A Verification of Improved Distributed Control in DC Microgrid based on Hardware-in-the-loop Simulation

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***Abstract*— An improved distributed control is proposed for enhancing a flexibility of changing the control strategy depending on the dc microgrid situation. The conventional distributed control has the limitation of changing control strategy because of its control method. In the proposed control method, a local controller of conventional distributed control divided into two layers. First, the local layer performs inner voltage and current loops. Second, the flexible layer performs the primary and secondary control. Since the flexible layer performs most of the control for operating dc microgrid, the control strategy can be changed easily by changing the primary and secondary control in this layer. Moreover, the burden of data processing at the local controller is reduced through the flexible layer of the proposed method. Therefore, it becomes easy to manufacture converters in multi-vendor without control platform standardization. The experimental results based on Typhoon HIL 402 are presented to demonstrate the proposed approach.**

***Keywords*— DC Microgrid, Distributed Control, Centralized Control, Droop Control, Hardware-in-the-loop simulation**

I. INTRODUCTION

Nowadays, environmental problems become a major concern with depleted energy sources. Governments and engineers are working to find solutions that are stable, efficient, and at the same time environment-friendly. Recently, many researches have been conducted on distributed power generation using renewable energy such as wind power, solar power, and fuel cell. Accordingly, the importance of microgrid (MG) which is a small-scale power network composed of renewable generators, energy storage devices, and loads, is increasing in the existing AC grid. In particular, the interest in dc MG has been growing as the penetration rate of dc renewable energy sources increases and the usage of dc load such as digital load increases. The dc MG highly reduce the problems of frequency synchronization and reactive power consumption, and has low cost as it does not require two-stage power conversion to link the power generated by each power source [1] - [3]. The general architecture of a dc MG is shown in Fig. 1.

One of the methods for controlling the dc MG is the droop control [4]. In general, the droop control is placed in the local controller, which called the local layer in this paper, of the converters are operated in parallel to avoid the circulating current. The droop control generates the voltage reference from the output current of the converter according to droop coefficients which is equivalent to virtual impedance [4]. The local layer of the converter performs inner loops, which are the voltage and current loops according to the newly generated voltage reference. However, in actual systems, there is a line resistance between the converters performing the droop control. Line resistance causes additional voltage deviation, which not only degrades the performance of the droop control but also causes improper load sharing [4]. To solve the limitations of the droop control, coordinated control has been studied [4] - [10]. The coordinated control can be categorized into two types according to whether there is a centralized controller or not.

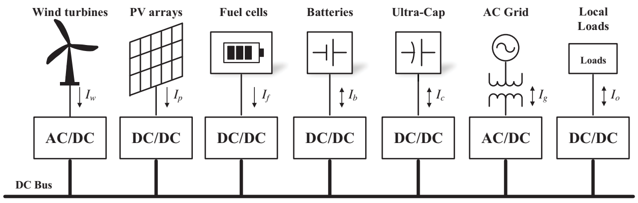

Fig. 1. General architecture of dc microgrid

In the case of centralized control, the entire system is operated using the Microgrid Central Controller (MGCC) with a communication network. In small-scale dc MGs, each converter can be directly controlled by the MGCC using the master/slave method in high bandwidth communication (HBC). However, in the case of a large-scale dc MG, a hierarchical control is mainly used in low-bandwidth communication (LBC) having a certain degree of discrepancy between different control levels as shown in the method of the hierarchical control, Fig. 2. The less dependency between different control levels makes the control system more stable compared to the master/slave method [5]. In hierarchical control, primary control and inner loops correspond to the local layer, and primary control mainly consists of droop control. The secondary control and tertiary control correspond to the global layer, of which secondary control is utilized to improve load-dependent voltage deviation and improper load sharing in primary control due to line resistance. Tertiary control is employed to control the power flow between the dc MG and the grid or between the dc MGs [4]. However, this centralized control still has the disadvantage of a single point of failure.

