Universal Smart Power Module Concept with High-speed Controller for Simplification of Power Conversion System Design

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***Abstract*— This paper proposes the modular power conversion systems based on an Universal Smart Power Module (USPM). In this concept, the Power Electronics Building Block (PEBB) is improved the flexibility and the expandability by integrating a high-speed power electronics controller, input/output filters among each USPM to realize the simplification of the power electronics design. The original point of USPM is that each power module operates independently because a high-speed power electronics controller is implemented on each power module. The power modules of PEBB are typically configured by the main power circuits and the gate driver. Therefore, the controller has to be designed specifically according to various applications although the advantages of PEBB are high flexibility and user-friendly. The contribution of USPM is the simplification of the system design including power electronics controller. On the other hand, autonomous distributed systems require the control method to suppress the interference in each module. In this paper, the configuration of USPM, example of the USPM system, and detail of the control method are introduced.**

Keywords—Universal smart power module, Autonomous decentralized control, Droop control, Isolation module, Wireless communication

I. INTRODUCTION

In recent years, the power electronics converters have been greatly adopted for various electric equipment such as the renewable energy solutions, industrial machines, and electric vehicles. The conventional power conversion technologies have been widely considered to focus on the circuit performance with approaches such as the circuit topology, the control methods and the modulation schemes [1-4]. In the general power converter design, the main circuit and the control circuit are designed specially according to the application to increase the lineup of the products with the different specifications. However, the circuit design requires specialized and multifaceted know-how such as the heat dissipation, the noise suppression, and the wide range of the power and the frequency. One of the impediments to expanding the use of the renewable energy and the electric vehicles is the large amount of time and cost incurred by trial and error in circuit development. The development method of the power converters with faster and lower cost is required when the demand for the power converters continues to increase in the future.

Power conversion systems based on the modular structure such as the PEBB concept have been widely considered in order to realize the high system reliability and high system extensibility for UPS, microgrids, and so on. [5-8]. These concepts constitute a power conversion system by stacking power conversion modules that integrate the main circuit and some auxiliary circuits. These systems have high productivity of the main circuit in terms of the reduction of the development cost and time even increasing the product lineup because its expandability allows the various current rating and the various voltage rating with changing the number of modules. In particular, the high productivity of the modular structure would become important in future power electronics systems because the demand of the power conversion systems drastically will increase owing to the utilization of electric energy, e.g. However, the system development requires the additional passive elements, the input/output filter and the central controller in addition to modules. Therefore, the development cost and time issues in conventional power conversion systems have not been completely solved because the optimal design of PEBBs requires dedicated designs other than modules.

This paper proposes a novel power converter system based on USPM concept which includes all power converter components in the module. USPM provides a system with speedy design, high expandability, high versatility, high usability, and high maintainability compared to other power conversion system based on a modular structure because the USPM system does not require specifically design. In addition, the USPM system has a significantly improved design flow compared to other modular converters. This paper describes the elemental technologies required in order to realize the USPM system.

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II. PEBB AND UNIVERSAL SMART POWER MODULE (USPM)

Figure 1 shows the system configuration of PEBB and USPM. In addition, Table1 shows the performance comparison with conventional modules. The conventional PEBB module consists of the main circuit, the gate drive unit including any passive components [9]. The PEBB concept reduces the development costs, and improves lineup expandability, maintainability, and reliability compared to conventional systems based on specifically designed main circuits. However, user-friendly design and flexibility of systems still have issues because the system controller and the other component such as the detection unit has to developed as well as the conventional power conversion system without PEBBs.

