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Direct Buck-type AC-AC Converters using VSC Method

***Abstract**. The researches on direct AC-AC converters have been an important field. The DC-modulated method, which was used in DC-DC converters before, is used in AC-AC converters to realize a direct AC-AC converting now. The traditional control method regulates the output by adjusting the duty ratio. Its' core is the PWM technology. In this paper, the variable structure control (VSC) strategy was utilized in Buck-type AC-AC converters. The simulations and experiments proved that the VSC controller was more efficient and faster response.*

***Streszczenie.** W artykule zaprezentowano różne typy strategii sterowania wykorzystywane w przekształtnikach AC-AC typu buick. Symulkacje i badania wykazały wyższość sterowników typu VBSC. (**Przekształtniki AVC-AC typu buck ze sterownikami VSC**)*

Keywords: VSC, Buck, AC-AC converters, chopper
Słowa kluczowe: sterowniki VSC, przekształtniki AC-AC.

Introduction

Nowadays, the AC-chopper technology has played a increasingly role in the researching field about voltage restorers or online conditioners. Applied the AC-chopper technology, direct AC-AC converters can be realized. Compared with the traditional AC-DC-AC converters, the direct AC-AC converters without the energy-storage component can be manufactured smaller, cheaper and more efficient.

Recent years, with the trend of building a smart grid, power electronic transformer gradually replaced traditional transformer has become an inevitable trend. One of the main directions of the AC chopper is the study of power electronic transformer. For the demand of small and medium power AC voltage regulators, AC voltage regulators using AC-chopper technology will play an important role in the future micro grid, vehicle power systems, shipboard power system, as well as the smart home power supply system.

Common AC chopper topologies are shown as following: Buck, the Boost, Buck-boost Z-source, and the quasi-Z-source and multi-level topology.[1-6]

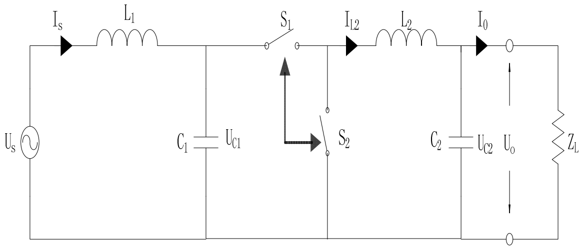

Fig.1. The typical Buck-type circuit

These topologies are derived from the topology of the DC chopper. Buck topology is the most basic one in all topologies because for the study of control strategies on the Buck topology can easily be applied to other topologies. This article is based on the Buck topology, researched its' control strategies, and proposed a control strategy based on variable structure control (VSC). The system simulation and experimental strudy has been done. The results show that compared with traditional control strategies, the variable structure control (VSC) has a faster response speed and higher control precision.

The mathematical model of a Buck circuit

As show in Figure 1, it is a typical figure of Buck topology AC chopper. S1, S2 are bidirectional switches. L1, C1 are the input LC filter and L2, C2 are the output LC filter. The simulations and experiments are based on this typical circuit.

Figure 2 shows the implementation of the commonly used two bidirectional switches, both of them have their own characteristics. The first approach using only one switch, low cost, reliable switching, but the current will flow through one switch tube and two diodes. The second switch mode, due to the two switch series inverting, has a flexible switch-mode. It can achieve the function of the inverting freewheeling diode. Compared with the first implementation, the second way can make the current less flows through a diode to reduce the conduction losses. Overall the two implementations have their own applicable applications. In this study the second one shown in figure 2(b) is applied.

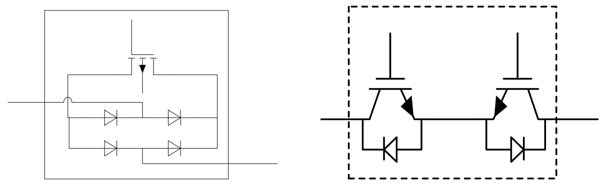

Fig.2. The bidirectional switches.