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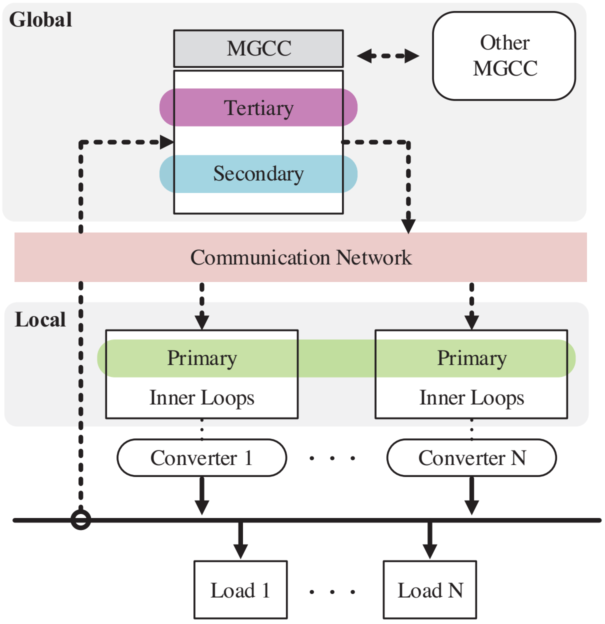

Fig. 2. Centralized control

In particular, if the MGCC or any major communication network fails, a control command will not be sent to each controller, and the corresponding objective is not possible to achieve.

The distributed control has been studied to reduce problem such as a single point of failure of the centralized control. The method of the distributed control is shown in Fig. 3. In the distributed control, inner loops, primary, and secondary control correspond to the local layer. The distributed control performs the secondary control by collecting information through LBC at the local layer of each converter without MGCC [6]. The secondary control is performed at the local layer, which reduces system dependence on communication and improves reliability [6] - [10]. However, since the distributed control performs overall control in the local layer due to its control method, it is difficult to change the control strategy according to the dc MG situation. In addition, it is difficult to manufacture in multi-vendor because the control standard for the local layer of the converter with distributed control is insufficient.

To address the aforementioned limitations, an improved distributed control is proposed. The proposed improved distributed control performs the coordinated control such as the primary and secondary control in the flexible layer by using an additional communication network. The proposed control is easy to change the control strategy because it uses the flexible layer, unlike the conventional distributed control. Moreover, it has advantage what the converter for dc MG distributed control can be easily manufactured by multi-vendors without control platform standard unification.

In order to validate the proposed improved distributed control, hardware-in-the-loop simulation (HILS) is adopted in this paper. For HILS, a real digital signal processor (DSP)

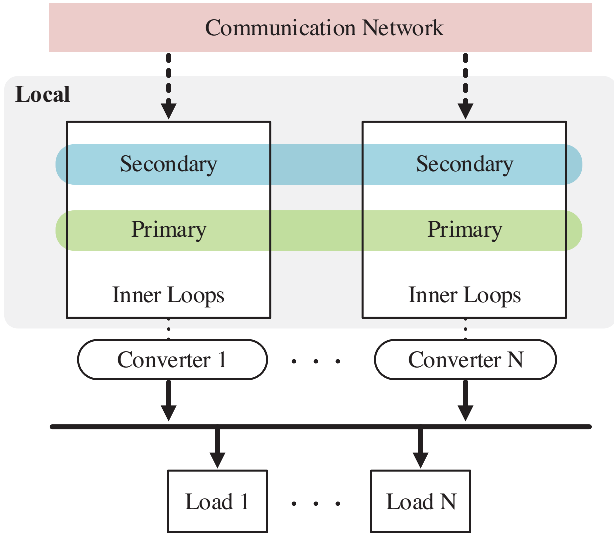

Fig. 3. Distributed control

controller can be tested in real-time embedded systems of complex systems [11]. In this paper, the proposed control will be verified with the local and flexible layer that can be implemented in DSP controllers and applying it to the dc MG prototype using HILS.

II. Proposed Distributed Control

Fig. 4 shows the method of the improved distributed control. The improved distributed control has three layers, which are the local, flexible, and global layer. The local layer performs the basic control for the operation of the converter, usually a converter controller such as inner loops. The flexible layer performs a control for dc MG operation, such as coordinated control of primary and secondary control can be located in this layer. The global layer controls the power flow between the other dc MGs and corresponds to the tertiary control of the MGCC.