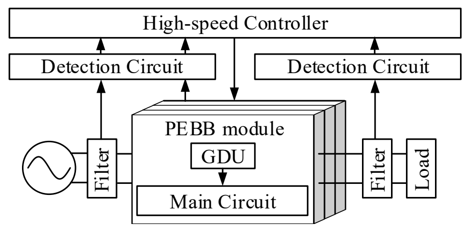
In order to solve these problems, USPM which includes all power conversion components such as the high-speed controller, the gate drive unit (GDU), and so on. USPM aims to improve productivity, expandability and versatility compared to others modular converter system. Note that USPMs and PEBBs are slightly inferior in size and efficiency performance compared to optimized conventional power conversion systems due to the increase in the number of components by the modular configuration. The difference between conventional PEBB and USPM is that USPM generates the necessary voltage and current waveforms independently because it includes a high-speed controller and the input/output filter. Thus, the USPM system improves versatility and usability because USPM realizes various types of the power conversion. Moreover, the system designer designs each element according to the system specifications when a completely new system is constructed in a conventional modular converter system. However, the design requires trial and error in consideration of noise, heat dissipation and e.g. by the simulations and the prototype experiments [10]. On the other hand, in the USPM system, the system designer only determines the configuration with USPM and the number of series or parallel connections of USPM. Therefore, the USPM system realizes simplification of the design flow and high productivity compared to the conventional PEBB system because the system is constructed without the need for a dedicated design.

III. TECHNICAL ELEMENTS FOR USPM SYSTEM

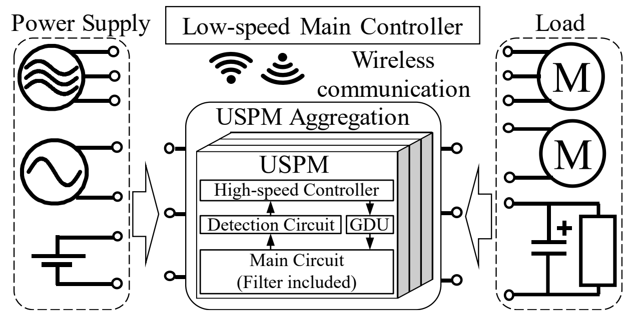
Figure 2 shows the single-phase power conversion system configuration with the series connected primary side USPM and the parallel connected secondary side USPM. The primary side USPM controls the grid current, and the secondary side USPM controls the load voltage. USPM has the H-bridge configuration including the LCL filter for usability and versatility. Note that the power conversion system with USPM flexibly change the configuration according to the required specifications. In this configuration, two USPMs with a voltage rating of 100 V are connected in series on the primary side for connection to 200V grid. Two USPMs are connected in parallel on the secondary side because the load voltage is 100 V. The series-parallel connection of USPMs is realized because the DC-DC converter connected between the primary

TABLE I. POSITIONING OF USPM SYSTEM.

	Conventional centralized control system	Modular converter system	USPM system
Productivity	Poor	Average	Good
Lineup expandability	Poor	Average	Good
Versatility	Poor	Average	Good
Maintainability	Poor	Average	Good
Reliability	Average	Good	Good
Noize	Good	Good	Good
Efficiency	Good	Average	Average
Size	Good	Average	Average

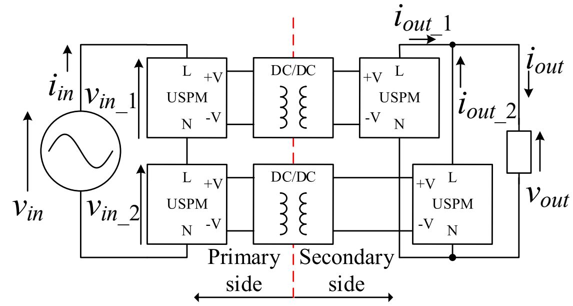


(a) Conventional system based on the PEBB concept

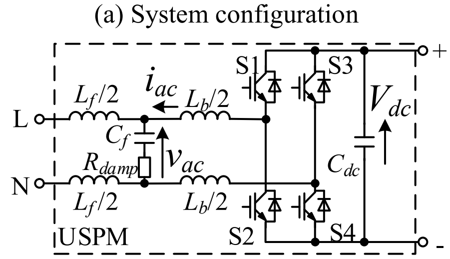


(b) USPM system

Fig. 1. High-speed controller is included in the USPM module compared to the conventional modular system. Various applications are applied by transmitting command to USPM with wireless communication.



