STUDY ON FRONT-END BIDIRECTIONAL DC/DC CONVERTER OF PHOTOVOLTAIC GRID-CONNECTED INVERTER

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Abstract - With the development of science and technology, virtual reality technology as a new technology has been applied to more and more areas. In the traditional shipbuilding industry, the shipbuilding period is usually long and frontline workers tend to make mistakes because of negligence of small details while making ship fitting according to the two - dimensional drawing of the ocean designer. In this study, virtual reality technology is applied to build a three - dimensional solid model in order to realize a vivid expression of the ship model and its assembly process. Compared with the traditional abstract drawing, the three-dimensional solid model allows designers and shipbuilders to be more unified, avoids wasting of resources in the construction process and makes it more convenient for the frontline workers to operate in reality, so as to improve the shipbuilding efficiency and shorten the shipbuilding cycle.

Keywords: Photovoltaic grid-connected inverter, Bi-direction, Direct current/direct current converter.

1. Introduction

With the all-round development of social economy, demands on energy become larger and larger. The development and application of green renewable energy has become an important approach for satisfying the demand of human being on energy [1]. Prof. Gheorghe [2] thought that challenges faced by the energy field were changeable and proposed strategies for controlling no power in photovoltaic parks and regulating national energy system capacity through inducing no power/capacitive power.

Tunlasakun T [3] put forward digital signal processing (DSP) based islanding protection for the underfrequency/ overfrequency and undervoltage/overvoltage of grid-connected inverter. He found that the prototype could close the relay between grid-connected inverter and public electric network when the frequency was higher than 48 Hz or 52 Hz and the voltage was lower than 200 V or 240 V. Grid-connected inverter as one hotspot in the research concerning energy renewability can be typed into single stage type and double stage type according to structures [4]. Photovoltaic grid-connected inverter is an important appliance for solar energy. Direct current/direct current (DC/DC) convertor is the topological structure of switching converters and also an important component of photovoltaic grid-connected inverters [5].

A photovoltaic grid-connected inverter increases or decreases the input voltage through conversion using DC/DC converter and realizes power maximization through regulating output. It can be considered that, the main function of DC/DC converter is to adjust uncontrollable direct voltage to controllable direct voltage [6,7]. DC/DC converter mainly includes unidirectional converter and bidirectional converter [8]. Generally, bidirectional DC/DC converter has larger research value and actual effect in practice [9]. Theoretically, bidirectional flow of energy can be realized by replacing the unidirectional switch and diode of unidirectional DC/DC converter into bidirectional switch using reasonable controlling method [10].

The topology of bidirectional DC/DC converter can be typed into isolated form and non-isolated form [11]. The current bidirectional DC/DC converter is featured by small volume, low weight, low price and good electrical property [12].

This study analyzed circuit topology and rules of bidirectional DC/DC converter and made a design based on it to realize systemic structure and DSP based control. The simulation results demonstrated the design was correct and feasible.

2. Grid-connected Photovoltaic Power Generation System

2.1 Introduction of grid-connected photovoltaic power generation system

Studies on photovoltaic grid-connected system started from the 1950s and 1960s. Photovoltaic grid-connected system is a subsystem of photovoltaic power generation system [13]. Since the 21 century, photovoltaic grid-connected power generation technology has been promoted in more and more countries. Grid-connected power generation system is used to invert electronics stored in solar photovoltaic cell and send it to load through power grid [14].

The typical structure of photovoltaic grid-connected system is composed of photovoltaic array, DC-DC converter, direct current–alternating current (DC-AC) converter and sampling protection device, as shown in figure 1. Photovoltaic grid-connected inverter can be typed into isolated photovoltaic inverter and non-isolated photovoltaic inverter. Isolated photovoltaic inverter can be typed into high-frequency isolated photovoltaic inverter and power frequency isolated photovoltaic inverter [15]. Compared to high-frequency isolated photovoltaic inverter, power frequency isolated photovoltaic inverter featured by stable performance and simple structure is used more frequently currently. But it also has defects such as large volume and low efficiency [16].