The communication network 1, which is located between the local layer and the flexible layer, transmits some information such as output voltage and current from the local layer to the flexible layer and transmits the voltage reference again to the local layer which is calculated in the flexible layer. The inner loops of the local layer receive the voltage reference from the flexible layer in real-time and operate the dc MG. Therefore, high reliability and high-speed communication are required. Meanwhile, the communication network 2, which is located between the flexible layer and global layer, is used for transmitting and receiving the necessary information for various control algorithms or for tertiary control of the MGCC. For this communication, LBC can be utilized which is often adopted in the hierarchical control and distributed control.

Fig. 5 shows an example of applying the proposed control. The flexible layer performs the coordinated control and the primary control is the droop control. Each of the flexible layers receives the output voltage $v_{o1,2}$ and current information $i_{o1,2}$ of the converters from the local layer through the communication

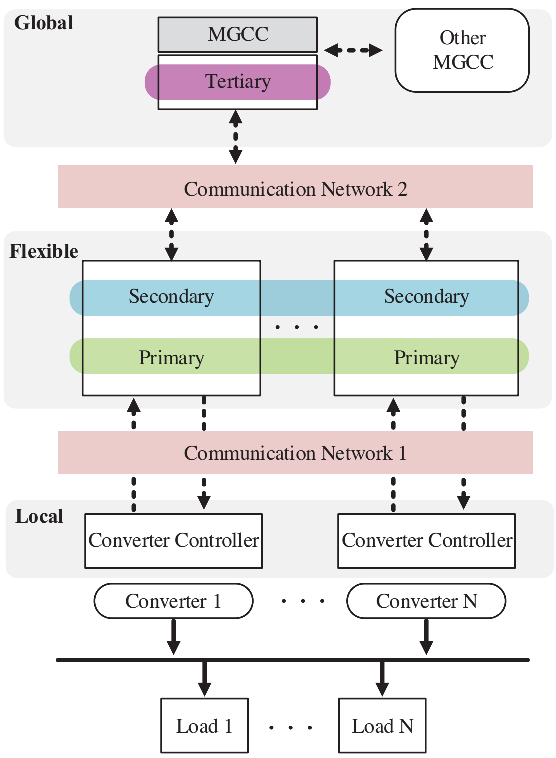

Fig. 4. Improved distributed control

network 1. At the same time, all of the flexible layers transmit and receive information necessary for the secondary control, such as output voltage v_o, output current i_o, droop gain R_D, and nominal voltage v_{nom} of the other converter through the communication network 2. The flexible layers calculate the voltage reference $v_{o1,2}^*$ by performing the coordinated control based on the received information. The calculated $v_{o1,2}^*$ are transmitted to each local layer through the communication network 1. Each converter operates the dc MG by performing inner loops according to the received $v_{o1,2}^*$. The pulse-width modulated (PWM) signal of the converter 1 and 2 are generated through these inner loops.

III. Real-time Implementation

A. Hardware-in-the-loop Simulation

In the case of the proposed control, the communication network 1 and the flexible layer are added. In order to validate the proposed control, it is essential to analyze the influence of the flexible layer and the corresponding communication network at the system level [11] - [13].

In the case of manufacturing a real dc MG system, it will take a lot of money and time to test the communication network and the actual controllers. Furthermore, actual controller tests such as limit test, failure test, and expensive test are difficult to test in real dc MG even when dc MG is manufactured [12].

Computer-based simulation is difficult to validate the proposed control because it cannot implement communication network, local layer, and flexible layer. Furthermore, there is a limitation to check the performance in unexpected situations. By using the complex real-time embedded technology, HILS, the above mentioned problems can be solved and verified the effects of the communication network and the actual controllers on the entire system to the virtually simulated dc MG.

