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태양광 기반의 가변속 하이브리드 시스템을 위한 직류 전압 제어

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DC-Voltage Regulation for Solar-Variable Speed Hybrid System

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Abstract

Recently, the interest in DC systems to achieve more efficient connection with renewable energy sources, energy storage systems, and DC loads has been growing extensively. DC systems are more advantageous than AC systems because of their low conversion losses. However, the DC-link voltage is variable during operation because of different random effects. This study focuses on DC voltage stabilization applied in stand-alone DC microgrids by means of voltage ranges, power management, and coordination scheme. The quality and stability of the entire system are improved by keeping the voltage within acceptable limits. In terms of optimized control, the maximum power should be tracked from renewable resources during different operating modes of the system. The ESS and VSDG cover the power shortage after all available renewable energy is consumed. Keeping the state of charge of the ESS within the allowed bands is the key role of the control system. Load shedding or power generation curtailment should automatically occur if the maximum tolerable voltage variation is exceeded. PSIM-based simulation results are presented to evaluate the performance of the proposed control measures.

Key words: DC microgrid, State of charge, DC voltage regulation, Variable speed diesel generator, Voltage variation.

1. Introduction

Renewable energy integration in today's power production system has been considered as a feasible solution in microgrid technology[1]. As the central controlled microgrid needs a real time feedback based on communication from the entire system to the central controller, it needs a high speed data exchange. But it is not preferable in stand-alone DC microgrid (DCMG) because it may result to the reduction of system reliability due to possible communication errors and delay time. Contrarily, the voltage droop control can be utilized so that all units may be controlled autonomously using real time data detected locally[2],[3].

DCMG control system has to make sure that some changes can occur in the system[4], for example one source, energy storage system (ESS) or some loads may be removed from or added to the system anytime depending on present circumstances. It should also be capable to assure the optimum power flow balance, and finally to enable the ESS to compensate the possible voltage fluctuation and to support the system to reduce or rise the power surplus or deficit

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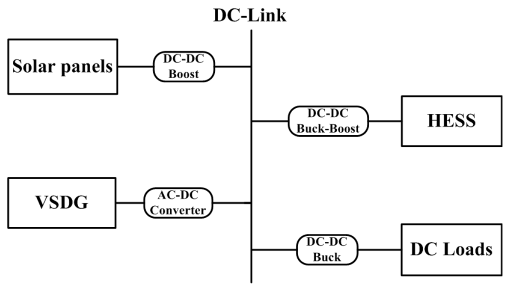

Fig. 1. Configuration of hybrid DC microgrid system.

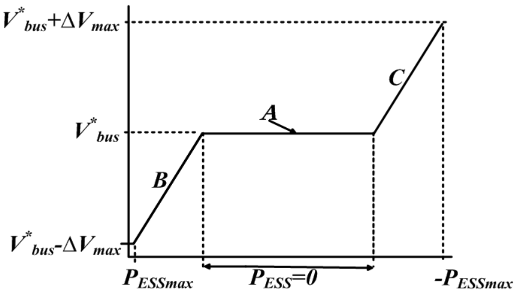

Fig. 2. Proposed operation system.

accordingly[2],[5],[6].

In principle, as previously studied[7], the diesel generator must be designed to meet the average load. The use of variable speed diesel generator (VSDG) in a stand-alone DCMG results to the improvement of energy efficiency[8] and the fuel consumption reduction compared to the constant speed diesel generator (CSDG) and this increases the reliability of whole system.

Various reports about DCMG control and its applications have been published, such optimal control strategies[9], droop control[10]-[12], supervisory control for energy cost management[13], Fuzzy control and Gain-scheduling technique[14], etc...

The decoupling of low and high frequency power components based method which used battery's current error component to control the super-capacitors (SC) was proposed[15]. The combined energy storage (batteries and SC) with high energy and power density to stabilize the power flow in the system was studied[16].

Many frameworks on AC/DC microgrids were reported. The operational mode classification of the hybrid AC/DC microgrid according to the power flow was discussed[17],[18]. The comparison between AC and DC microgrids with distributed energy resources was studied[19]. This comparison reveals that DCMG systems will be the right candidates for the energy systems in the future with the influence of the electrical system projected to increase the number of DC powered components for residential and industrial application.

