Proposal for the System of Dynamic Wireless Power Transfer Connected with Photovoltaic in the Off-Grid Environment

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***Abstract*—Electric Vehicles (EVs) are becoming increasingly popular as we move toward carbon neutrality. Dynamic Wireless Power Transfer (DWPT), which wirelessly supplies power to EVs while they are running, is being actively researched by organizations in various countries as a technology to solve the shortcomings of EVs. In addition, by obtaining the energy needed for EVs to run from renewable energy sources such as solar power, it can make a significant contribution to the achievement of carbon neutrality. Few studies have been conducted on systems that install Photovoltaic (PV) cells on the shoulder of a DWPT road and connect them directly to the DWPT system, and few of them are practical. In this paper, we propose a PV+DWPT system that combines a PV system and a DWPT system in an off-grid condition without being connected to the grid. Experiments with equipment simulating a DWPT confirmed that the proposed system works properly and demonstrated the effectiveness of the system.**

Keywords—Dynamic Wireless Power Transfer, Photovoltaic, Maximum Power Point Tracking.

I. INTRODUCTION

The recent trend toward carbon neutrality has led to the widespread use of Electric Vehicles (EVs). However, EVs have disadvantages such as long charging time, short cruising range, heavy battery, and large amount of greenhouse gas emissions during battery production. A solution to these shortcomings is Dynamic Wireless Power Transfer (DWPT), which wirelessly supplies power to moving EVs. DWPT is a technology that can reduce battery requirements while maintaining cruising range, so it is being actively researched by organizations in many countries [1]-[12].

The widespread use of EVs will reduce greenhouse gas emissions while driving. Furthermore, by obtaining the energy needed for EVs to run from renewable energy sources such as solar power, it can make a significant contribution to achieving carbon neutrality.

Few studies have been conducted on systems in which Photovoltaics (PV) are installed on the shoulder of a DWPT roadway and connected directly to the DWPT system, and few of these systems are practical [13]-[17]. In this paper, we propose a PV+DWPT system that combines a PV system and a DWPT system under off-grid conditions without being connected to the grid, and validate the system through experiments using equipment that simulates a DWPT.

II. PHOTOVOLTAIC + DYNAMIC WIRELESS POWER TRANSFER (PV + DWPT)

This chapter describes the configuration and control of the PV+DWPT system.

A. Fusion of PV System and DWPT System

When implementing the proposed system, it is clear that a large amount of PV will be installed to cover the electricity consumption in the DWPT system. As the amount of PV installed increases, the duck curve phenomenon must be taken into account. This phenomenon is a phenomenon in which real electricity demand is low during the daytime because PV power generation covers electricity consumption, and real electricity demand increases sharply after the evening, when electricity demand peaks. The proposed system is independent of the grid, so it does not affect the duck curve phenomenon. In addition, the DWPT system, which increases electricity demand during the daytime, is a good match for the PV system, which supplies more electricity during the daytime. The combination of these two systems will enable the mass deployment of PV and contribute significantly to achieving carbon neutrality.

B. Proposal System

The overall view of the proposed system is shown in Fig. 1 and a schematic diagram is shown in Fig. 2. The PV is

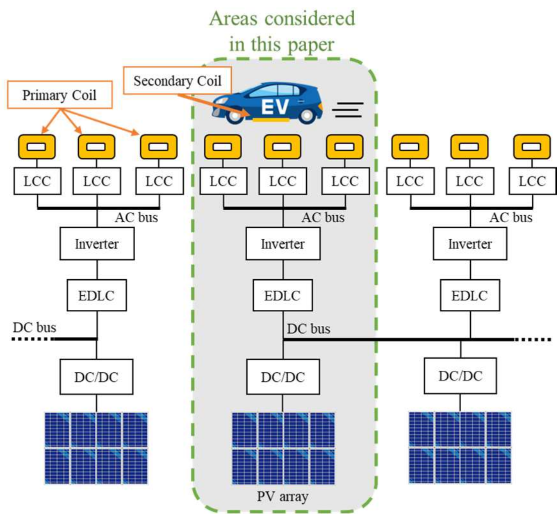


Fig. 1. Overall picture of PV+DWPT system (Off-Grid)