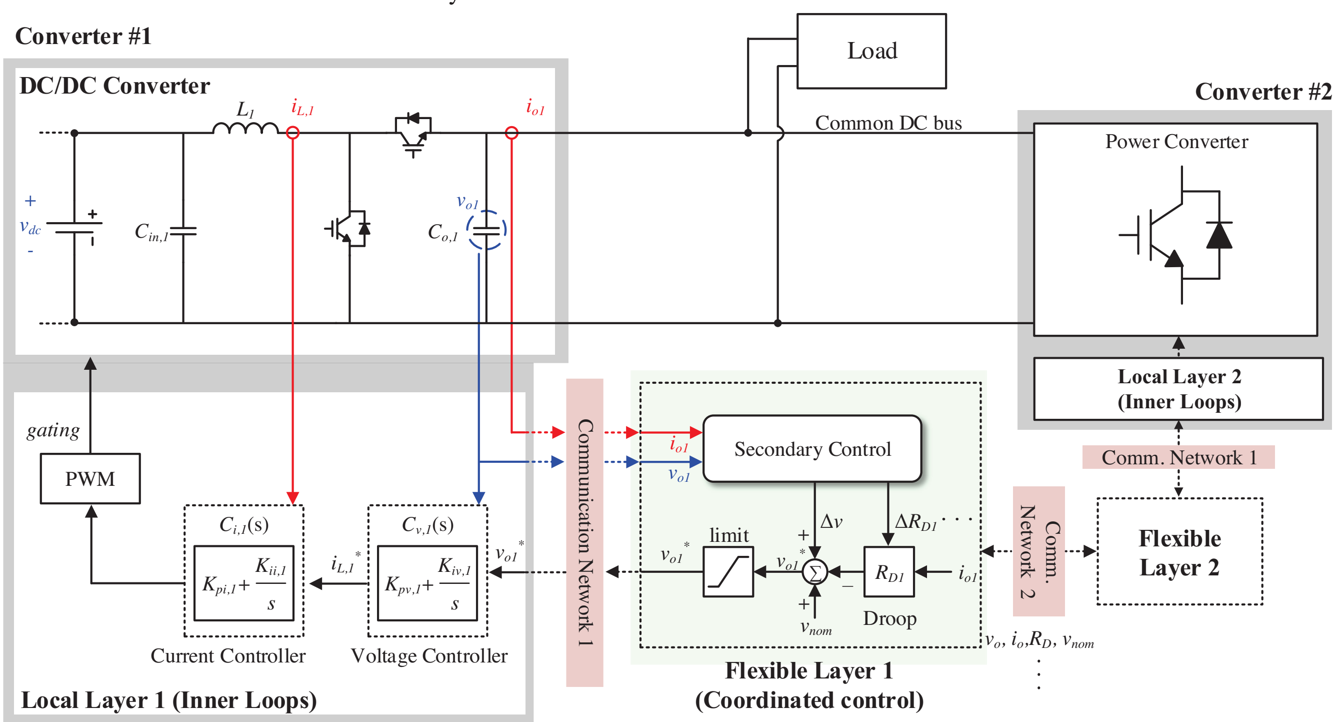

Fig. 5. Control diagram example of the proposed improved distributed control

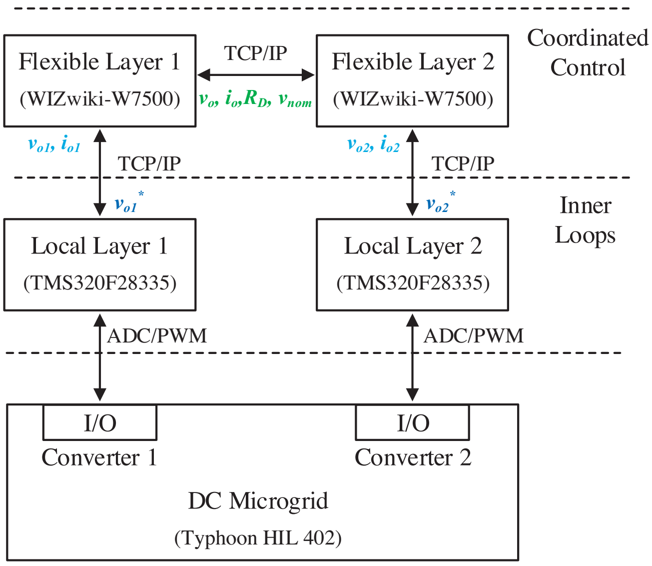

Fig. 6. HILS based prototype setup for dc microgrid

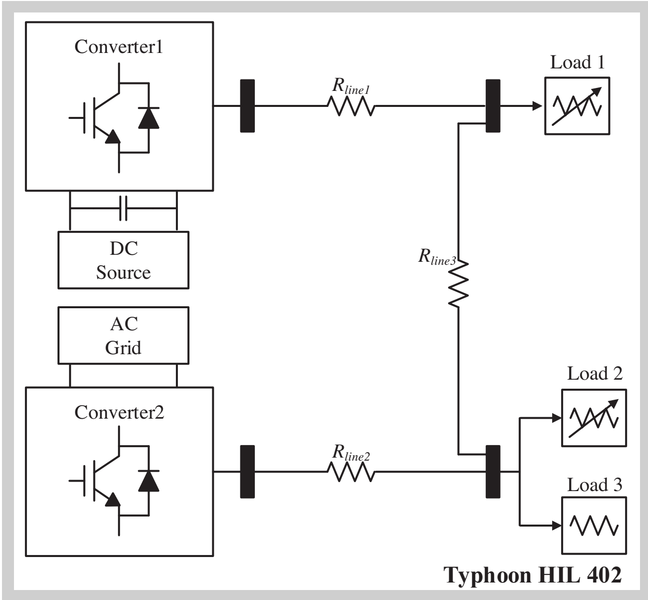

Fig. 7. DC microgrid using HIL

B. *System Configuration*

Fig. 6 shows the dc MG prototype setup to verify the proposed control. As shown in Fig. 6, the dc microgrid block is configured through HILS, and the Typhoon HIL 402 is applied to implement the real-time operation [15].

In order to test the local and flexible layer in real-time, the local layer for performing the inner loops is implemented using the TI TMS320F28335, and the flexible layer for performing the coordinated control is implemented using the ARM cortex-M0 chip. The reasons for adopting each product and specifications are as follows.

1) DC Microgrid block : Fig.7 is a detailed dc microgrid block in Fig. 6. The dc MG implemented in the Typhoon HIL 402 consists of a bi-directional dc/dc converter with a dc source as input, a voltage source converter with an AC source as input, and dc loads. The dc loads consist of variable loads 1, 2 and resistive load 3. For Typhoon HIL 402, accurate testing of the proposed control is possible because it has 20ns high resolution of digital input and analog output[15]. Detailed parameters of the dc MG are shown in Table I.

