Seamless Transfer Strategy Considering Power Balance in Parallel Operation

Seung-Jun Chee, Younggi Lee, Young-Kwang Son
and Seung-Ki Sul
Department of Electrical and Computer Engineering
Seoul National University
Seoul, Korea
cheesj80@eepel.snu.ac.kr,
younglee@eepel.snu.ac.kr, ykson@eepel.snu.ac.kr
and sulsk@plaza.snu.ac.kr

Changjin Lim and Sungjae Huh

R&D Institute
LG Electronics Co.
Seoul, Korea
changjin.lim@lge.com and sungjae.huh@lge.com

Abstract—**This paper presents a power reference modifier for seamless transfer considering the power balance in the parallel operation. When the PCS (Power Conditioning System) is disconnected from the grid, the PCS should operate in the stand-alone mode to supply energy to the critical loads. If multiple PCSs work as one PCS, slave PCSs maintain the current control mode even if master PCS change its control mode from the current control to the voltage control. If the power references of slave PCSs are not changed properly based on the load condition, the power balance condition may not be met. In that case, the voltage applied to the critical loads might be beyond or below the rated voltage. To avoid this phenomenon, the power values absorbed into the loads should be monitored consistently and the power references of the slave PCSs should be modified properly based on them. But the master PCS which transfers the power references to the slave PCSs and works as voltage source in stand-alone mode can obtain it indirectly by calculating its own power values without monitoring the power consumed by critical loads. Using those, simple controller for modifying the power references of the slave PCSs can be configured. The effectiveness of the proposed power reference modifier has been verified through the experimental results. By applying the proposed method, the transition from the grid-connected mode to the stand-alone mode works satisfying Computer Business Equipment Manufacturers Association (CBEMA) curve.**

I. INTRODUCTION

Owing to the energy problem, the interest in distributed generation systems is gradually increasing. For the distributed generators (DG) to interface with the grid, the power conditioning system (PCS) is commonly used. In general, for three phase utility systems, the two level three leg topology is widely used due to its simple structure and control. However, usage of the multi-level topologies is increasing thanks to gradually decreasing price of the power semiconductor. Furthermore, it helps the filter size to be smaller and the efficiency to be higher. Among multi-level converters, three level converters such as the T-type topology are most popular due to their relatively simple control methods and better efficiency compared to neutral point clamped (NPC) type [1].

While one PCS can be configured in the DG, multiple PCSs also can be configured in it. It is called parallel operation and it makes larger power be transferred by operating multiple PCSs with multiple small power capacity PCSs [2]. Even if a PCS is out of order, the other PCSs could work. So the parallel operation increases the reliability of the DG. Also in the light load condition, the number of the operating PCSs can be reduced so as to increase the efficiency of the DG. In addition, one PCS can be manufactured in the form of a module. It reduces the cost of the production and makes the maintenance easier.

Whether there exist the communication wires between the PCSs or not, PCSs can be controlled by active sharing method or droop method [3]. The droop method does not share data of other PCSs, so it is relatively reliable and expandable method. But it has poor dynamic performance and cannot assure equal load sharing [4-6]. On the other hand, active load sharing method which needs communication system guarantees equal load sharing and it improves the quality of the output voltage [7]. Besides, when the DG is disconnected from the grid, the DG must supply the power to the critical loads alone. Hence, a proper control strategy for the seamless transfer from the grid-connected operation to the stand-alone operation is required [8].

In this paper, the power reference modifier for seamless transfer to the stand-alone mode considering power balance is presented under the assumption of communication wires between PCSs.. The target system consists of 5 parallel PCSs with a battery, as shown in Fig. 1, and active load sharing method (master/slave control) is utilized [9, 10]. The experimental results verifying the performances of the proposed power reference modifier are shown.

II. GRID-CONNECTED OPERATION

If there is no problem with the grid, the PCSs are connected to the grid. All PCSs are operated in current control mode.