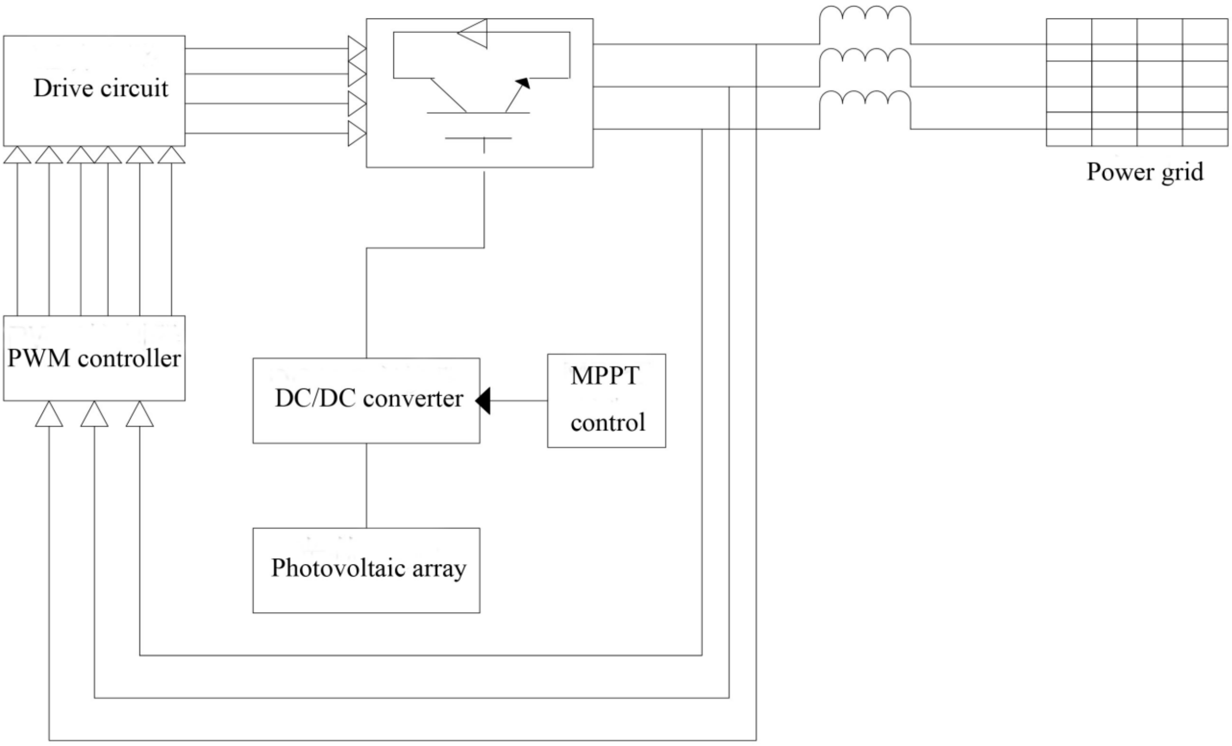

Figure 1: The structure of photovoltaic grid-connected system

2.2 Solar cell

With the changes of weather, sunlight strength and air temperature, the output power of solar photovoltaic cell will also change [17]. To keep the output of photovoltaic cell at the maximum value, corresponding controlling method was adopted.

Solar cell is a voltage source which can automatically transform into current source when it works with light energy. The circuit of solar cell is shown in figure 2.

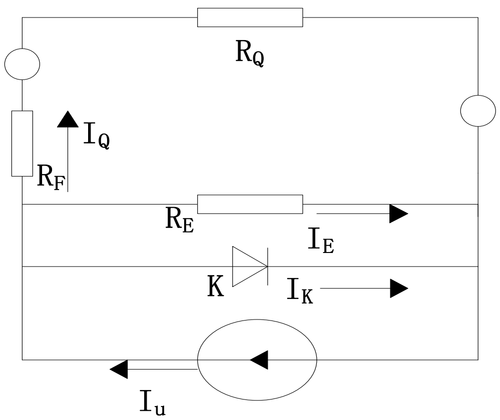

Figure 2: The circuit of a solar cell

In the figure, RF refers to cascade equivalent resistance, RE refers to parallel resistance, and RQ refers to the load of the cell. An ideal solar cell is with relatively small RF and relatively large RE.

