

A photovoltaic power generation system with peak cut function

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Abstract

This paper presents a photovoltaic-peak power cutting (PV-PPC) system capable of cutting peak load power. The proposed system is composed of a PV generator, DC-DC converter, storage battery, and an inverter. The function of the proposed PV-PPC system is to use PV energy to cut the peak load power in response to the change in the load demand and generating power. Four possible power flow scenarios are examined in detail through the bidirectional operation of the DC-DC converter and inverter, through the charging and discharging of the battery. The suggested PV-PPC system operation algorithm first selects the operational state by using differentiated charge and load information, with a simple structure to enable stopping in case of system failure, and operates depending on the selected state. Then, the analysis modeling and operational control algorithm of the PV-PPC generation system are performed in detail. Finally, the simulation and experimental results are presented to confirm the validity of the system.

Keywords: PV system, peak power cut, battery, photovoltaic-power conversion system

1. Introduction

Nowadays, the interest in clean energy sources is a focus in countries across the world due to the environmental pollution caused by fossil fuels. PV, wind, fuel, and biomass are becoming promising sources of clean energy for the future. [1]-[3] Moreover, the Kuwait government declared a policy of 'Lower Carbon and Green Growth' for the national development of renewable energy. PV energy, among all of these new regeneration energies, has the advantage to minimize the costs of operation and maintenance differently from other new regeneration energies, and studies regarding PV cells and power converters have been actively performed for some time. [4]-[9].

The existing PV-PCS (Photovoltaic-Power Conversion System) is used as an energy source. The algorithm of the existing PV-PCS has a simple structure in that the energy generated from the PV is sent to the grid. Therefore, the existing PV-PCS has the disadvantage that energy generation depends on the value of the PV radiation and temperature.[10]-[12] Therefore, it is impossible to expect a reduction effect on the peak load. A local power failure event occurred on Sept. 15, 2011 in Korea. The power failure event occurred while trying to meet preliminary power by performing a partial power failure in the country, since the preliminary wattage managed by KEPCO (Korea Electric Power Corporation) failed to respond to a sudden increase in load. The above situation suggests that cutting the peak load is important, as well as determining the time and power that the distributed power supplies will generate considering the status of the load.

This study handles the composition and control of the PV-PPC (Photovoltaic-Peak Power Cut) system that has a peak load cutting function by using energy storage devices, and suggests the operation algorithm of the system. In addition, this study intends to verify feasibility through simulation and experimental case studies of the suggested operation algorithm.

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2. PV-PPC System

Fig. 1 represents a block diagram of the conventional PV power generating system as an existing energy source method. In this case, the time that the system can generate power varies depending on the amount of PV radiation, and it has a low use-level. However, since the users of the current PV power generating system endure a low use-level and perform operations accurately for the energy source, the system is operated without actual effect in respect to cutting the peak load, in spite of users' or consumers' actual burden of large costs. Fig. 2 represents the block diagram of the proposed PV power generating system with the peak power cutting function. This system is composed of a simple structure with a battery added, similar to the PV power generating system as an energy source, but the operation method of the system is different due to the addition of the battery. With storage of the PV energy and the system energy in a battery, the system has the peak power cutting function to discharge power when energy amounts requested by the load are greatly increased.

3. Configuration and Control of PV-PPC System

The PV-PPC system consists of a DC/DC converter, a battery as an energy storage device, and a DC/AC inverter. The PV-PPC system generates power or charges the battery by using PV energy, depending on the status of the amount of PV radiation and the load. The composition of the power circuits, the modeling, and the control of each part are described as follows.

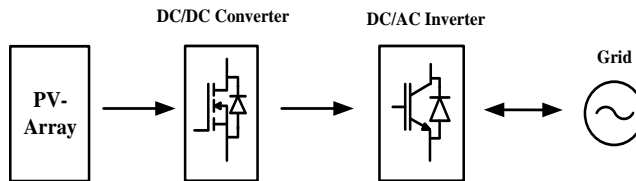


Fig. 1. Conventional PV system.

