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Control Strategy in DC Microgrid for Integrated Energy Balancer: Photovoltaic Application

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ABSTRACT

Renewable energy is energy that can be used indefinitely. As a result, renewable energy sources such as solar photovoltaics developed. Conventional converters, typically used to connect the microgrid to the battery, only change the voltage. To link the microgrid to the battery, bidirectional converters are required. A bidirectional converter is available in a variety of configurations. The control structure is highly sophisticated to obtain a satisfactory output. This article proposes a bidirectional DC-DC buck-boost converter for controlling current in DC microgrids, solar systems, and loads. A bidirectional DC-DC Buck-Boost converter is required to transmit and receive energy from the battery to the DC microgrid. When voltage is sent to the DC microgrid, the battery voltage is reduced. Otherwise, the charging voltage is increased when a battery is charged by voltage. This converter produces a better output voltage than an AC-DC Buck-Boost Converter, and its switching frequency is double that of typical converters. The modified DC-DC converter has the simplest form and the advantage of having the highest responsiveness.

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INTRODUCTION

Along with the times, advanced technological improvements are implemented to create a new electrical energy source. Currently, electrical energy is the main thing needed by many people [1-3]. Therefore, many technologies have been developed to produce electrical energy from renewable energy sources, one of which comes from solar energy. The system converts solar energy into electrical energy using a PV module stored in a battery with a DC energy source [4]. A DC-AC converter is needed to convert the electricity generated by PV to AC electricity. When the conversion process occurs, there is a loss of energy from electricity. Therefore, a DC microgrid avoids energy loss in the conversion process on the DC-DC converter [5-8].

A microgrid combines loads, energy storage systems, and micro-generators. Microgrid control is an important issue to make a microgrid a single controllable unit [9-10]. The microgrid control strategy is realized by converter control. Photovoltaic sources are emission-free and reliable. The benefits of a microgrid include high constant [11]. Therefore, a PV system connected to a DC microgrid is a viable energy source. Solar PV-based DC microgrids can be cheap, flexible, and energy-efficient for users. PV has a detriment when it comes to low DC voltages. Thus, the PV cannot correctly supply the load [12]. Therefore, using a DC converter connected to a DC Microgrid produces a ripple-free output voltage and outputs current [13, 14]. The voltage generated by the PV is used to charge the battery. When the battery is in use, a converter must step up the voltage because the battery voltage is higher than the microgrid voltage and step down the voltage to send energy from the battery to the microgrid. These processes need to use a buck-boost converter. When sending and receiving power requires a converter that can do both things, a bidirectional converter is required [15-17]. The distribution system works in parallel and consists of a microgrid DC, PV, and bidirectional buck-boost converter.

The detriment of the conventional converter used on the microgrid can only lower the voltage. A bidirectional converter is needed to send and receive voltage from the battery to the grid. There are several types of bidirectional

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converters. To get good output results, a complex converter structure is needed. This modified converter work at three levels [18,19]. Therefore, this paper proposes A Buck-Boost converter bidirectional DC-DC with a microgrid DC energy balancer to be used as a current balancer. The modified converter uses two diodes, four energy semiconductor switches, and two capacitors to perform 3-levels. The operating model is based upon a phase-shifted carrier signal [20-23]. The current balancing system controls the current in DC microgrids, photovoltaic systems, and loads. Current flow in the DC microgrid, photovoltaic system, and load determine whether the converter uses, sends energy to the DC grid, or receives power from the DC grid.

MATERIAL AND METHODS

DC-DC microgrid configuration

This converter operates in 2 modes, namely buck mode and boost mode. Buck mode is used to lower the voltage from the battery when sending voltage to the DC microgrid. When buck mode is used, only two energy switches are used, namely switches S1 and S4. Boost mode is used to increase the voltage from the DC microgrid, which has a lower voltage than the battery with a higher voltage. When the boost mode is used, only two energy switches are operating, namely the S2 and S3.

Figure 1 is a configuration circuit of A Buck-Boost converter bidirectional DC-DC. The PV distribution system helps absorb solar energy and produce DC voltage output. During the day, the load used tends to be lower than the load at night, and the voltage generated by PV during the day is more significant. The supply voltage on the load comes from the DC grid and the PV. Because the voltage sent from the PV to the load is small, the voltage is sent to the converter to charge the battery. When charging the battery, the converter uses the boost method to increase the voltage because the voltage from the battery is greater than the voltage on the DC grid.