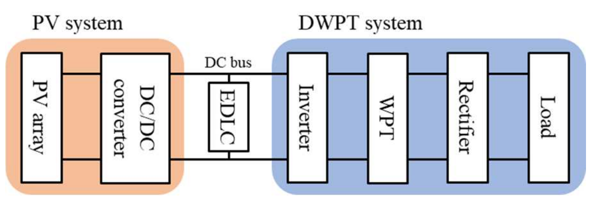


Fig. 2. Schematic diagram of PV+DWPT system (Off-Grid)

controlled by the DC/DC converter with Maximum Power Point Tracking (MPPT) and output to the DC bus. In the PV+DWPT system, the power supply of the PV system fluctuates due to weather changes, and the power demand of the DWPT system fluctuates greatly due to vehicle traffic. The Electric Double Layer Capacitor (EDLC) is connected to absorb these fluctuations. The inverter outputs a square wave at 85 kHz and uses a Double-LCC circuit as a Wireless Power Transfer (WPT) compensation topology. The details of the system are described in the following sections.

C. Maximum Power Point Tracking (MPPT)

In the proposed system, the PV output power is MPPT-controlled by a DC/DC converter. MPPT control is a control method that can automatically track the optimum voltage and current values that maximize the output during PV power generation. There are several MPPT methods, but this paper uses the Perturbation and Observation (P&O) method, which is a classical method and easy to implement [18]-[20]. As shown in Fig. 3, the output power of a PV varies with the output voltage. Therefore, there is an optimal operating point where the PV output power is maximized. In the P&O method, the voltage is increased or decreased in one direction, and when the increase or decrease in power is reversed, the direction of voltage change is reversed. By repeating this process, the optimal operating point is controlled. The flowchart of the P&O method used in the proposed system is shown in Fig. 4.

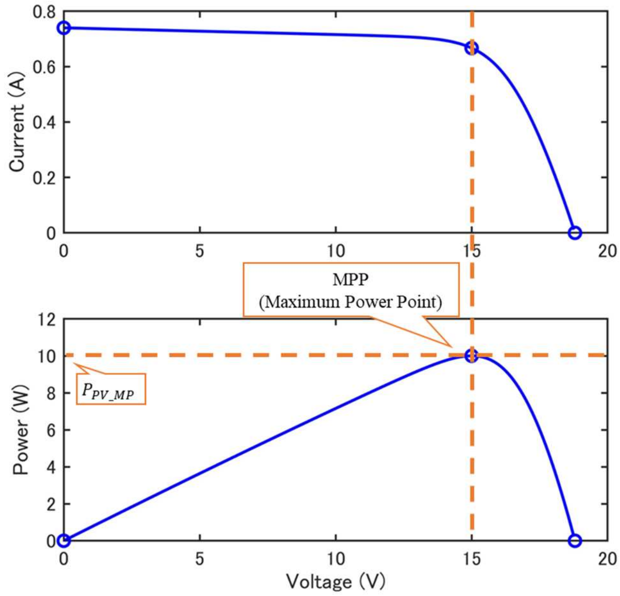


Fig. 3. Example of I-V curve and P-V curve of a photovoltaic

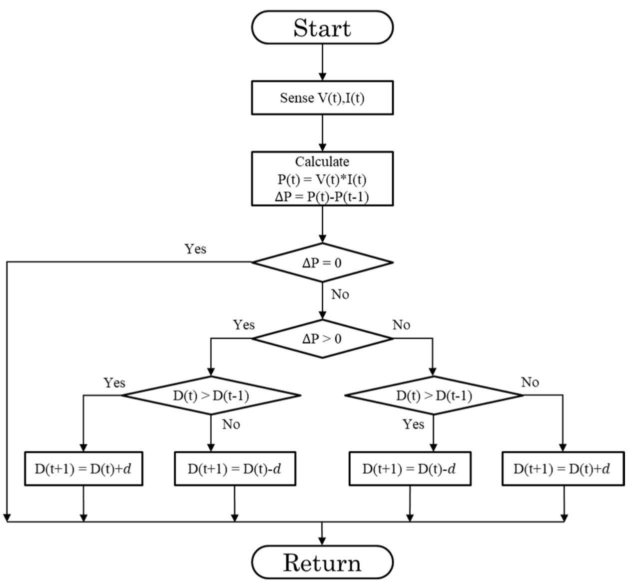


Fig. 4. Flowchart of MPPT control (P&O method)