The freewheeling problem and switching strategy of Buck circuits has been solved well, so in this paper for the dead time of the switch control signal, and the filter inductor freewheeling, will no longer be additional discussion and will be ignored in the whole modelling and simulation process.

According to the marks in figure 1, the state equations are writing for the Buck circuit.

When S_1 is closed and S_2 is opened. The state function of the buck circuit is equation (1).

$$(1)\quad \begin{cases} \dfrac{dU_{C1}}{dt} = \dfrac{1}{C_1}(I_{L1} - I_{L2}) \\ \dfrac{dU_{c2}}{dt} = \dfrac{1}{C_2}(I_{L2} - I_O) \\ \dfrac{dI_{L1}}{dt} = \dfrac{1}{L_1}(U_s - U_{C1}) \\ \dfrac{dI_{L2}}{dt} = \dfrac{1}{L_2}(U_{C1} - U_{C2}) \end{cases} .$$
$$U_O = U_{C2}$$

When S_1 is opened and S_2 is closed. The state function of the buck circuit is equation (2).

$$(2)\quad \begin{cases} \dfrac{dU_{C1}}{dt} = \dfrac{1}{C_1} I_{L1} \\ \dfrac{dU_{c2}}{dt} = \dfrac{1}{C_2}(I_{L2} - I_O) \\ \dfrac{dI_{L1}}{dt} = \dfrac{1}{L_1}(U_s - U_{C1}) \\ \dfrac{dI_{L2}}{dt} = \dfrac{1}{L_2}(-U_{C2}) \end{cases}$$

$$U_O = U_{C2}$$

According to the state-space average method (SSAM), the state-space average model of the buck circuit is equation (3).

$$(3)\quad \begin{cases} \dfrac{\Delta U_{C1}}{T} = \dfrac{1}{C_1}(I_{L1} - DI_{L2}) \\ \dfrac{\Delta U_{c2}}{T} = \dfrac{1}{C_2}(I_{L2} - I_O) \\ \dfrac{\Delta I_{L1}}{T} = \dfrac{1}{L_1}(U_s - U_{C1}) \\ \dfrac{\Delta I_{L2}}{T} = \dfrac{1}{L_2}(DU_{C1} - U_{C2}) \end{cases}$$

$$U_O = U_{C2}$$

In the equation (3), D is the duty of one switch period and T is the switch period. When the L_1, L_2, C_1 and C_2 are large enough, the U_{C1},U_{C2},I_{L1},I_{L2} can be seen as constant or change a little in one switch period. Then the equation (4) can be seen right.

$$(4)\quad \begin{cases} I_{L1} - DI_{L2} = 0 \\ I_{L2} - I_O = 0 \\ U_s - U_{C1} = 0 \\ DU_{C1} - U_{C2} = 0 \end{cases} .$$

$$U_O = U_{C2}$$

In fact, the equation (4) is just an approximatively correct equation. Because the switch frequency is much higher than the frequency of AC voltage source (50Hz), it is assumes that the input voltage can be seen as a DC source in several switch periods time. In the other hand, the parameters of L_1, L_2, C_1 and C_2 are must be large enough. So the ripple waves of U_{C1}, U_{C2}, I_{L1} and I_{L2} can be small enough to be ignored.

Almost all traditional control strategies are based on the equation (3) and equation (4). But the VSC is different and will be discussed in behind section.

At the same time, on the basis of the equation (3), the system transfer function can be got by the traditional methods of Laplace transform. But it has nothing to do with this article, it is no longer listed.

In addition, there is another modelling method. The switching function dealt with Fourier transform can transform the non-linear model into a linear model. It can get an approximate time-domain model by ignoring the higher harmonics. The analyses in this article are based on the state function.

