Master's Thesis
석사 학위논문

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Advisor : Professor Taejoon Park
Co-advisor : Doctor Sangwoo Lee

By

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

12. 2. 2013

Approved by

Professor Taejoon Park ________( Signature )
(Advisor)

Doctor Sangwoo Lee ________( Signature )
(Co-Advisor)

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[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

# A Decentralized Control Scheme for Power Quality Enhancement in Smart Microgrids

Bae Hyo Joon

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

12. 2. 2013

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## ABSTRACT

We present power quality enhancement methods for smart microgrids that employ the concept of decentralized control based on state feedback and droop control. Existing power systems suffer from many problems. For example, large-scale power plants are located far away from consumers. The increasing usage of renewable energy sources leads to severe voltage distortion and voltage fluctuation. Hence, power conditioning equipment such as power filters and static synchronous compensators (STATCOMs) are needed to assure power quality and generate electricity from renewable energy sources efficiently. However, when power electronic converters are used in parallel in microgrids, circulating currents can flow across the converters, leading to bad effects in power systems or microgrids. We propose two methods for power quality enhancement by reducing circulating currents. One is to design DC-DC converter voltage regulation by using state feedback control. Another method is to reduce circulating current generated along buses by using an advanced Phase Shift Pulse Width Modulation (PSPWM) DC-DC converter between High Voltage DC Bus (HVDC) and Low Voltage DC Bus (LVDC). To validate the proposed methods, we develop a microgrid simulator using MATLAB/Simulink and evaluate the benefits of our scheme using this simulator. As a result, we demonstrate, through the two simulation results, the power quality in DC microgrids is improved when the power is transferred.

**Keywords:** power quality, state feedback control, circulating current, PSPWM DC-DC converter, DC-DC boost converter

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# I. INTRODUCTION

A few years ago, the existing power system was a one-directional power system. Power suppliers only supplied power to consumers. With the growth in IT technology, the power grid was able to integrate IT technologies and exchange information about power grid between suppliers and consumers. This power grid is called a smart grid.

A smart grid is essentially a centralized management system. Smart meters are power devices that collect power, voltage, and phase information from power suppliers and power consumers and transmit this information to the central management center in real-time. Through analyzing the collected information and predicting the amount of power usage in the future, it can predict the required amount of power generation.

A power grid consists of power generation & transmission systems and power consumers. Power consumers consume power as loads and these loads consist of electronic devices, lights, electric motors, and other similar devices. There may be a power dearth because use of electrical and electronic equipment is increasing rapidly. To overcome this situation, smart microgrids utilizing distributed power generation are emerging as a solution. Smart microgrids with distributed generation are economical and useful on grid-connected because distributed generation does not require long distance transmission lines. As power systems include distributed generation, there's an increasing need for smart microgrids to dispersively control each distributed generation [1].

Renewable energies in distributed generation are emerging as new alternative energy sources; however, they give many problems in terms of power quality. For example, in the case of wind energy, irregularity of the source may cause detrimental effects in the power generation system. These effects can negatively affect the entire power system, especially if there is any cooperation with existing power systems. [2-3].

A power quality conditioner with a shunt and a series inverter has been presented for interfacing microgrids to the utility grid. The conditioner has been already shown to raise the quality of power within the microgrid and the quality of currents flowing between the microgrid and the utility [4]. The Direct Current (DC) microgrid studied in this paper is composed of two common DC buses, one being High Voltage DC Bus (HVDC) and Low Voltage DC Bus (LVDC). Moreover, a Phase Shift Pulse Width Modulation (PSPWM) DC-DC converter can be placed between the two buses [5-6]. In order to generate power efficiently, a power generator is linked to HVDC. By contrast, an energy storage system is connected to LVDC in order to manage and maintain extra power. Power transmission between the two buses is bidirectional and supports galvanic isolation [5-6].

Existing power systems suffer from many problems. For example, large-scale power plants are located far away from consumers. When the power is transmitted from plants to consumers over a long distance, power dissipation increases. To counter these problems, microgrids utilizing distributed power generation are emerging as an alternative solution thanks to their desirable properties such as low cost power facilities and reduced power transmission loss [7].

Power quality may impact electrical equipment lifespan at the consumer end, and is a measure of efficiency of power generation, power transmission loss, and accurate power grid monitoring [4]. Below are the examples.

- Electrical devices use electric power directly. If a low electric power supply feeds into electrical devices, the lifespan of electrical devices decreases.

- If power generation systems generate electric power in a low power quality environment, resources are wasted when electric power is generated.
- When low quality electric power is transmitted from suppliers to consumers, the consumers receive less electric power than generated power from suppliers.
- If the power grid’s information (voltage, current, phase) is inaccurate due to low power quality when each smart meter measures the information of the power grid in order to maintain and manage the power grid, power grid management will be difficult.

Due to these reasons, power quality enhancement is an important area of research. This paper presents power quality enhancement on DC microgrids for effectively using renewable energy sources in power generation.

There are many challenges to be overcome in order to realize the real deployment of microgrids. One such challenge is the circulating current that occurs in the power system when many microgrids operate concurrently. It is important to remove or at least mitigate the effect of circulating current as it negatively impacts the power system, degrading its power quality [8]. One possible solution would be to install a resister to absorb the circulating current, but doing so is very expensive and energy-inefficient.

First of all, circulating current, which may occur between the two DC-DC converters, can be reduced by using a virtual resistance. Using a droop control method, a virtual resistor is inserted into the Pulse Width Modulation (PWM) controller in order to reduce circulating current. Details are discussed in the next session. This method is good in terms of cost efficiency because it does not use the actual resistance and power quality of the power grid is enhanced by reducing the effect of circulating current.

Circulating current also occur between HVDC bus and LVDC bus. It can be reduced by using an advanced PSPWM DC-DC converter instead of a traditional Phase Shift Full-Bridge

(PSFB) converter. An advanced PSPWM DC-DC converter [9] is originally used in Plasma Display Panels (PDP). However, due to the improvement of each electrical device's specification, we exploit this DC-DC converter in DC microgrids. A PSPWM DC-DC converter regulates output voltage required by grid buses by shifting the phase. Circulating current, which occurs on the primary side of the transformer in traditional PSFB converter, can be reduced by using an advanced PSPWM DC-DC converter.

We implement a simulated circuit and evaluated its performance using MATLAB/Simulink. We demonstrate in the simulator that the virtual resister method indeed reduces the effect of circulating current, and thus improves power quality. As an advanced PSPWM DC-DC converter is placed between HVDC bus and LVDC bus, reducing circulating current is demonstrated. Reduced circulating currents in power transmission and power generation are proved that there is a positive effect. In the future, simulation can be helpful to apply these methods in real power grids. The proposed microgrid scheme can be connected to an AC grid also.

This thesis is organized as follows. Section II presents background knowledge and related work. Section III introduces our DC microgrids simulator and its main components. Section IV proposes and discusses two methods to enhance power quality in DC microgrids by reducing circulating current. Sections V and VI present performance evaluations and conclusions.

# II. BACKGROUND

## 2.1 Smart microgrids – decentralized control on DC microgrids

### *2.1.1 Microgrid simulator - decentralized control on DC microgrids*

We develop a microgrid simulator using MATLAB/Simulink. It consists of DC power generation units, power converters, and voltage controllers for each power generation unit, all of which are interconnected through two DC grid buses (HVDC and LVDC) with resistive loads [6]. This simulator can reproduce power quality degradations in a microgrid due to circulating current as well as by other factors such as inefficient Power Conditioning System (PCS), transient phenomena of switches in power converter, control signal delay, etc.

### *2.1.2 Power converter – PSPWM DC-DC converter*

The power converter can convert input voltage into any output voltage desired. A DC-DC converter operates with DC input and output voltages. If the output voltage is higher than the input voltage, the converter becomes a boost converter. If the output voltage is lower than the input voltage, the converter becomes a buck converter. Depending on the application, many types of converters exist.

We use a PSPWM DC-DC converter and DC-DC boost converter among many types of converters. The PSPWM DC-DC converter is used to regulate the voltage of the DC buses and isolate between them [9]. A DC-DC converter was used to regulate output voltage in the power generator. Each converter has a controller to regulate voltage or current. To obtain the desired voltage requires a well-designed controller.

## 2.2 State feedback and droop control

Each distributed power generator has a controller in the power conversion equipment. Each converter, respectively, has a state feedback controller to regulate the output voltage level. The state feedback method can monitor internal parameters and adjust states effectively. A virtual resister that is calculated by droop control using monitored parameters is inserted in the state feedback controller and reduces circulating current.

### 2.2.1 *State feedback*

We designed the power system to use a state feedback method in contrast to Proportion Integral (PI) control. PI control methods require control value decision processes and stable pole positions. However, using state feedback control, we can set the pole positions which assure stability and generate control values directly.