3. Topology of Bidirectional DC/DC converter and its Modeling

3.1 Topology of bidirectional DC/DC converter

The common bidirectional DC/DC converter topology includes bidirectional Buck-Boost, Flyback, Push-Pull, etc [18]. As to isolated converter, compound transformer is difficult to be designed, because current is large when low voltage is input and more turns of primary side are needed when high voltage is input. But non-isolated bidirectional Buck-Boost converter can transform energy at the highest power. In this study, non-isolated converter was selected because isolation was not needed.

Figure 1 demonstrates the operation rules of Buck-Boost converter. Bidirectional Buck-Boost converter is a commonly used non-isolated bidirectional DC/DC circuit.

As shown in figure 3, L1 and L2 are fully-controlled switches. In forward work, L2 is in a closed state and Pulse-width modulation (PWM) control is performed on L1. D2, the diode of S2, is responsible for follow current, i.e., energy flow from top to bottom, when S1 is closed. In this stage, the circuit is in the Buck working state and the accumulator is charged by the bus. When L1 is closed, the circuit is in the boost state and the energy returns to the bus from the accumulator. The connectivity of L1 and L2 at the same time is impossible for bidirectional Buck-Boost converter.

The topological structure of bidirectional Buck-Boost converter is shown in figure 2. The position of inductor Q and L1 was exchanged. When L1 is closed, PWM control is performed on L2, the circuit is in the boost mode, and energy returns from the accumulator to the bus; when L2 is closed, the circuit is in the Buck mode and the accumulator is charged by the bus. When L1 and L2 are connected at the same time, the working mode of the converter turns to be alternation.

The topology is usually used in the switching power supply of bidirectional DC/DC converter.

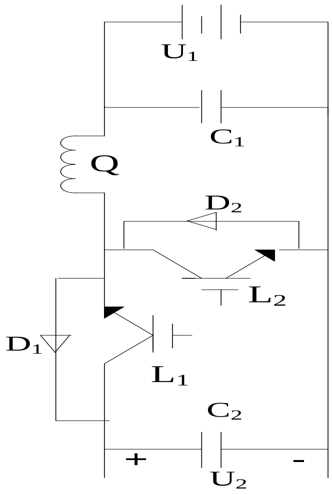

Figure 3: Schematic diagram of bidirectional Buck-Boost converter

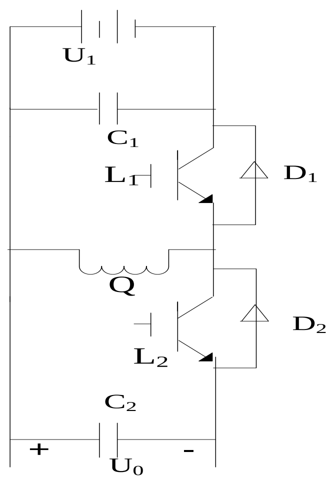

Figure 4: Topology of bidirectional Buck-Boost converter

$$\dot{x} = F(\mathrm{x}, \mathrm{a}, s) \tag{1}$$

was used to represent the state equation of the circuit. The working point of the circuit was supposed as , then the Taylor's series of formula (1) was:

$$\begin{aligned}\dot{x} &= F(x_0, a_0, s_0) + \frac{\partial F(x_0, a_0, s_0)}{\partial x}(x - x_0) + \frac{\partial F(x_0, a_0, s_0)}{\partial a}(a - a_0) + \frac{\partial F(x_0, a_0, s_0)}{\partial s}(s - s_0) \\ &+ R(x - x_0) + R(a - a_0) + R(s - s_0)\end{aligned} \tag{2}$$