The research about control strategies

For the AC chopper circuits, the basic control strategy is to control the switch duty ratio. The magnification is different between the different topologies of the input voltage and output voltage, such as the Buck-types' is D, the Boost-types' is 1/(1-D), the Buck-Boost-types' is D/(1-d), and so on. To get the desire output voltage, different topology control methods are also different. The simplest one is Buck-type circuits because the relation between the voltage magnification and the duty ratio is a linear relation. On the contrary, the relation of any other topology is a non-linear relation. It needs additional compensation in the control strategy.

The most widely used control method is the conventional PI or PID control. As used in the references [1,4,7-12] is the traditional closed-loop feedback PID control. Yurkevich proposed a PI controller design via singular perturbation technique for Buck-Boost-type topology [13].

In addition, there are some improved controlling methods, the controller core is still the conventional PI or PID controller, but they introduced more feedback quantities. Such as the current feedback control, the current programmable control and the instantaneous voltage feedback control in single-stage three-level AC/AC converter, predictive current control of AC/AC modular multilevel converters [14-18]. These control methods get the desired output by increasing the state variables.

However, the AC/AC converter has its own characteristics, that is, the input voltage varies periodically, so the error is cyclical changes. In addition, due to the cyclical changes of the input sinusoidal voltage, the controller can hardly work near the voltage zero point. This makes the PID controller is difficult to stabilize in a dynamic and cyclical adjusting process. At the same time, the error effect will accumulate easily near the input voltage zero point and bring a disturbance following the instantaneous voltage increasing. So there is a dilemma of choice, to improve the response speed or to improve the system stability. A nonlinear control method must be used to improve the both two.

In the references [19,20], the neural networks control method is used into the PID controller, it improved the response speed significantly. In the references,[21] Sundareswaran used genetic algorithm to reduce the harmonics of the PWM AC chopper.

Furthermore, Bherulal, Y.V. Hote, and J.R.P. Gupta used QFT(Quantitative Feedback Theory, QFT) based robust controller for single-phase AC/AC Buck converter to improve the stability under the condition of complex loads. That can cope with some uncertainty parameters in the AC/AC converter control [22].

The variable structure control (VSC)

VSC was also known as sliding mode control or sliding mode variable structure control. It is an effective nonlinear control method.

The control methods mentioned earlier, the core is to adjust the duty in one switching cycle to achieve the output. However, the VSC is entirely different.

Depending on the state of switching devices, the circuit has two different structures corresponding to the state equations (1) and (2). The conversion of the structure is judged by the judgement equation $S(U_S, U_O, U_{target})$. The

In the judgement equation:

U_S is the input voltage;

U_O is the output voltage;

U_{target} is the output target voltage;

Of course, the control effect can also be improved by adding other state variables in the judgment equation.

The equation (5) is the judgment equation in this article. U_S and U_{target} are synchronized with different amplitudes. Therefore U_S can be ignored.

(5) $$S = U_{target} - U_O$$

The sliding surface is defined by equation (6).

(6) $$S = U_{target} - U_O = 0$$

Figure 3 shows the circuit simulation model. The RC circuits are used to reduce the switching impact.

D1 ~ D4 are four IGBTs, while defined:

(7) $$D_i = \begin{cases} 1, & Di \text{ is closed;} \\ 0, & Di \text{ is opened;} \end{cases} (i = 1, 2, 3, 4;)$$

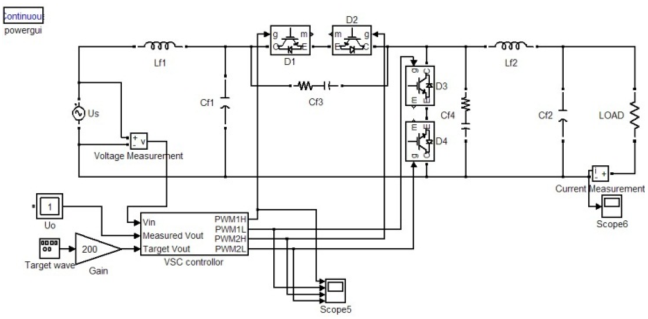

Fig.3. the simulation model of Buck-type AC-AC converter

The control signals of D1~D4 are controlled by the following control strategy:

When Us>=0, S>0; D1=1, D2=1, D3=0, D4=1;
When Us>=0, S<=0; D1=0, D2=1, D3=1, D4=1;
When Us<0, S<=0; D1=1, D2=1, D3=1, D4=0;
When Us<0, S>0; D1=1, D2=0, D3=1, D4=1;

So, when Us>=0, S>0 or Us<0, S<=0, the equivalent circuit is just like the Figure 4 and the state equations is the equation (1).