### 2.2.2 *Droop control method*

When some converters operate concurrently, each converter creates regulated voltage errors by sensor errors, controller errors, or transmission line impedance. When a controller is regulating voltage, a difference value can occur. Through the difference value calculation by droop curve, droop control can regulate voltage by subtracting the difference value from the desired voltage value by using the measured value of the output voltage in steady state condition.

## 2.3 Circulating current

Distributed generation requires power converters for voltage level regulation so that the units can be connected to a DC bus. Typically, PWM-controlled switching power converters are used. As multiple generators are connected to the bus, any discrepancies of PWM duty ratios between power converters (different switching frequencies, different power stage parameters or different switching dead time) may cause a large circulating current [8].

## 2.4 Related work

Many researchers have analyzed power quality during power transfer in microgrids or power systems. Now, due to the emergence of renewable energy as a power generation resource, the increased use of renewable energy sources leads to severe voltage distortion and voltage fluctuation [10]. Power conditioning equipment such as power filters and static synchronous compensators (STATCOMs) are needed to assure power quality and generate electricity from renewable energy sources efficiently [11]-[13]. By using inverter-based distributed generations (DGs), instead of installing power-conditioning equipment, power quality can be improved. In order to improve power quality by inserting DGs in power grids, the DGs should be operated cooperatively and supervisory algorithms such as droop control and low-bandwidth communication are required to maintain DGs [14], [15].

Islanded microgrids have many uses such as avionic, automotive, marine, or rural areas [16]-[21]. When electronic power converters are used in parallel in microgrids, circulating currents can flow among the converters. Circulating currents lead to bad effects in power systems or microgrids. For mitigating bad effects by circulating currents without the use of any communication between converters, the droop control method is often used [22]–[26]. In this thesis, two methods present to improve power quality in DC microgrids and its performance evaluate.

# III. SYSTEM CONFIGURATION

This chapter is to present DC microgrids configuration and to derive a mathematical model of each component such as DC-DC boost converter, isolated bidirectional DC-DC converter. The reason why simulated design was implemented by using MATLAB/Simulink is to find problem (such as blackout, current leakage, and fault) and to improve power system when system related the power is designed in real situation. In this thesis, we implement DC microgrids simulation for improving power quality. Therefore, in this simulation circuit or power system, the real transmission lines are assumed to ideal transmission lines. The complex renewable energy generation using solar or fuel cell is replaced by a simple DC source. Finally, if a DC microgrids simulator is used, we can simulate the enhancement of power quality by reducing circulating currents that are generated in DC-DC converters and PSPWM DC-DC converter.

## 3.1 DC microgrids with HVDC bus and LVDC bus

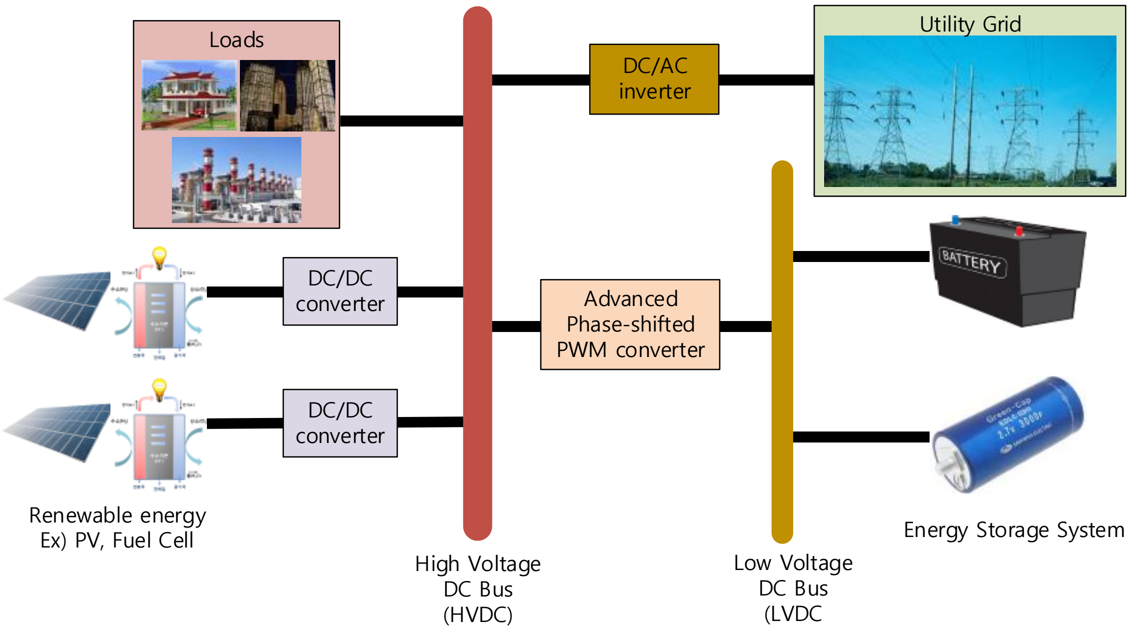


Figure 1: DC microgrids with HVDC bus and LVDC bus

In microgrids, interconnected loads, distributed energy resources, and distributed energy storage systems can be well conjugated and integrated to realize power distribution between energy generation systems and storage systems by bidirectional DC-DC converters (BDCs). Also, galvanic isolation for BDC is required for the flexibility of system reconfiguration, meeting safety standards, voltage matching and galvanic isolation between the utility grid and the energy storage systems [5, 27–30]. Therefore, bidirectional DC-DC converters with galvanic isolation have been proposed as the interface between high-voltage busses with distributed energy resources and low-voltage busses with energy storage devices in microgrids, etc., as shown in Figure 1 [31].

## 3.2 DC-DC boost converter

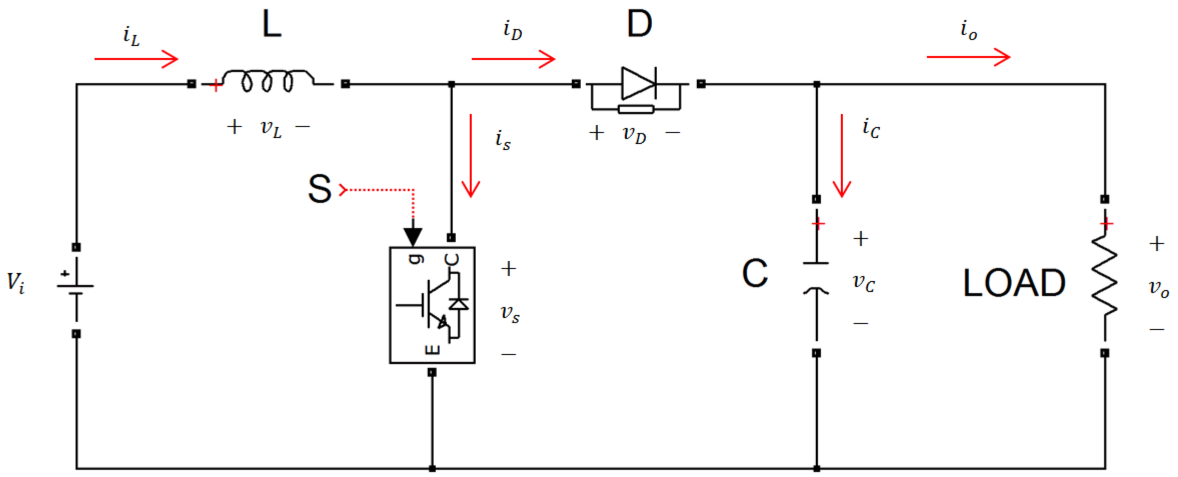
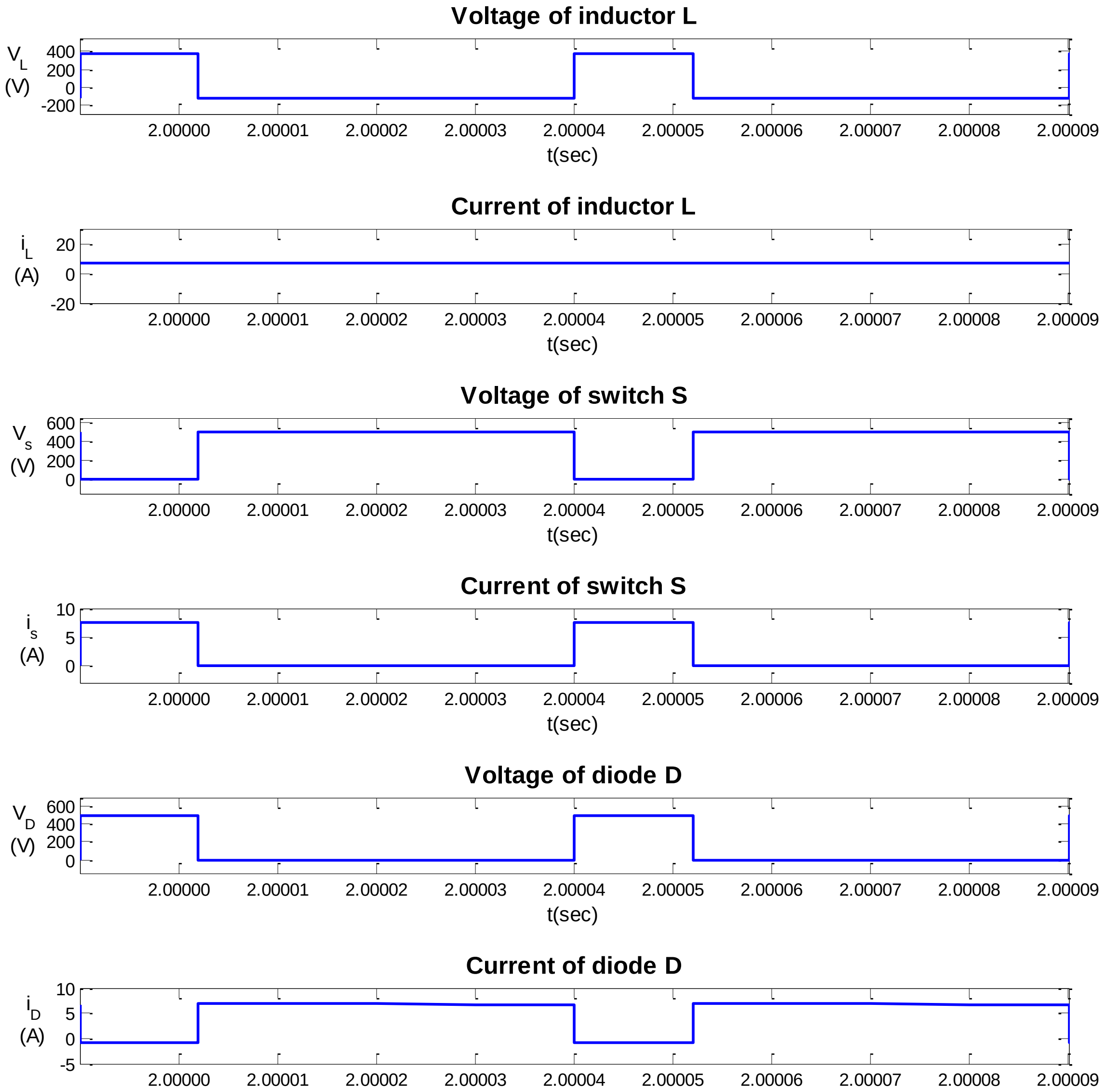


