. Configuration of microgrid power and control system, and AC power system

These values are similar with real 3-phase voltage level. A large-scale load represents many different types of loads connected with electric power distribution. The PV system consists of a PV array and a DC-DC converter for boosting the array voltage to a higher level of DC voltage. According to operation modes, battery-energy storage system (BESS) mitigates power fluctuations of solar system, or shifts the power generation to regulate the power transferred into the grid. The BESS is divided into battery storage and a buck-booster that is a bidirectional DC-DC converter for charging or discharging the battery storage. The battery converter connects the interior of battery and DC bus, whose voltage levels are mutually different, and controls the current flow between the two levels. In some previous applications [11], [12], [13], battery storage was directly connected to a DC bus without using a converter. This structure requires more battery stacks than using a DC-DC converter, and so lowers the system power loss. Also, the lifetime of battery may be short without appropriate control of battery current and voltage. The grid-interface inverter transfers into grid DC power generation from the PV array, and BESS in the form of AC power. The control system of microgird generation is divided into local controllers and a supervisory controller. Local controllers include a PV array controller, a battery controller, and a grid-inverter controller. The supervisory control system is the combination of energy management computer for remote control and monitor, and wireless communication network with the local controllers. The supervisory system monitors the entire microgrid system and regulates power generation of the individual energy sources.

Ⅳ. CONTROL STRATEGIES

4.1 Supervisory Control Strategies

Fig. 3 shows the supervisory control strategies of the grid-connected microgrid system. It suggests three possible modes of operation, which are charge, discharge, and rest operations. A supervisory control system monitors parameters of the local controllers and transfers control directions to them according to the mode selected by an operator. Supervisory control strategies in three possible modes of operation are as follows.

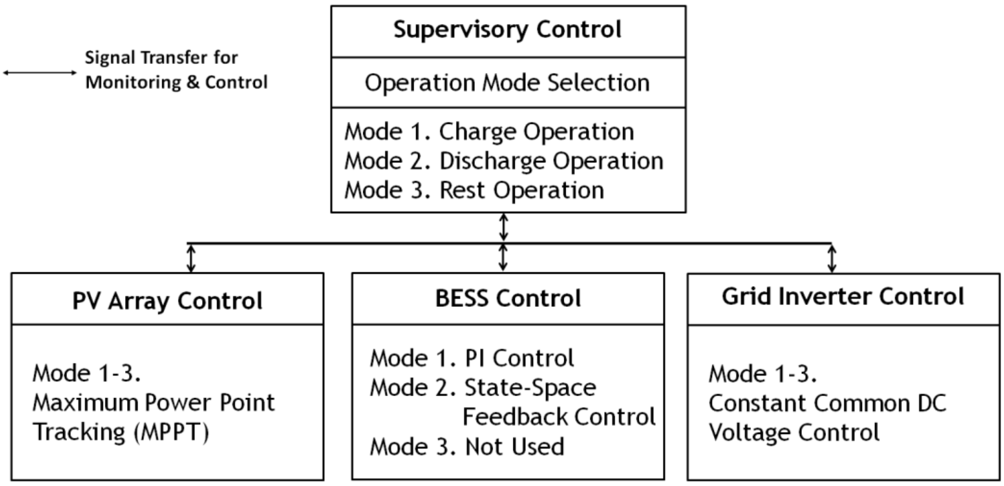


Fig. 3. Supervisory control strategies of a grid-connected microgrid system

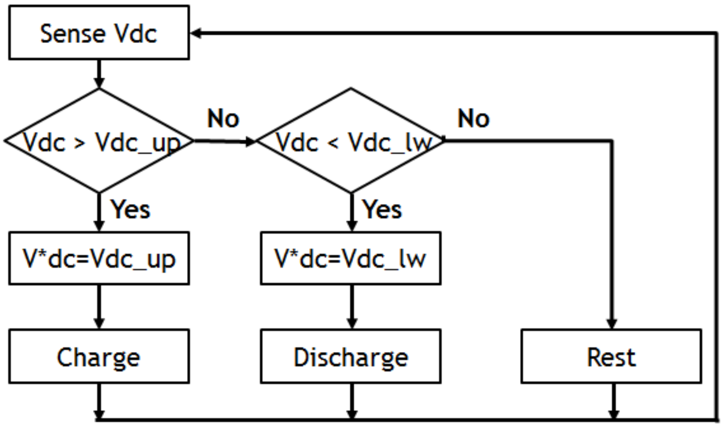


Fig. 4. Operation mode selection algorithm of supervisory control

1) Mode 1-charge operation: The microgrid system and the AC power system transfer as much power into the DC bus as the PV array and power generator can generate. Solar irradiance has irregular profile [14], PV array generates power when there is sunlight and different quantity as irradiance angle. In addition, power remains after large-scale load spends the power. Unstable and oversupply power are affected on power quality, voltage level, and other components. In the charge operation, the grid inverter is directed to maintain transferring to DC from three-phase AC. The energy management system measures all power generation from PV array sources and remaining resources of AC grid, determines amount of charging power in the battery-energy storage. After that, the manager sends charge command for operating the buck converter of BESS. For the most efficient operation, the PV array is controlled at all times to produce the maximum power under the given weather conditions.

2) Mode 2-discharge operation: The supervisory control knows the desired power injection to the load. Therefore supervisory control tries to deliver the regular power to the load because energy loss and load faults occur as the power demand and supply imbalance increases. Battery is used to compensate power mismatch between generation of PV array and load amount. Power fluctuations are unavoidable in a solar system. Therefore, without appropriate discharging control, load cannot use the frequent power. In this thesis, a control strategy is implemented in the battery charger/discharger to reduce power and voltage level fluctuations. Details will be described in the Section D.

3) Mode 3-rest operation: The purpose of this mode is to converse the voltage level between the DC bus, the PV array, and the load. This improves the quality of power delivered to the load. This mode of operation mitigates the voltage and harmonic variation with DC grid.

The primary goal of the battery converter is to regulate the common DC bus voltage. The battery load current rapidly changes according to changes in weather conditions and power command for grid inverter [13]. DC bus voltage must be regulated to stay within a stable region regardless of the battery-current variation. To do this, DC bus voltage stabilizing is carried out in the supervisory control that applies a modified hysteresis-control strategy [24]. The concept of this strategy is to regulate the DC voltage within a specific band, for example, a hysteresis band. Therefore, the charge/discharge operations are controlled in such a way that the DC bus voltage should not violate the specified upper and lower limits, V_{dc_up} and V_{dc_lw}, as shown in Fig. 4. A decision criterion for charging/discharging becomes the level of the common DC bus voltage, and the charge/discharge operation mode determines according to the scheme as below:

If $V_{dc} > V_{dc\_up}$, then charging → $V^{*}_{dc} = V_{dc\_up}$

If $V_{dc} < V_{dc\_lw}$, then discharging → $V^{*}_{dc} = V_{dc\_lw}$

If $V_{dc\_lw} \leq V_{dc} \leq V_{dc\_up}$, then no control (rest)

When the DC voltage V_{dc} becomes larger than the upper limit, the charge operation mode begins with the voltage command V*dc equal to the upper limit, sends a charging operation command, and continues until the DC voltage reaches the limit. If V_{dc} goes below the lower limit, then the voltage target is bound at the lower limit and the discharge operation mode starts operating in a boost mode as a discharging operation command is delivered at BESS.

4.2 Local Control of the Microgrid System

Fig. 5 shows the configuration of the microgrid system and its local controllers. The solar system consists of a boost controller and a Maximum Power Point Tracking (MPPT) [15]. The PV converter regulates the array voltage V_{PV} at the reference voltage V^{*}_{PV} commanded by the maximum power point tracking (MPPT) controller and boosts it to the level of common DC voltage. Error between the ordered and real voltage is processed through the voltage controller into the ordered current i^{*}_{PV}, which is compared with the array current i_{PV}. A DC-DC converter for BESS should be capable of controlling the battery current i_{BESS} in both directions. In a battery-charging mode, the current flows from the DC bus to the battery, and in a discharging mode, the current flows in the opposite direction. Therefore, the BESS converter should be a type of a buck and booster, which may operate in buck mode for battery charging and in boost mode for battery discharging. In buck mode, the series switch (S1) turns activated and the parallel switch (S2) deactivated, and in boost mode, S1 turns activated and S2 deactivated. The BESS-mode controller determines whether to charge or discharge battery storage and outputs the DC voltage command V^{*}_{dc}. The voltage command is compared with the actual voltage V_{dc} and processed into the reference current i^{*}_{BESS} that is regulated by the current controller. A grid-interface inverter injects the power from the individual source components into the grid. A control structure of the grid-side inverter is basically identical to that of the wind converter except for an upper level controller. The grid-operation controller regulates power injection into the grid according to operation modes of the microgrid system.