(a) System configuration



(b) Main circuit in USPM

Fig. 2. Single-phase power conversion system configuration. Two USPMs with a voltage rating of 100 V are connected in series on the primary side for connection to 200V grid. The USPM on the secondary side has L_f removed to control the output voltage.

and secondary USPMs provides insulation to prevent short circuits.

A. *Autonomous distributed operation with high response*

The conventional module requires to control multiple main circuit modules with one high-speed controller because it does not have the current control and the voltage control. On the other hand, USPM has all power converter components including the high-speed controller, detection circuit, gate drive unit (GDU), input/output filter and main circuit. Therefore, USPM behaves a highly responsive power supply that accurately generates the required voltage and current waveforms. In addition, USPM operates as a single unit or multiple units. Multi-unit operation not only increases the voltage and the current capacity of the power converters in the multi-series and the multi-parallel configurations but also enables any power converter configuration with a combination of USPMs. However, the voltage or the current interference problems occur due to distributed control when USPMs are connected in series or in parallel. Multiple solutions have been proposed for the interference problem [11-12]. The droop control is a non-interference control with excellent modularity that does not require sharing of information such as voltage and current among the modules [13-16]. Droop control is advisable to be implemented by default in the USPM control because it is very compatible with the USPM concept. Therefore, the droop control was adopted as a non-interference control of the series-connected control current sources.

B. *Voltage droop control and current droop control*

Figure 3 shows the equivalent circuits of the voltage droop control, where the voltage sources v_1, v_x, and v_m are the voltages output by each voltage source module, v_{out} and i_{out} are the output voltage and the output current applied to the load. In addition, the subscript x in the voltage source indicates an x-th module of the parallel-connected voltage source modules, and the subscript m indicates the number of modules of the parallel-connected voltage source modules. The detection delay or gain imbalance may occurs due to sensor temperature drift when the control power supplies are connected in parallel. In this case, the voltage control interferes between modules. The voltage droop control suppresses the interference of the voltage sources connected in parallel by providing the control voltage source a drooping characteristic. The voltage droop control is achieved by connecting a droop impedance Z_d in series to the voltage sources connected in parallel.

Figure 4 shows the equivalent circuit of the current droop control where the current sources i_1, i_x, and i_m are the currents output by each current source module, v_{out} is the grid voltage, and i_{out} is the current flowing into the grid. In addition, the subscript x in the current source indicates any module in the series-connected current source module, and the subscript m indicates the number of modules in the series-connected current source module. The detection delay or gain imbalance may occurs due to sensor temperature drift when the control power supplies are connected in series. The current droop control is considered as the duality of the voltage droop theory. Therefore, the current droop control suppresses the interference

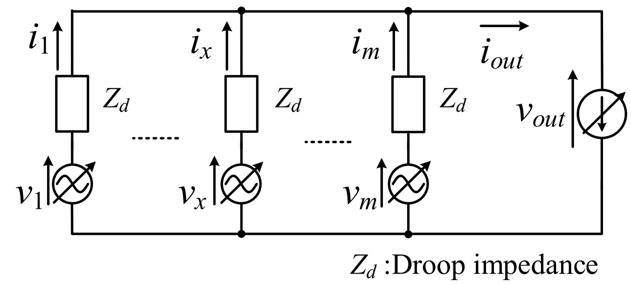


Fig. 3. Equivalent circuit of voltage droop control. The voltage droop control suppresses interference in the voltage control among parallel modules by using virtual impedance.