At night the load used is more significant therefore, the supply voltage from the grid to meet the requirements of the load is less than the battery and supply voltage to the load because PV does not produce voltage at night. In this method of operation, the converter use bucks mode to lower the voltage from the battery and send it to the DC grid.

There is one condition where the converter is not sending and receiving energy. This happens when the current generated by the PV is equal to the current required by the load. Then the PV supplies only to the load therefore, the converter does not receive energy, and the converter also does not send energy because the load used has received enough power from the PV. This condition is called a balanced condition, where the PV current is equal to the load current.

Control strategy

Figure 2 shows an energy circuit and control to configure the DC microgrid, DC-DC converter, and load. This control system has three ways of working: PV sends energy to the load and converter, PV sends power to the load, and PV sends energy to the converter. This system determines how the converter works when sending and receiving energy.

In the first operation, the energy generated by the PV is sent to the DC microgrid. When the load on the DC microgrid is small, the power is sent to the converter to charge the battery. The load gets energy from the DC microgrid and PV in this operation. The battery receives energy from the DC microgrid and PV. The voltage on the grid is the same. Therefore, the energy flow is the same as the current flow. The battery is charged using energy from the PV using the boost mode of the converter. This operation can be formulated as Equation (1).

$$I_{Balancer} = I_{Load} - I_{PV} \tag{1}$$

In the second operation, the load used is significant. The energy required on the load is also more incredible

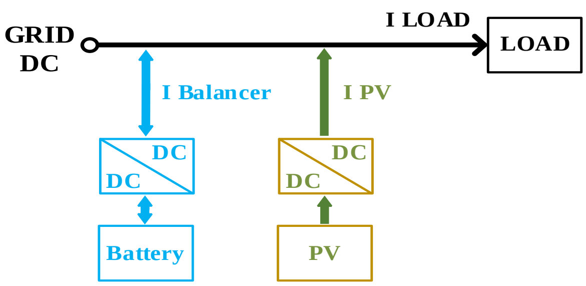


Figure 1. DC microgrid configuration

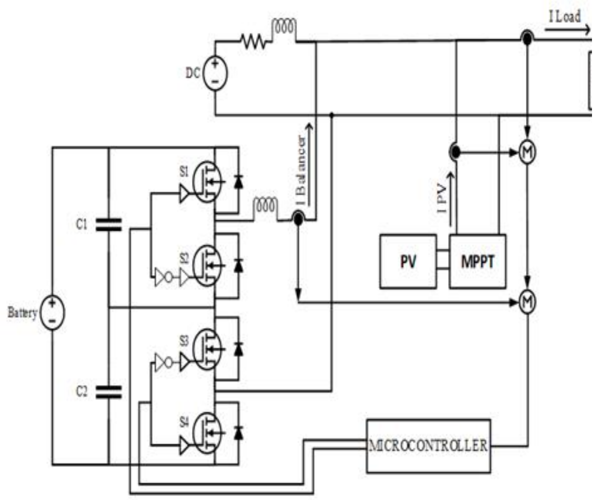


Figure 2. System control connections

therefore, the power from the PV is sent to the load to meet the necessary energy. When the energy transmitted from the PV to the balancer is lacking, the balancer sends power to the load using the buck mode of the converter, and it can be formulated as Equation (2).

$$I_{Load} = I_{Balancer} + I_{PV} \tag{2}$$

In the third operation, the load used requires sufficient energy. PV work to send power to the DC microgrid to meet the energy requirements of the load. Still, PV cannot transmit energy to the converter because the energy required by the load is as considerable as the energy generated by PV. In this condition, the converter is not working. This operation can be formulated as Equations (3 and 4).

$$I_{Load} = I_{PV} \tag{3}$$

$$I_{Balancer} = 0 \tag{4}$$

Operation modes and switching

Based on Table 1, rows 1-4, the switching cycle of the buck operating mode, and Figure 3, where the current flow and output voltage are observable in Table 1. The output voltage measured here is the output before the inductor filter to see the switching process, and the voltage after the inductor filter is the same as the DC grid voltage. In the first operation, the energy switches used are switches S1 and S4. When switches S1 and S4 are on simultaneously, it produces the same voltage output as the battery (E). In this operating system, the current flows from the battery to switches S1 and S4 and then to the filter L, the DC grid.