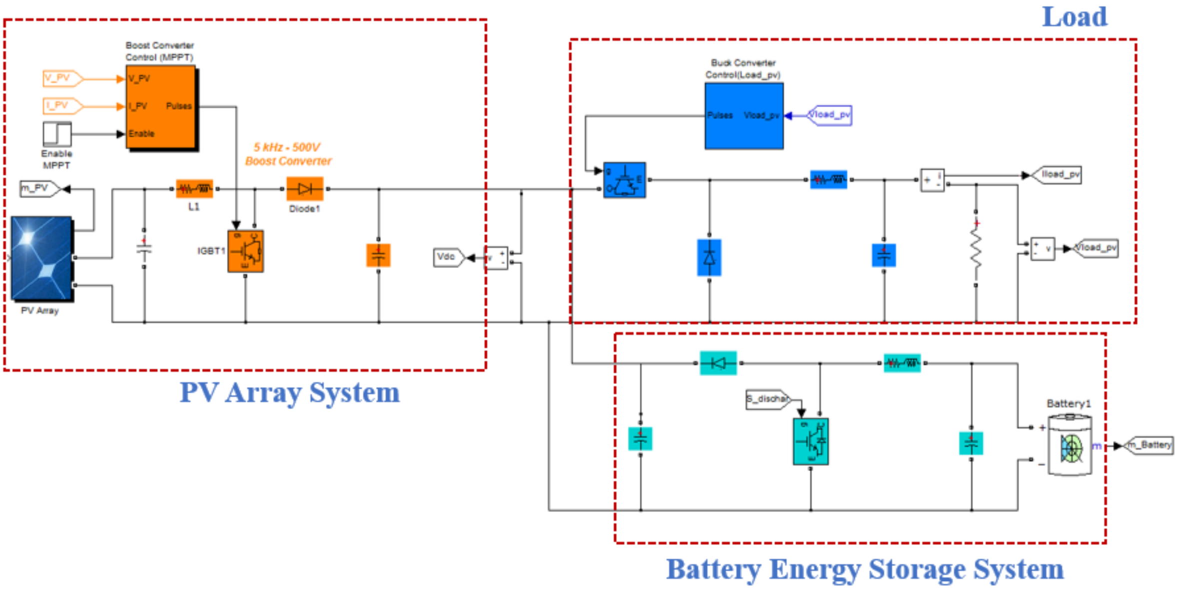


Fig. 5. Configuration of the microgrid system and its local control schematic

4.3 PV Array Control

Power output of a PV array depends on the voltage level where it operates under a given condition of irradiance and cell-surface temperature. For efficient operation, a PV array should operate near the peak point of the V−P curve. Various MPPT techniques have been proposed [16]–[19]. The incremental conductance (IncCond) method was implemented in this thesis [20]. The MPPT block in Fig. 6 senses the PV array current i_{PV} and array voltage V_{PV} and returns the array voltage command.

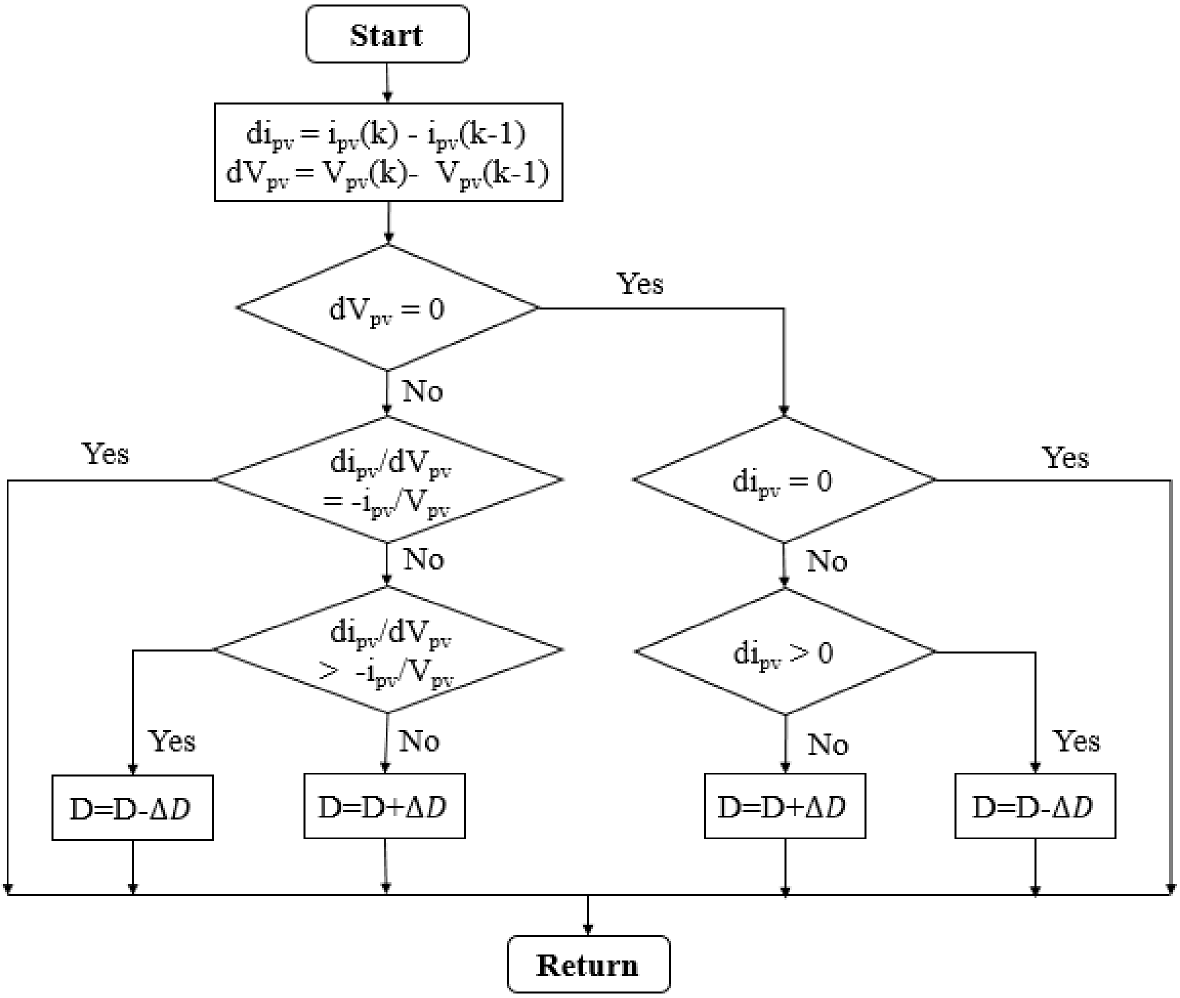


Fig. 6. MPPT control block (IncCond method)

4.4 Battery Energy Storage System Control

Battery Energy Storage System (BESS) control aims to achieve a balance of power in a power system. Then, BESS steers the difference between the total production and consumption of power to zero. To do this, BESS operates charging/discharging using bi-directional buck-boost converter as received command from supervisory control in Fig. 7. BESS in two possible modes of operating are as follows.

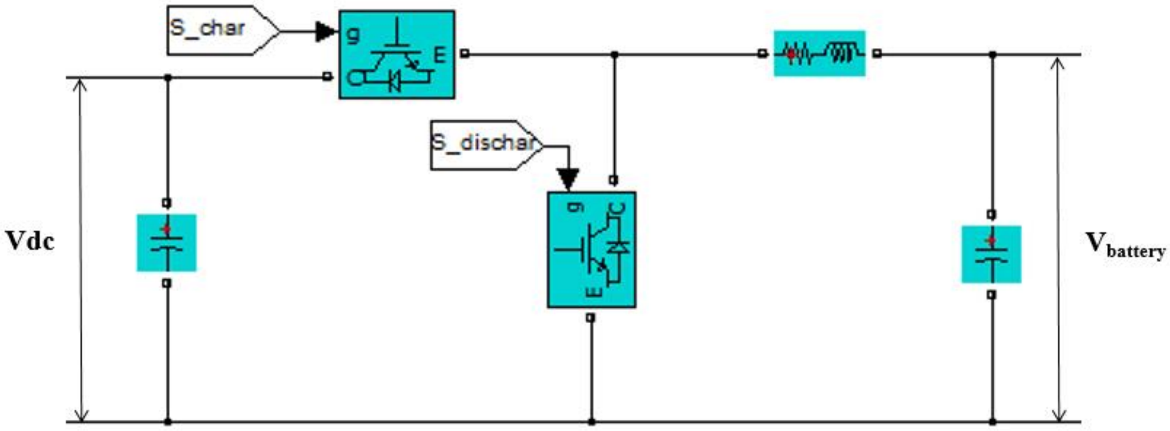


Fig. 7. Bi-directional buck-boost converter circuit in BESS

4.4.1 Charging mode: PI Control

If the supervisory control sends a charge operation command, S_char flows on ‘1’ and turns on buck converter in Fig. 8. Oversupply power in DC is injected into energy storage though switch (S1). The DC bus voltage is regulated at constant value V_{dc_up} so that the entire microgrid system notifies that battery charging is implemented. Fig. 9 shows the voltage controller in the buck converter for power regulation. The voltage controller uses PI control for fixing voltage level.