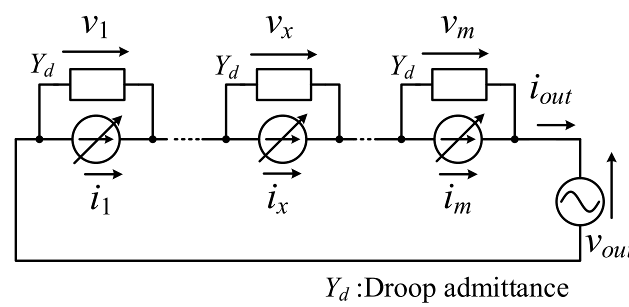


Fig. 4. Equivalent circuit of current droop control. The current droop control has a duality with the voltage droop control.

of the current sources connected in series by connecting a droop admittance Y_d in parallel to the current sources connected in series. The current droop control is obtained by subtracting the droop current i_{droop} from the current command. In the current droop control, a first-order Low-pass-filter (LPF) is inserted. The purpose of LPF is not only to avoid recursive operations but also to avoid instability due to an increase in the droop gain. The current control of the module becomes unstable when LPF is replaced to one-sampling delay with very large current droop gain. The droop current is given by;

$$i_{droop} = Y_d \frac{1}{1+\frac{1}{2\pi f_{lpf}}s} v_L^* \quad (1),$$

where v_L^* is the input of the current control, and f_{lpf} is the cutoff frequency of LPF used for the current droop control. These droop controls realize non-interference between the control power supplies when multiple series or multiple parallels are used. As a result, the voltage and the current capacity is easily expanded.

C. *Power sharing among USPMs*

A power sharing method is required to avoid designing with more margin than necessary when the load power of each power converter is unbalanced due to detection error or load unbalance in USPM. USPM generates the voltage or current command value to match the output power from the voltage and current information integrated in the master controller. This paper describes a power-sharing method for USPM that the controls series-connected currents.

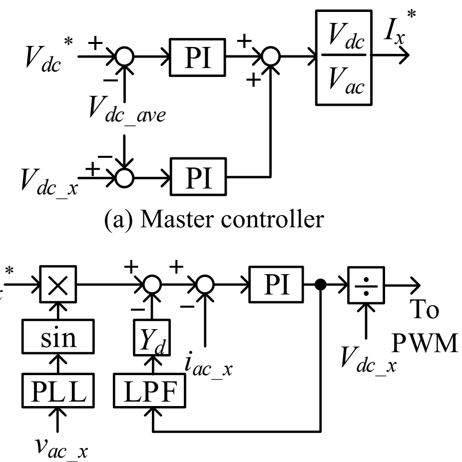
Figure 5 shows the control block diagram of the USPM for the output current control. Note that the current control implements the current-droop control described in Figure 4. The power of series-connected USPMs is matched by keeping the DC link voltage constant without load unbalance and DC link voltage detection error. In this paper, the DC link voltage average control and the DC link voltage balance control are applied to achieve the matching of the output power while avoiding the divergence of the voltage control due to the detection gain error and load unbalance. The DC link voltage average value control generates the output current command value in order to match the DC link voltage command value with the average value of the DC link voltage obtained through wireless communication with each USPM. This control method avoids divergence of the voltage control even in the case of the detection gain error or the load unbalance. The voltage balance control generates a current command value in order to match the DC link voltage of each USPM with the voltage average value. Furthermore, this current command value is added to the current command value generated by the DC link voltage average control. Note that the response frequency of the DC link voltage average control and the DC link voltage balance control may become low to satisfy Nyquist's law because the voltage detection values are obtained at low speed by wireless communication from each USPM.

D. Isolation circuit with fixed voltage conversion ratio

The USPM type also has a module configuration that only insulates because the short circuit may occur in the configuration using multiple voltage and current source modules. An isolated DC-DC module is only the input / output isolation and the input / output voltage conversion according to the turn ratio. Thus, the output voltage is simply controlled by controlling the input voltage. In this paper, Voltage Transformation Module (VTM) with fixed voltage conversion ratio was adapted as the isolated DC-DC converter. Moreover, it was composed of eight VTMs connected in series to support the 200V system. VTM realizes the isolated module without the module controller because it is activated only by inputting a pulse voltage.