Therefore, to maintain the DC voltage of grid, the description of designing a controller that based on the combination of current mode control (CMC) and linear quadratic regulator (LQR) control method was studied[20].

This paper discusses a method to regulate DC voltage that follows a proposed operating scheme of power management and power sharing priorities in DCMG, as well as coordinating its components using well-designed controllers that present high performance with constant power loads (CPLs). Fig. 1 shows the configuration of DCMG to consider in this paper.

Furthermore, this paper is organised as follows: Section Ⅱ presents the operation modes and control methods to achieve a voltage regulation. Section Ⅲ contains the simulation results of the system in different cases. The conclusion is made in section Ⅳ.

2. Proposed operation and control strategies

2.1 Operation system

Fig. 2 shows the proposed operation ranges of DCMG system. It can be divided into three operation ranges that operate in two modes (VSDG ON or OFF).

Operation range A:

In this range, the system operates properly at a regulated voltage which equals to the DC-reference bus voltage V_{bus}^{*} and the total available power meets the load demand in a coordinated way as described by flowcharts shown in Fig. 3 and Fig. 4. The ESS is operated to eliminate the voltage fluctuations from the system, so it can be charging or discharging in order to maintain the bus voltage constant.

In mode 1 (VSDG OFF), the PV power P_{PV} and the ESS power P_{ESS} together meet the load demand. The ESS may be in charging or discharging mode but the main concern in this range is that the voltage variation stays approximately zero ($\Delta V \approx 0$).

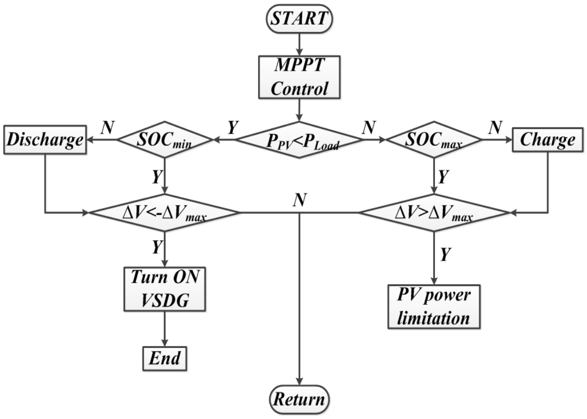

Fig. 3. Proposed operation algorithm for mode 1.

$$P_{PV} + P_{ESS} = P_{Load} \tag{1}$$

In mode 2 (VSDG ON), the voltage variation keeps being approximately zero; firstly, after the generator power P_G is increased or added to the system, and/or after the load shedding is applied on the system when the voltage variation ΔV gets under the minimum tolerable voltage degradation ($\Delta V < -\Delta V_{\max}$). Secondly, after the generator power is decreased or removed from the system, and/or after the PV power is curtailed when the voltage variation ΔV gets over the maximum tolerable voltage degradation ($\Delta V > \Delta V_{\max}$). In this case, the ESS may be in charging or discharging mode.

$$P_{PV} + P_G + P_{ESS} = P_{Load} \tag{2}$$

Operation range B:

The system is said to be operating in range B if the total output power (PV power, generator power, and ESS power) is lower than the load demand under the condition that $-\Delta V_{\max} \le \Delta V < 0$. In such conditions, the ESS stays in discharging mode and its power is noted P_{ESS_D}.

In mode 1, the photovoltaic power P_{PV} and the ESS discharging power P_{ESS_D} both cannot satisfy the load demand. The voltage variation ΔV remains lower than zero and greater than or equal to the minimum tolerable voltage degradation.

$$P_{PV} + P_{ESS_D} < P_{Load} \tag{3}$$

In mode 2, the same condition may occur even when the VSDG runs at any speed if a negative ΔV is still greater than or equal to $-\Delta V_{\max}$.