2) Local layer : In the case of the local layer, three different functions are performed. First, ADC is required to measure the output voltage and current value of each converter in HILS, dc MG. Second, PWM regulation is required to control the duty ratio of the converter to regulate the output voltage. Third, communication functions must be possible to transmit the output voltage and current values and to receive the calculated voltage reference. In addition, since the voltage reference is received in real-time and the inner loops will generate the PWM with this voltage reference, the data processing speed must be fast.

Therefore, in this prototype setup, the TMS320F28335 DSP board, which can implement ADC, PWM, and communication with a high-speed data processing, is used as the local layer.

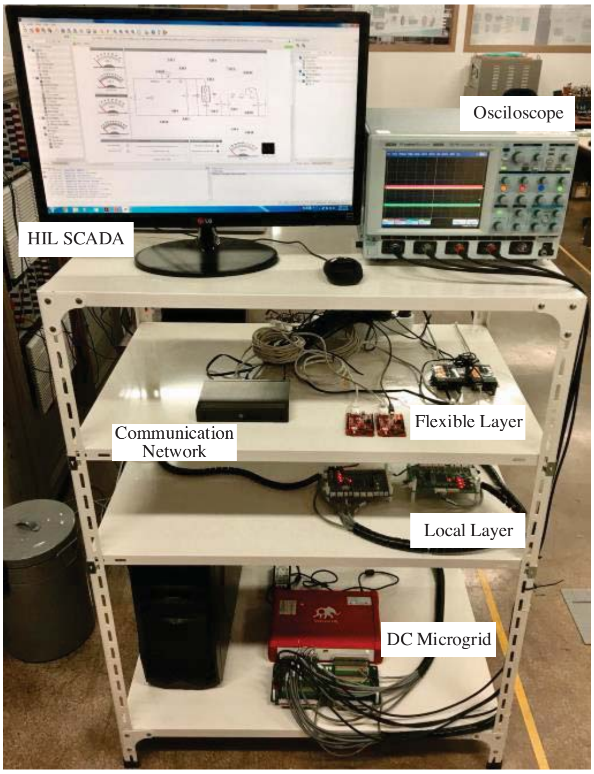

Fig. 8 Experimental dc MG prototype setup using Typhoon HIL 402

3) Flexible layer : In the case of the flexible layer, two functions are indispensable. First, it needs communication capability. The flexible layer must be able to communicate with the local layer and between the flexible layers. Second, data processing must be possible. The data processing function is essential because it performs coordinated control based on various information such as the output voltage and currents of the converters.