D. Electric Double Layer Capacitor (EDLC)

The EDLC is a large-capacity capacitor, which plays a role in absorbing power fluctuations in the proposed system. In the PV+DWPT system, the power supply of the PV system fluctuates due to weather changes, and the power demand of the DWPT system fluctuates greatly due to vehicle traffic. Without a buffer to absorb these fluctuations, the DC bus voltage becomes very unstable. Therefore, the MPPT control of the PV cannot keep up with the fluctuations in the output voltage of the DC/DC converter, and the PV cannot be maintained at maximum output. To solve this problem, a buffer is needed to absorb power fluctuations. The requirements for the buffer include the ability to withstand intense charging and discharging, and the ability to store and release power rapidly. EDLCs have little degradation due to charging and discharging, can be charged and discharged for hundreds of thousands to millions of cycles, and can be charged and discharged rapidly. In summary, EDLCs meet the requirements of buffers, and therefore, EDLCs are used in the proposed system.

E. Double-LCC Circuit

In the proposed system, the Double-LCC circuit shown in Fig. 5 is used as the WPT compensation topology [21]-[24]. The Double-LCC circuit is designed so that LC resonance occurs in each closed circuit, and when the resonance frequency is f_0, the inductance and capacitance satisfy the resonance condition in (1).

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_{1p}}} = \frac{1}{2\pi}\sqrt{\frac{C_{1p}+C_{1s}}{L_1 C_{1p} C_{1s}}} = \frac{1}{2\pi\sqrt{L'_0 C_{2p}}} = \frac{1}{2\pi}\sqrt{\frac{C_{2p}+C_{2s}}{L_2 C_{2p} C_{2s}}} \tag{1}$$

When there is no receiving coil on the transmission coil, that is, when the coupling coefficient (k) is $k = 0$, no current flows from the power source (E). Therefore, when there is no vehicle on the transmission coil, no power flows from the inverter. In other words, the output of the inverter switches passively in response to vehicle traffic and can be operated without external control.

Even if multiple transmission coils are connected to a single inverter, the proposed system uses the Double-LCC circuit as the WPT compensation topology because standby losses are low and no control is required.

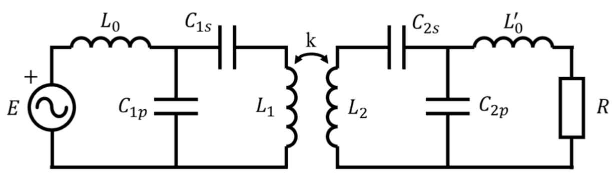


Fig. 5. Equivalent circuit of Double-LCC topology

F. Control Method of PV+DWPT System

The proposed system works passively in changing conditions, such as changing weather and increasing or decreasing traffic, and it works so that the PV system's power supply and the DWPT system's power demand are always in balance. However, if either system has an extreme amount of power, the amount of power must be controlled according to circuit ratings and requirements. The operation of the two patterns is described below, with P_{PV} as the PV system's power supply and P_{DWPT} as the DWPT system's power demand.

1) When $P_{PV} > P_{DWPT}$

Surplus power is stored in the EDLC and the DC bus voltage increases. Therefore, the transmission voltage of the DWPT increases and the transmitted power also increases. Thus, the power demand of the DWPT system increases and P_{PV} and P_{DWPT} are balanced. At this time, when the DC bus voltage is close to the rating of the EDLC elements, the power supply from the PV system must be curtailed. Therefore, the proposed system controls to stop the operation of the DC/DC converter, discharge the EDLC to a certain voltage, and then resume the power supply from the PV system.