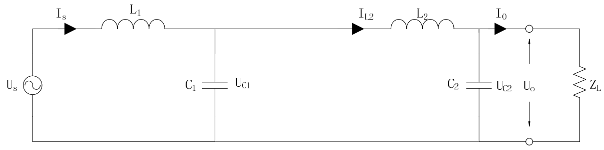

Fig.4. The equivalent circuit for equation (1)

And when Us>=0,S<0 or Us<0,S>0, the equivalent circuit is given in the Figure 5 and the state equations is the equation (2).

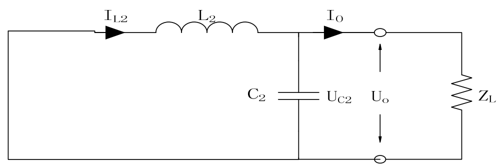

Fig.5. The equivalent circuit of equation (2)

From the two equivalent circuits, it can be seen that the two states represent the drive state with input voltage and freewheeling state without input voltage. The core of this control strategy is to decide whether supplied by input power according to the instantaneous values of U_O and U_{target}.

The effective value of input voltage is 220V and the frequency of input voltage is 50Hz. Setting the amplitude of U_{target} is 200V, and the frequency is also 50Hz. The simulation results are shown in Figure 6.

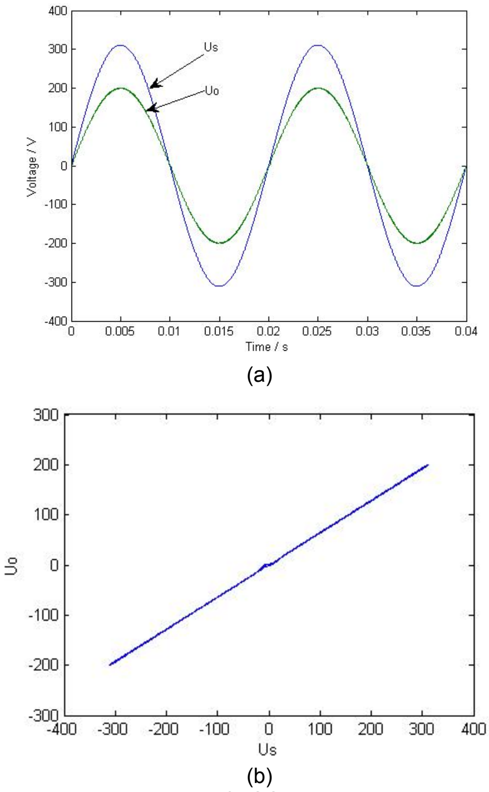

Fig.6. The simulation results of VSC control

In the Figure 6(b), the waveform is almost a straight line. There is a small oscillation near the two peaks and a small phase shift near the zero point.

The Figure 7 is the switch control pulses. From the small window in the top right corner, it can be seen that the switch periods is not unchanged.

Compared to the PID controller, the switch frequency of VSC can be controlled dynamically. When the input voltage is high the MOSFET switched faster, and on the contrary, when the input voltage is low the MOSFET switched slower. This function can reduce unnecessary switching loss while it is maintaining the same error level.

In the same time, the VSC has faster response speed. When the system left the switching plane, the VSC controller can draw the system back to the switching plane as fast as it can. However, the problems about stability are more complex to analyze and control.