E. Wireless communication with low-speed main controller

The USPM system supposed multi-series and multi-parallel configuration uses the wireless communication between USPMs because the communication wiring becomes complex and large volume. In addition, the main controller does not need the high-speed controller because USPM controls the output voltage or the output current at high speed. Thus, the main controller is controlled by a low-speed and low-cost embedded microcomputer because it does not require a high-speed controller. Therefore, the main controller communicates with the USPM controller through wireless communication of the voltage and current RMS values and the frequency-based information. The wireless communication avoids the increase in the system volume and the wiring man-hours due to the communication wiring. In order to perform the wireless communication, the main controller requires to specially design the communication environment. However, the system designer does not need to develop wireless communication environment by developing the main controller for USPM including the communication standard.



(a) Master controller

(b) USPM controller

Fig. 5. Control block diagram of the USPM for the output current control. DC link voltage balance control and DC link average voltage control are implemented in the master controller. The Current control with additional current-droop control is implemented in the USPM controller.

TABLE II. EXPERIMENTAL CONDITIONS.

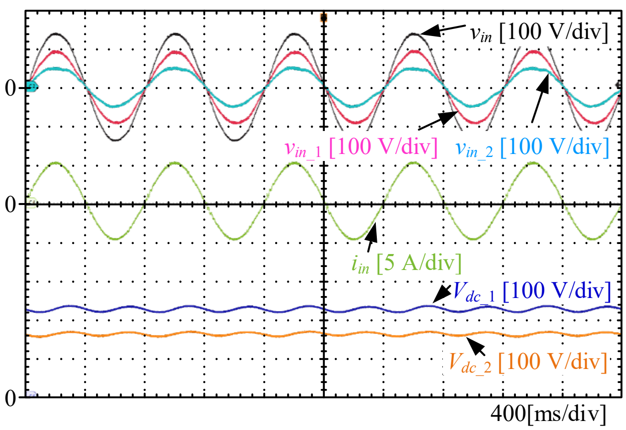
USPM Parametar		
Rated Power	P	500 W
AC Rated Voltage	V_{acn}	100 V
Input and Output Frequency	f_{in}, f_{out}	50 Hz , 60 Hz
DC link Voltage	V_{dc}	200 V
Filter Inductor	L_f	324 μH(%Z:0.51%)
Filter Capacitor	C_f	1.56μF(%Y:0.98%)
Boost Inductor	L_b	324 μH(%Z:0.51%)
Damping Resistor	R_{damp}	2 Ω
DC link Capacitor	C_{dc}	480 μF(H:19.2 ms)
Switching and Sampling Frequency	f_{sw}, f_{samp}	80 kHz
Dead-Time	T_d	200 ns
Controller Parameter		
Cutoff Freq. of Current	f_{c_acr}	5000 Hz
Cutoff Freq. of DC Voltage	$f_{c\_avr\_DC}$	3 Hz
Cutoff Freq. of AC Voltage	$f_{c\_avr\_AC}$	800 Hz
Voltage Det. Gain (Module 1, 2)	K_{e_1}, K_{e_2}	0.9 , 1.0

IV. EXPERIMENTAL RESULTS OF CURRENT DROOP CONTROL

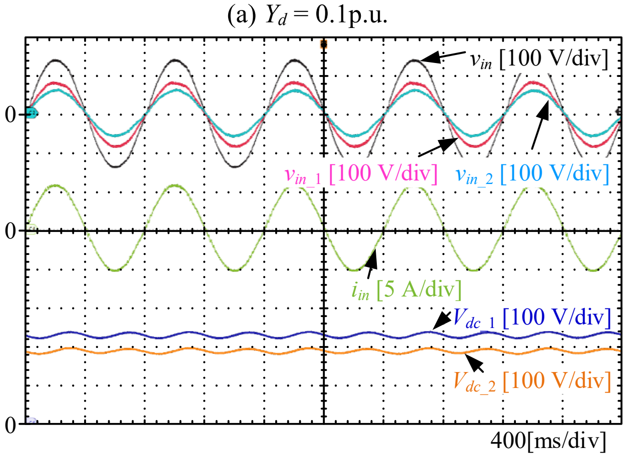
Table 1 shows the experimental parameters of the single-phase AC power conversion system based on USPM. The current detection gain of the primary USPM1 was decreased by 10% to confirm the operation of the current droop control. The current droop gain was set to 0.1p.u. and 0.2p.u. with the current source module's rated admittance as 1p.u. Note that the system considered in Figure. 6 and 7 is directly connected to a resistive load without DC link voltage control in order to completely eliminate the influence of the secondary side.