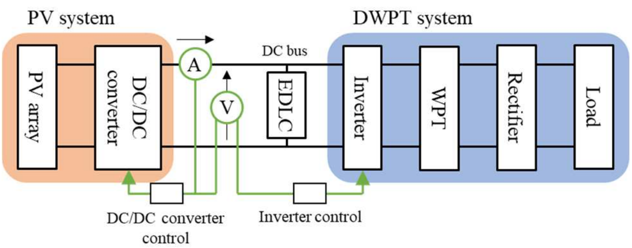


Fig. 6. Schematic diagram of the circuit showing voltage sensor, current sensor, and control action destination

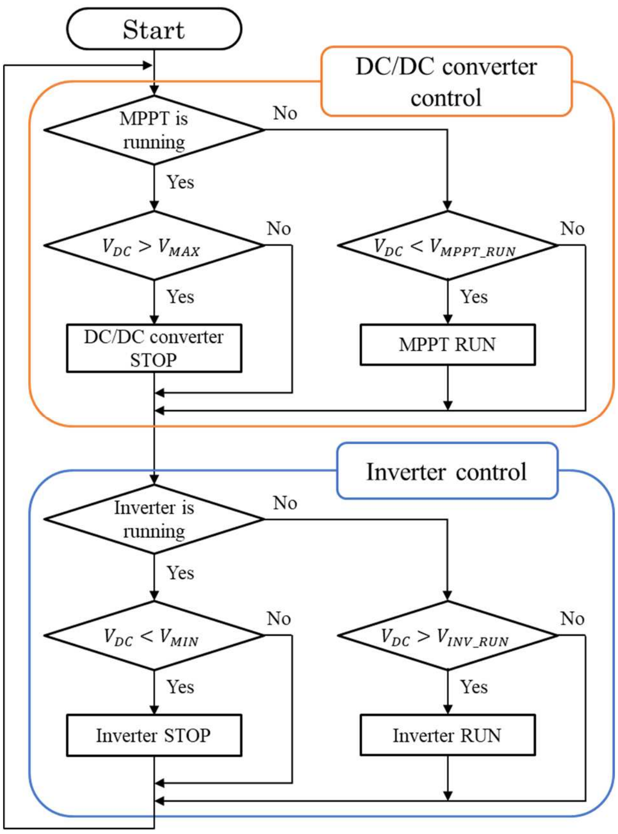


Fig. 7. Flowchart of control method of PV+DWPT system

2) When $P_{PV} < P_{DWPT}$

The missing power is compensated from the power stored in the EDLC and the DC bus voltage drops. Therefore, the transmission voltage of the DWPT drops and the transmitted power also drops. Thus, the power demand of the DWPT system decreases and P_{PV} and P_{DWPT} are balanced. Since the proposed system uses a Boost converter for the DC/DC converter, the MPPT control will not work properly if the DC bus voltage becomes lower than the voltage at the optimal PV operating point. Therefore, in the proposed system, when the DC bus voltage drops, if the DC bus voltage becomes close to the voltage at the optimal operating point of the PV, the inverter operation is stopped to charge the EDLC to a certain voltage, and then the control is performed to resume power supply to the DWPT system.

A schematic diagram of the circuit showing the voltage sensor, current sensor and where the control acts is shown in Fig. 6. The flowchart of the above control is also shown in Fig. 7. Here, the DC bus voltage is V_{DC}, the rated voltage of the EDLC is V_{MAX}, the voltage to resume power supply from the PV system is V_{MPPT_RUN}, the minimum voltage at which the MPPT control operates normally is V_{MIN}, and the voltage to resume power supply to the DWPT system is V_{INV_RUN}.