Figure 2: Electric circuit of DC-DC boost converter

A DC-DC boost converter regulates the output voltage by a state of switch turned on or off [32]. Figure 2 presents an electric circuit from a DC-DC boost converter using diode *D* and Insulated Gate Bipolar mode Transistor (IGBT) *S*. IGBT is a high frequency switching device. Figure 3 indicates voltage waveform and current waveform according to IGBT switch *S* operating turn-on or turn-off.

Switching period *T* of IGBT *S* is constant, switching frequency of converter is $f_s$. When the switch *S* operates at duty ratio *D* in switching period *T*, the turn-on section of switch *S* is *DT* and the turn-off section of switch *S* is $(1-D)T$.



DT T,

| | | | | |
|---|---|---|---|---|
| | S: ON | S: OFF | S: ON | |
| | D: OFF | D: ON | D: OFF | |

Figure 3: Graphs of voltage and current in each part

In Figure 3, when switch $S$ is turned on, switch S's voltage $v_S$ becomes 0. Voltage across the inductor $L$ is input voltage $V_i$ and output voltage across the diode *D* becomes $v_o$. Switch $S$ is turned off, current $i_L$ of inductor transmits to output through the diode *D* and voltage $v_D$ of diode *D* becomes 0. Therefore, switch S's voltage $v_S$ becomes output voltage $v_o$. If the filter is designed ideally, ripple components of output voltage is ignored. When the average value of the output voltage is $V_o$, the inductor voltage $v_L$ is presented in Figure 3. The average value $V_L$ of inductor voltage $v_L$ can be expressed as:

$$V_L = V_i * D + (V_i - V_o) * (1 - D) \tag{1}$$

However, the average value of the inductor voltage $v_L$ should be 0. If the average value of the inductor voltage is not 0, the inductor current $i_L$ continuously increases or decreases. The average voltage $V_L$ of the inductor is 0 in a single period. The ratio of the transformation of voltage at the input port to the transformation of voltage at the output port can also be called as the voltage transfer ratio and the voltage transfer ratio $G_v$ is derived by (1).

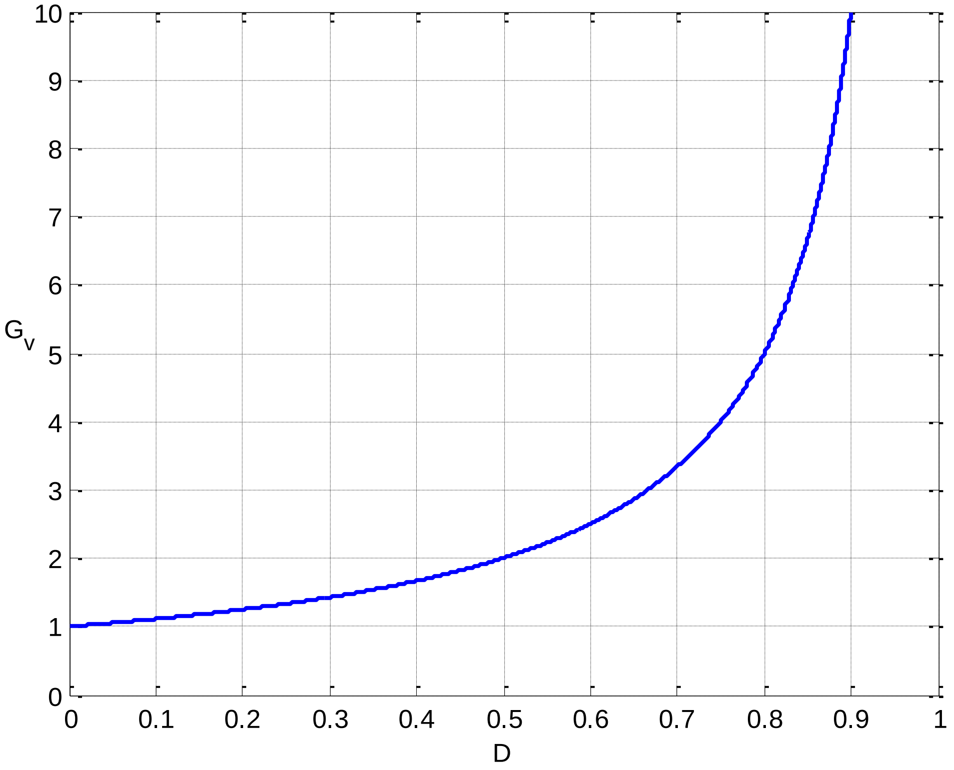


Figure 4: Relation between $\boldsymbol{G_v}$ and $\boldsymbol{D}$

$$G_V \equiv \frac{V_o}{V_i} = \frac{1}{1-\mathrm{D}} \tag{2}$$

The relation between duty ratio D and voltage transfer ratio $G_v$ is in inversely proportion to $(1-D)$ in (2) and is indicated in Figure 4. In Figure 4, the $G_v$ of the boost converter is 1 at $(D=0)$. When $D$ is equal to 1, the $G_v$ of the boost converter will be infinite. Therefore, the output voltage $v_o$ of the converter can be controlled to the input voltage or higher by varying $D$ from 0 to 1 in (2) and Figure 4.

## 3.3 Isolated bidirectional DC-DC converter for galvanic isolation

Existing energy storage systems employ a 50 Hz or 60 Hz transformer for voltage matching and galvanic isolation [5], replacing the line-frequency transformer with a high-frequency isolated bidirectional DC-DC converter (IBDC) would make energy storage systems more compact and flexible. Due to its soft-switching properties, high power density, high reliability and low number of passive components [33–36], the IBDC based on the single-phase and H-bridge topology with a high-frequency isolation transformer has become a promising alternative as a power electronic interface in microgrids [5].

IBDC is generally needed to actively control the power flow between the energy storage and the load while regulating bus voltage as the energy source and load voltage changes. Since energy source and load voltage are not always regulated, it further requires the IBDC to have the capability to deliver power over a wide input voltage and output power range [6].

# IV. PROPOSED METHODS

Our purpose is to improve power quality in DC microgrids. Through the two methods, we improve power quality. One method is to design DC-DC converter voltage regulation by using state feedback control. Another method is to reduce circulating current generated along buses by using an advanced PSPWM DC-DC converter between HVDC and LVDC.

## 4.1 State feedback control for voltage regulation

The power generated by a renewable energy source is transferred through the transmission line. However, the output voltage of the converter can fluctuate because of the fluctuation in the process of renewable energy generation. Thus, a voltage regulation controller is required to regulate voltage fluctuation. Existing converters include PI controller. PI controllers place poles after existing poles placement evaluation through root locus. We use state feedback controllers in order to place poles directly.