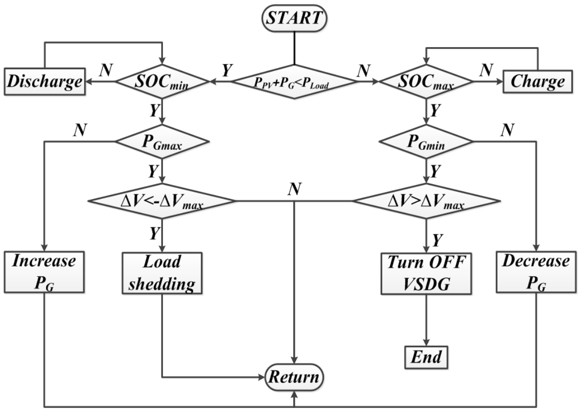

Fig. 4. Proposed operation algorithm for mode 2.

$$P_{PV} + P_G + P_{ESS_D} < P_{Load} \tag{4}$$

Operation range C:

The voltage variation is caused by the power flow unbalance due to the lower load demand or the higher power production. In this range, the voltage variation condition is $0 < \Delta V \le \Delta V_{\max}$. The ESS keeps the charging mode in this conditions and its power is noted P_{ESS_C}.

In mode 1, the photovoltaic power P_{PV} is much higher than the load demand, so the ESS charging power P_{ESS_C} cannot remove all excessive power from the system. Depending on the power surplus amount, the voltage variation ΔV varies between zero and $\Delta V_{\max}$ as defined above.

$$P_{PV} + P_{ESS_C} > P_{Load} \tag{5}$$

In mode 2, this situation may occur when VSDG is running. If the voltage variation keeps being in the range C's band at any speed of the generator, (even at the minimum speed), in this case, the system is said to be in the range C of mode 2.

$$P_{PV} + P_G + P_{ESS_C} > P_{Load} \tag{6}$$

2.2 Control system

2.2.1 Droop control for DC microgrid

Consider two parallel sources sharing a common load as shown in Fig. 5. Any voltage difference

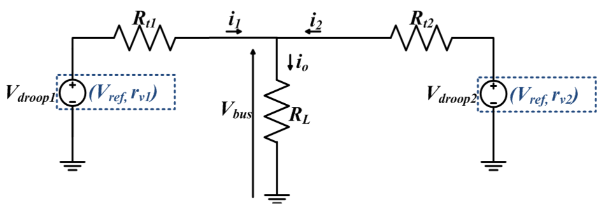

Fig. 5. Equivalent circuit of DC grid with two sources.

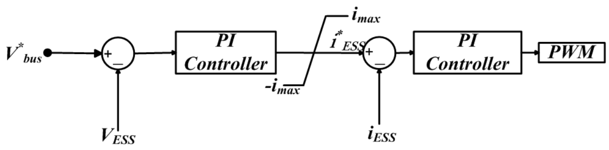

Fig. 6. ESS control block diagram.

between sources must result in current circulation between DC sources. This control regulates the output reference voltage by means of reducing linearly the output rated voltage as the output current increases with virtual output impedance of sources.

The regulated V^*_{droop} is used by the controller so that the stable operation can be ensured.

$$V^*_{droop_2} = V_{ref} - r_{v_2} i_2 \tag{8}$$

2.2.2 Storage control

In storage control system as shown in Fig. 6, the ESS output voltage V_{ESS} is compared to the reference bus voltage V^*_{bus} and the error is sent to the PI controller to find the reference current of the storage system i^*_{ESS}. The current limiter is added to assure the ESS protection by limiting i^*_{ESS} in $[-i_{\max}, i_{\max}]$ interval. Then the difference between i^*_{ESS} and the storage current i_{ESS} is sent to the next PI controller to generate the PWM signal.

2.2.3 PV control

The solar generator is controlled to meet the maximum power point tracking (MPPT). The PV voltage V_{PV} and PV current i_{PV} are checked by MPPT to obtain the reference PV voltage V^*_{PV} and this later is compared to V_{PV}. The error undergoes PI control to find an appropriate duty ratio for PWM so that V_{PV} may be regulated. The PV control block diagram is shown in Fig. 7.

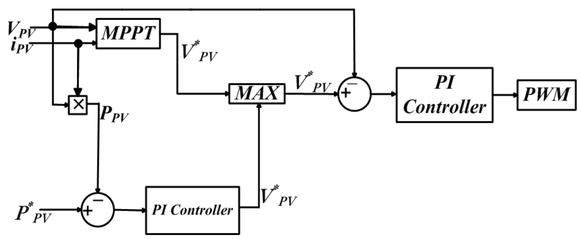

Fig. 7. PV control block diagram.