III. Experiments With Equipment Simulating DWPT

A. Experimental Structure

The circuit configuration of the experiment is shown in Fig. 8, the overall view is shown in Fig. 9, and an external view of the equipment simulating the DWPT is shown in Fig. 10. The transmitting and receiving coils used in the experiment are shown in Fig. 11, the receiving coil mounted on the equipment is shown in Fig. 12, and the parameters of the elements are shown in TABLE I. The size of all three transmission coils (Tx1-Tx3) is 500 mm × 250 mm, and the size of the receiving coil is 250 mm × 250 mm. The

TABLE I. Parameters Used in the Experiments

(a) WPT parameters

Parameters	Tx1	Tx2	Tx3
L_1	206.9 μH	206.7 μH	206.4 μH
L_0	53.6 μH	49.8 μH	49.6 μH
C_{1p}	65.4 nF	70.4 nF	70.8 nF
C_{1s}	22.9 nF	22.3 nF	22.3 nF

Parameters	Rx
L_2	111.4 μH
L_0'	49.2 μH
C_{2p}	71.2 nF
C_{2s}	56.4 nF

(b) Other parameters

Parameters	Value
f_{dc}	10.0 kHz
f_0	85.0 kHz
P_{PV_MP} (1000 W/m^2)	10.0 W
P_{PV_MP} (400 W/m^2)	4.00 W
L_{con}	3.50 mH
C_{con}	200 μF
C_{EDLC}	1.67 F
C_{out}	500 μF
R	100 Ω

transmission coils (Tx1-Tx3) were spaced 500 mm apart below the equipment. The receiving coils (Rx) were mounted on the equipment and moved back and forth over the transmitting coils (Tx1-Tx3) at 5 km/h. The distance between the transmission and receiving coils was 80 mm. The PV was reproduced by SAS (Solar Array Simulator). The SAS output the PV curve as shown in Fig. 3, where the maximum output power (P_{PV_MP}) is 10 W when the irradiance is $1000\ \mathrm{W/m^2}$ and the maximum output power (P_{PV_MP}) is 10 W when the irradiance is $400\ \mathrm{W/m^2}$. The DC/DC converter and inverter are controlled by the DSP (Digital Signal Processor). The switching frequency (f_{dc}) of the DC/DC converter is 10 kHz, and the inverter outputs an 85 kHz square wave.