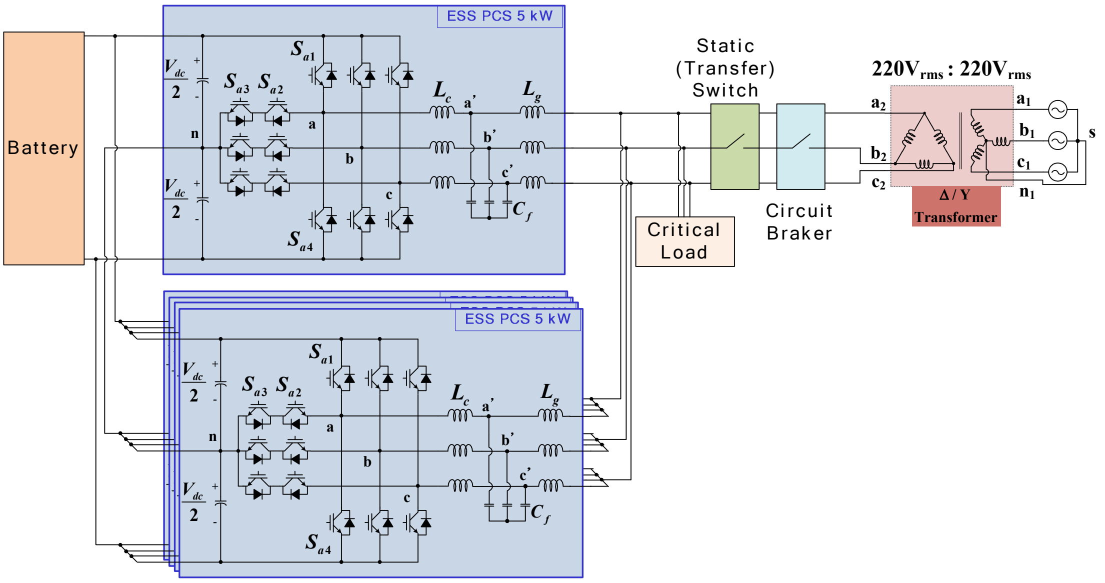


Fig. 1. System configuration of 5 parallel PCSs

If the total power references are transferred to the master PCS from the energy management system (EMS), it calculated the power references of each PCSs using (1) and (2) based on the number of PCSs which are turned on. The calculated reference value is transferred to each slave PCS using the communication line.

$$P_{each\_1}{}^{*} = P_{each\_2}{}^{*} = P_{each\_3}{}^{*} = P_{each\_4}{}^{*} = P_{each\_5}{}^{*} = P_{total}{}^{*}/5. \quad (1)$$

$$Q_{each\_1}{}^{*} = Q_{each\_2}{}^{*} = Q_{each\_3}{}^{*} = Q_{each\_4}{}^{*} = Q_{each\_5}{}^{*} = Q_{total}{}^{*}/5. \quad (2)$$

,where $P_{total}{}^{*}$ and $Q_{total}{}^{*}$ are the total power references which come from the EMS.

In each slave PCS, d and q axes current references can be calculated as (3) and (4).

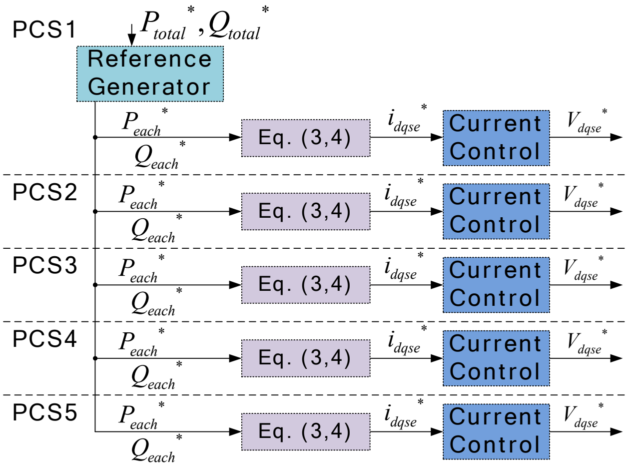


Fig. 2. Overall control block diagram of conventional system in case of grid-connected operation

$$i_{dse\_k}{}^{*} = \frac{2}{3}\frac{Q_{each\_k}{}^{*}}{V_{qse}}. \quad (3)$$

$$i_{qse\_k}{}^{*} = \frac{2}{3}\frac{P_{each\_k}{}^{*}}{V_{qse}}. \quad (4)$$

,where k and V_{qse} mean kth PCS and the magnitude of the grid voltage, respectively. The overall control block diagram can be depicted as Fig. 2.