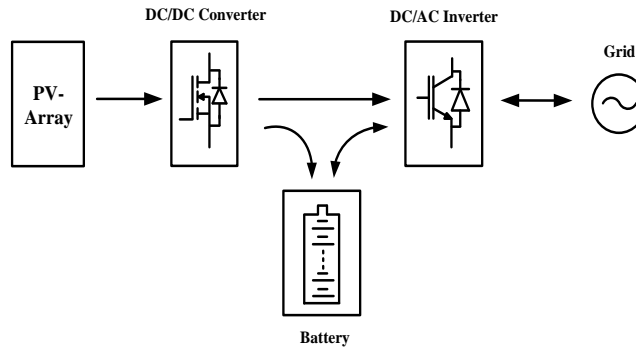


Fig. 2. Proposed PV system.

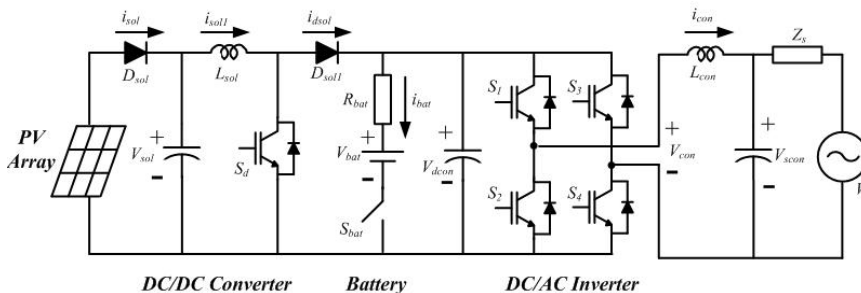


Fig. 3. The power circuit of the PV-PPC system.

3.1. Power circuit and modeling of PV-PPC system

The PV-PPC system shown in Fig. 3 is composed of a DC/DC converter to boost the voltage of the PV, a battery to recharge or discharge the power from the PV or grid, and a DC/AC inverter interconnected to the grid. If applying Kirchhoff's voltage law to the power generation direction from the DC/AC inverter to the system, the voltage equations are expressed as Eqs. (1) through (9), where v_s is the grid voltage, v_{sol} is the PV voltage, v_{dcon} is the DC-link voltage, i_s is the grid current, i_{sol} is the PV current, and i_{bot} is the battery current.

$$v_{scon} = L_s \frac{di_s}{dt} + R_s i_s + v_s \quad (1)$$

$$C_{con} \frac{dv_{scon}}{dt} = i_{con} - i_s \quad (2)$$

$$L_{con} \frac{di_{con}}{dt} + v_{scon} = v_{con} (= s_{con}(t) \cdot V_{dcon}) \quad (3)$$

here, $s_{con}(t) = \begin{cases} 1 & s_1, s_4 \text{ on} \\ -1 & s_2, s_3 \text{ on} \end{cases}$; the inverter switching function are:

$$C_{cond} \frac{dv_{dcon}}{dt} = i_{sol2} - i_{cond} \quad (4)$$

$$i_{con} = s_{con}(t) \cdot i_{cond} \quad (5)$$

$$V_{sol} = L_{sol} \frac{di_{sol1}}{dt} + v_{sw} \quad (6)$$

$$v_{sw} = v_{dcon} \cdot (1 - s_{dc}(t)) \quad (7)$$

here, $s_{dc}(t) = \begin{cases} 1 & s_{dc} \text{ on} \\ 0 & s_{dc} \text{ off} \end{cases}$; the boost converter switching function are:

$$i_{sol2} = i_{sol1} \cdot (1 - s_{dc}(t)) \quad (8)$$

$$C_{sol} \frac{dv_{sol}}{dt} = i_{sol} - i_{sol1} \quad (9)$$

If ignoring the power loss, the instantaneous power balance equation can be expressed as Equations 10 through 12.