Figure 5 shows a DC-DC boost converter with capacitive input filter [39]. A DC-DC boost converter has a voltage transfer ratio $G_v = \frac{v_o}{v_s} > 1$. Let $D'(t)$ be the switch state function, which takes only 0 or 1. When $D'(t) = 0$, $S_1$ is closed and $S_2$ is open, and when $D'(t) = 1$, $S_1$ is open and $S_2$ is closed.

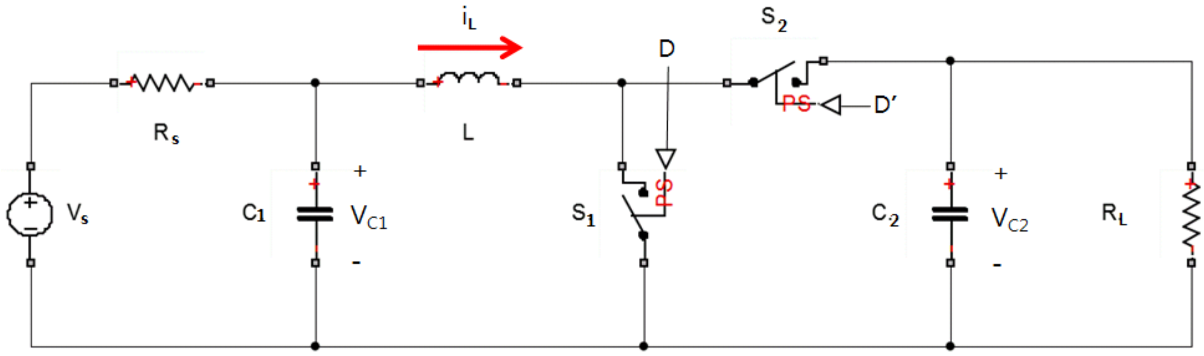


Figure 5: A boost converter with capacitive input filter

The goal of the system is to regulate one of the three port quantities $(v_{C1}, i_L, v_{C2})$. The converter is controlled through $D'(t)$.

In terms of converter operation principle, three equations can be derived by using the Kirchhoff's Law in order to design boost converter as a mathematical form.

$$\frac{dV_{C1}}{dt} = -\frac{1}{C_1 R_S} V_{C1} - \frac{i_L}{C_1} + \frac{V_S}{C_1 R_S} \tag{3}$$

$$\frac{di_L}{dt} = \frac{V_{C1}}{L} - \frac{D' V_{C2}}{L} \tag{4}$$

$$\frac{dV_{C2}}{dt} = \frac{i_L \, D'}{C_2} - \frac{V_{C2}}{R_L C_2} \tag{5}$$

States of the plant are $V_{C1}$, $i_L$, $V_C$, and input and output of the plant are $D'$ and $V_{C2}$, respectively. This plant is a non-linear system due to the operation of the switch. Linearization is required as shown in the following steps.

Step 1) Equations (3), (4), (5) can be written in the state space form:

$$x \;\; = \begin{bmatrix} V_{C1} \\ i_L \\ V_{C2} \end{bmatrix}, u = [D']$$

Step 2) The equilibrium condition is found on taking *f(x,u)=0*. Denote the solution by *(x*, u*)*. There may be more than one equilibrium.

$$x^* = \begin{bmatrix} V_{C1}^* \\ i_L^* \\ V_{C2}^* \end{bmatrix}, u^* = [D'^*]$$

Step 3) Find the Jacobian

$$\frac{\partial f}{\partial x} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \qquad \frac{\partial f}{\partial u} = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_m} \end{bmatrix}$$

Step 4) Evaluate the Jacobian at each equilibrium and denote by A and B.

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}_{x=x^*,\, u=u^*} \qquad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_m} \end{bmatrix}_{x=x^*,\, u=u^*}$$

Step 5) Write linearized system equation. *z* and *v* are deviation in each values.

$$z = x - x^*,\ v = u - u^*,\ \rightarrow\ \dot{z} = Az + Bv$$

$$\dot{z} = \dot{x}$$

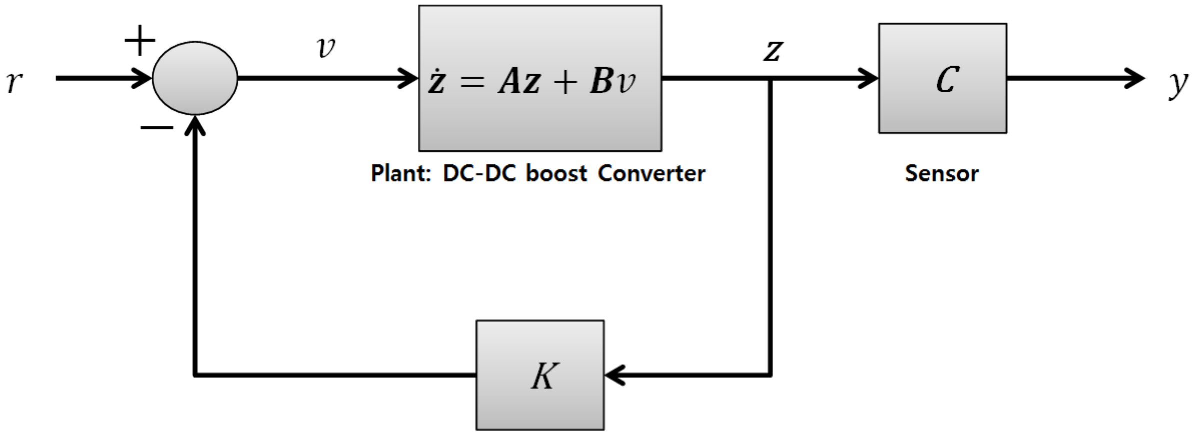
$$f(x,u) = f(x^*,u^*) + \left.\frac{\partial f}{\partial x}\right|_{x^*,u^*} (x - x^*) + \left.\frac{\partial f}{\partial u}\right|_{x^*,u^*} (u - u^*) + H.O.T$$

$$\dot{z}\ = f(x,u) \approx \left.\frac{\partial f}{\partial x}\right|_{x^*,u^*} z + \left.\frac{\partial f}{\partial u}\right|_{x^*,u^*} v = Az + Bv$$

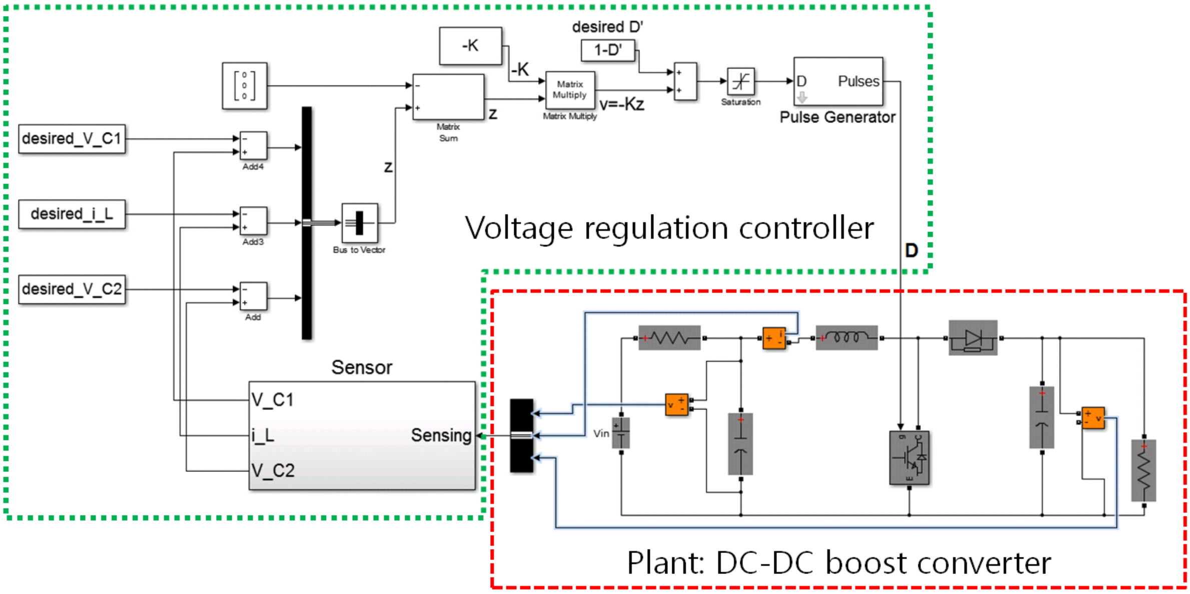
Using step 1) ~ 5), equation (6) can be derived from equations (3) ~ (5).

$$\dot{z}\ = \begin{bmatrix} -\frac{1}{R_S C_1} & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & 0 & -\frac{D'^*}{L} \\ 0 & \frac{D'^*}{C_2} & -\frac{1}{C_2 R_{Load}} \end{bmatrix} z + \begin{bmatrix} 0 \\ -\frac{V_{C2}^*}{L} \\ \frac{i_L^*}{C_2} \end{bmatrix} v \tag{6}$$

This equation is $\dot{z} = Az + Bv$ form. Due to linearization, state feedback can be applied to this plant.