III. STAND-ALONE OPERATOIN

A. Control at Stand-alone Operation

If a grid voltage is severely distorted or the grid is disconnected from the PCSs intentionally by a grid administrator, the STS (Static Transfer Switch) in front of PCSs would be opened. In that case, the PCSs should supply energy to the critical loads and one (usually master PCS) of

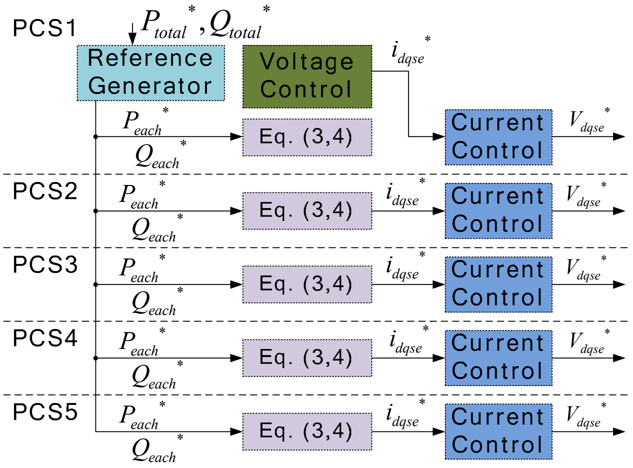


Fig. 3. Overall control block diagram in case of stand-alone operation

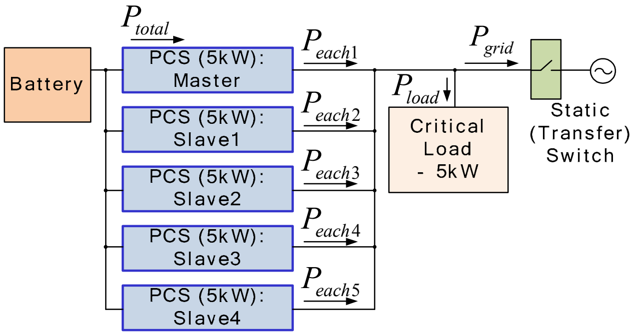


Fig. 4. Power Flow of the system with 5 PCSs whose rated power is 5 kW

parallel PCSs should work as a voltage source acting a swing bus [11-16]. The other slave PCSs continue to operate in current control mode. The conventional control block diagram in case of stand-alone operation is shown in Fig. 3.

B. Power Balance Analysis

The power flow is shown in Fig. 4. In the grid-connected operation, the power consumed by the critical loads, P_{load}, can be transferred from the battery energy storage system (BESS) or the grid. But in stand-alone operation, it should be transferred only from the BESS. In conventional method shown in Fig.3, the power references of slave PCSs maintain its previous value which was used in grid-connected mode as (5).

$$P_{each\_2}{}^{*} = P_{each\_3}{}^{*} = P_{each\_4}{}^{*} = P_{each\_5}{}^{*} = P_{total}{}^{*}/5. \tag{5}$$

Assuming that the power output of the slave PCSs is same as the power reference, the power output (P_{each_1}) of the master PCS should be as (6).

$$P_{each\_1} = P_{load} - \tfrac{4}{5}P_{total}. \tag{6}$$

For seamless transfer, the power required for the master PCS should be within its capacity.

$$-P_{PCS\_rated} \le P_{each\_1} \le P_{PCS\_rated}. \tag{7}$$

If the rated power of one PCS is 5 kW as an example, which is the value of the system in this paper, and the load power is 5 kW, then according to (6) the condition of the total power for seamless transfer is written as (8).