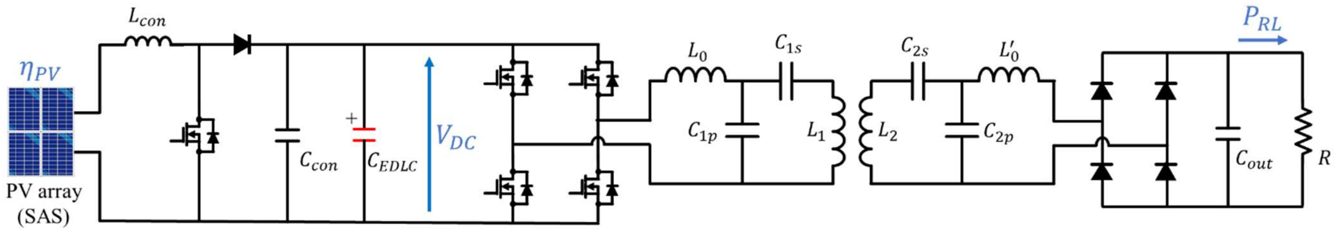


Fig. 8. PV+DWPT system circuit configuration of experiments

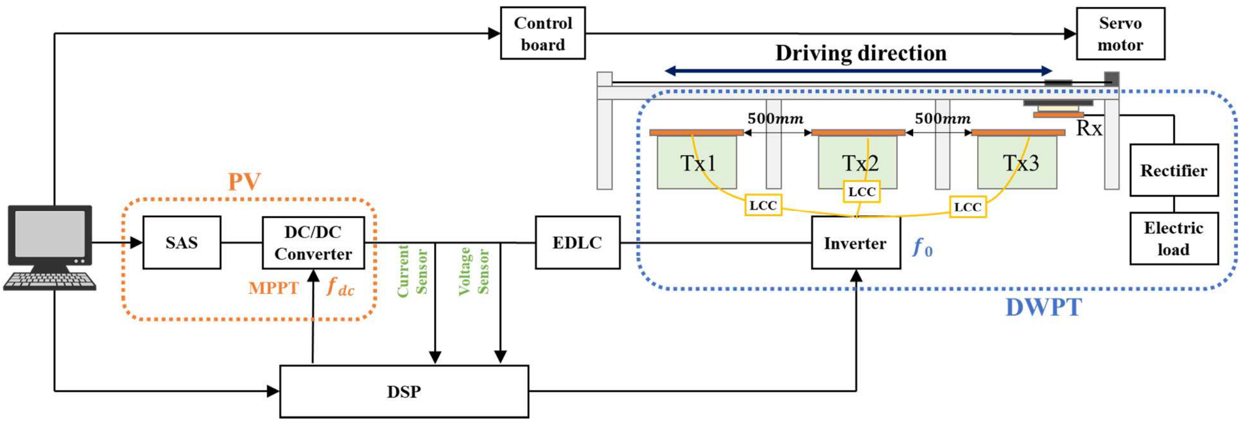


Fig. 9. Overall view of the PV+DWPT experimental system

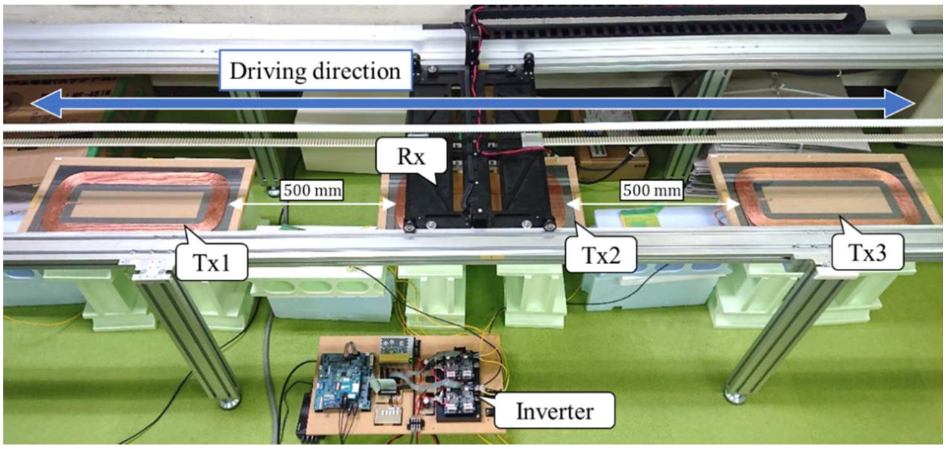


Fig. 10. Appearance of the experimental equipment (DWPT simulator)

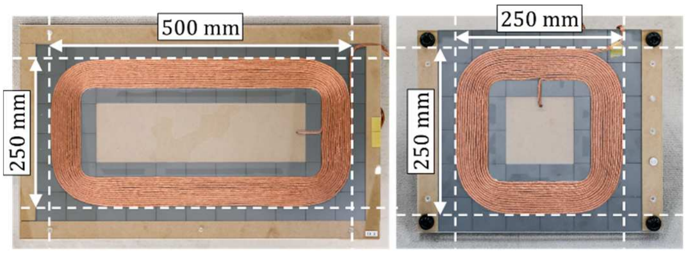


Fig. 11. The transmission and receiving coils used in the experiment

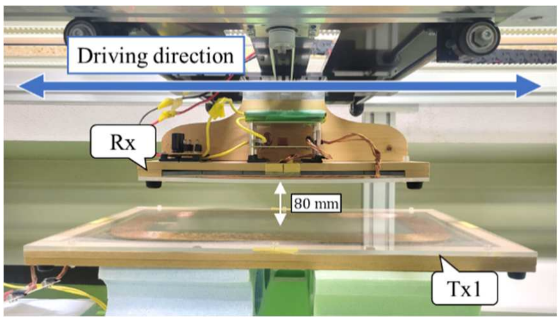


Fig. 12. The receiving coil mounted on the experimental equipment

B. Experimental Details

Experiments were conducted with four patterns shown in TABLE II, varying the irradiance and traffic volume. The irradiance was varied by changing the SAS setting, and the traffic volume was varied by changing the time (T_{wait}) that the receiving coil stops when it reaches the end of the equipment. The DC bus voltage (V_{DC}) conditions for the control of the DC/DC converter and inverter shown in Fig. 7 are shown in TABLE III.