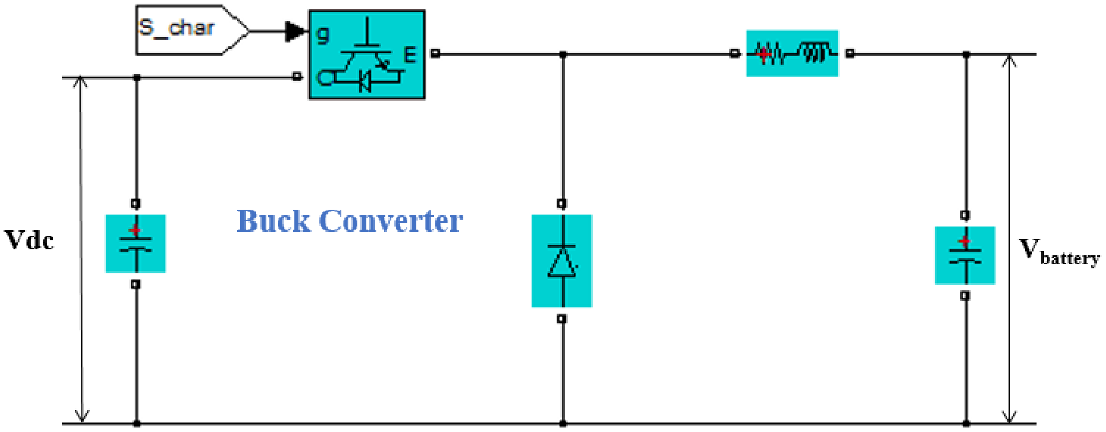


Fig. 8. Buck converter circuit in BESS

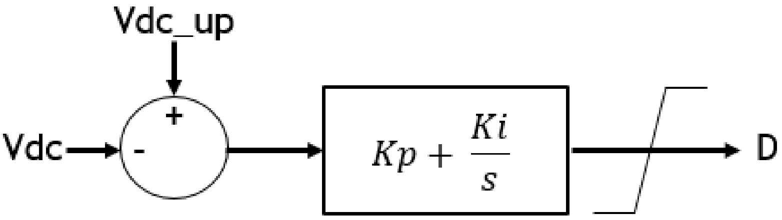


Fig. 9. PI control in buck-converter

4.4.2 Discharging mode: State-Feedback Control

If the supervisory control transfers a discharge operation command, S_dischar flows on '1' and turns on boost converter in Fig. 10. The power from energy storage releases the power in DC though switch (S2) for supply to load. The DC bus voltage is regulated at constant value V_{dc_lw} so that the entire microgrid system informs that battery discharging is implemented. Fig. 11 shows the voltage controller in the boost converter for power regulation. The voltage controller uses state-feedback control for adjusting three states, because the BESS discharge state model is unstable. To stabilize, it needs an N-order system controller. The state-feedback controller regulates three variables simultaneously. It is more efficient than to use multiple PI controllers. Raising the voltage level and streaming the power from battery voltage to DC must coincide.

Accordingly, state-feedback control satisfies simultaneous action. This control considers battery voltage, DC voltage, and inductor current. By controlling inductor current, boost converter can coordinate quantity of current.

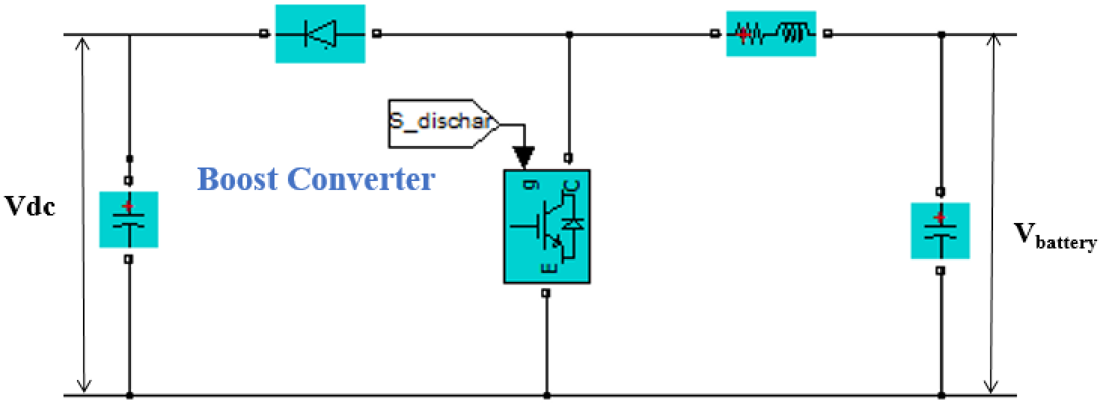
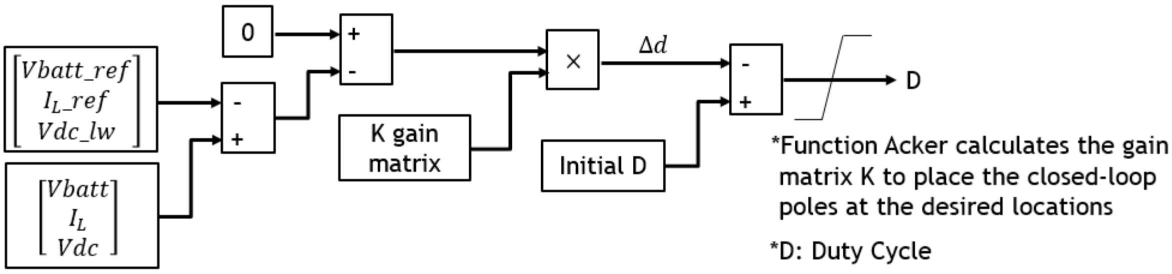


Fig. 10. Boost converter circuit in BESS



*Function Acker calculates the gain matrix K to place the closed-loop poles at the desired locations

*D: Duty Cycle

Fig. 11. State-feedback control in boost-converter

4.5 Grid-Inverter Control

A power controller of the grid inverter in Fig. 2 may be constructed in two types according to the operation modes of the microgrid system.

1) Mode 1-grid-connected mode: The common DC bus voltage is regulated at a constant value so that real power generation from the grid into the microgrid system. In addition, AC-DC converter mitigates the power fluctuation for stability of DC grid.

2) Mode 2-islanded mode: The microgrid controller regulates the real power balance between PV array, load, and energy storage. That always monitors the amount of power stream and controls voltage level at a DC grid.

4.6 Current Controller for multiple microgrids

Previous supervisory control techniques considered a microgrid control strategy for improving demand and supply power balance using BESS. However, this technique regulates only common DC bus voltage level. To utilize multiple microgrids, the controls require not only a voltage controller but also a current controller. Each microgrids has a microgrid control center. That center monitors demand and supply power of own microgrid. In addition, it compares both monitored and reference values of demand and supply power. First, the voltage controller operates for adjusting the DC voltage level. After that, each microgrid carries out the current controller operation that is similar to the voltage controller concept. The current control is to regulate the DC current within a specific band in each microgrid. By the current control, the charger/discharger operations are determined in such a way that the DC current should not violate the specified upper and lower limits, I_{load_up} and I_{load_lw}. The BESS operation mode determines according to the scheme as below:

If $I_{load} > I_{load\_up}$, then charging → $I^*_{load} = I_{load\_up}$

If $I_{load} < I_{load\_lw}$, then discharging → $I^*_{load} = I_{load\_lw}$

If $I_{load\_lw} \leq I_{load} \leq I_{load\_up}$, then no control (rest)

If the DC current I_{load} becomes larger than the upper limit, it regards the state as oversupply. At that time, the charge operation mode begins with the current command I^*_{load} equal to the upper limit, a release charging operation command, and continues until the DC current reaches the limit. When I_{load} goes below the lower limit, then the current level is bound at the lower limit and the discharge operation mode starts operating in boost mode as delivered discharging operation command at BESS. Each microgrids carries out independently to operate their own BESS control operation.