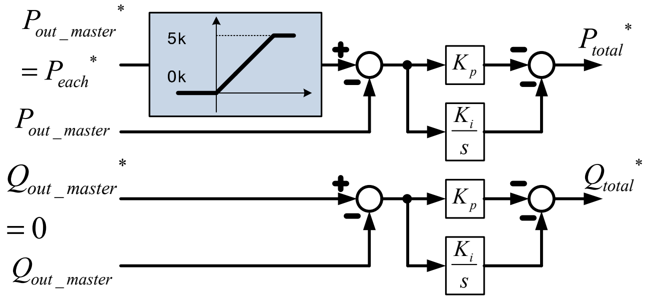


Fig. 5. Proposed power reference modifier

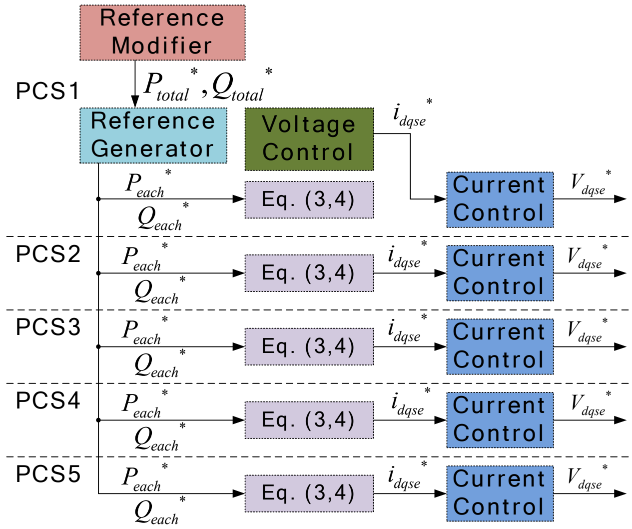


Fig. 6. Proposed control block diagram in case of stand-alone operation

$$0\,W \le P_{total} \le 12{,}500\,W. \tag{8}$$

It means that the total power reference ($P_{total}{}^{*}$) in grid-connected mode should satisfy the condition as (8). But $P_{total}{}^{*}$ can be varied from -25,000 W to 25,000 W as expressed in (9) because 5 units with the capacity of 5 kW each are operated in parallel.

$$-25{,}000\,W \le P_{total}{}^{*} \le 25{,}000\,W. \tag{9}$$

From (8) and (9), it can be found that there exist abnormal conditions as (10) and (11) except for normal condition given by (8).

$$-25{,}000\,W \le P_{total}{}^{*} < 0\,W. \tag{10}$$

$$12{,}500\,W < P_{total}{}^{*} \le 25{,}000\,W. \tag{11}$$

C. Proposed Reference Modifier

If $P_{total}{}^{*}$ is in the condition as (10) and (11), seamless transfer cannot be done properly. And, $P_{total}{}^{*}$ should be adjusted properly. If there exist current sensors in the critical loads, the load power can be monitored. Then, the total power reference can be adjusted properly for the stand–alone operation. Even if those sensors do not exist, that is usual case, P_{load} can be acquired indirectly from the calculated power of the master PCS. Equation (6) can be rewritten as (12).

$$P_{each\_1} - P_{each\_1}{}^{*} = P_{load} - P_{total}{}^{*}. \tag{12}$$

If P_{each_1} is larger than $P_{each\_1}{}^{*}$, $P_{total}{}^{*}$ is smaller than P_{load}. In this case, it is desirable to increase $P_{total}{}^{*}$ for equal load sharing. In the other case, $P_{total}{}^{*}$ should be increased. Based on these relationships, a PI controller, working as the power reference modifier, can be incorporated as shown in Fig. 5. The inputs of the controller are power references and calculated output power of the master PCS, the outputs are the total power references. The output power values of the master PCS can be calculated as (13) and (14).

$$P_{each\_1} = \frac{3}{2}\left(V_{dse} i_{dse\_1} + V_{qse} i_{qse\_1}\right). \tag{13}$$

$$Q_{each\_1} = \frac{3}{2}\left(V_{qse} i_{dse\_1} - V_{dse} i_{qse\_1}\right). \tag{14}$$

For example, $P_{total}{}^{*}$ is set to -5,000W and P_{load} is 5,000W. When the grid is disconnected from the PCSs, the master PCS should supply 9,000W which is beyond the capacity of the master PCS. For seamless transfer, the power references of slave PCSs should be increased. Initially the power reference of the master PCS was -1,000W. But the output power of the master PCS becomes 9,000W just after disconnection to the grid. However, by using proposed power reference modifier, the total power reference is automatically increased. The total power reference stops changing when the power reference and output power of the master PCS is equal. It means that the load power is shared equally by all PCSs. The proposed control block diagram in case of stand-alone operation is shown in Fig. 6.