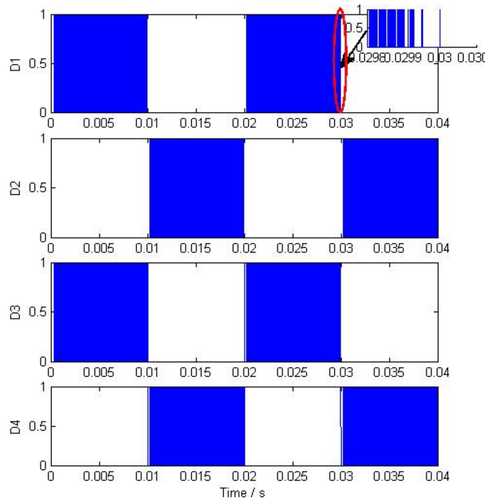

Fig.7. Switch control pulses in VSC

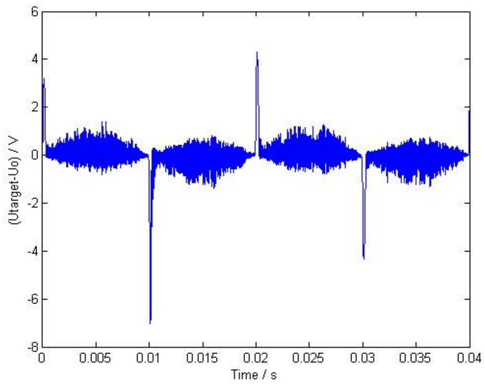

Fig.8. The waveform of S

Figure 8 is shown the waveform of switching function S. It is also the error between U_O and U_{target}.
From the waveform of S, the VSC controller can control the system running near the switching plane almost all time but in a small region is closing zero. The reason is the Us can be ignored when the input is closing to zero. Then the two structures become similar and the VSC controller can't work again. The same problem is also existed in the traditional control for Buck and Buck-Boost topologies.

Figure 9 shows the output voltage can remain unchanged when the input voltage amplitude changing.

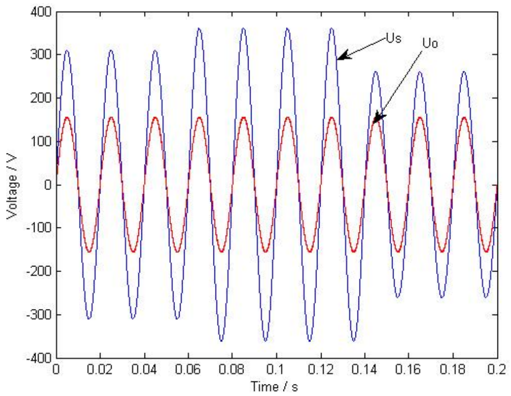

Fig.9. The simulation results under changing input

Figure 10 shown the relation between U_{target} and U_O on the condition that the input voltage amplitude was changing.

The energy changing of L_{f1}, L_{f2}, C_{f1} and C_{f2} lag the changing of input Us. How to through the zero point smoothly is a main point of the VSC strategy which will needs further research.

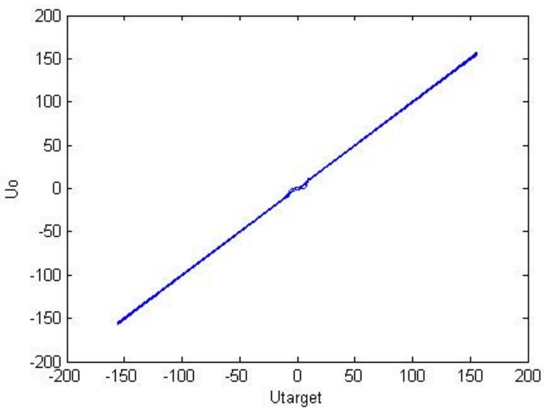

Fig.10. The waveform of U_{target}-U_O

In fact, there always are small oscillation depended on the instantaneous value of the voltage source. When the instantaneous value of input voltage is small the amplitude of oscillations is also small and when the instantaneous value is larger the amplitude of oscillation is also larger. This is the way the oscillation near the two peaks is more unambiguous. It can be seen more clearly in the simulation based on the other group parameters.