The second operating system where the energy switch is used here is only the S1 switch, while the other switches are turned off. When current flows, C1 wastes energy while C2 fills power. Hence, The current flows from S1 to the battery and plugs into the capacitor C2. The current flows to the diode S3 and goes to the inductor filter (L) sent to the DC grid. When the two capacitors have a balanced voltage in this operating system, the DC grid is half the battery voltage (E/2).

The third operating system where the energy switch is used is only the S4 switch, while the other switches are turned off. The current flows from the diode on S3, fills C1 to S1, and flows into the L filter, while C2 wastes energy. When the voltage on the capacitor is balanced, the voltage on the DC grid is half of the battery voltage (E/2).

The fourth operating system where all energy switches are in the off position. The operating system that occurs is freewheeling. The voltage flow continues until the voltage slowly drops and runs out in this operation. Then the output voltage to the grid is zero volts. When operating, the current flows from diode S2 to S3 and then to the DC grid. The resulting output voltage can be formulated in Equation (5) below in the four operating modes when the converter works in buck mode.

$$V_o = V_{in} \ x \ D \tag{5}$$

In boost mode, seen in Table 1, rows 5-6, and Figure 4, where the current flows. The first operation of energy switches S2 and S3 are ON. When S2 and S3 are ON, the same as short-circuiting the converter's output, the voltage generated here is zero, and the current is stored in the filter L.

In the second operation, the energy switch S2 and S3 are OFF therefore, at this time, the current in the filter L flows to the diodes at S1 and S4 and then charges the battery. The resulting voltage at the converter's output is equal to the voltage at the battery. This operating system can be formulated with the Equation (6) below. In Equations (5 and 6), V_o is the output voltage, V_{in} is the input voltage, and in this equation, D is the duty cycle. The duty cycle is the ratio between the ON time and the period.

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{6}$$

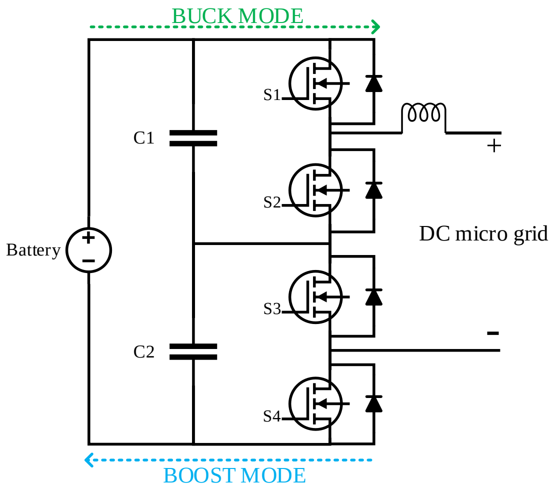


Figure 3. Operation buck and boost mode

Table 1. Switching PWM, output, and mode

PWM				Vout	MODE
S1	**S2**	**S3**	**S4**		
ON	OFF	OFF	ON	E	BUCK
ON	OFF	OFF	OFF	E/2	
OFF	OFF	OFF	ON	E/2	
OFF	OFF	OFF	OFF	0	
OFF	ON	ON	OFF	0	BOOST
OFF	OFF	OFF	OFF	E	

Control algorithm

The control algorithm of the energy balancer converter is observable in Figure 4. The controller reads the output current as feedback, the current from the load, and the current from the PV. Here there is a proportional-integral (PI) controller used. First, the current reading from the load and PV is calculated, generating the first error current signal. The first error current signal is calculated with the output current from the output to produce a second error current signal that the PI controller processes. The output signal from the PI controller must be given a limiter. Therefore, the current follows the ability of the battery so as not to damage the battery. Then the output signal is processed for carrier signal modulation to produce PWM, which is used to control the energy switch of the bidirectional converter. The resulting signal from the converter pass through a filter therefore, the output signal has less noise. K_p is the proportional gain, K_i is the integrator gain, $e(t)$ is the error value, and dt is the change of time. By using the PI controller, the steady-state error is close to zero. The program flowchart is observable in Figure 5.