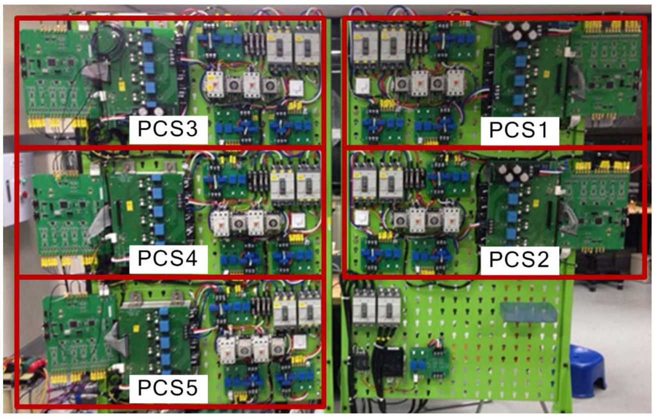
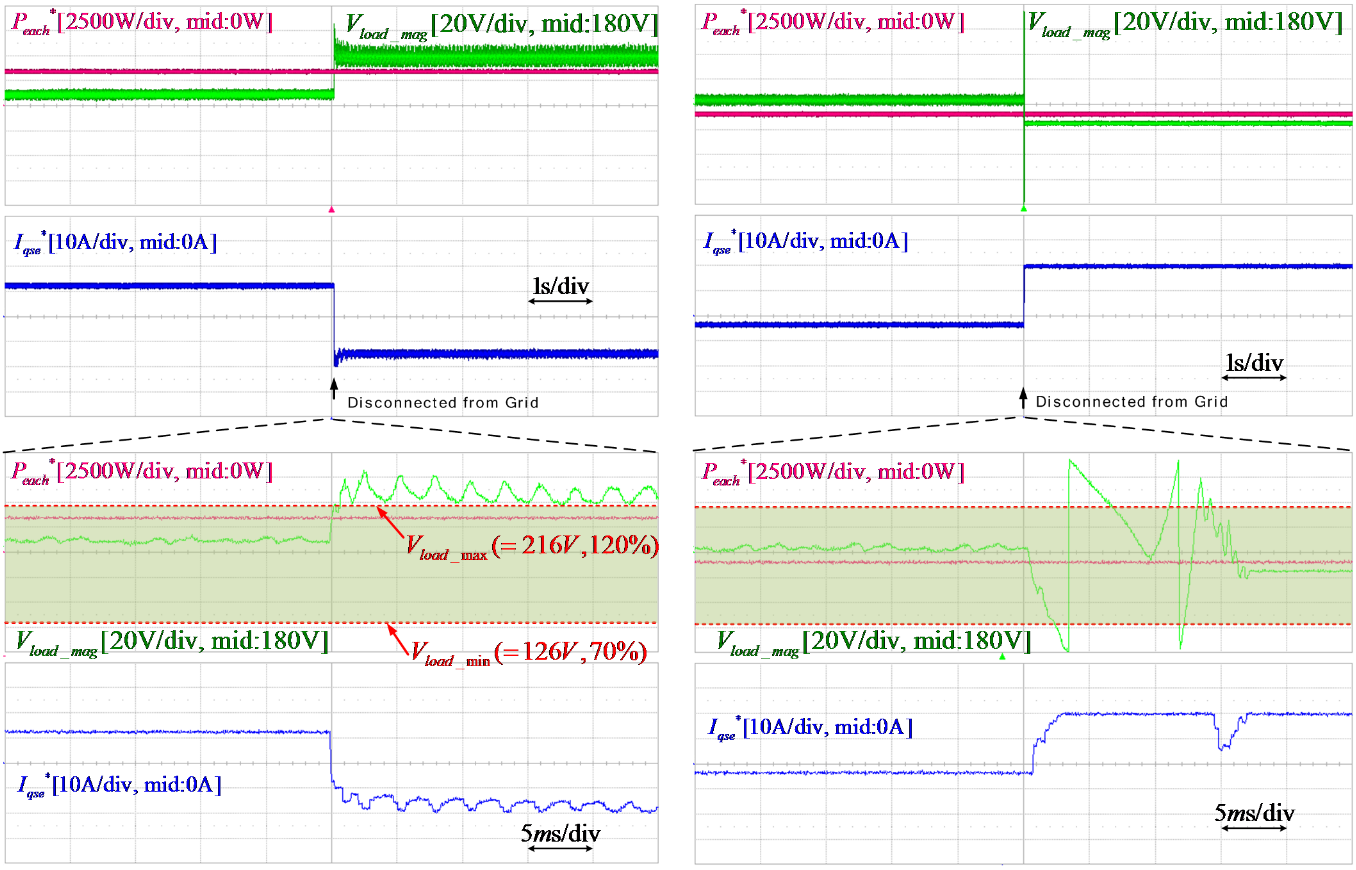