(a) Block diagram of state feedback control for DC-DC boost converter



(b) Simulation configuration for DC-DC boost converter in MATLAB/Simulink

Figure 6: Voltage regulation controller with state feedback in MATLAB/Simulink

Using the Matlab function, we can place the desired poles and gain a control gain K through the state feedback control in Figure 6. Controller output duty-ratio (D = 0~1) in order to regulate switching period. According to switching operation based on duty-ratio from voltage regulation controller, Controller can regulate steady voltage level of HVDC bus.

## 4.2 Exploiting advanced PSPWM DC-DC converter in a DC microgrid

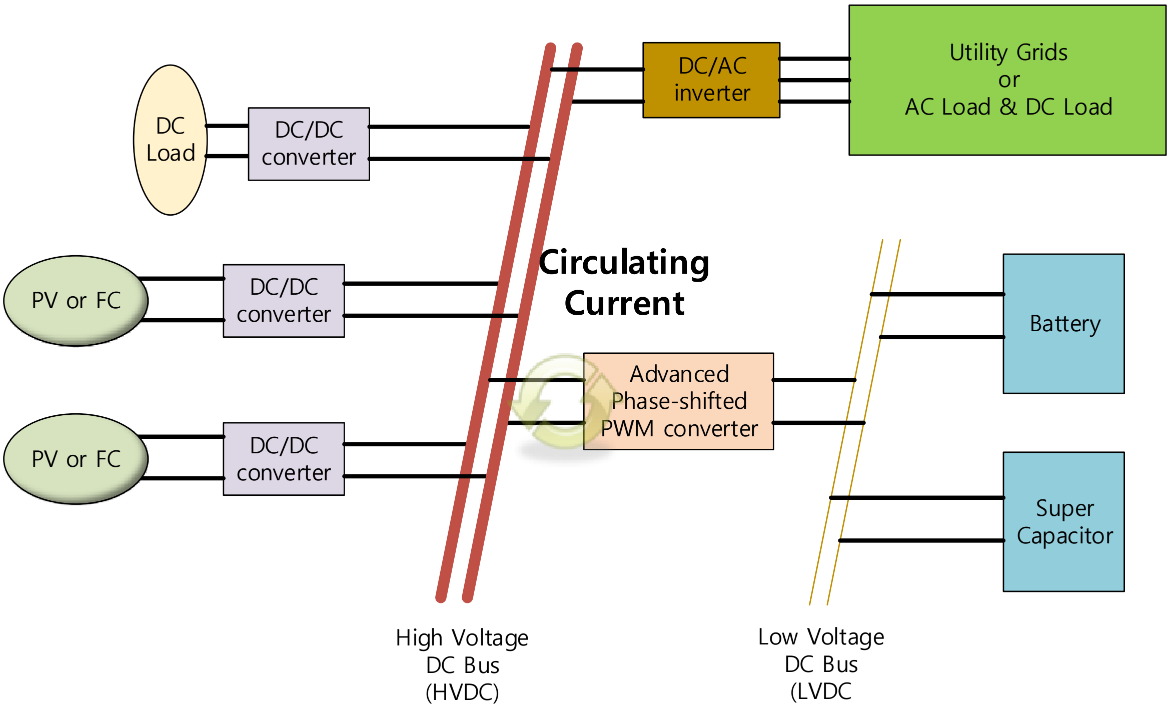


Figure 7: Proposed system description – DC microgrids with HVDC bus and LVDC bus

As stated in Section III, we present DC microgrids with HVDC and LVDC buses. The proposed DC microgrid structure in [6] inserts an isolated bidirectional full-bridge DC-DC converter for galvanic isolation but it does not consider the aspect of circulating current. An isolated bidirectional full-bridge DC-DC converter is a kind of PSPWM DC-DC converter. In order to reduce circulating current in the primary voltage (in HVDC bus), we replace the isolated bidirectional full-bridge DC-DC converter with an advanced PSPWM DC-DC converter as shown in Figure 7.

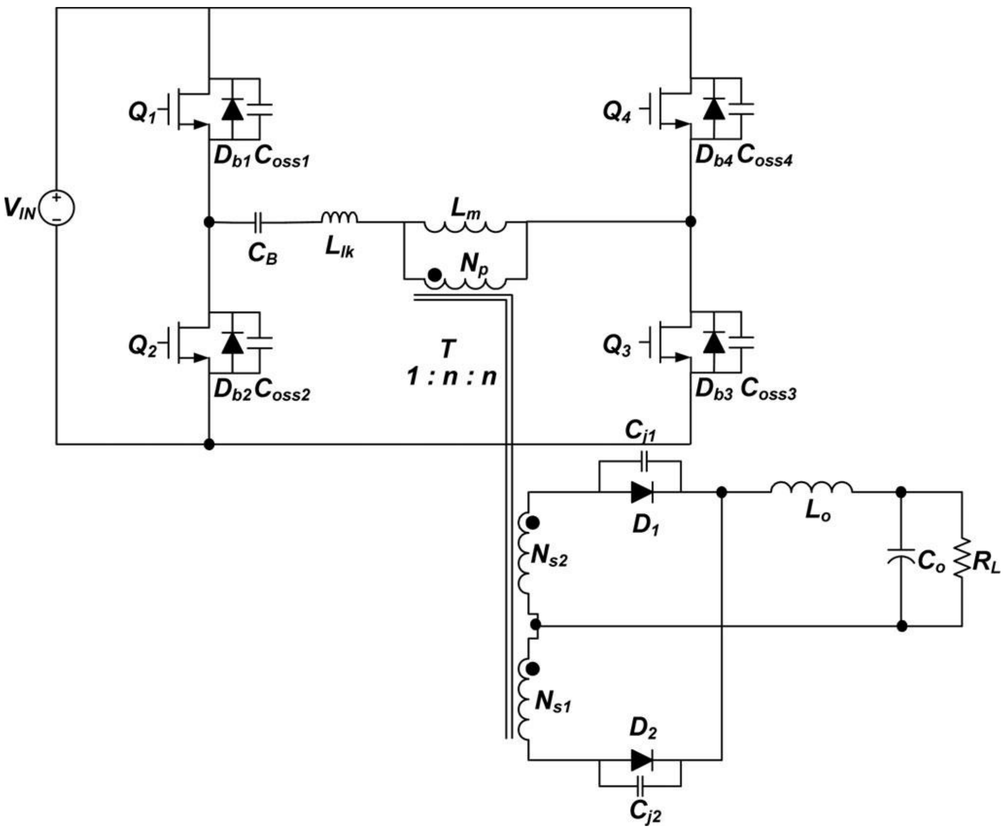


Figure 8: Traditional Phase Shift Full-Bridge (PSFB) converter [9]

If the converter in Figure 8 is fit for a relatively wide input voltage range due to the design considerations such as the hold-up time requirement, the steady-state duty cycle becomes small and the freewheeling interval lengthens under normal operating conditions. Then, excessive circulating current appears on the primary side during the freewheeling interval, increasing the primary-side conduction losses and turn-off switching losses of the lagging-lag switches [37], [38]. We exploit the advanced PSPWM converter to reduce circulating current.

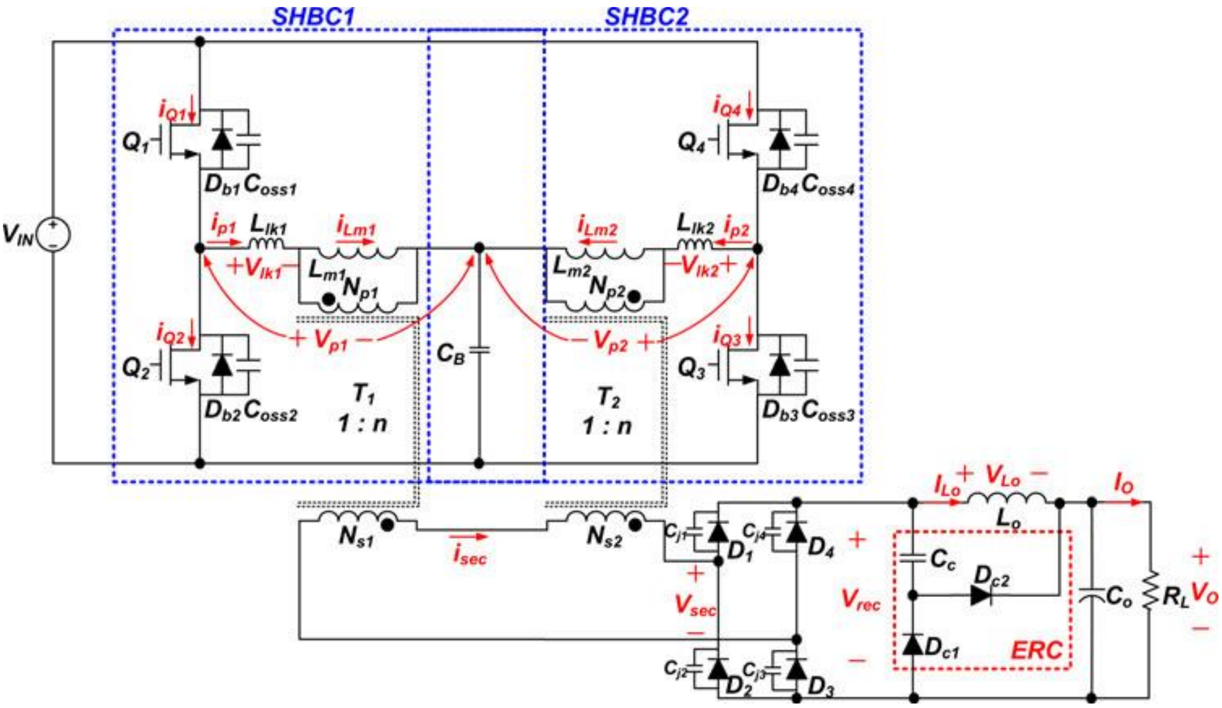


Figure 9: Advanced PSPWM DC-DC converter [9]