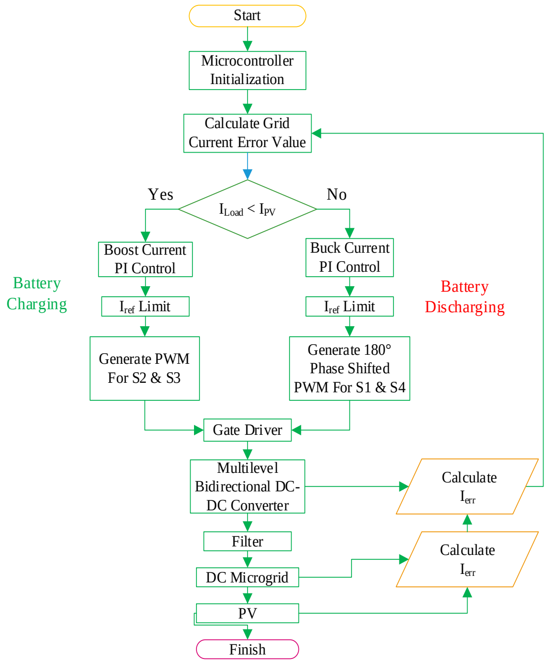


Figure 5. Flowchart for program algorithm

RESULTS AND DISCUSSION

This bidirectional buck-boost converter was proposed and simulated using Power Simulator Software. After being simulated, the circuit simulation from Figure 2 is implemented into hardware to prove whether the simulation runs well after becoming hardware, as shown in Figure 6 shows a hardware implementation. Parameters of simulation and hardware observable in Table 2 on hardware that has been implemented to control or program the hardware using STM32F407VET6. The current sensor detects current from the load, PV, and balancer using the current sensor HX-10P. The PWM switching is generated by driver IRFP350 controlling the power switches.

Shows in Figure 7 indicate the current from the PV source is lower than the current in the load. Therefore, the converter work in buck mode. In this condition, the current probe on the oscilloscope is at x10. The current based on simulation at the load is 4.75 A, the current in the balancer is 4.25 A, and the current from the PV source is 0.5 A. The current based on hardware at the load is 1.75 A, the current in the balancer is 1.25 A, and the current

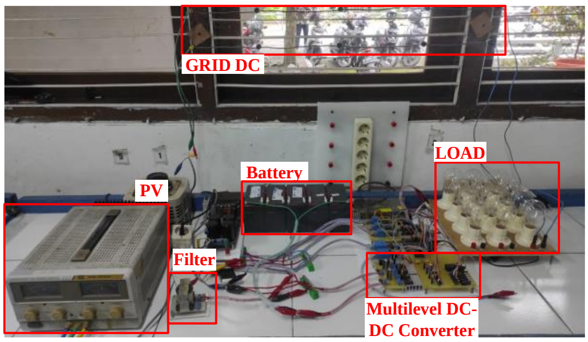


Figure 6. Hardware implementation in laboratory test

Table 2. Hardware parameters in simulation and hardware

Parameter	Value
DC microgrid voltage	48 V_{DC}
Battery voltage	60 V_{DC}
Inductor filter	5 mH
Capacitor filter C1, C2	220 uF
Load resistance	30 Ohm
Switching frequency	25 kHz