TABLE II. EXPERIMENTAL PATTERN

Pattern	Irradiance	Traffic volume
1	High (1000 W/m^2)	High (T_{wait} = 0 s)
2	High (1000 W/m^2)	Medium (T_{wait} = 2 s)
3	High (1000 W/m^2)	Low (T_{wait} = 7 s)
4	Low (400 W/m^2)	High (T_{wait} = 0 s)

TABLE III. DC BUS VOLTAGE CONDITIONS

Parameters	V_{DC}
V_{MAX}	35 V
V_{MPPT_RUN}	30 V
V_{INV_RUN}	25 V
V_{MIN}	20 V

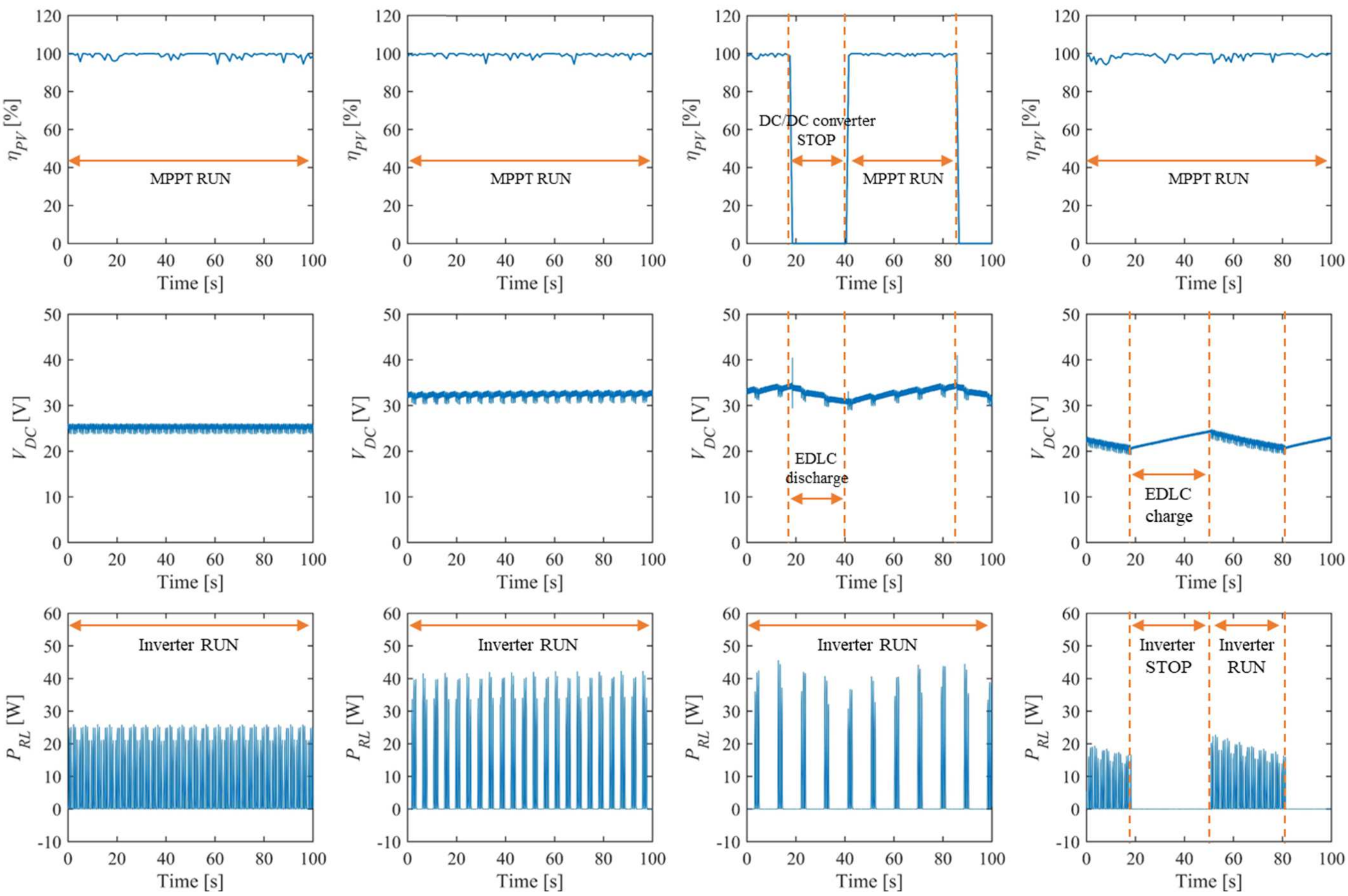
C. Experimental Results and Discussion

The experimental results for the four patterns are shown in Fig. 13, where the ratio of the SAS output to the maximum output power (P_{PV_MP}) is η_{PV}, the DC bus voltage is V_{DC}, and the power consumption with resistive load is P_{RL}.

From Fig. 12, it can be seen that η_{PV} is kept above 94% even if the DC bus voltage (V_{DC}) fluctuates when the MPPT control is operating. This confirms that the MPPT control is working properly.

From Fig. 13(a) and (b), the DC bus voltage (V_{DC}) is constant, indicating that the amount of power supplied by the PV system is balanced by the amount of power demanded by the DWPT system. This confirms that the system functions passively in response to changes in traffic. It can also be seen that the DC bus voltage (V_{DC}) is decreasing while power is being supplied to the receiving coil. The reason for this is that a significant amount of power is released from the EDLC when the power is being fed to the receiving coil, which leads to a larger voltage drop that is caused by the ESR of the EDLC.

In Fig. 13(c), when the DC bus voltage (V_{DC}) rises to 35 V, the rated voltage of the EDLC (V_{MAX}), the DC/DC converter stops operating and stops supplying power from the PV system. Then, the EDLC is discharged as power flows to the DWPT system, and when the DC bus voltage (V_{DC}) drops to 30 V, the voltage at which the power supply from the PV system resumes (V_{MPPT_RUN}), the MPPT is resumed. This confirms that the "DC/DC converter control" part of the flowchart shown in Fig. 7 is operating normally. It can also be



(a) Pattern1 (b) Pattern2 (c) Pattern3 (d) Pattern4