In Figure 9, due to the use of an Energy Recovery Circuit (ERC), the primary-circulating currents in the freewheeling intervals are reduced, which decreases the primary-side conduction and turn-off switching losses [9]. As a result, we get the effect of reducing circulating current.

# V. PERFORMANCE EVALUATION

## 5.1 Converters output voltage regulation with state feedback control

In Section IV, we design a model of a DC-DC boost converter by using state feedback control. A DC-DC boost converter with a state feedback control should output state parameters which are of the desired value. In our experiment, two converters are connected to a common HVDC bus as shown in Figure 10. Each controller in the converter is designed by using state feedback control. We set the parameter $V_{C2}$=500V and verified that the converters output was the desired value. The results for the first 2.5 seconds showed a transient response (see Figures 11 & 12), so this study focused mainly on the steady-state response obtained after the 2.5-second mark. In Figure 11, when the input voltage in the converters is the same, two renewable energy sources supply power of the same voltage level, the voltage on the common HVDC bus is the same and regulates a constant value. Another experiment is to measure the voltage of a common HVDC bus when two power sources supply different voltage. In Figure 12, the output voltage shared with the HVDC bus is the same as Figure 11. Although the voltages of the converters are different, state feedback controllers regulate the voltage of the common HVDC bus, which is an electric contact of two converters, as a constant voltage level. In this process, we did not get pole placement through root locus. Consequently, a state feedback controller output the desired voltage.

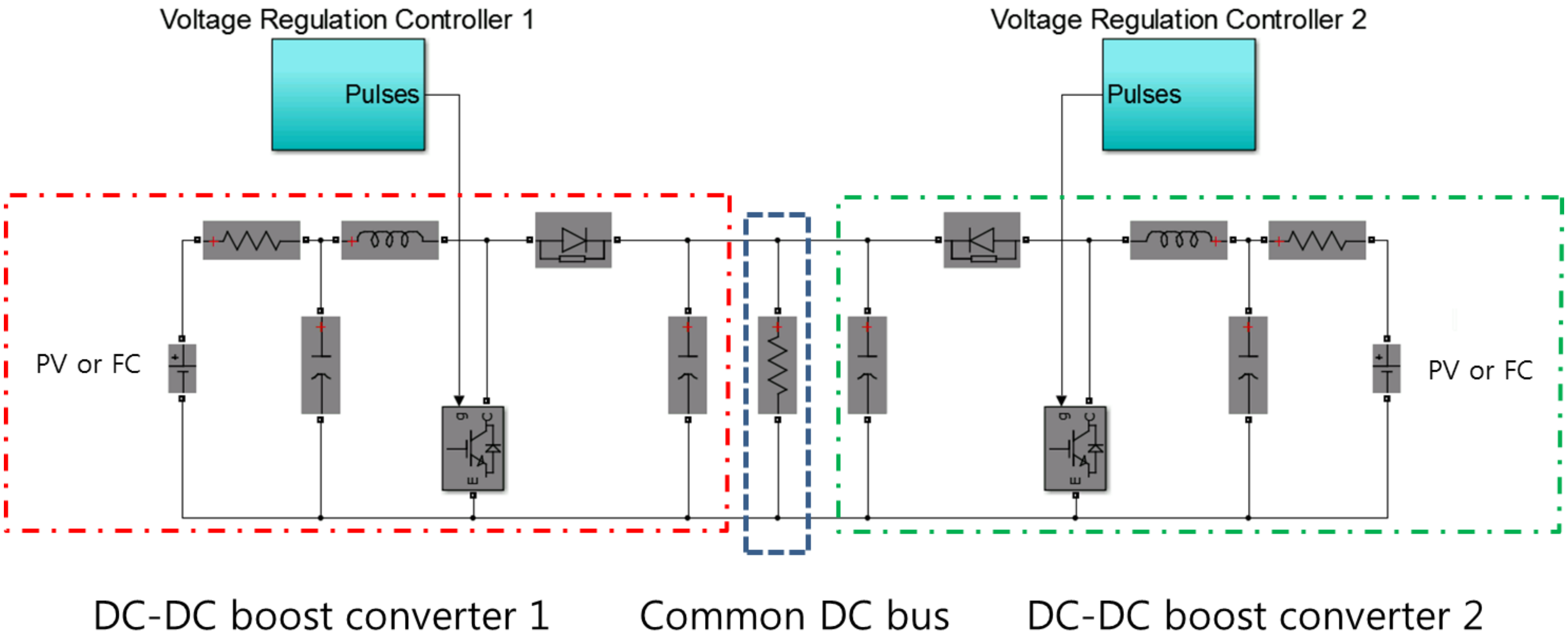


Figure 10: DC-DC boost converters with voltage regulation controller based on state feedback control

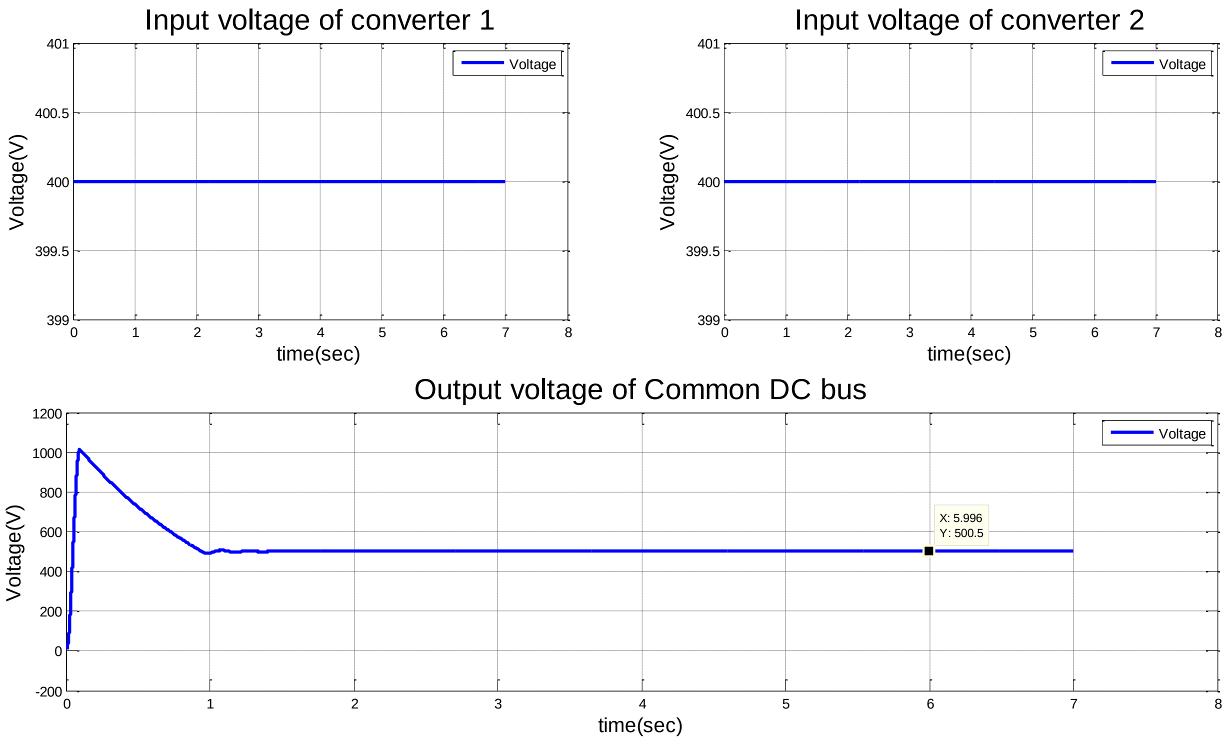


Figure 11: Tracking control parameters ($V_{PV1} = V_{PV2}$)