$$v_{scon} i_{con} + \frac{1}{2} L_{con} \frac{di_{con}^2}{dt} = v_{con} i_{con} = -\frac{1}{2} C_{dcon} \frac{dv_{dcon}^2}{dt} + v_{dcon} i_{sol2} \quad (10)$$

$$v_{dcon} i_{sol2} = v_{sw} i_{sol1} = -\frac{1}{2} L_{sol} \frac{di_{sol1}^2}{dt} + v_{sol} i_{sol1} \quad (11)$$

$$v_{sol} i_{sol1} = -\frac{1}{2} C_{sol} \frac{dv_{sol}^2}{dt} + P_{sol} \quad (12)$$

here, $P_{sol} = v_{sol} i_{sol}$

3.2. Control of PV-PPC system

1) Control of the DC/DC converter

The DC/DC converter consists of an MPPT (Maximum Power Point Tracking) control to maximize the power generated in the PV, a voltage controller to control PV voltage ordered by the MPPT control, and a current controller to control the current of the PV, and the details are as follows. Fig. 4 represents the control composition diagram.

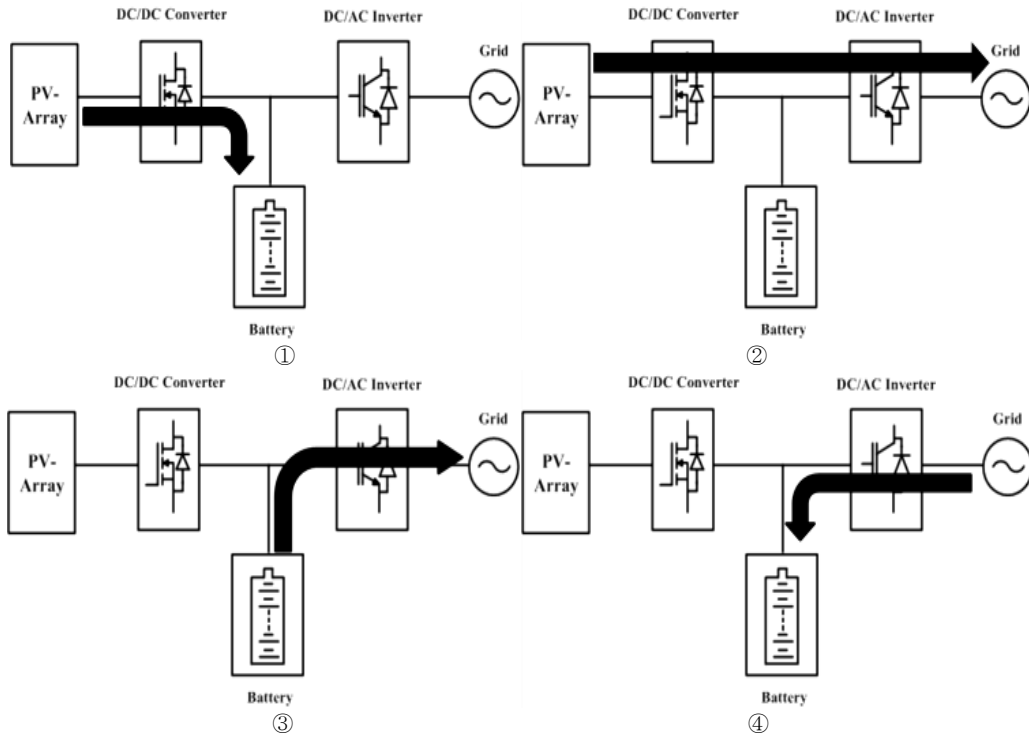


Fig. 6. The possible power flow of the PV-PPC system.

Table 1. The fee schedule of KEPCO by season and time

Type	Season	Time Zone			Fee rates
		Light-load	Heavy-load	Maximum-load	
Industry	Summer	23~09	18~23	09~18	1:1.9:2.8
	Spring and fall	23~09	18~23	09~18	1:1.6:1.9
	winter	23~09	09~18	18~23	1:1.9:2.3
Domesticity	Summer	23~09	09~11, 12~13, 17~23	11~12, 13~17	1:2.2:3.8
	Spring and fall	23~09	09~11, 12~13, 17~23	11~12, 13~17	1:1.6:2.2
	winter	23~09	09~18	18~23	1:2.0:2.8

Currently, Korean electrical charges are classified as residential, general education, industry, agricultural, and street light. Among them, industrial use and general use have differentiated charge systems by season and time zone as shown in Table 1. Pattern information by the time zone of the load for cutting the peak load and differentiated charge information (by season and time zone) for electrical charge saving are required. The suggested PV-PPC operation algorithm first calculates the date and time and selects the state by using differentiated charge information and load information, and is composed of a simple structure where the system stops in failure and operates depending on the selected state.