2.2.4 VSDG control

The main concern of VSDG control system is the high efficiency and energy cost issues. Different researches proved that the VSDG should be designed based on the average load in microgrid and it has to be able to meet the critical load for short periods. Typically, a VSDG presents a high efficiency and minimum fuel consumption when it is running between its minimum loading and rated values[21]. When a VSDG is working together with batteries in hybrid system, it results to the economic operation of VSDG. In mode 2 of operation, if the load power P_{Load} is greater than $P_{PV}+P_G$; the difference in power should be generated by the batteries, if P_{Load} is lesser than $P_{PV}+P_G$ then the surplus power must be stored in batteries. But when the state of charge (SOC) is out of limits or when the ESS cannot handle the power flow unbalance alone, the VSDG should be responsible of the power shortage or surplus in the microgrid by varying its output power depending on the need in the system.

In fact, as the first case, if $P_{PV}+P_G+P_{ESS_D} < P_{Load}$, then (9) and (10) are valid;

$$P_{Load} - P_{PV} + P_G + P_{ESS_D} = \Delta P \tag{9}$$

$$\text{Generator output power} = P_G + \Delta P \tag{10}$$

As the second case, if $P_{PV}+P_G+P_{ESS_C} > P_{Load}$, then (11) and (12) are valid;

$$\text{Generator output power} = P_G - \Delta P \tag{12}$$

$$P_{PV} + P_G + P_{ESS_C} - P_{Load} = -\Delta P \tag{11}$$

Generally, the VSDG output power varies on the range $[P_{G_{\min}}, P_{G_{\max}}]$ where,

$$P_{G_{\min}} \le (P_G - \Delta P) < P_G < (P_G + \Delta P) \le P_{G_{\max}}$$

3. Simulation results

PSiM simulator is used as a tool to test and valid a proposed standalone DCMG system operation. The simulated photovoltaic power is averaged to be 1200W and the rated power of VSDG is 1500W. The capacity of storage system is 750W and the load power varies from 500W to 1000W. The DC-link voltage for this study is 200V, and the maximum tolerable voltage variation ΔV_{max} equals 5% of the DC voltage link which is 10V.

Fig. 8(a) shows a stable DCMG, where the voltage remains regulated in given conditions, no matter what change in load, $\Delta V \approx 0$. The PV and ESS powers alone are enough for any load condition.

In Fig. 8(b), the behavior of the system is represented. From 0s to 0.8s, the system is balanced for different load changes. The DC-link voltage stays at a regulated value following the reference DC voltage that equals to 200V and the system operates in range A as previously defined. As the ESS stays in charging mode from 0.55s, the battery reaches the maximum state of charge, (SOC) at 0.8s. Then the charging power becomes zero, the DC voltage goes up around 204V and the system operates in range C ($\Delta V \approx 4V$).

In Fig. 8(c), the PV power is weakened from 0.2s. From 0.25s, the ESS starts the discharging mode to help PV to cover the load demand as the PV power kept being lowered. From 0.28s, ESS and PV output powers are no longer able to satisfy the load demand as the load increases and the ESS power reaches its maximum capacity, then the system operates in range B. At 0.4s the voltage degradation tends to go out of boundaries ($\Delta V \simeq \Delta V_{max}$), but the VSDG starts automatically to cover the power shortage and regulates the DC voltage to follow the reference DC voltage.

In Fig. 8(d), the voltage is regulated from the beginning till 0.4s when the PV power raises its power production from 600W to 1000W. At that time, the voltage tends to vary but the ESS changes quickly from discharging mode to charging one to stabilize the system, and then keeps eliminating fluctuations. At 0.55s, the radiation on PV cell is increased and the PV power generation changes from 1000W to 1200W, and DC voltage goes up to 202V. As the ESS is not able to consume all surplus power but the VSDG responds immediately to decrease its input power from 1200W to 800W and returns the DC voltage back to 200V. At 0.75s, the SOC upper limit was detected and the voltage starts to increase. The system operates in range B until the 0.8th second where the VSDG is turned off due to the voltage variation that is about to pass the boundaries.

4. Conclusion

This paper presents an idea of regulating the DC voltage in standalone DCMG. It proposes the way to manage the solar source, ESS and VSDG source by means of voltage ranges using a power management scheme. The droop control method can be one of the safest means to achieve the best performance of the system. The proposed operation system is verified by PSIM simulation results that shows a good performance of the system.