As $\dot{x} = F(\mathrm{x}, \mathrm{a}, s)$, thus we have:

$$\dot{x}-\dot{x}_0=\frac{\partial F(x_0,a_0,s_0)}{\partial x}(x-x_0)+\frac{\partial F(x_0,a_0,s_0)}{\partial a}(a-a_0)+\frac{\partial F(x_0,a_0,s_0)}{\partial s}(s-s_0)+R(x-x_0)+R(a-a_0)+R(s-s_0) \quad (3)$$

Thereinto

$$\frac{\partial F}{\partial x}=\begin{bmatrix}\frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} & \cdots & \frac{\partial F_1}{\partial x_m}\\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} & \cdots & \frac{\partial F_2}{\partial x_m}\\ \cdots & \cdots & \cdots & \cdots\\ \frac{\partial F_n}{\partial x_1} & \frac{\partial F_n}{\partial x_2} & \cdots & \frac{\partial F_n}{\partial x_m}\end{bmatrix}$$

$$F=\begin{bmatrix}F_1\\F_2\\\cdots\\F_n\end{bmatrix} \quad x=\begin{bmatrix}x_1\\x_2\\\cdots\\x_m\end{bmatrix} \quad (4)$$

When m = n, suppose $\hat{x}=x-x_0$, $\hat{a}=a-a_0$ and $\hat{s}=s-s_0$ we have:

$$\dot{\hat{x}}=\frac{\partial F(x_0,a_0,s_0)}{\partial x}\hat{x}+\frac{\partial F(x_0,a_0,s_0)}{\partial a}\hat{a}+\frac{\partial F(x_0,a_0,s_0)}{\partial s}\hat{s} \quad (5)$$

Let

$\frac{\partial F(x_0,a_0,s_0)}{\partial x}$=A, $\frac{\partial F(x_0,a_0,s_0)}{\partial a}$=B, $\frac{\partial F(x_0,a_0,s_0)}{\partial s}$=C, then we got the following model:

$$\dot{\hat{x}}=A\hat{x}+B\hat{a}+C\hat{s} \quad (6)$$

where: $x=\begin{bmatrix}u_q\\p_\beta\end{bmatrix}$ a= $[a_u]$

x stands for input vector, a stands for output vector, u_q and p_β stand for state variable, and a_u stands for input voltage.

3.2.2 Small signal model of bidirectional Buck-Boost circuit

$$\dot{\hat{x}}=A\hat{x}+B\hat{a}+C\hat{s}$$

thereinto

$$A=\begin{bmatrix}0 & -\frac{1-s_0}{Q}\\ \frac{1-s_0}{C} & -\frac{1}{RC}\end{bmatrix}, B=\begin{bmatrix}\frac{s_0}{Q}\\0\end{bmatrix}a,$$

$$C=\begin{bmatrix}0 & \frac{1}{Q}\\ -\frac{1}{C} & 0\end{bmatrix}x_0+\begin{bmatrix}\frac{1}{Q}\\0\end{bmatrix}a_0 \quad (7)$$

Then the transfer function of $\hat{x}$ and $\hat{a}$ was obtained:

$$(lI-A)^{-1}B=\begin{bmatrix}\frac{Cl+1/R}{QCl^2+Q/R\times l+(1-s_0)}\\ \frac{1-s_0}{QCl^2+Q/R\times l+(1-s_0)}\end{bmatrix} \quad (8)$$

The transfer function of $\hat{x}$ and s was:

$$(lI-A)^{-1}B=\frac{\begin{bmatrix}1-s_0 & (lC+1)/R\\ -lQ & 1-s_0\end{bmatrix}x_0+\begin{bmatrix}\frac{1}{Q}\\0\end{bmatrix}a_0}{QCl^2+Q/R\times l+(1-s_0)^2} \quad (9)$$

4. The Design of Simulation Experiment

4.1 Design of bidirectional DC/DC converter

The design of bidirectional DC/DC converter is shown in figure 5.