Ⅴ. PERFORMANCE EVALUATION

Simulation was carried out to analyze the dynamic performance of the proposed control strategies. A 100-kW PV/BESS microgrid system was considered. The PV array, battery storage, and load were represented by models available in [21]-[23].

5.1 Control Performance of the microgrid system

Control performance of the microgrid system and its individual components was simulated. The microgrid system was set to a power-rest mode. PV system response to changes in solar irradiance is presented in Fig.12, where PV array voltage traced the desired value well. Fig. 13 shows the MPPT performance. The curves are power versus voltage curves of the PV array for various solar conditions, and the dots are array-operation points The PV array was operating very close to the peak points under the varying solar condition. Fig. 14 presents the load control performance. In the DC grid voltage maintained between the upper (504V) and lower (496V) limits, load voltage level is regulated by PI control at 220V within tolerance (τ). Fig. 15 presents the BESS control performance. The DC grid voltage was maintained between the upper voltage and lower voltage limits, which did not cause excessive mode shifts in BESS. Fig. 16 resents power-generation curves for the microgrid system and its components. The grid inverter injected power into the grid during the simulation time. The PV source was operating at each maximum power point. When the summed power of grid and PV sources became larger than the pre-set value, the battery started being charged and its power turned negative. Once the two sources could not generate the set value, the battery started operating in discharging mode so that the grid-injected power became the set value.