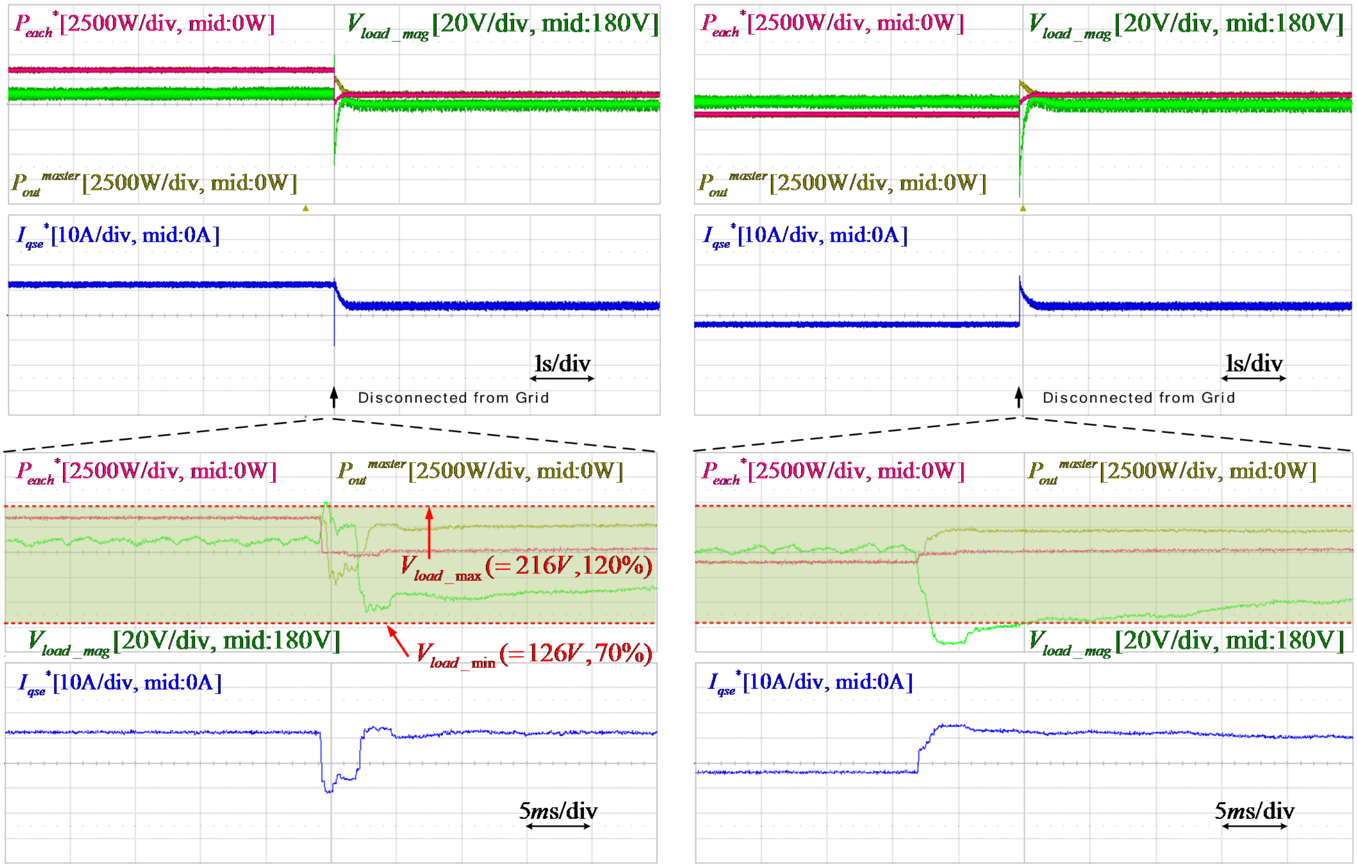
Fig. 7. Experimental set-up: 5 parallel PCSs

IV. EXPERIMENTAL RESULTS



(a) (b)

Fig. 8. Experimental results without reference modifier (a) $P_{total}{}^{*} = 17{,}500W$, (b) $P_{total}{}^{*} = -5{,}000W$



(a) (b)

Fig. 9. Experimental results with reference modifier (a) $P_{total}{}^* = 17{,}500W$, (b) $P_{total}{}^* = -5{,}000W$

A PCS system consisted with five 5 kW parallel PCSs was implemented as shown in Fig. 7 to verify the operation of the proposed power reference modifier and overall control algorithm. The topology of each PCS is three level (T-type) three leg converter and LCL filter is utilized to attenuate the harmonics of the output current. The DC-link voltage is kept as 400V and the magnitudes of the grid voltages are 220 $V_{l-l,rms}$. For the communication protocol from the master PCS to the slave PCSs, the CAN (Controller Area Network) is used. The communication is executed periodically at every 2.5ms. For emulating the critical loads, the resistor with a value 9.6 Ω in each phase, corresponding to 5 kW at the rated voltage, is used. To suppress the circulating current in parallel converters sharing common DC and AC sources, the operation, the zero sequence controller with a feed-forward term is applied [17] and the circulating current has been minimized.