Meanwhile, unlike the conventional distributed control, the proposed control requires an additional cost to construct the flexible layer. The cost generated in making the flexible layer should be considered. For this reason, WIZwiki-W7500 is selected for the flexible layer which is able to implement various coordinated control through ARM cortex-M0 chip and can perform TCP communication using the hardwired TCP/IP core. Also, the price is as low as $30[17].

4) Communication : Communication between the local layer and the flexible layer and the communication between the flexible layers adopts the transmission control protocol/internet protocol (TCP/IP) protocol widely used as the standard communication protocol of most dc MG systems. In the case of TCP/IP protocol, a number of routing protocols support is possible. Because it is the client-server structure, it is scalable because multiple connections are possible.

IV. Experimental Results

In order to verify the validity of the proposed improved distributed control, a test bed is constructed using HILS as shown in Fig. 8. As shown in Fig. 8, the HIL 402 for dc MG is located on the first floor of the test bed, the local layer using the TMS320F28335 chip is located on the second floor, and the communication network and the flexible layers using the

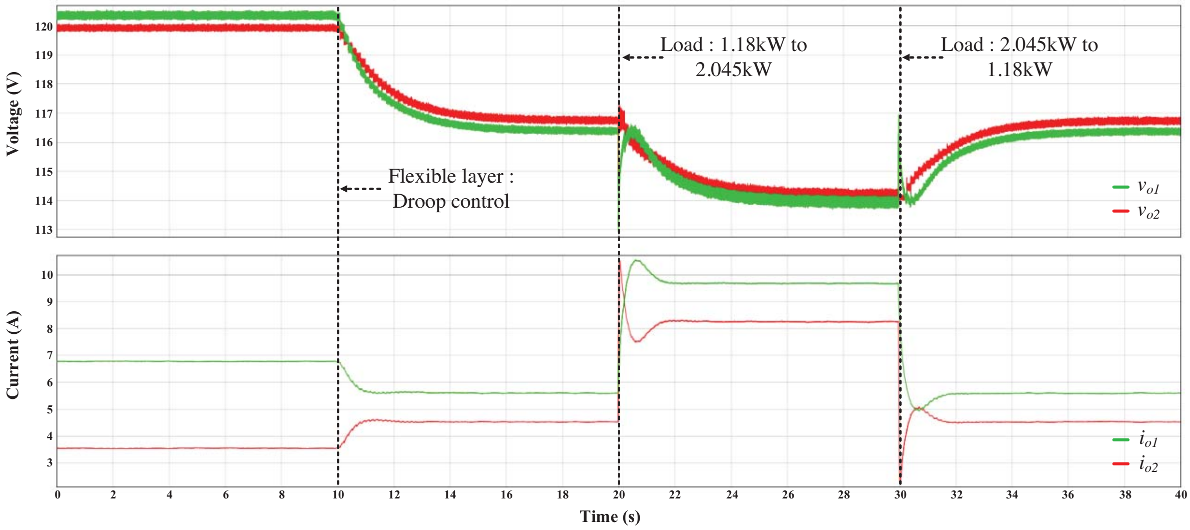

Fig. 9. Applying droop control to the flexible layer and testing the dynamic performance with load fluctuations