The suggested PV-PPC operational algorithm first calculates date and time, and then selects state by using different charge and load information. The operational algorithm is composed of a simple structure where the system stops in failure and operates depending on the selected state. Fig. 7 represents the block diagram of the operational algorithm, and Fig. 8 shows the detailed operation by state. Table 2 shows the explanation of Fig. 8.

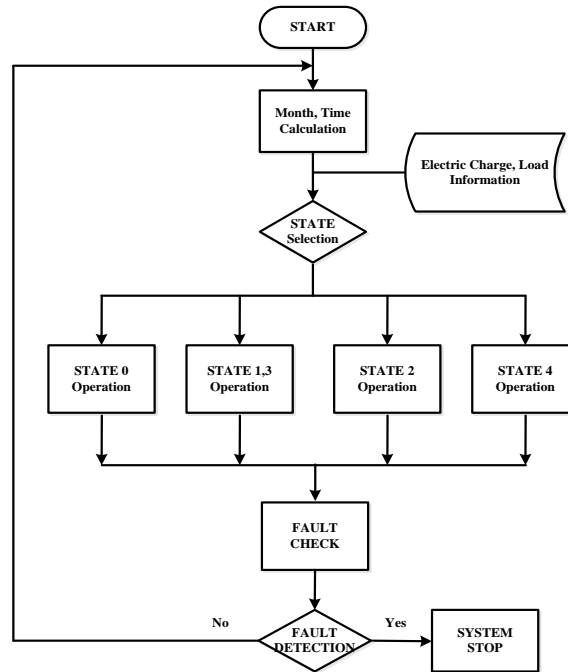


Fig. 7. The operational algorithm of the PV-PPC system.