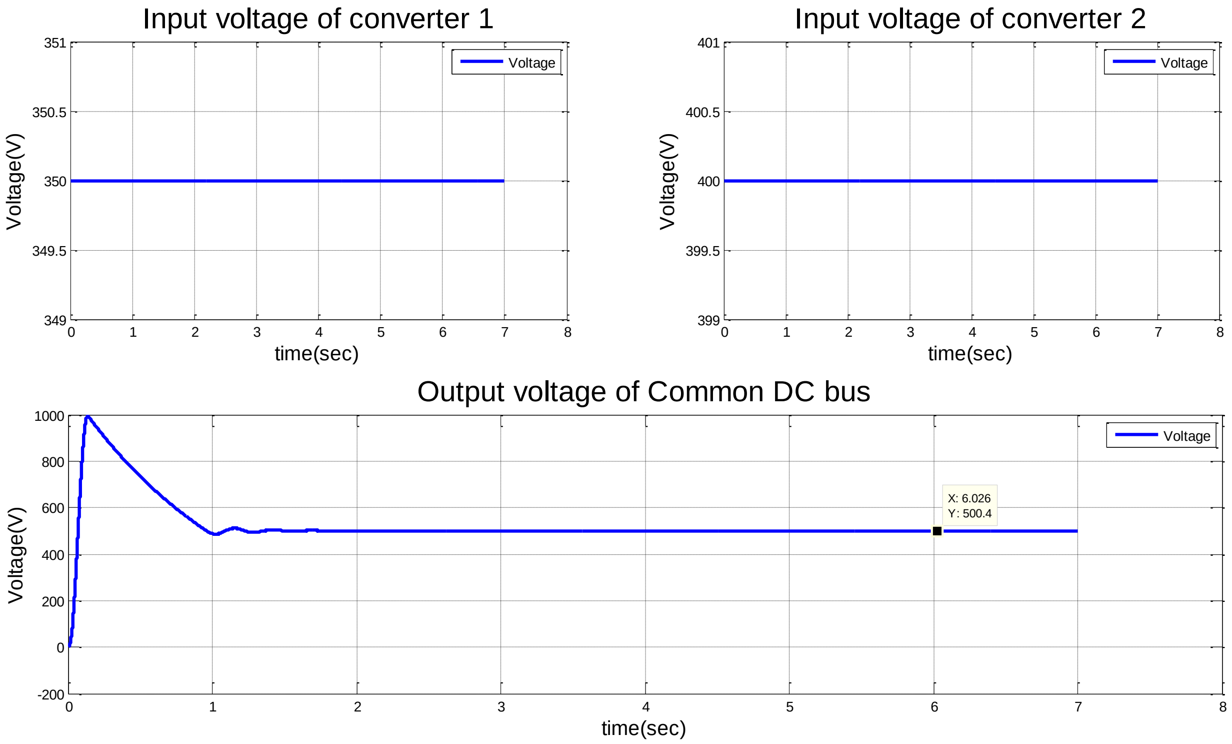
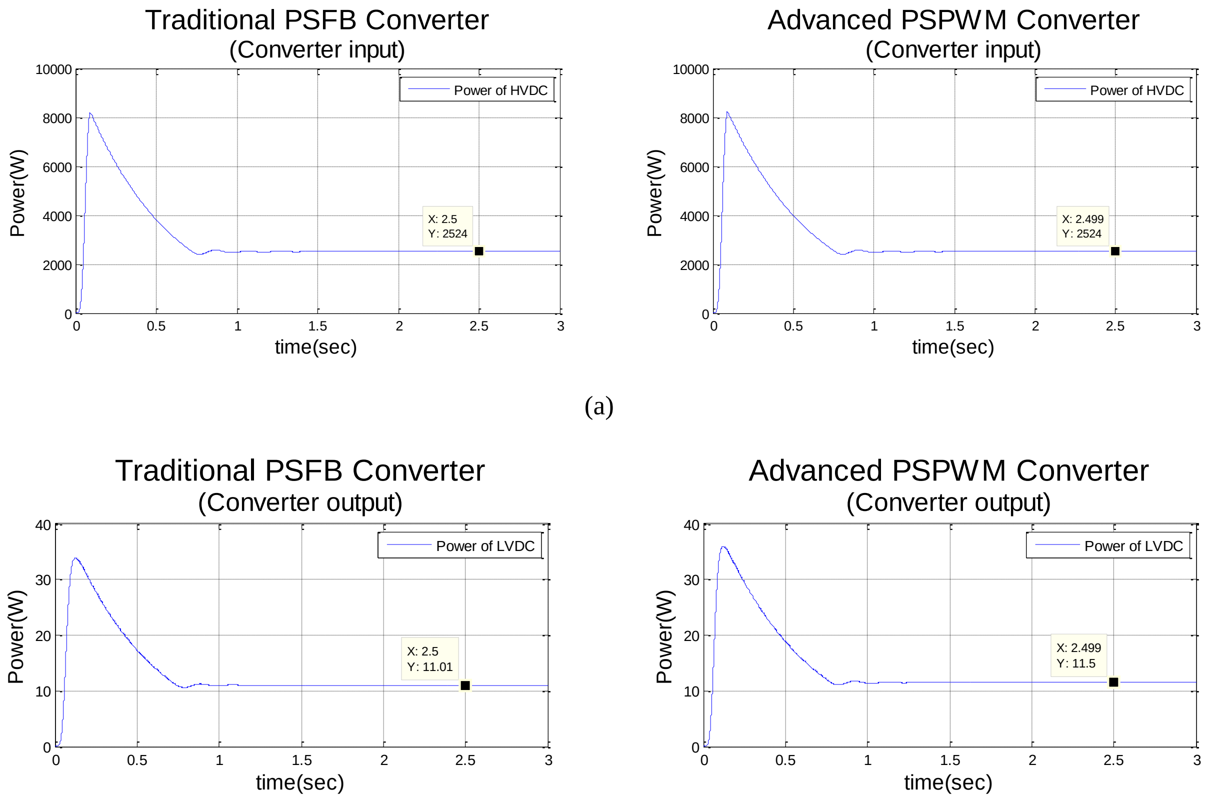


Figure 12: Tracking control parameters ($V_{PV1} \neq V_{PV2}$)

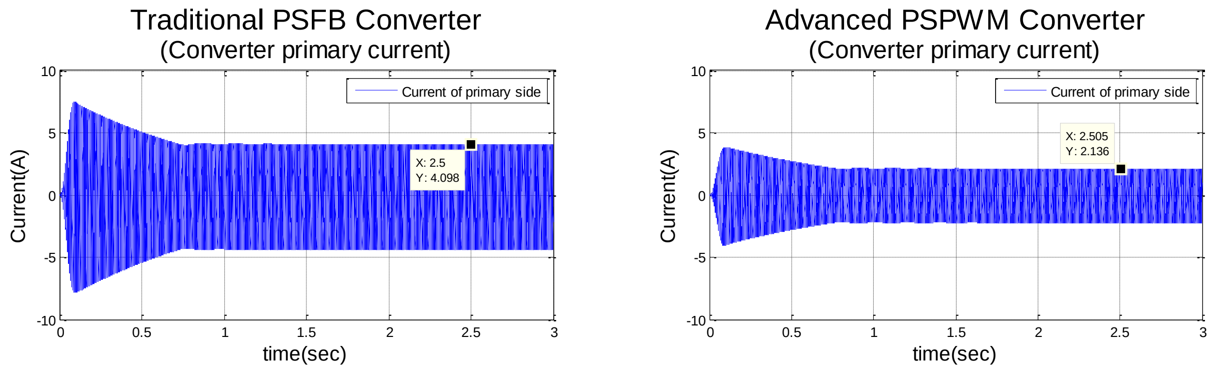
## 5.2 Reducing circulating current and voltage stress

Figures 13 &14 plot the performance comparison of traditional PSFB converter and an advanced PSPWM DC-DC converter. In Figure 13, even if the amount of power delivered to the two converters is the same (In Figure 13, (a) and (b)), the primary current of the advanced PSPWM DC-DC converter decreases (in Figure 13, (c)). As a result, circulating current between the HVDC and PSPWM DC-DC converter is reduced. When the power is transferred from power generation to an energy storage system or a consumer, a little current in the HVDC means that power dissipation is low. Therefore, this result is more efficient power transfer.