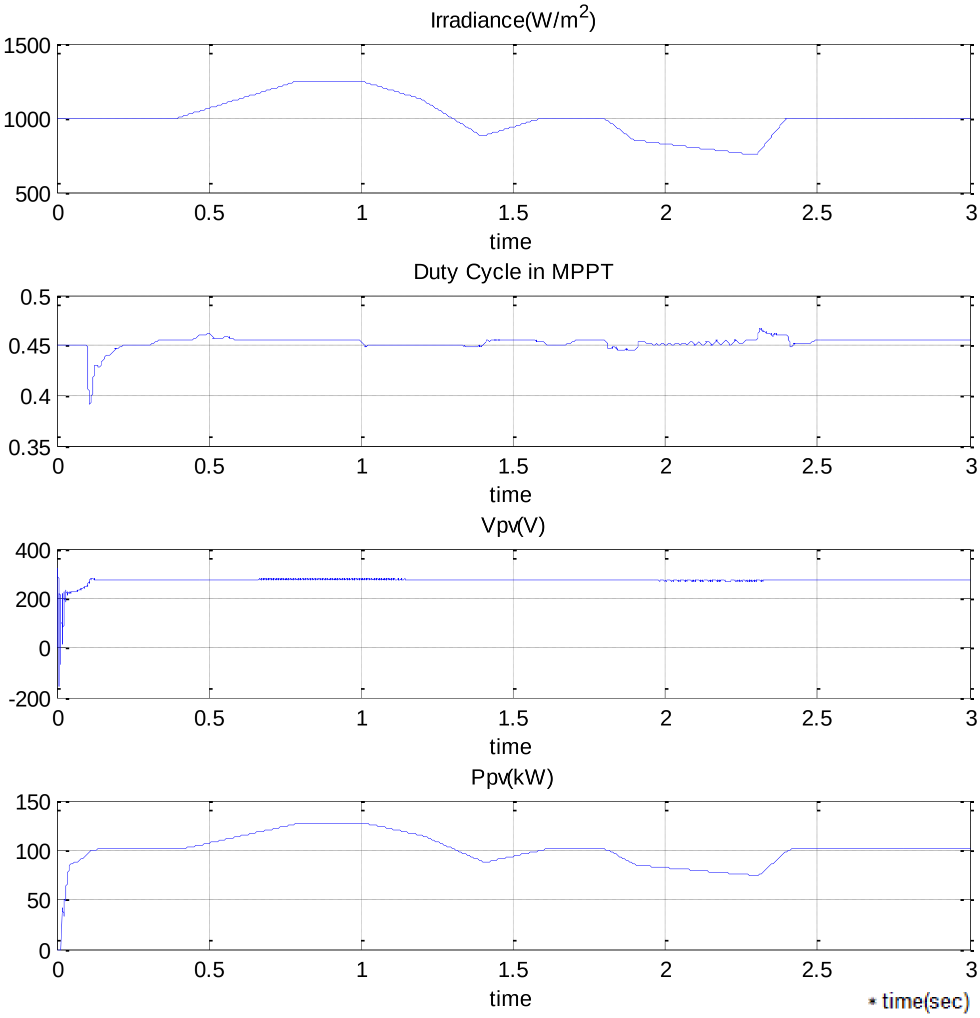


Fig. 12. PV system performance

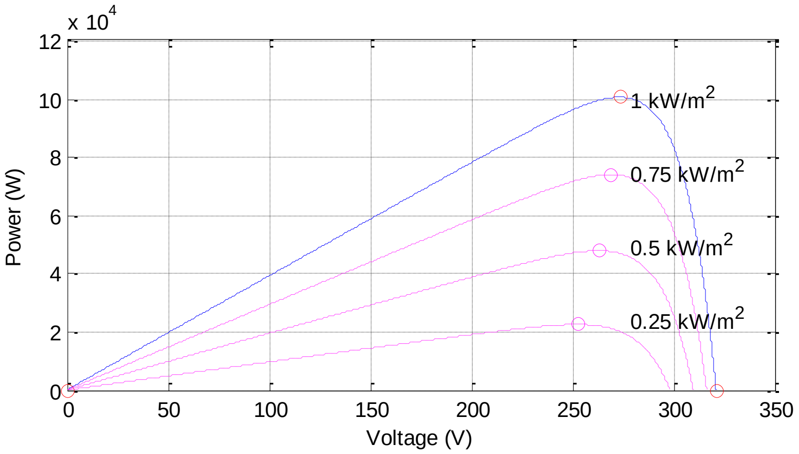


Fig. 13. MPPT performance

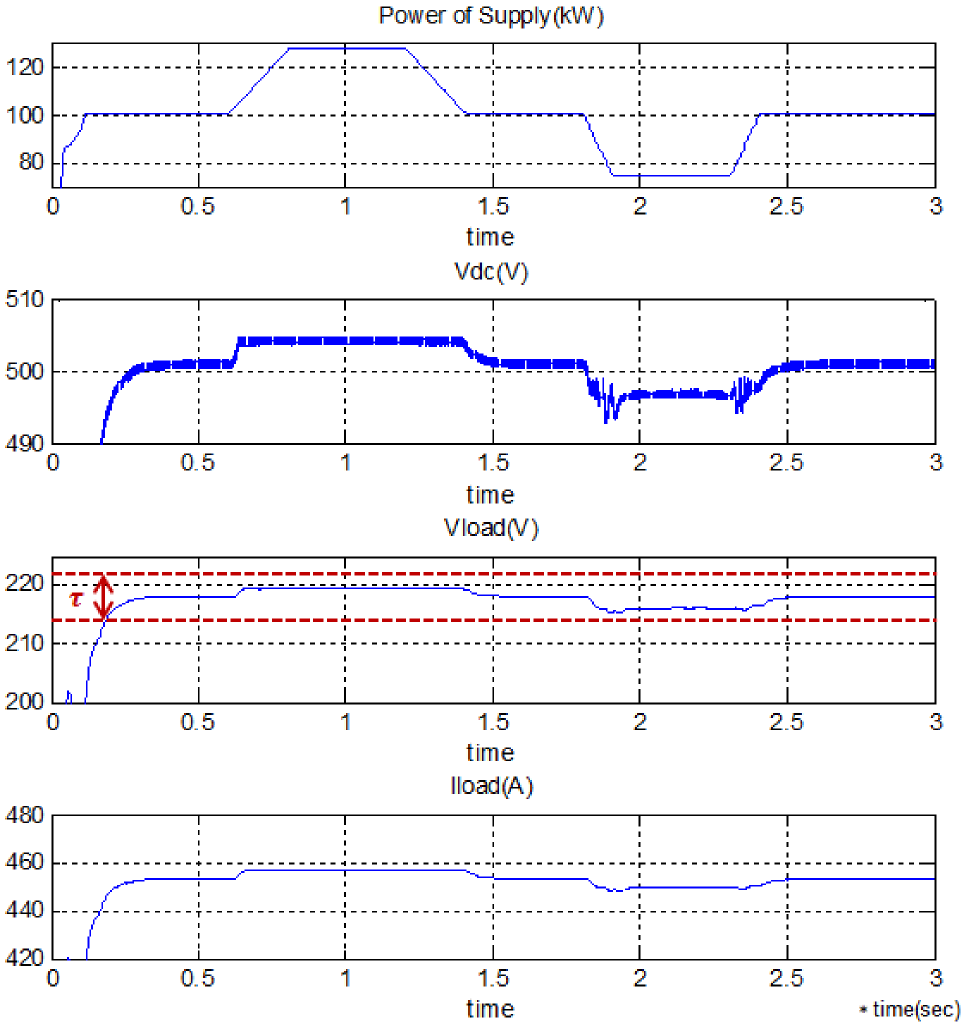


Fig. 14. Load Control performance

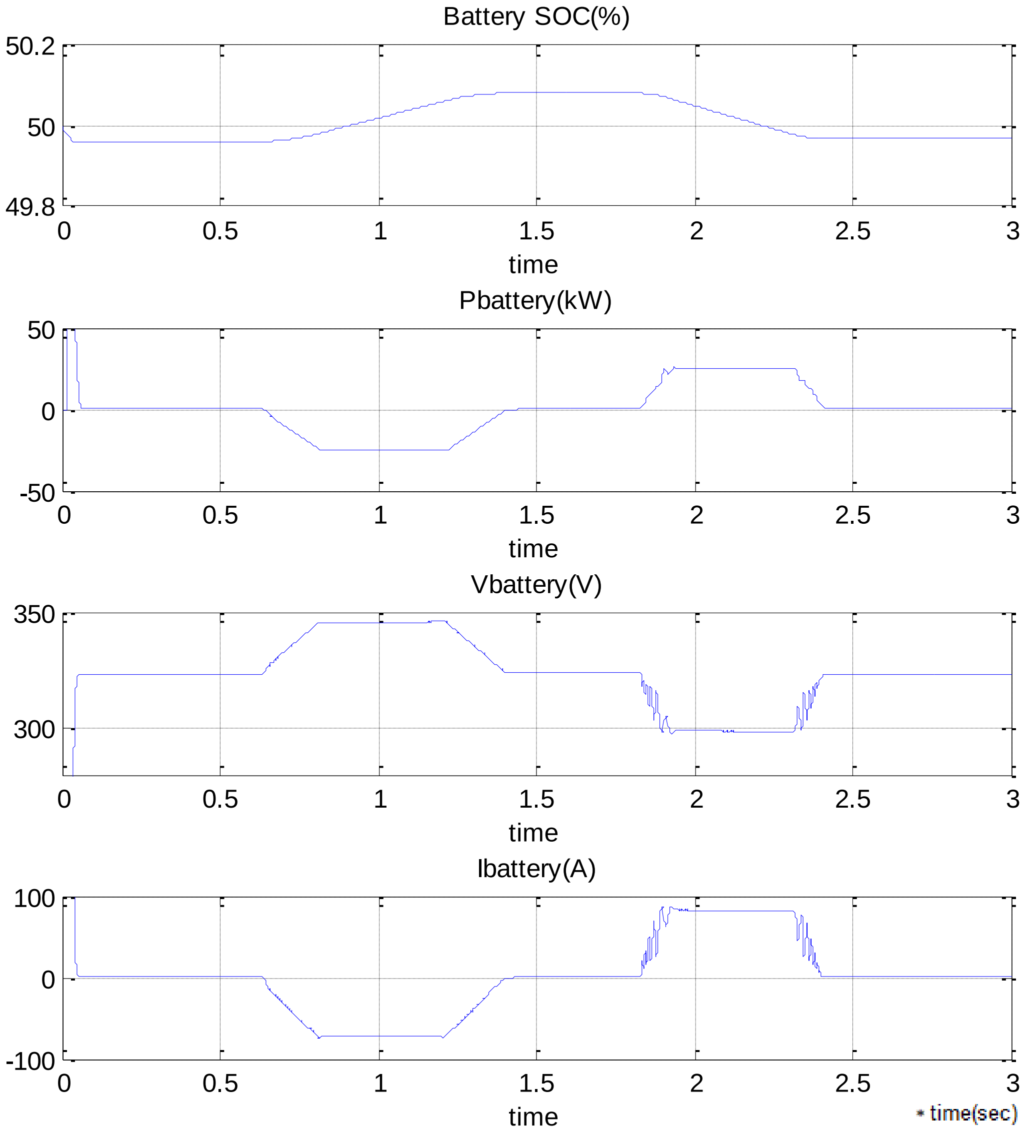


Fig. 15. BESS performance

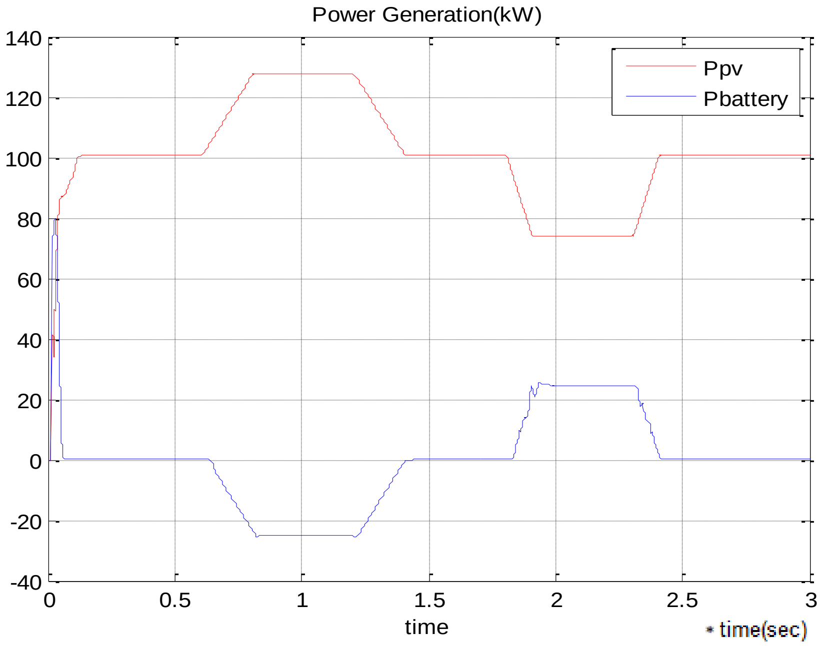


Fig. 16. Power generation of the microgrid system

5.2 Microgrid Operation Performance

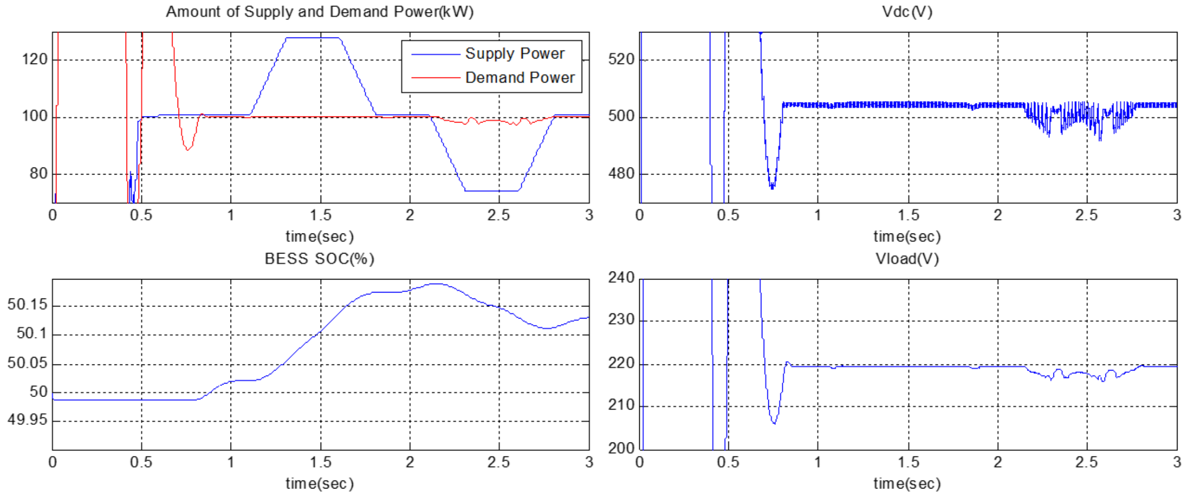


Fig. 17. Microgrid Operation in grid-connected mode

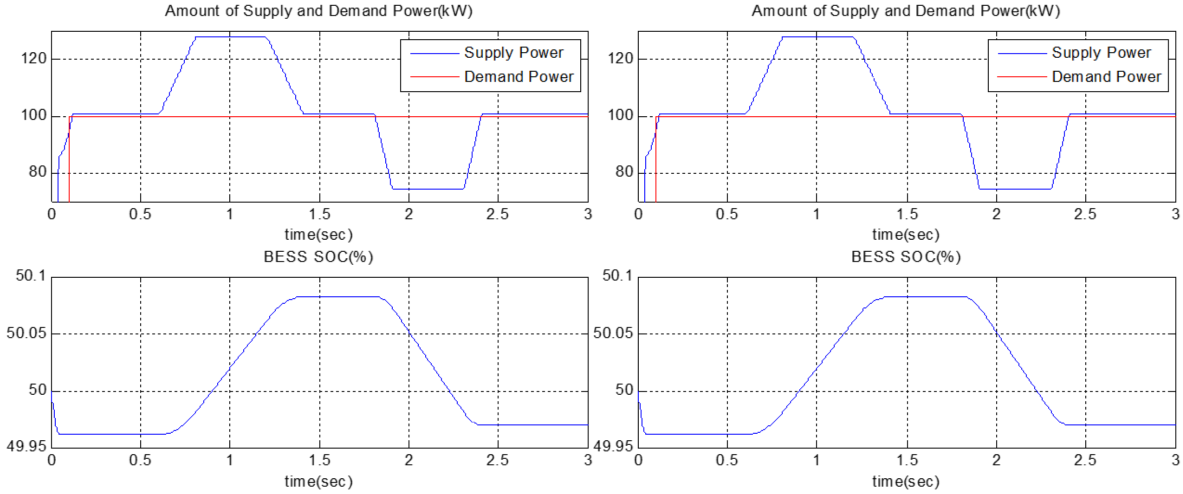


Fig. 18. Microgrid operation in Islanded mode

Microgrid system operates in two modes, which are a grid-connected mode and an-islanded mode. The grid-connected mode connects with utility-grid and operates AC-DC inverter for converting three-phase from DC voltage and current. Left power injected to microgrid system, should operate supervisory controller and mitigates voltage level at 500V. Fig. 17 shows grid-connected mode operation in the microgrid system. The microgrid controller turns on at t=0.8s (second) to see the effect. Previous 0.8 second states do not care but turning on state is different. Supply and demand power amount follow desired-power amount. In addition, the voltage level of the DC grid and load include the desired scope. The islanded mode operates independent, disconnect with the utility-grid. So, if the supply is lack, energy storage supplies the lack of power to load. Microgrid controller monitors supply and demand power amount. When the lack of power occurs, it turns on discharging mode of energy storage system. On the contrary to this, in case of exceed power, the controller turns on charging mode of energy storage system. In result, energy efficiency improves because certain power does not waste anywhere. Fig. 18 shows the result of microgrid system well. When supply amount is larger than the demand power, voltage level is regulated by charging controller at 504V. On the other hand, when demand power amount is larger than the supply power, voltage level is regulated by discharging controller at 496V.

5.3 Multiple Microgrid Performance