Fig. 13. Experimental resalts

seen that the DC bus voltage (V_{DC}) rises significantly for a moment when the DC/DC converter stops. This is thought to be because the energy of the coil (L_{com}) in the DC/DC converter is released to the DC bus when the DC/DC converter stops. This phenomenon could be addressed by loosening the duty ratio change when the DC/DC converter stops.

In Fig. 13(d), when the DC bus voltage (V_{DC}) drops to 20 V, which is the minimum voltage (V_{MIN}) at which the MPPT control operates normally, the inverter stops operating and the power supply to the DWPT system is stopped. The EDLC is then charged by power supplied from the PV system, and when the DC bus voltage (V_{DC}) rises to 25 V, the voltage at which power is resumed to the DWPT system (V_{INV_RUN}), the operation of the inverter is resumed. This confirms that the "Inverter control" part of the flowchart shown in Fig. 7 is working properly.

Based on the above, the normal operation of the proposed system was confirmed.

IV. Conclusion

In this paper, we propose the PV+DWPT system, which combines the PV system and the DWPT system in an off-grid environment, and verify the system through experiments using equipment that simulates the DWPT system. In the PV+DWPT system, the power supply of the PV system fluctuates due to weather changes, and the power demand of the DWPT system fluctuates significantly due to vehicle traffic. Without a buffer to absorb these fluctuations, the DC bus voltage becomes very unstable. Therefore, the MPPT control of the PV cannot keep up with the fluctuations in the DC bus voltage, and the PV cannot be maintained at maximum output. It was shown that connecting an EDLC as a buffer solves this problem and directly connects the PV system to the DWPT system. In addition, it was confirmed that the system can passively respond to changes in irradiance and traffic by controlling the DC/DC converter and inverter, and can operate normally, demonstrating the effectiveness of the system.

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