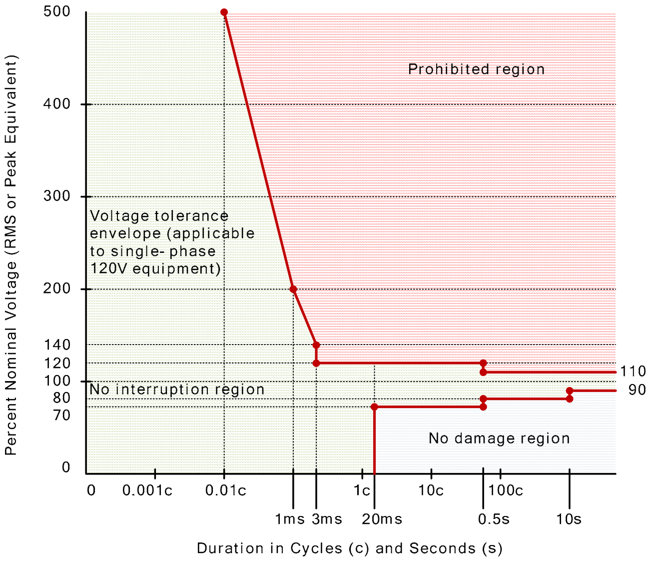


Fig. 10. CBEMA Curve

In Fig. 8 (a), the experimental result is shown when total power references ($P_{total}{}^*$) is 17,500W and the control method as in Fig. 3 is applied. In grid-connected mode, the power reference ($P_{each}{}^*$) of each PCS is 3,500 W. When the DG is disconnected from the grid, the STS opens. And the mater PCS changes its control mode from current control to voltage control. At that time, slave PCSs maintain current control mode with the same power references as used in grid-connected mode. Then the output power summation of slave PCSs is 14,000W. And, 5,000W among 14,000W is consumed in the critical loads. The master PCS which works as a voltage source should sink the remaining, 9,000W. It tried to control the magnitude of loads' voltage to be 180V, but necessary current is beyond its capacity. Fortunately, the fault didn't happen. However, the magnitude of phase voltage applied to the load is settled to over 216V which is larger than the rated voltage by 20%. It violated the regulation of the Computer Business Equipment Manufacturers Association (CBEMA) as shown in Fig. 10. The locus of the voltage to the critical load is out of CBEMA curve. Fig. 8 (b) is the experimental result when P_{total}^* is -5,000W and the control method as in Fig. 3 is applied. In grid-connected mode, the power reference (P_{each}^*) of each PCS is -1,000 W. When the DG is disconnected from the grid, the output power summation of slave PCSs is -4,000W. And, 5,000W is consumed to the critical loads. The master PCS should sink the remaining, -9,000W (that is, supplying 9,000W to the system). It tried to control the magnitude of loads' voltage to be 180V, but necessary current is beyond its capacity. Unfortunately, the fault happened and the system halts.

Fig. 9 (a) and (b) are the experimental results when the proposed reference modifier is applied as in Fig. 6. Their experimental conditions are same as Fig. 8 (a) and (b), respectively. In grid-connected mode, P_{each}^* are 3,500W and -1,000W, respectively. But when the DG is disconnected from the grid, P_{each}^* of both experiments are controlled to 1,000W by the reference modifier because the consumed power of the critical loads are the same in both experiments. It means that the consumed power is shared equally by 5 parallel PCS. Therefore the magnitude of the load voltage is well controlled to 180V.

V. CONCLUSION

This paper has proposed a power reference modifier for seamless transfer considering the power balance in parallel operation. It does not need additional current sensors for monitoring the consumed powers of the critical loads. Instead of those sensors, the consumed power values can be estimated indirectly from the calculated power values of the master PCS which works as a voltage source in stand-alone operation. The calculated power values of the master PCS are utilized in the power reference modifier to modify the total power references. The modified references guarantee equal load sharing between all PCSs. To verify the validity of the proposed methods, experiments were carried out based on five 5 kW parallel PCSs. From the experimental results, it has been verified that the seamless transfer satisfying equal load sharing and simultaneously CBEMA curve was well conducted.