(a)

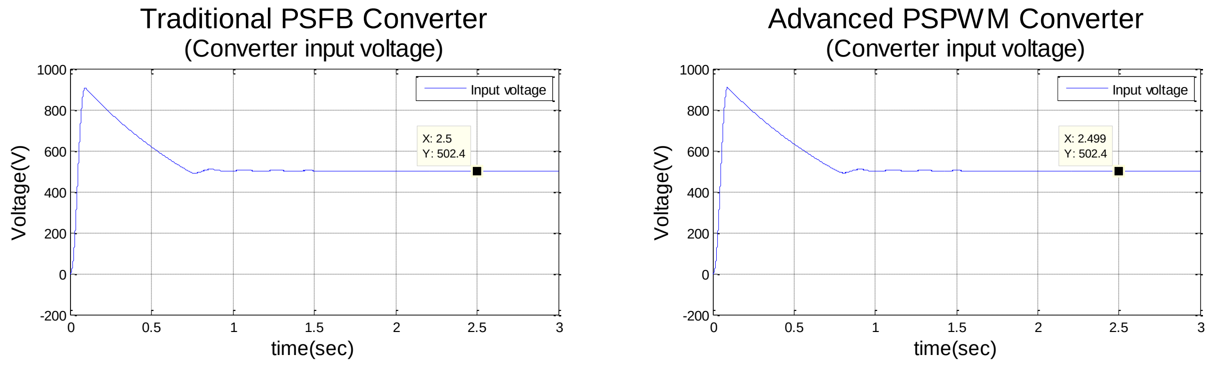
(b)



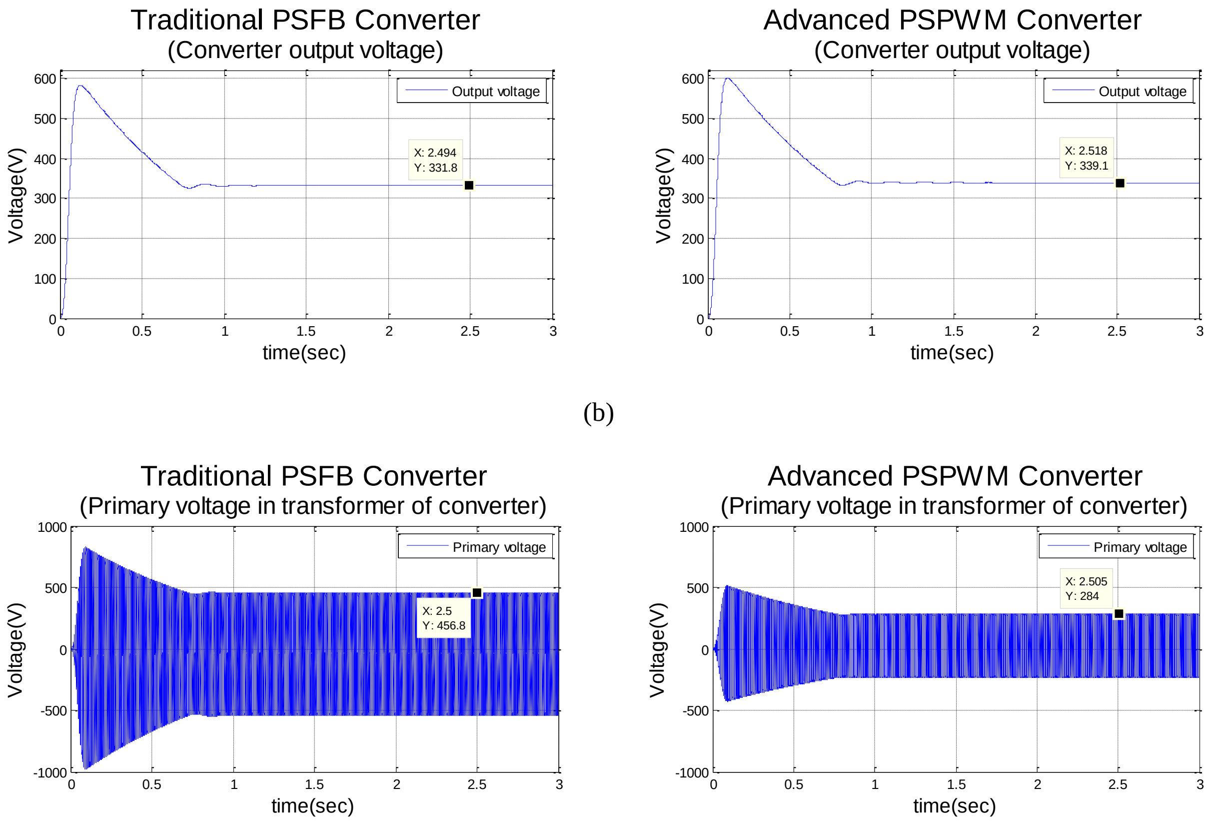
(c)

Figure 13: Reducing the circulating current between the HVDC and the PSPWM DC-DC converter

In Figure 14, the input voltages of two converters stay the same, and so do their output voltages (in Figure 14, D and F). However, the voltage stress of the advanced PSPWM converter is lower than the voltage stress of the traditional PSFB converter (in Figure 14, E). As a result, voltage stress in the transformer in the advanced PSPWM DC-DC converter is almost half the voltage stress in the transformer in the traditional PSFB converter. Therefore, the lifespan of the transformer in the advanced PSPWM DC-DC converter can be long. These results suggest that the converter performance improves.



(a)



(b)

(c)

Figure 14: Reducing the voltage stress in the transformer of the PSPWM DC-DC converter

As a result, through the two simulation results, we improve the power quality and lighten the load of power component in DC microgrids when the power is transferred.

# VI. CONCLUSION AND FUTURE WORK

This thesis proposes methods for power quality enhancement in DC microgrids. First, instead of PI, PID control, we exploit state feedback control to a DC-DC converter in power generation. Therefore, when we design microgrids, we can place poles and zeros easily. We show that state feedback control also regulates HVDC voltage and tracks the desired output voltage and desired input current. In the case of our simulator, although microgrids have many DC-DC converters, the voltage of common DC buses are excellently regulated by state feedback control. To regulate the voltage of common DC bus indicates the power quality enhancement when power is transferred.

Second, we replace the traditional PSFB converter with an advanced PSPWM DC-DC converter in DC microgrids with HVDC bus and LVDC bus. As a result, the circulating current of the primary voltage (in HVDC bus) can be further reduced by using a traditional PSFB converter. In power transfer, by reducing the circulating current between the common DC bus and DC-DC converter, it can enhance power quality and monitor each power component more accurately for gathering power information. Another advantage is to reduce voltage stress of the power transformer in the PSPWM DC-DC converter more than in the existing PSPWM DC-DC converter. If the power transformer has a small voltage stress, its life span is both longer and cheaper.

By applying these methods, we can realize the high-quality power transfer in DC microgrids. There are many future works that are ahead of this study. First, a PSPWM DC-DC converter applies state feedback control according to the specifications desired by the user who designs the controller. The state feedback method can monitor internal parameters and adjust states effectively. By using the relation between phase shift times and output variables, the state feedback controller can be designed. Another work is to suppress circulating current for power enhancement in renewable energy power generation by inserting a virtual resistor in controller. This virtual resistor is not real hardware. This method is used in PI controllers but we apply a virtual resistor into a state feedback controller. Overall, through future research, this research is expected to the power quality of smart microgrids.

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# 요약문

## 스마트 마이크로 그리드에서의 전력 품질 개선을 위한 두 가지 방법

우리는 상태 피드백 제어와 드룹제어를 기반으로 한 분산 제어의 개념을 사용하는 스마트 마이크로그리드에서의 전력 품질을 개선하기 위한 방법을 제시했다. 기존의 전력 시스템은 많은 문제를 가지고 있다. 예를 들면, 큰 규모의 발전소는 전력 소비자로부터 멀리 떨어져있다. 신 재생에너지원의 사용이 증가는 심각한 왜곡 전압 및 전압 변동을 이르게 한다. 전력 필터와 정지형 동기 조상기와 같은 전력 조절 장치는 전력 품질을 보장하고 신 재생에너지원으로부터 효율적이게 전기를 생산하기 위해 필요로 한다. 전력 변환 장치가 마이크로 그리드에서 병렬로 사용될 때, 각 전력 변환 장치 사이에 순환전류가 발생할 수 있다. 순환전류는 마이크로그리드나 전력 시스템에 악영향을 가져온다. 우리는 순환전류를 줄임으로써 전력 품질 향상시키는 두 가지 방법을 제안한다. 하나는 상태 피드백 제어를 사용하여 DC-DC 컨버터의 전압 조절기를 설계하는 것이다. 또 다른 방법은 HVDC 와 LVDC 사이에 개선된 PSPWM DC-DC 컨버터를 사용하여 버스를 따라 생성된 순환 전류를 감소시키는 방법이다. 제안된 방법의 유효성을 확인하기 위해, 우리는 MATLAB/Simulink 를 사용하여 마이크로그리드 시뮬레이터를 개발하고, 시뮬레이터를 사용하여 우리가 제안한 방법의 이점을 평가했다. 결과적으로, 두 개의 시뮬레이션 결과를 통해, 우리는 DC 마이크로그리드에서 전력 전달 시 전력 품질을 향상시켰다.

핵심어: 전력 품질, 상태 궤환 제어, 순환 전류, PSPWM DC-DC 컨버터, DC-DC 부스트 컨버터