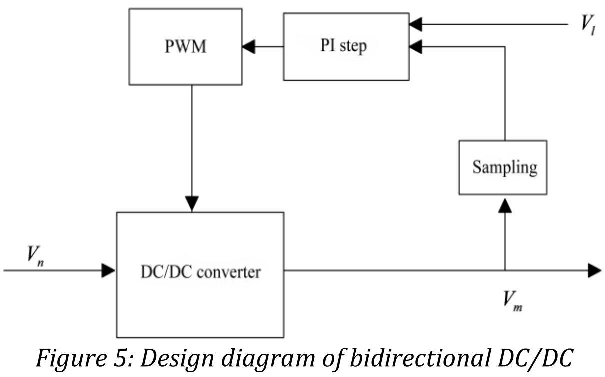

Figure 5: Design diagram of bidirectional DC/DC converter

The voltage which is output by bidirectional Buck-Boost circuit was compared with after the sampling step according to the ratio of 0.01. The error signal of the two voltages was compared with triangular wave after being amplified by the PI step; then a square-wave pulse whose width changes along with the changes of output voltage was obtained. The square-wave pulse signal was connected with the switching tube on the main circuit as a driving signal. The other driving signal was obtained by connecting the square-wave pulse with NOT gate. Then two complementary pulse signals were obtained, which could realize the complementary breakover of the switching tube.

4.2 The closed-loop step of bidirectional DC/DC converter

Before experiment, different steps in closed loop of the system should be realized. The schematic diagram is as follows.

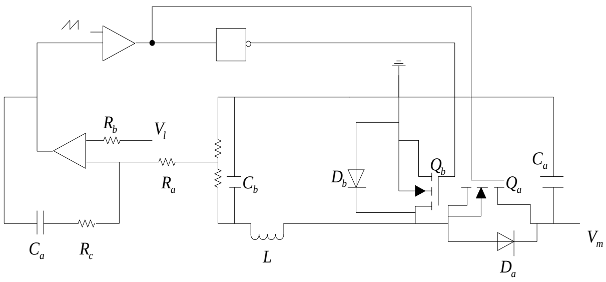

Figure 6: The schematic diagram of the closed loop of bi-directional DC/DC converter

The sampling step was realized by Voltage Controlled Voltage Source (VCVS). The compensation step was completed by PI regulator. The step of pulse width regulation was completed by SG3525 chip.

4.3 The design of closed-loop regulator

The closed-loop control of a DC/DC converter includes current control mode and voltage control mode [19]. As to current control mode, the following performance, stability and portability are poor and current and the power of converter cannot be controlled, which is not beneficial to the parallel connection of converter. This study investigated bidirectional DC/DC converter by means of industrial design. Determination of regulator parameters and requirements on stability and accuracy should be paid attention to in the design of regulators using industrial design method. The expression of open-loop transfer function of the control system was:

$$W(l)=\frac{Z\prod_{\lambda=1}^{\rho}(\sigma_{\lambda}l+1)}{l^{r}\prod_{\gamma=1}^{\vartheta=r}(\kappa_{\gamma}l+1)} \quad \vartheta \geq \rho \tag{10}$$

where Z stands for open-loop gain, σ_λ and k_y stand for constants, and r stands for the multiple number of pole on the origin of coordinate (r = 1, 2, 3…, corresponding to type I, II, III…). Type I and II systems were used. Before design, the characteristics of the two types of systems should be known. Type I system had poor following performance, small overshoot and weak anti-interference capacity, while type II system is featured by large overshoot, good following performance and anti-interference capacity.

4.4 Simulation experiment of bidirectional DC/DC converter

The mathematical model aforementioned was established in saber simulation software. Modular design was adopted. The circuits included power supply circuit, bidirectional DC/DC converter circuit, VCVS circuit, PI compensator circuit, peripheral circuit, circuit generated by driving signal and working mode switching circuit.

After modeling, the parameters were set: power: 12 KW, input voltage: 360 V ~ 540 V, and output voltage: 240V. Resistive load was used. The switching frequency was 20 kHz, filter inductance was 1.3 mH, and filter capacitor was 500 uf.