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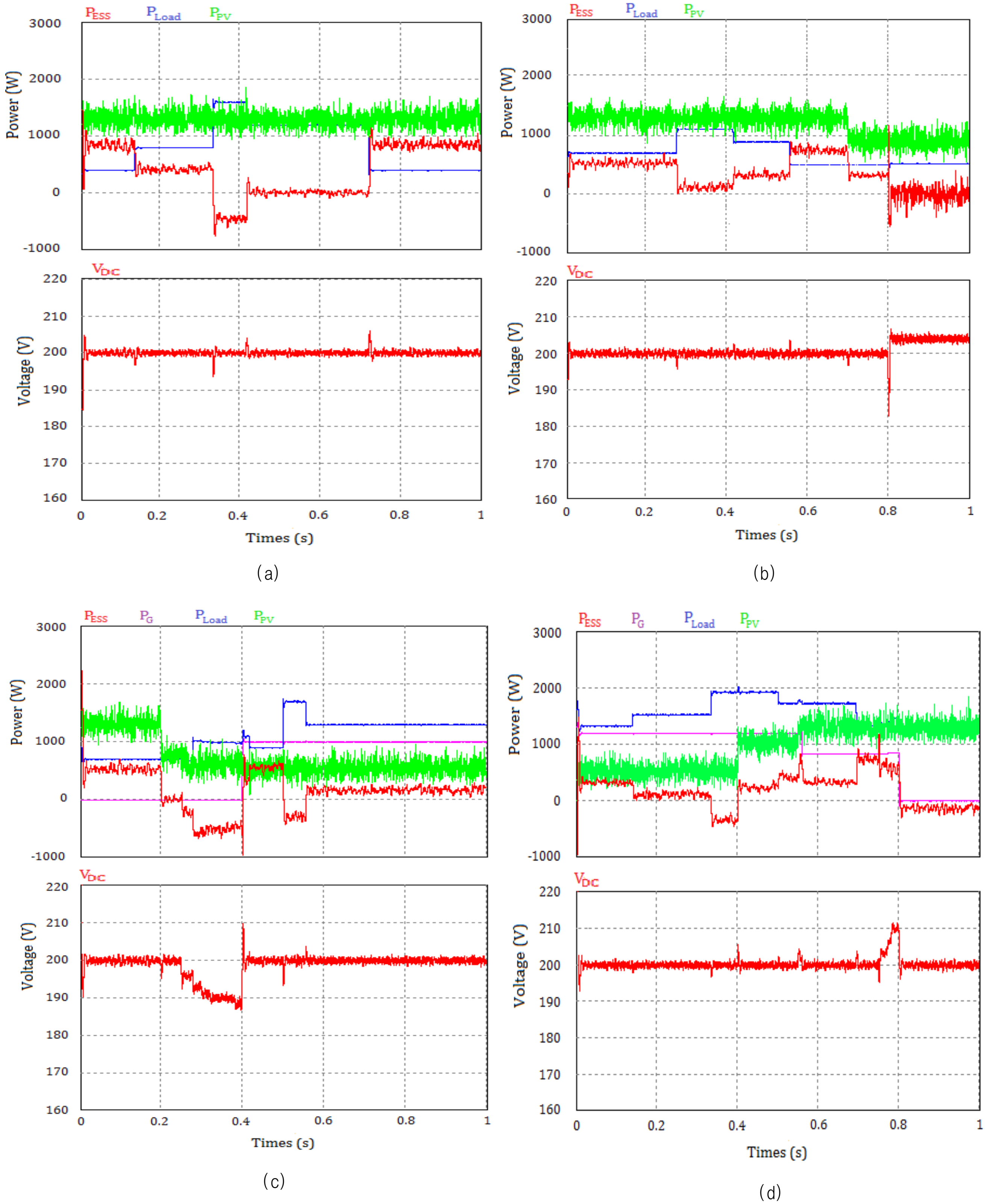

Fig. 8. Simulation results for power flow and voltage behavior: (a) Normal operation test, (b) SOC response test, (c) Emergency generation test by VSDG, (d) Fuel consumption and energy cost reduction test.

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