REFERENCES

[1] M. Schweizer, I. Lizama, T. Friedli, and J. W. Kolar, "Comparison of the chip area usage of 2-level and 3-level voltage source converter topologies," in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 391-396.

[2] S. Zhangping, Z. Xing, W. Fusheng, and C. Renxian, "Modeling and Elimination of Zero-Sequence Circulating Currents in Parallel Three-Level T-Type Grid-Connected Inverters," *Power Electronics, IEEE Transactions on,* vol. 30, pp. 1050-1063, 2015.

[3] J. M. Guerrero, H. Lijun, and J. Uceda, "Control of Distributed Uninterruptible Power Supply Systems," *Industrial Electronics, IEEE Transactions on,* vol. 55, pp. 2845-2859, 2008.

[4] A. Tuladhar, K. Jin, T. Unger, and K. Mauch, "Parallel operation of single phase inverter modules with no control interconnections," in *Applied Power Electronics Conference and Exposition, 1997. APEC '97 Conference Proceedings 1997., Twelfth Annual*, 1997, pp. 94-100 vol.1.

[5] M. C. Chandorkar, D. M. Divan, and R. Adapa, "Control of parallel connected inverters in standalone AC supply systems," *Industry Applications, IEEE Transactions on,* vol. 29, pp. 136-143, 1993.

[6] J. M. Guerrero, L. Garcia De Vicuna, J. Matas, M. Castilla, and J. Miret, "Output Impedance Design of Parallel-Connected UPS Inverters With Wireless Load-Sharing Control," *Industrial Electronics, IEEE Transactions on,* vol. 52, pp. 1126-1135, 2005.

[7] A. P. Martins, A. S. Carvalho, and A. S. Araujo, "Design and implementation of a current controller for the parallel operation of standard UPSs," in *Industrial Electronics, Control, and Instrumentation, 1995., Proceedings of the 1995 IEEE IECON 21st International Conference on*, 1995, pp. 584-589 vol.1.

[8] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, "Control of parallel converters for load sharing with seamless transfer between grid connected and islanded modes," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-7.

[9] C. Jiann-Fuh and C. Ching-Lung, "Combination voltage-controlled and current-controlled PWM inverters for UPS parallel operation," *Power Electronics, IEEE Transactions on,* vol. 10, pp. 547-558, 1995.

[10] P. Yunqing, J. Guibin, Y. Xu, and W. Zhaoan, "Auto-master-slave control technique of parallel inverters in distributed AC power systems and UPS," in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, 2004, pp. 2050-2053 Vol.3.

[11] T. Thanh-Vu, C. Tae-Won, L. Hong-Hee, K. Heung-Geun, and N. Eui-Cheol, "PLL-Based Seamless Transfer Control Between Grid-Connected and Islanding Modes in Grid-Connected Inverters," *Power Electronics, IEEE Transactions on,* vol. 29, pp. 5218-5228, 2014.

[12] Y. Zhilei, X. Lan, and Y. Yangguang, "Seamless Transfer of Single-Phase Grid-Interactive Inverters Between Grid-Connected and Stand-Alone Modes,"

Power Electronics, IEEE Transactions on, vol. 25, pp. 1597-1603, 2010.

[13] M. J. Yang, F. Zhuo, X. W. Wang, H. P. Guo, and Y. J. Zhou, "Research of seamless transfer control strategy of microgrid system," in *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on*, 2011, pp. 2059-2066.

[14] C. Xin, W. Yan Hong, and W. Yun Cheng, "A novel seamless transferring control method for microgrid based on master-slave configuration," in *ECCE Asia Downunder (ECCE Asia), 2013 IEEE*, 2013, pp. 351-357.

[15] D. S. Ochs, P. Sotoodeh, and B. Mirafzal, "A technique for voltage-source inverter seamless transitions between grid-connected and standalone modes," in *Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE*, 2013, pp. 952-959.

[16] L. Zeng and L. Jinjun, "Indirect Current Control Based Seamless Transfer of Three-phase Inverter in Distributed Generation," *Power Electronics, IEEE Transactions on,* vol. 29, pp. 3368-3383, 2014.

[17] S. Young-Kwang, C. Seung-Jun, L. Younggi, S. Seung-Ki, O. Jaeyoon, L. Changjin*, et al.*, "Suppression of Circulating Current in Parallel Operation of Three-Level Converters," in *Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE*, 2016.