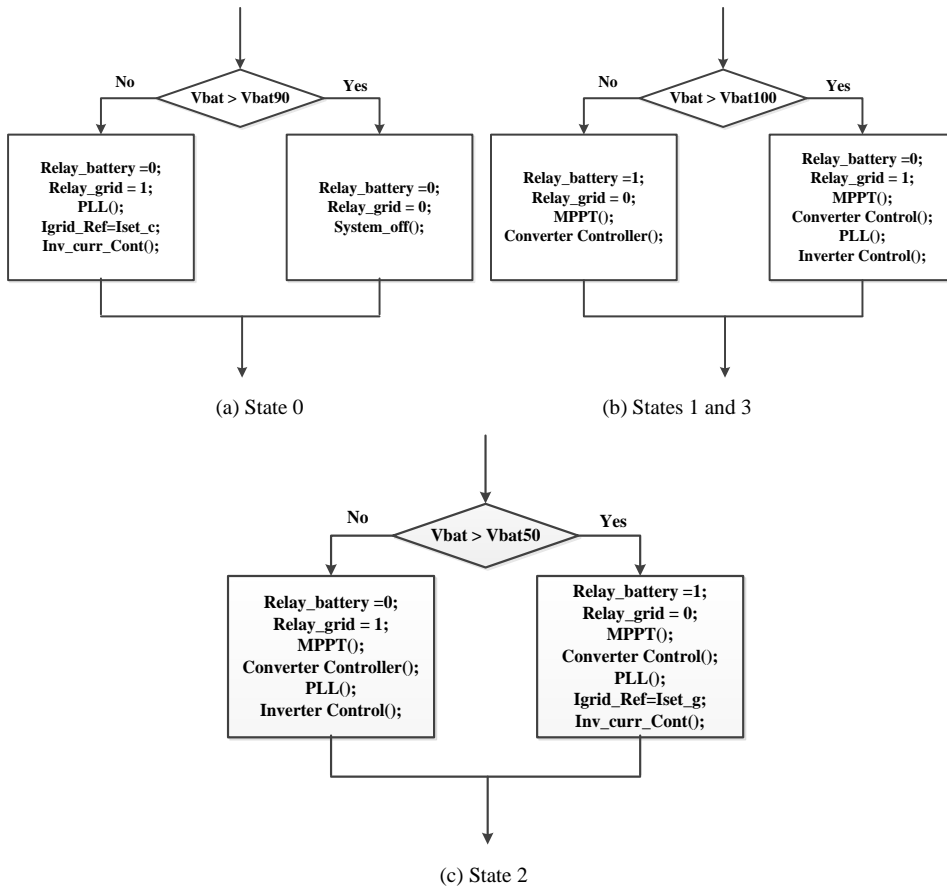


Fig. 8. The detailed operation by state.

Table 2. The explanation of Fig. 8

Notation	Explanation	Remark
Vbat	Battery voltage	Vbat50 : Voltage of 50% charge state Vbat90 : Voltage of 90% charge state Vbat100: voltage of 100% charge state
Relay_battery	Battery switch	0 : Off
Relay_grid	Grid switch	1 : On
PLL()	Function of PLL	Tracking the grid phase
Converter_Control()	Function of Converter control	This function consists of MPPT, voltage and current controller.
Inverter_Control()	Function of Inverter control	This function consists of voltage and current controller
System_off()	System off	System Stop
Igrid_Ref	Reference value of grid current	Iset_c : charging current Iset_g : generating current

STATE 0: This is the time to charge the battery by using cheap electricity at night. During this time, the relay of the grid and the battery must turn on to connect the system and the battery to the grid, and current control of the inverter must be performed by establishing current to recharge the battery from the system according to the voltage phase of the system. If the voltage of the battery becomes the reference value (90% of the complete recharge), operation STATE 0 is completed.

STATES 1 and 3: This is the time that PV power generation is possible, but the load is not peak load. During this time, the power generated by the PV charges the battery, and if the battery is completely charged, battery charging stops and the PV power is generated to the grid.

STATE 2: This is the peak load time. The power of the battery and the PV is generated toward the grid. In this state, the relays of both the battery and grid system remain on.

If the voltage of the battery drops below a constant value (50% of complete recharging voltage), the relay of the grid is turned off and the battery is charged by PV power.

STATE 4: There is no operation in this state.

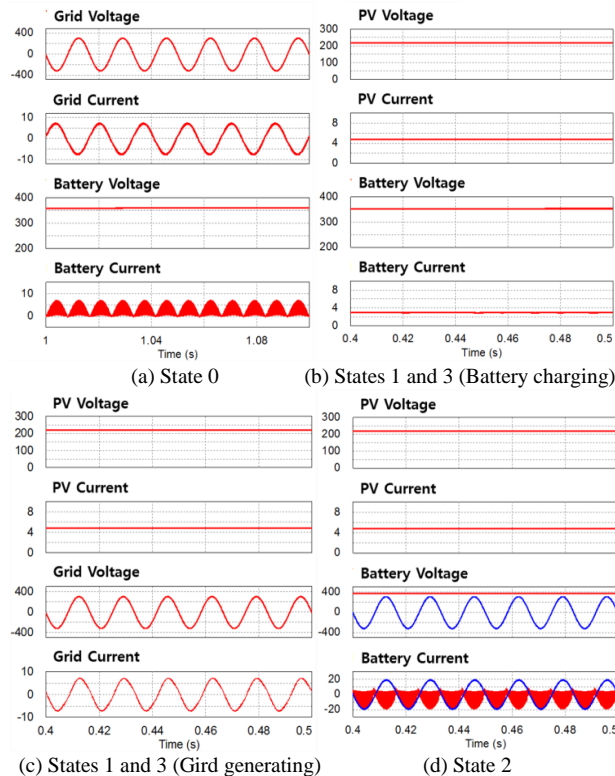


Fig. 9. Simulation of PV-PPC system by state.