Fig 20-23 shows multiple microgrid performance applying our control strategy. Existing battery controller only controlled using measured V_{dc}. However, multiple energy storage systems are linked in the grid, each microgrids should not control independently. In other words, power of microgrid 1 transfers into microgrid 2 without any command from the microgrid control manager. Fundamental measurement value is voltage, current, and phase in the power network. Our previous control strategy only uses voltage measurement. That cannot control power stream of multiple microgrids. We introduce the current controller in supervisory control. Using the measured current value, each BESS only regulate their microgrid power. To confirm function improvement, microgrid 1 and microgrid 2 are connected as shown in Fig. 19. The simulation carries out possible various scenarios as follows.

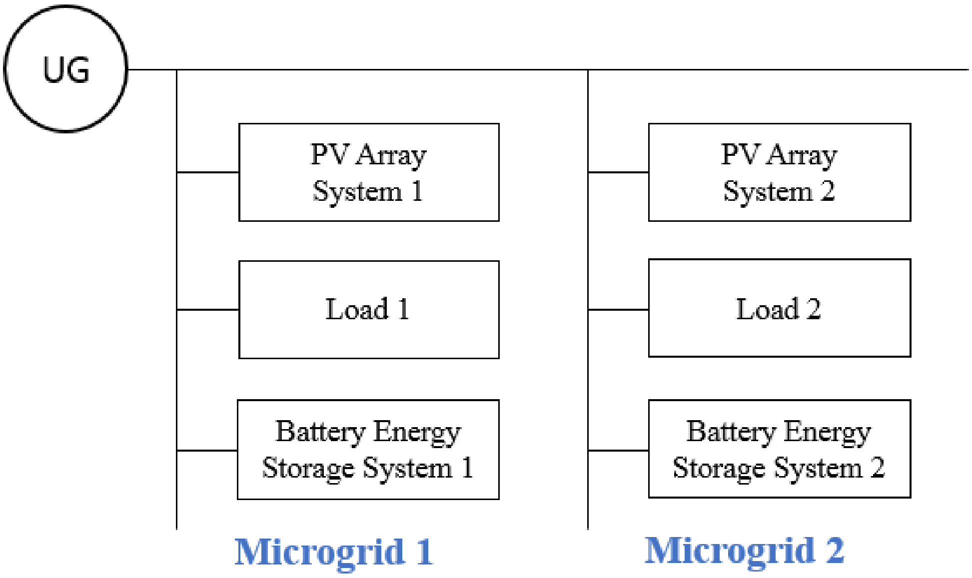


Fig. 19 Linked microgrid 1 and micrgrid 2

1) Microgrid 1: Supply > Demand or Supply < Demand, Microgrid 2: Supply=Demand
   Microgrid 1: Supply=Demand, Microgrid 2: Supply > Demand or Supply < Demand

   In microgrid 1, supply power is larger than demand at 1.2s~1.8s in Fig. 20. That time, microgrid 1 energy storage SOC increases, in other words power charging operates. In comparison with microgrid 1, microgrid 2's balance between consumption and production is constant and the difference error is close at 'zero'. In addition, microgrid energy storage SOC does not change. Moreover, microgrid 1 and microgrid 2 is acceptable added current controller. The result is same if the situation of microgrid 1 and microgrid

2 is exchanged in Fig. 21.

2) Microgrid 1: Supply > Demand, Microgrid 2: Supply > Demand
Microgrid 1: Supply < Demand, Microgrid 2: Supply < Demand

These scenarios have same situation with microgrid 1 and microgrid 2 in Fig. 22-23. If the current controller is not, remaining power will charge single energy storage. It's the same situation that only energy storage will discharge the power into multiple microgrids if the current controller does not operate. Microgrid 1 and 2 change the production at 0.8s~1.7s in Fig. 22. That time, energy storage SOC of microgrid 1 and microgrid 2 rises up. The DC voltage level is V_{dc_up} because all microgrids are charging operating. The result is same that the power of microgrid 1 and microgrid 2 is lack in Fig. 23.