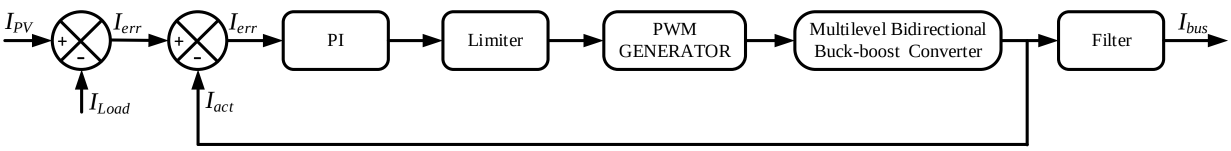
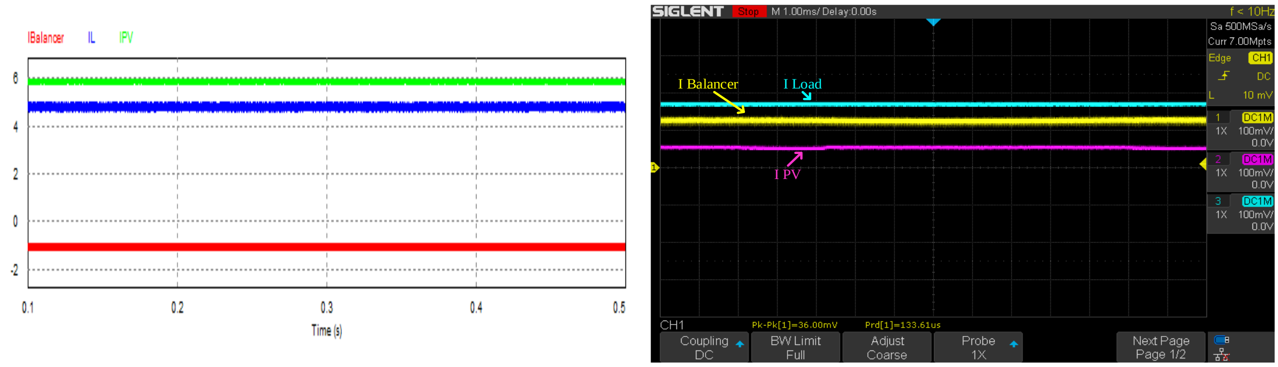


Figure 4. Control algorithm for bidirectional Buck-boost converter

from the PV source is 0.5 A. This condition is observable as Equation (2) with the buck mode converter.

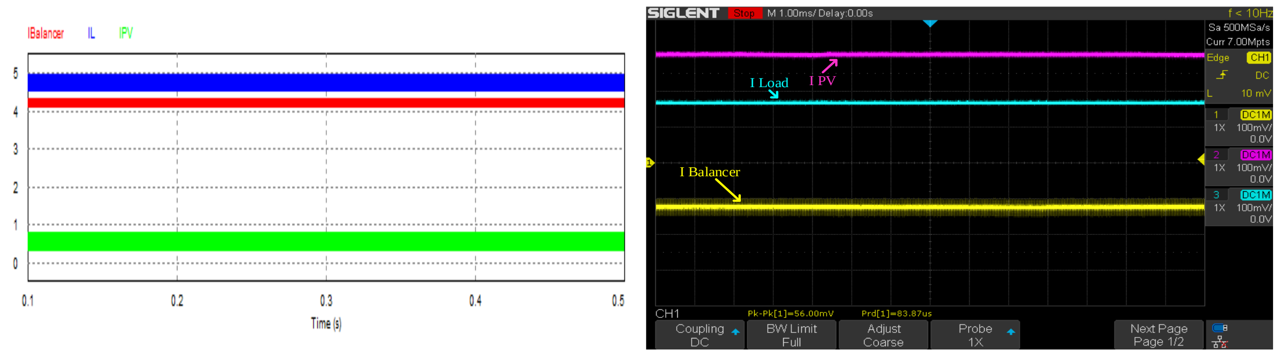
When the current generated by the PV source is greater than the load, the converter work here in boost mode, as seen in Figure 8. Therefore, it can be formulated as Equation (2) when the current generated by the PV source is greater than the load, the converter work in boost mode. The current based on simulation at the load is 5 A, the current in the balancer is -1 A, and the current from the PV source is 6 A. The current based on hardware at the load is 1.75 A, the current in the balancer is -1.25 A, and the current from the PV source is 3 A. This condition is observable the same as Equation (1). In this condition, the current in the balancer is negative because the balancer receives current to charge the battery.

Figure 9 is a state where the PV and load current are the same. The converter produces zero current or does not work. Based on the simulation, the load is 5 A, the current in the balancer is 0 A, and the current from the PV source is 5 A. The current based on hardware at the load is 1.75 A, the current in the balancer is 0 A, and the current from the PV source is 1.75 A. This condition is observable in Equations (3 and 4), called the balance condition.