Using the simulation model designed above, bidirectional DC/DC was simulated under different control modes. The flow direction of energy was changed by opening and closing the voltage switch, When the switch is closed, the converter was at BUCK mode; when the switch is open, it was BOOST mode. The model at BUCK mode, BOOST mode and the switching between the two modes and the designed closed-loop regulator were tested.

5. Simulation Results

5.1 Simulation results at BUCK mode

As shown in figure 7, when the bidirectional DC/DC system operated at BUCK mode, the inductive current flew forward continuously. Therefore, the energy in the system flew from V_a to V_b. The average value of voltage was 240.06V, the average value of current was 45.637A, and the ripple wave of inductive current was 5A.

It could be noted that the data obtained in the experiment was basically same with the parameter given in the preceding text, satisfying the design requirements.

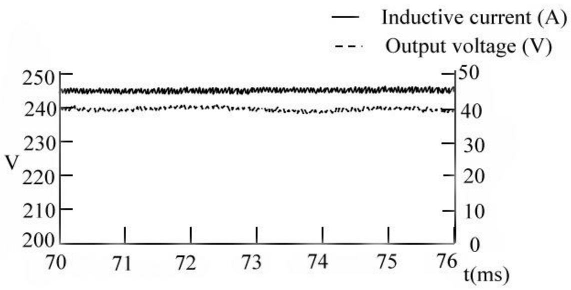

Figure 7: The waveforms of the output voltage and inductive current at BUCK mode

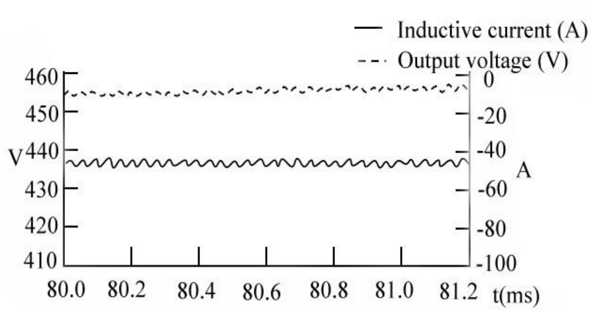

Figure 8: The waveforms of the output voltage and inductive current at BOOST mode

As shown in figure 8, when the system operated in BOOST mode, the inductive current flew in reverse direction continuously. Therefore, the energy in the system flew from V_b to V_a.

The comparison of the simulation results of the inductive current in figure 7 and 8 suggested the same value but the opposite direction. In the simulation results, the average value of voltage was 455.25V, the average value of current was 48.139A, and the ripple wave of the inductive current was 5A. It could be noted that the data obtained in the experiment was basically same with the parameter given in the preceding text, satisfying the design requirements.

5.3 Simulation results at the switching of the two modes

Before the simulation experiment, four switches were designed for controlling BUCK source, BUCK load, BOOST source and BOOST load. The switching between BUCK mode and BOOST mode was realized through the complementary breakover of BUCK source, BUCK load, BOOST source and BOOST load. The simulation results are shown in figure 9.

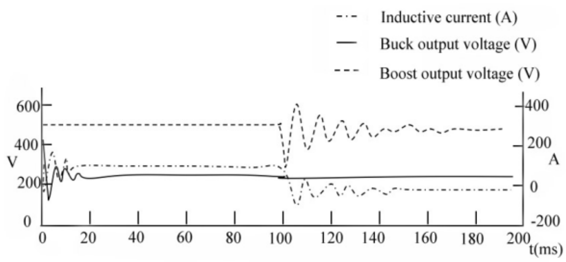

Figure 9: The waveforms of the output voltage and inductive current at the condition of bidirectional work

During bidirectional work, the current before 100 ms was forward current at BUCK mode, and the current after 100 ms was reverse current at BOOST mode. In the process of mode conversion, the inductive current transformed from positive direction to negative direction, realizing the bidirectional flow of energy.

5.4 Simulation of current protection of regulator

Whether the regulator protected the current passing through should be further simulated. The time was set as 0.25 s; load resistance was as 6.77 Ω, but turned to be the original value at 0.3 s. Results are shown in figure 10.