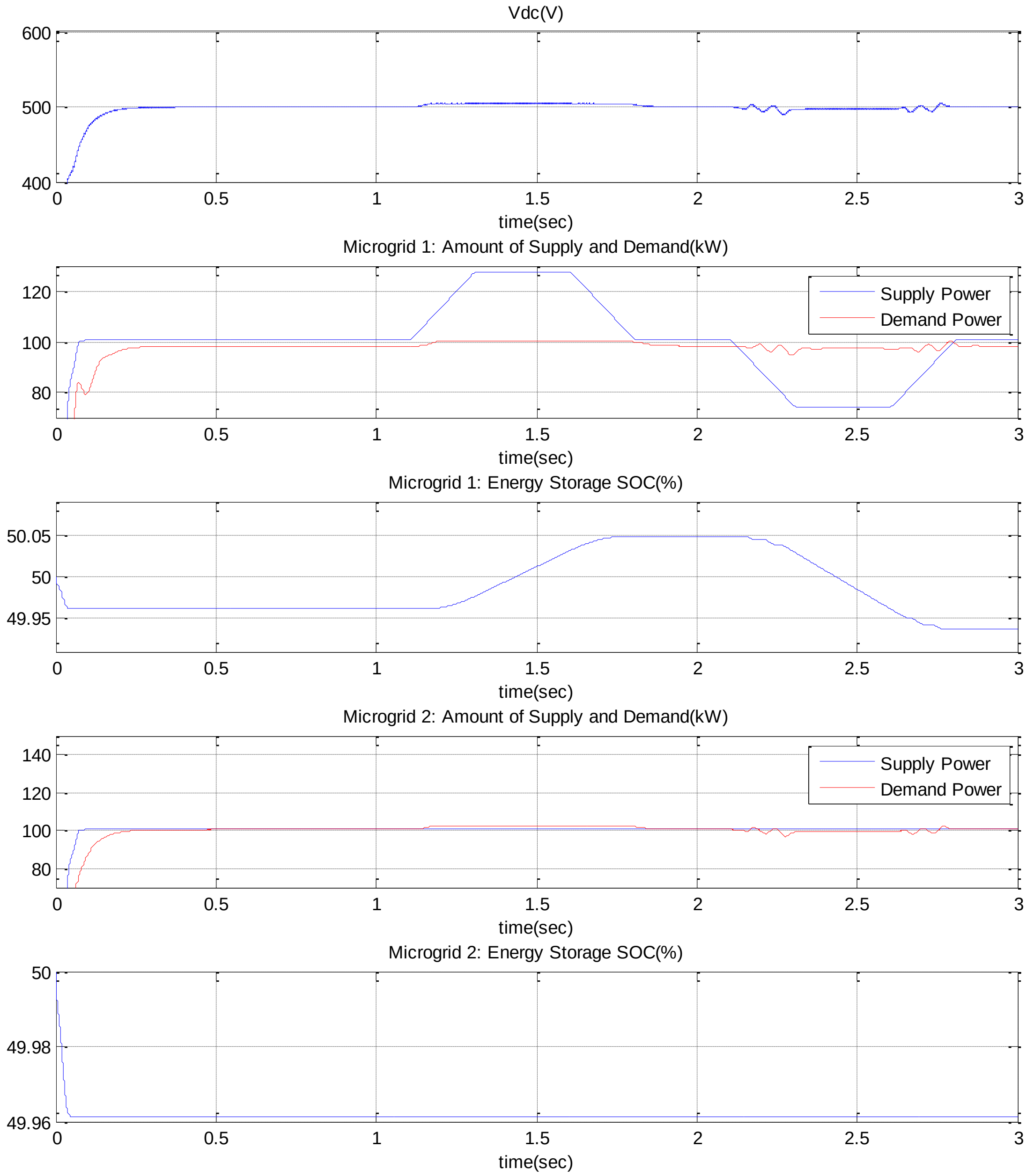


Fig. 20. Microgrid 1: Supply > Demand or Supply < Demand

Microgrid 2: Supply = Demand

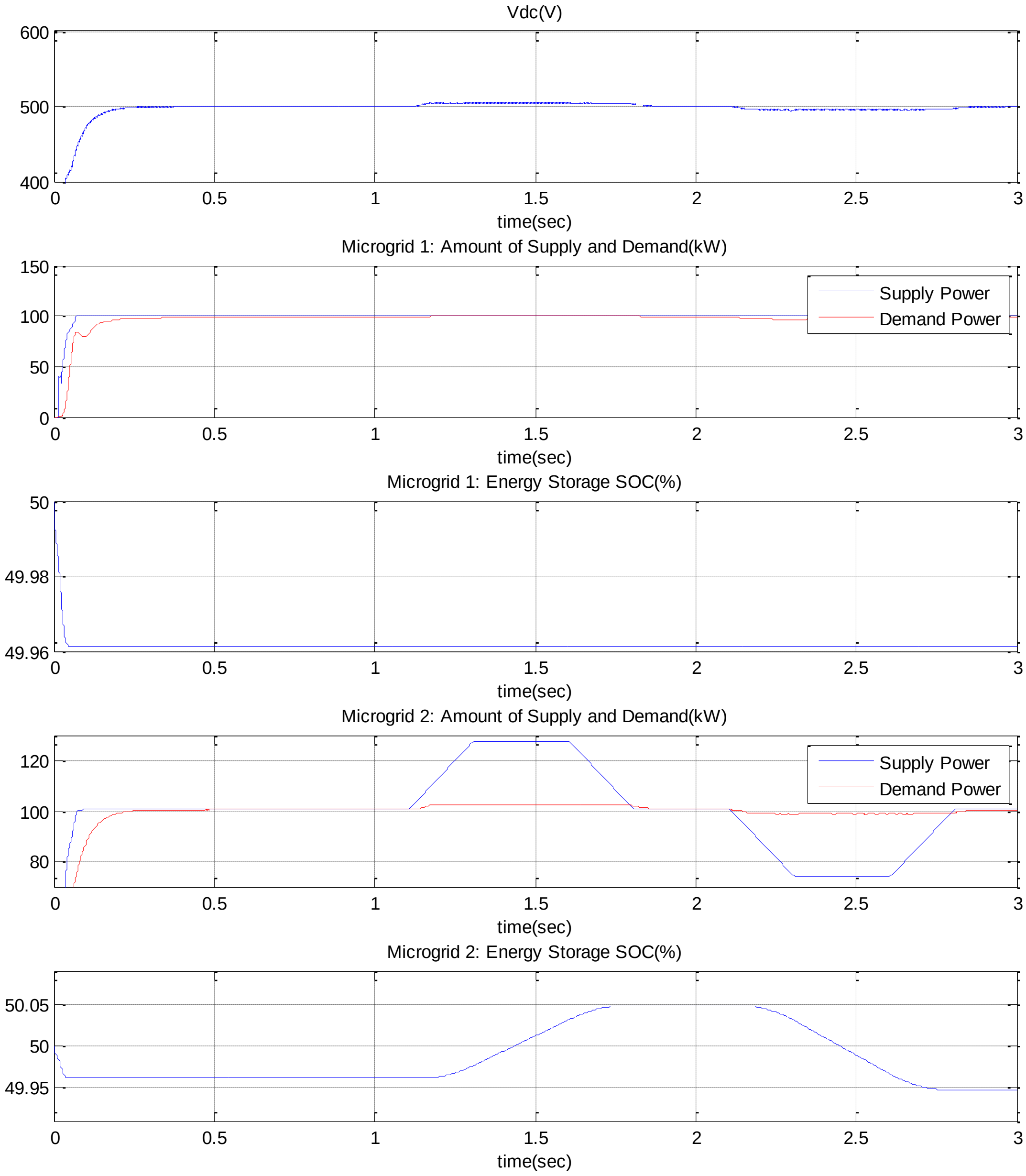


Fig. 21. Microgrid 1: Supply = Demand

Microgrid 2: Supply > Demand or Supply < Demand

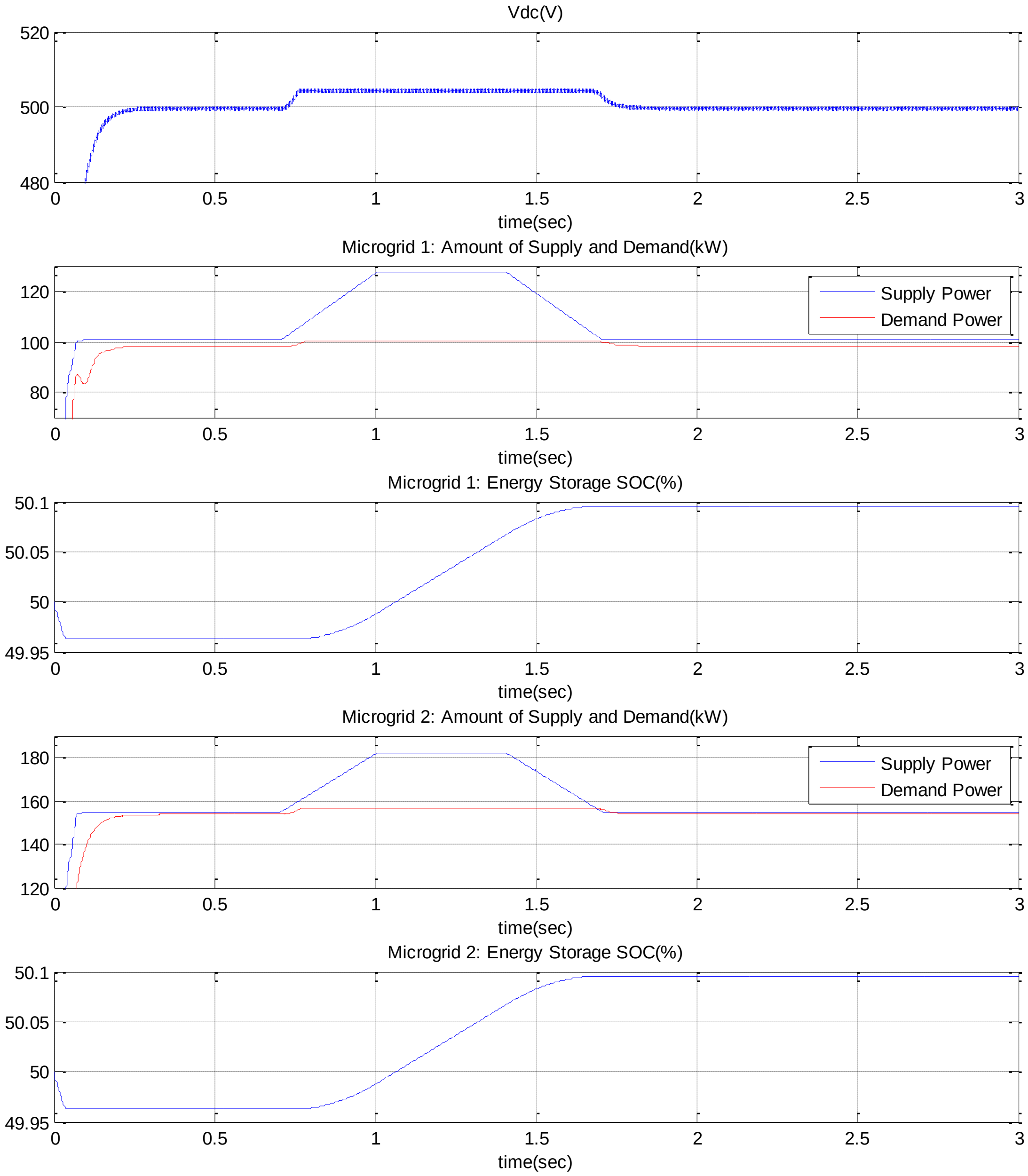


Fig. 22. Microgrid 1: Supply > Demand

Microgrid 2: Supply > Demand

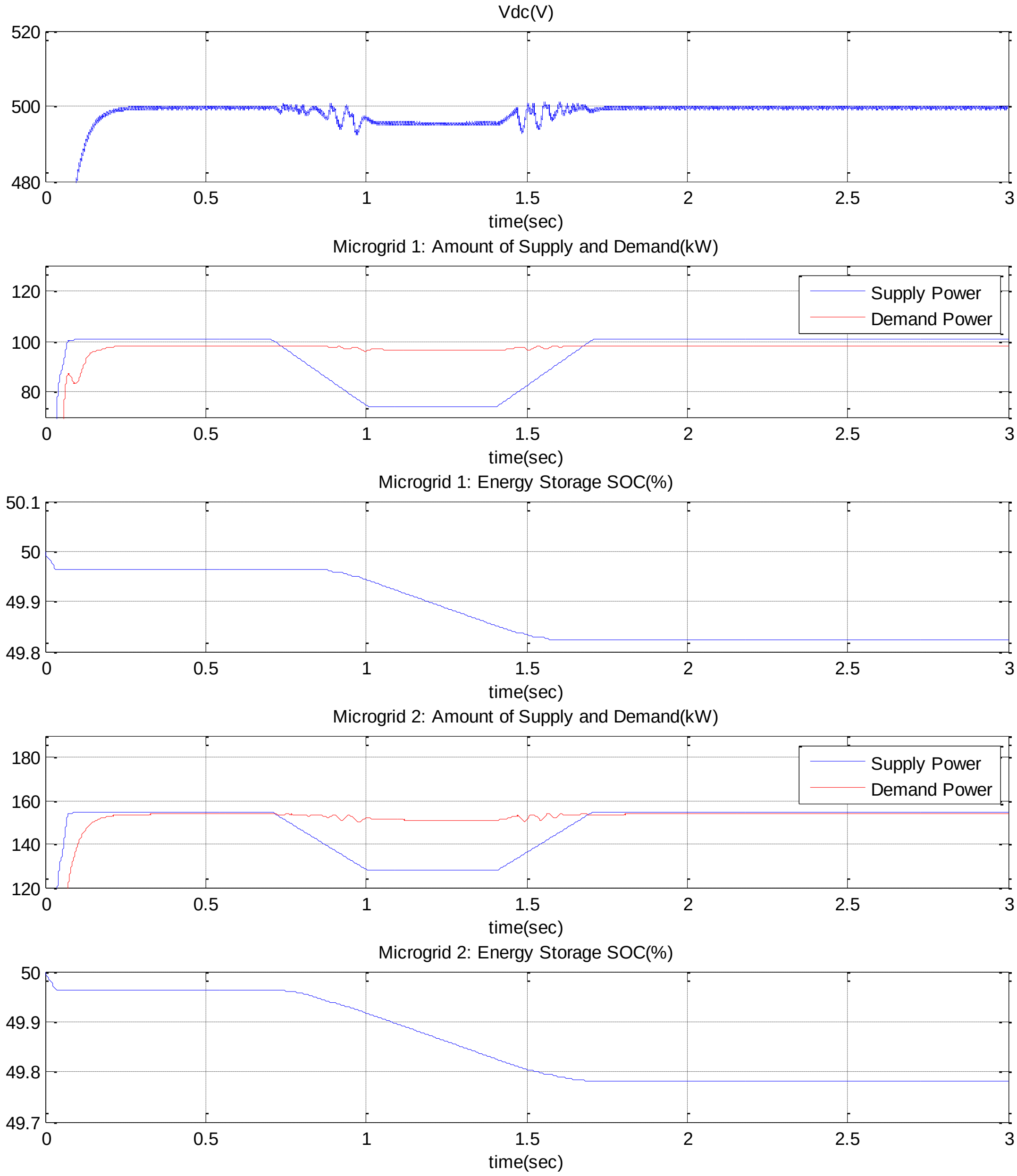


Fig. 23. Microgrid 1: Supply < Demand

Microgrid 2: Supply < Demand

Ⅵ. CONCLUSION

In this thesis, supervisory-control strategies for improving power efficiency of a grid-connected PV/BESS microgrid system have been proposed. Charging and discharging modes of operation were added for flexible operation and improvement in the quality of power delivered to the energy storage. A state-feedback control was applied for relieving the excessive use of battery storage. The proposed control offers grid- or user-friendly options in operating modes. Dynamic modeling and simulations of the microgrid system under the proposed control strategies were carried out using MATLAB/Simulink. A 100-kW microgrid system and its supervisory-control system was developed and tested. Simulation results provided various dynamic characteristics of the proposed control scheme, which enabled comprehensive quantitative and qualitative analysis. Simulation results confirmed the feasibility of the proposed control and showed the effect of energy storage introduction. Simulation results showed good qualitative agreements in dynamic performance of the proposed control schemes. From simulation results, we verified the following.