Experimental results

An experimental prototype of a Buck-type AC-AC converter was built. The converter was fed from a isolation transformer, 110V, 50Hz, input. It utilized DSPIC30F4011 as the controlling core.

The Figure 11 is the experimental plat. It was consisted of three parts: the DSP controller, the main circuit, the drive and detection circuit. The load utilized a power resistor.

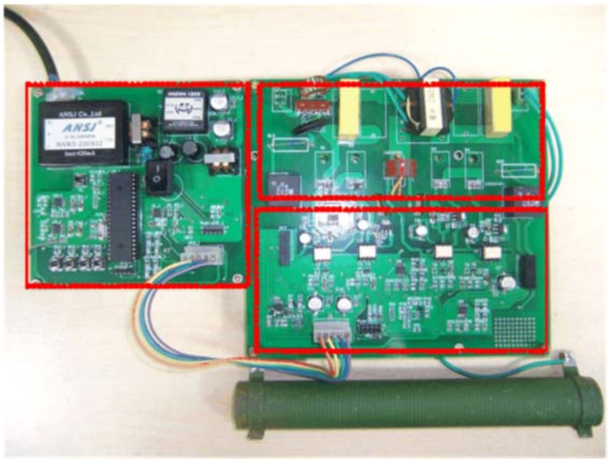

Fig.11. The experimental plat

In the experiment, the changing of input voltage amplitude was simulated. As the Figure 12 shown, the output voltage remained unchanged in this process. The output target voltage was 50V / 50Hz.

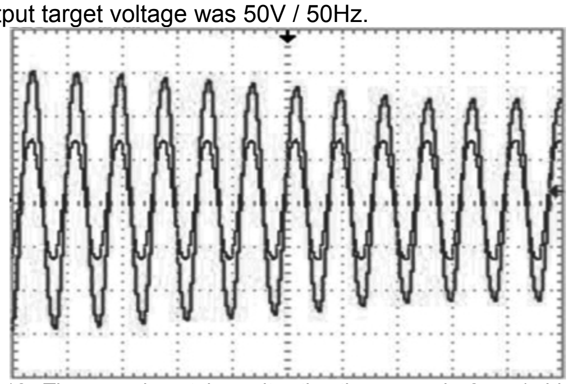

Fig.12. The experimental results, the time axes is 25ms/grid, the voltage axes is 50V/grid.

The following Figure 13 is the waveform of chopper output voltage before the LC filter.

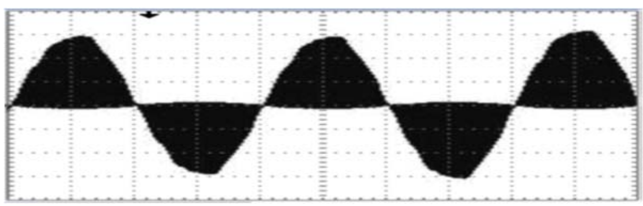

Fig.13. The chopper output voltage, the time axes is 5ms/grid and the voltage axes is 50V/grid

It can be seen from the experimental results, the VSC can achieve the desired control effect. The experimental results verify the system simulation results and confirmed the effectiveness and practicality of the VSC.

Conclusion

The control strategies based on Buck-type AC-AC converters were studied in this article. Compared with traditional PID control, the VSC strategy was proposed to replace the traditional PID control.

Simulation results show that the VSC has better dynamic performance, faster response and more precise control. The VSC controller is more effective and can almost eliminate the phase shift between input and output. In the other hand, the switch period can be regulated following the error. So a balance between reducing switching loss and improving quality of output and a smaller response time can be gained.

The experimental results verified the reliability and validity of the VSC controller and proved the correctness of the simulation studies. It shows that the VSC controller can work well and output the desired voltage.

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