Figure 6 shows the primary voltage and current waveform when Y_d is 0.1p.u. and 0.2p.u. The DC link voltage is unbalanced as well due to the unbalanced AC voltage amplitude under the condition of Y_d = 0.1p.u. in Figure 6(a). Thus, the series connected USPM system may unstable due to the decrease of the DC link voltage when the current detection gain is in error any more or when the load on the USPM with small voltage amplitude becomes large. Here, the unbalance rate of the DC link voltage is 15.6%, the input current THD is 1.58%, and the current deviation is 19.9%. Under the condition of Y_d = 0.2 in Figure 6(b), The unbalance rate of the DC link voltage is 8.86% because the current droop control suppresses the voltage unbalance compared to the condition in Figure 6(a). However, the responsiveness is deteriorated because the current deviation becomes large due to the characteristics of the current droop control at 34.9% current deviation. Here, the current THD is 1.44%, about the same as in Figure 6(a).

Figure 7 shows the primary side voltage and current waveforms when each voltage control is applied. In the independent voltage control condition shown in Figure 7(a), the DC link voltage diverges due to the imbalance of the current detection gain immediately after startup. On the other hand, the system is not destabilized because the DC link voltage unbalance has been reduced under the condition of the DC link voltage average value control only in Figure 7(b). This stable operation is because the system is insensitive to the current detection gain imbalance due to the DC link voltage control by the average value. The DC link voltage is not unbalanced because the voltage balancing control compensates for the unbalance caused by the current detection gain error even though the DC link voltage response is slow under the

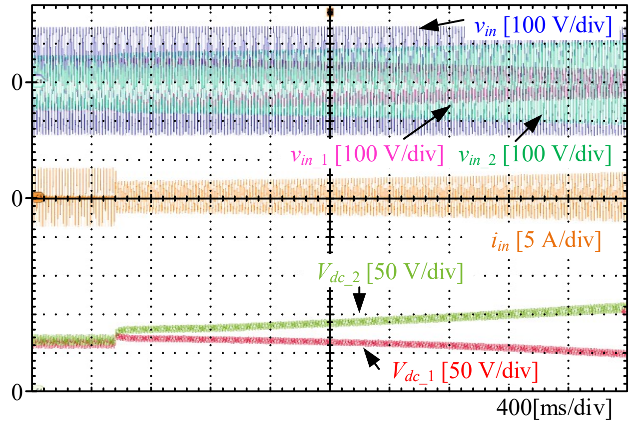


(a) Y_d = 0.1p.u.

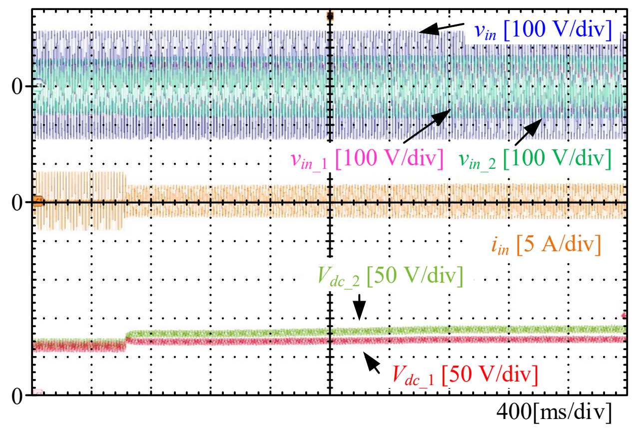


(b) Y_d = 0.2p.u.