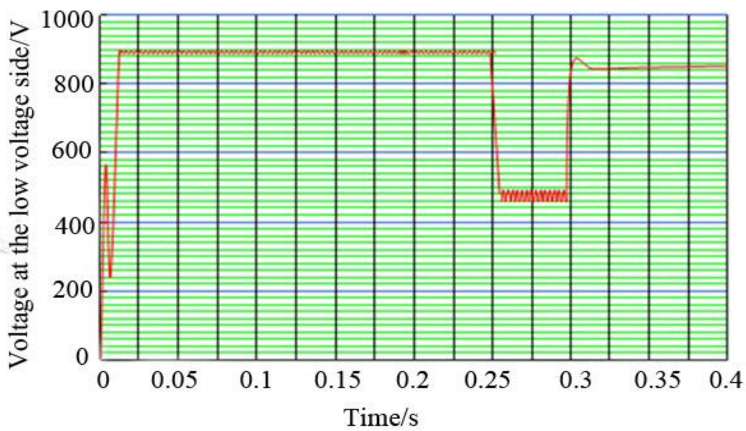

Figure 10: Changes of load voltage

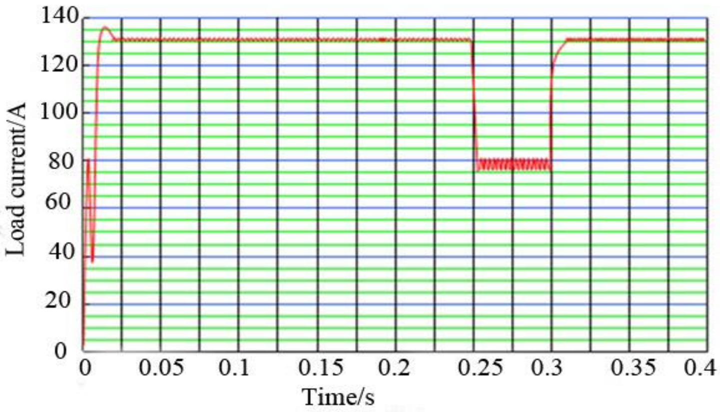

Figure 11: Changes of load current

In general condition, current would increase by 2 times if there was no protection from regulators, which could cause severe damages to regulators and equipment. As shown in figure 10 and 11, when the resistance turned to be half of the original value, the regulator would reduce voltage and current to half of the original values. Thus it could be concluded that, the regulator could protect the device.

6. Discussion and conclusion

Currently, studies on front-end bidirectional DC/DC converter mainly focus on isolated high-frequency DC/DC converter which is usually used in the reduction of high input voltage, but concern little about the transformation from high voltage to low voltage and from low voltage to high voltage. In real life, low-voltage and high-current power system is needed in many occasions. Xiong YS et al. [20] proposed a maximum power point tracing method for photovoltaic power generation system. Using this method, the working point was adjusted to the position around the maximum power point. Thus every module needs precise setting. The first application of bidirectional DC/DC converter in battery charger which aims to improve the power density and overall efficiency of energy flow has been extensively concerned [21]. With the constant deepening of studies, multiple types of topological structures have been proposed and the controlling methods become more and more accurate. By selecting Buck-Boost DC/DC converter suitable for large and medium-sized power, this study figured out small signal transfer function through modeling. Based on topological structure, bidirectional Buck-Boost DC/DC converter was simulated. The simulation experiment suggested that the bidirectional DC/DC system could satisfy the bidirectional flow of energy and the designed regulator could protect the device. In this study, the controlling step of voltage and current of the bidirectional DC/DC converter was designed; however, the research was not comprehensive and the other parts need to be investigated. In conclusion, the design of bidirectional DC/DC converter has certain effectiveness and operability.

Acknowledgement

This work was supported by the D class Six Talent Peak Project in Jiangsu – the development of grid-connected inverter in distributed photovoltaic power generation system (Program No.: 2015-XNY-017).

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