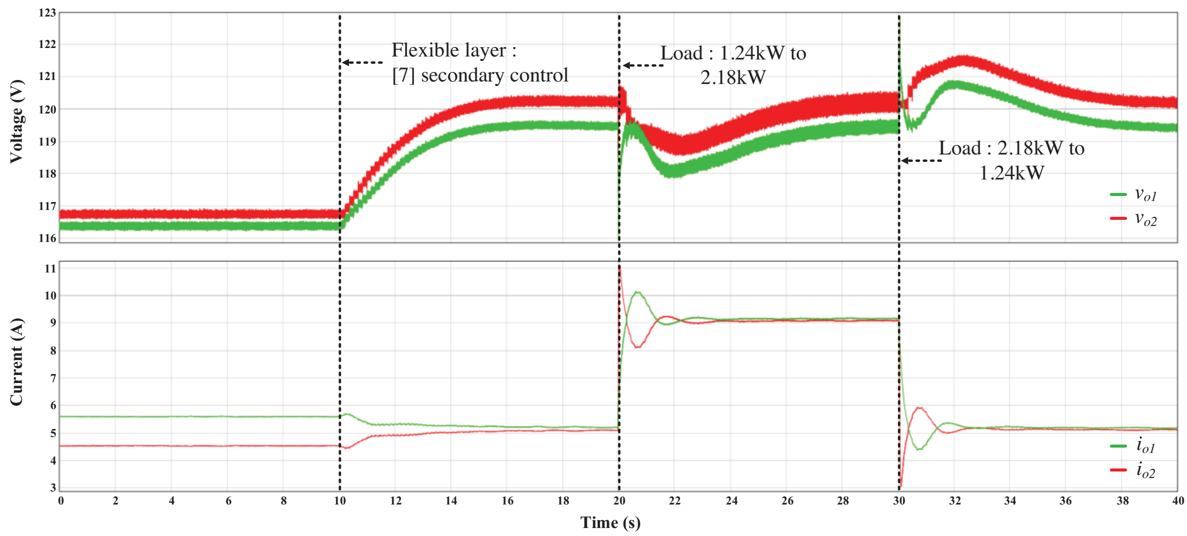

Fig. 10. Applying [7] conventional secondary control to the flexible layer after the droop control and testing the dynamic performance with load fluctuations

TABLE I. SYSTEM PARAMETERS

Symbol	Description	Values
V_{nom}	Nominal voltage	120V
P_{rated}	Rated power	3kW
f_{SW}	Switching frequency of converter 1, 2	10kHz
$R_{D1,2}$	Droop coefficient of converter 1, 2	0.7 Ω
Load 1, 2	Capacity of load 1, 2	1kW
Load 3	Resistance of load	18.8 Ω
R_{line1}	Line resistance 1	0.25 Ω
R_{line2}	Line resistance 2	0.252 Ω
R_{line3}	Line resistance 3	0.253 Ω

WIZwiki-W7500 are located on the third floor. At the top, HIL SCADA which is the Typhoon HIL 402 software for monitoring and an oscilloscope are located.

Fig. 9 shows the HILS waveform with the load changed by applying the droop control to the flexible layer. For 10 seconds, a 120V voltage control is performed and after that, the droop control is applied to the flexible. After the droop control is applied, the load is divided according to the droop coefficient. At this time, loads 1, 2 and 3 consume 233W, 233W, and 714W respectively. The loads are increased to 684W, 684W, and 677W, respectively at 20 seconds. At 30 seconds, the loads are reduced to 233W, 233W, and 714W respectively. The converters 1 and 2 share the load steadily after the droop control is applied to the flexible layer and the load fluctuation as well.

Fig. 10 shows the conventional secondary control applied to the flexible layer during the droop control and shows the load fluctuation thereafter. The conventional secondary control is a technique for voltage restoration of voltage deviation due to the droop control to a nominal voltage and an average current regulation method for the equal load sharing of parallel converters [7]. Fig. 10 shows the droop control is applied to the flexible layer during the first 10 seconds. At 10 seconds, the secondary control of [7] is applied to the flexible layer. According to the secondary control of the [7], the voltage is compensated to the nominal voltage 120V and the converters 1 and 2 with the equal load sharing. From 10 to 20 seconds, loads 1, 2 and 3 consume loads of 240W, 240W, and 760W, respectively. At 20 seconds, the load 1, 2, and 3 increased to 720W, 720W, and 740W respectively. At 30 seconds, the load is reduced to 240W, 240W, and 760W respectively. The converters 1 and 2 share the load equally after the secondary control is applied to the flexible layer and the load fluctuation as well.

V. CONCLUSION

The proposed improved distributed control reduces the burden of data processing of the converter local layer by performing the primary and secondary control in the flexible layer. This also can improve the flexibility of changing the control strategy in an easy way. Moreover, it has the advantage that converters for distributed control can be manufactured by multi-vendor without a control standardization. In this paper, the flexible layer and the local layer of the improved distributed control are implemented through the DSP controllers and tested in the HILS environment. The validity and the performance of the proposed control are verified through the experiment by applying the droop control and the secondary control to the flexible layer with load fluctuations.

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