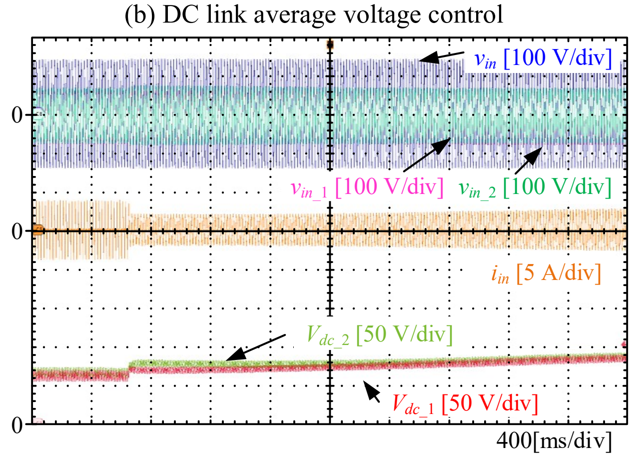
Fig. 6. Experimental result when droop gain is changed. Voltage unbalance among series-connected modules is improved by increasing the current droop gain.



(a) Independent voltage control



(b) DC link average voltage control



(c) DC link voltage control with voltage balance function

Fig. 7. Input waveforms at startup in each voltage control. The divergence of the system is eliminated by DC link voltage control with voltage balancing function.

condition of voltage control with balancing function in Figure 7(c). This reduction in DC link voltage unbalance indicates that the power of the series-connected modules is shared by the voltage balance control.

Figure 8 shows the input and output waveforms of single-phase power conversion system at rated power. In Figure 8, the secondary side USPM is connected to the load independently without parallel connection to the other secondary-side USPMs in order to separate the control from the primary side. In addition, USPM on the secondary side is driven by the open loop control. The input voltage is balanced even though there is an unbalance in the current detection gain due to the DC link voltage control with voltage balance function. This input voltage balance indicates that the power of each USPM is matched. Here, the input current THD is 1.55% and the efficiency is 89.2%.

V. Conclusion

This paper proposed the modular power conversion systems based on USPM including all power conversion components in order to achieve the development with low-cost and speedy. The USPM system drastically simplifies the design flow because USPM allows users to configure complex power converters without the dedicated design. Moreover, the USPM system is highly expandable, versatile, and maintainable compared to the conventional modular converter system. The experimental results demonstrated that the current droop control suppresses the interference among USPMs even in the case of the current sensing imbalance when USPMs are connected in series. In this configuration, the output power is shared by the voltage control with the voltage balance function. The voltage control is planned to consider the influence of the secondary side control in the future.

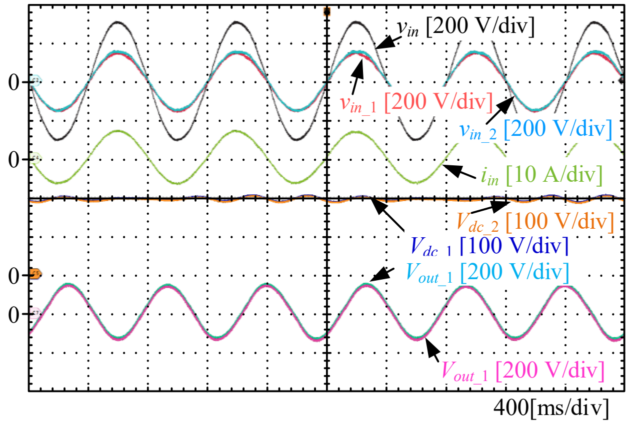


Fig. 8. Input and output waveforms of single-phase power conversion system at rated power. The input voltage is balanced even though there is an imbalance in the current detection gain.

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