1) The supervisory control successfully coordinated the individual components of the microgrid system to operate in a dynamically stable way under the proposed modes of operation for improving power efficiency.
2) The individual sources, PV array, could generate the maximum power regardless of not only behaviors of the grid inverter or battery but also operation modes of the microgrid system.
3) The state-feedback control of the battery enabled the microgrid system to efficiently operate, particularly in terms of dynamic behavior, in the proposed modes of operation

under demand and supply power imbalance.

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요 약 문

전력 효율성 개선을 위한 스마트 그리드 제어 전략

우리나라는 여름철과 겨울철에 전력의 과다 사용으로 인하여 전력 수급에 대한 문제가 발생되고 있다. 이에 전력 수요와 공급의 차이를 완화시켜서 전력 수급에 대한 문제를 해결하고자 한다. 따라서 본 논문에서는 마이크로그리드 시스템의 에너지저장장치를 이용하여 전력 수급에 대한 문제점을 개선시키기 위해 스마트그리드 제어 전략을 연구하였다. 마이크로그리드 시스템은 태양광 시스템, 수용가, 그리고 배터리 에너지 저장장치로 결합되어 있고 모두 직류 배전과 연계되어 있다. 스마트그리드 제어 전략들은 마이크로그리드의 독립적 모드와 계통 연계 모드를 가능하게 하는 동작을 포함하고 있으며, 배터리 사용이 불필요한 휴먼상태, 전기 에너지 충전, 그리고 전기에너지 방전 상태로 정의 된다. 최상위 제어는 제안된 상태를 동작시키기 위해 각 장치와 구성원들의 전력 생산을 규제하였다. 또한, 본 논문에는 마이크로그리드의 시스템의 원리와 제어 개념들이 설명되어 있다. 시뮬레이션과 모델링은 MATLAB/Simulink 를 이용하였으며, 100kW 의 전력 수요와 생산이 이루어지는 마이크로그리드 제어 시스템을 구현하였다. 시뮬레이션 결과로는 제안된 동작 상태가 구현된 마이크로그리드 시스템에서 다양한 시나리오를 실험하여 전력 수요와 공급의 차이를 완화시킬 수 있음을 확인하였다.

핵심어: 스마트 그리드, 에너지 저장장치, 마이크로 그리드, 스테이트 피드백 제어