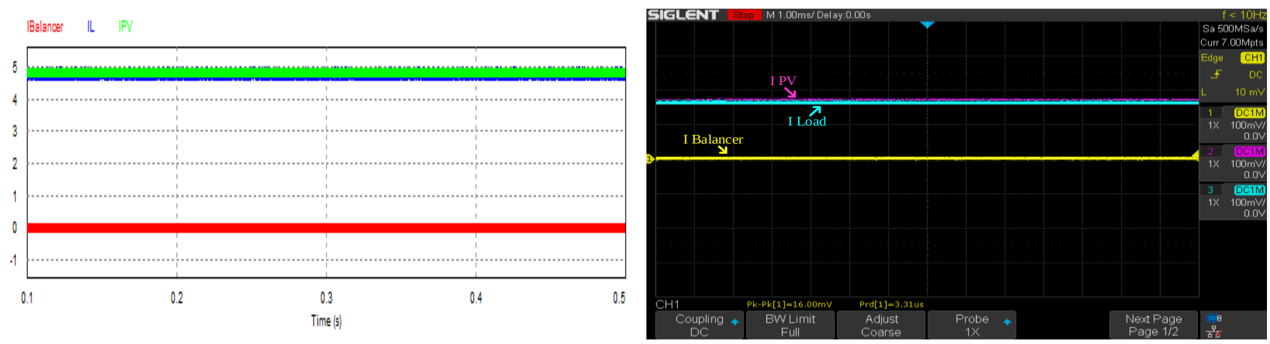
(a) (b)

Figure 7. Buck mode current waveform on simulation (a) and hardware (b)



(a) (b)

Figure 8. Boost mode current waveform on simulation (a) and hardware (b)



(a) (b)

Figure 9. The idle current waveform on simulation (a) and hardware (b)

CONCLUSION

Hardware that has been made works well as it has been simulated. The microgrid requires a converter to connect to the battery, add a renewable source to use PV, and be loaded to test it. This hardware uses three current sensors to detect the current in the converter, PV, and load. Therefore, the converter adequately controls the detected current to determine how the converter works. The detection results are handled using a PI controller's closed-loop control system. This converter work in two modes, namely bucks mode and boost mode. When in buck mode, the converter sends current from the battery to the grid to help the PV meet the current needs of the load. In boost mode, the converter receives excess current from the PV when the load supplied is overloaded, which the current sensor detects. Therefore, the converter works well to increase the voltage from the microgrid to the battery and lower the voltage from the battery to the microgrid. Observable from the experimental results is that the converter hardware produces a current that has minimal noise. The proposed implementation of this Buck-Boost converter bidirectional AC-DC with current detection works as expected with a current output with a slight ripple and simple structure.

ACKNOWLEDGEMENT

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Persian Abstract

چکیده

انرژی‌های تجدیدپذیر نوعی انرژی است که می توان به طور مداوم از آن استفاده کرد. در نتیجه، منابع انرژی تجدیدپذیر مانند سامانه‌های فتوولتائیک خورشیدی توسعه یافتند. مبدل‌های معمولی که معمولا برای اتصال ریزشبکه به باتری استفاده می‌شوند، فقط ولتاژ را تغییر می‌دهند. برای اتصال ریزشبکه به باتری، مبدل‌های دو طرفه مورد نیاز است. یک مبدل دوجهته در پیکربندی‌های مختلف موجود است. ساختار کنترل برای به دست آوردن خروجی رضایت بخش بسیار پیچیده است. این مقاله یک مبدل تقویت‌کننده باک دوطرفه DC-DC برای کنترل جریان در ریزشبکه‌هایDC ، سیستم‌های خورشیدی و بارها پیشنهاد می‌کند. یک مبدل دوطرفه DC-DC Buck-Boost برای انتقال و دریافت انرژی از باتری به ریزشبکه DC موردنیاز است. هنگامی که ولتاژ به ریزشبکه DC ارسال می‌شود، ولتاژ باتری کاهش می‌یابد. در غیر این صورت، هنگامی که باتری با ولتاژ شارژ شارژ می‌شود، ولتاژ شارژ افزایش می‌یابد. این مبدل ولتاژ خروجی بهتری نسبت به مبدل AC-DC Buck-Boost ایجاد می‌کند و فرکانس سوئیچینگ آن دو برابر مبدل‌های معمولی است. مبدل DC-DC اصلاح شده دارای ساده‌ترین شکل و مزیت آن، داشتن بالاترین پاسخگویی است.