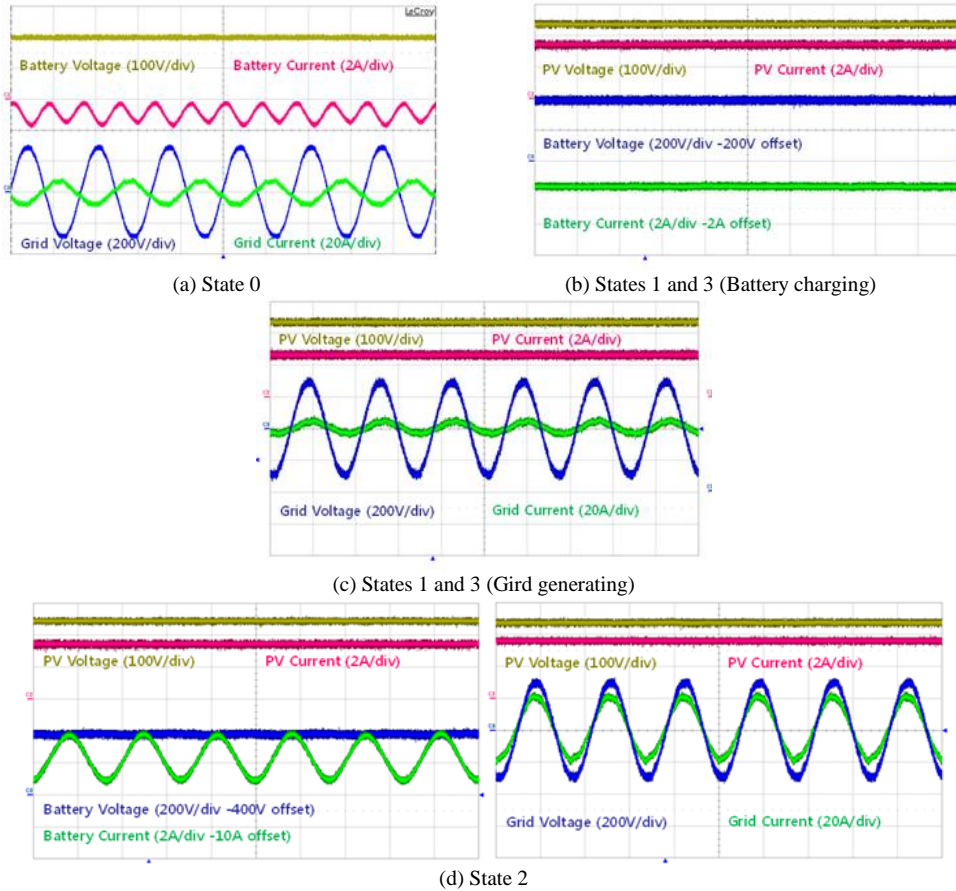


Fig. 10. Experiment of the PV-PPC system by state.

4. Simulation and Experiment

The simulation was performed by using the PSIM (9.0 PowerSim) to implement the operation of the PV-PPC system before the experiment. The simulated results are shown in Fig. 9. In Fig. 9 (a), the power of the PV (1100 W) is recharged in the battery, and Fig. 9 (b) shows the waveforms that the power of the PV is generating into the system. In the Fig. 9 (c), the PV and the battery are generating into the system. Fig. 9 (d) shows the recharging of the battery from the system by using the cheap time zone at night. Fig. 10 shows the experimental results which are similar to the simulation. In the experiment, the TMS320F28335 was used to control the system.

5. Conclusion

A PV-PPC power generation system with the peak load cutting function to reduce the peak load power effect of the power system is presented in this paper. Simulation analysis was performed using the PSIM software to validate the different operational modes of the power flow of the proposed PV-PPC system during the on-peak and off-peak periods. During on-peak operation, the power is managed to flow from the PV and the storage battery to help meet peak demands and reduce daily utility peak demands.

During the periods of off-peak demand, the PV power can be stored in the system battery or fed to the utility grid. The feasibility of the proposed system has been verified practically through experimental results. Through the simulation and experimental results given in this paper, the system can effectively alleviate the peak load power hours efficiently which shows its potential to reduce utility electricity costs.

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