Research on Variable Structure Control Strategy Based on Direct BUCK AC-AC Converter

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Abstract—The researches on direct AC-AC convertors have been an important field. The DC-modulated method, which was used in DC-DC convertors before, is used in AC-AC convertors to realize a direct AC-AC converting now. The method as regulating the duty of switch periods can control the circuit to output an acceptable sinusoid voltage wave. But this method can always bring forth a small phase shift between input and output. In this paper, variable structure control (VSC) is used in BUCK circuit. Simulations for these different control strategies based on the Simulink platform are used to analyze and compare. The result shows that the VSC can reduce the phase shift hardly to zero. In the same time, the switch period of VSC is not unchanged. It's changing following the error. Compared to PWM control method, the VSC can gain a smaller response time and a balance between reducing switching loss and improving quality of output.

Index Terms—AC-AC converter, Buck, PID, VSC, control stragety

I. INTRODUCTION

The researches on direct AC-AC convertors have been an important field. Compared with the traditional AC-DC-AC convertors, the direct AC-AC convertors in which the energy-storage component is not equipped can be manufactured smaller and cheaper.

Furthermore, the direct AC-AC convertors have been widespread concern and in-depth research for its quick response, single-stage transformation, and outputting AC voltage without low orders harmonics.

Recent years, the development of Smart Grid needs smarter transformers to make the grids more controllable and more efficient. It is likely that future power generation and distribution will involve a lot of distributed renewable energy resources and power grids. The need for power semiconductor devices with high-voltage, high-frequency, and high-temperature operation capability is growing. The AC-AC convertor can contribute more for the Smart Grid in the future. Nowadays, several kinds of basic topologies can be applied to realize a direct AC-AC convertor. Such as Buck, Boost, Buck-Boost, Z-Source, Quasi Z-Source, Push-Pull, and so on.^[1-5]

The Figure 1 is the Buck-Type AC-AC convertor. It can support a controlled output AC voltage source which is smaller than the input AC voltage source. The amplification factor K is smaller than 1.



Figure 1. The Buck-Type AC-AC converter The figure 2 is the Boost-Type AC-AC convertor. The amplification factor K of Boost circuit is bigger than 1.



Figure 2. The single-stage Boost-Type AC-AC convertor The figure 3 is the Buck-Boost-Type AC-AC convertor. The amplification factor K of Buck-Boost-Type circuit is less than 0.



Figure 3. The Buck-Boost-Type AC-AC convertor

The Figure 4 is the Z-Source AC-AC convertor. The amplification factor K of Z-Source can be any real in

theory. It is different from above convertors that the Z-Source AC-AC convertor can output not only the in phase voltage but also the inverse voltage just like the showing in Figure 5.





These topologies have a common characteristic that each of them contains two relatively complementary bidirectional switches. So, each of these circuits has two different state equations.

The buck type and boost type circuits are the basic topologies on which other topologies are developed. So the control strategies of Buck and Boost topologies almost can be easily applied in other topologies.

The buck circuits can be regulated linearly. But it can only output lower voltage than input voltage. On the contrary, the boost circuit can output higher voltage, even infinity in theory, but its model is nonlinear. In most engineering, the function of boost voltage is not necessary and controllability is more important. So the buck circuits are applied more widely than the boost circuits.

There are several control strategies which can be used in the buck circuits, just like the constant duty chopper, the PID/PI controlling, the neural networks controlling, and so on. [6-8]

In these traditional control strategies, the core is controlling the duty in one switch period. The PWM technology which used in the DC switching power supply is applied to realize AC-AC converter.

In this paper, variable structure control (VSC) strategy is applied. This method is different from those traditional control methods. There is no longer the duty concept. The VSC controls the circuit changing between two different structures to gain a faster response speed. This control method has been used in comprehensive fields successfully, but hardly been used in direct AC-AC converter. The simulations have been done to analyze and compare the control strategies and show the advantages of VSC.

II. THE BUCK CIRCUIT MODEL

State-Space Model Α.

The typical buck circuit is shown in the Figure 1. The two switches S1 and S2 are both bi-directional switch and the two realizations of bi-directional switch are given in the Figure 6. In the following simulation the Figure 6(b) is adopted.





Since the dead time and the follow current problem for buck circuits have been solved perfectly, they are ignored in this paper. The switch S_1 and S_2 are ideal switches and they close complementarily.

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

$$\begin{cases} \frac{dU_{c1}}{dt} = \frac{1}{C_1} (I_{L1} - I_{L2}) \\ \frac{dU_{c2}}{dt} = \frac{1}{C_2} (I_{L2} - I_o) \\ \frac{dI_{L1}}{dt} = \frac{1}{L_1} (U_s - U_{c1}) \\ \frac{dI_{L2}}{dt} = \frac{1}{L_2} (U_{c1} - U_{c2}) \\ U_o = U_{c2} \end{cases}$$
(1)

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

$$\begin{cases} \frac{dU_{C1}}{dt} = \frac{1}{C_1} I_{L1} \\ \frac{dU_{c2}}{dt} = \frac{1}{C_2} (I_{L2} - I_0) \\ \frac{dI_{L1}}{dt} = \frac{1}{L_1} (U_s - U_{C1}) \\ \frac{dI_{L2}}{dt} = \frac{1}{L_2} (-U_{C2}) \\ U_0 = U_{C2} \end{cases}$$
(2)

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

$$\begin{cases} \frac{\Delta U_{c1}}{T} = \frac{1}{C_1} (I_{L1} - DI_{L2}) \\ \frac{\Delta U_{c2}}{T} = \frac{1}{C_2} (I_{L2} - I_o) \\ \frac{\Delta I_{L1}}{T} = \frac{1}{L_1} (U_s - U_{C1}) \\ \frac{\Delta I_{L2}}{T} = \frac{1}{L_2} (DU_{c1} - U_{c2}) \end{cases}$$

$$U_0 = U_{c2}$$
(3)

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.

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

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.

B. Other Models

There are also some other mathematical modeling to describe the Buck converter. Many experts such as Sira-Ramirez, Czarkowski, Ilic, Cuk, Middlebrook, Lee, Smedley, Cheng and Erickson devoted in mathematical modeling[9-20].

In traditionally, the switch function is replaced by its Taylor series. Then the nonlinear equation can be changed to a linear one. But, in this case, the duty must be a constant. It can only describe the steady-state characteristic well.

Energy storage in power electronics converters has been paid attention long time ago. The professor Luo FangLin proposed a new method of modeling the Buck circuit in 2004. He had theoretically defined a new concept – energy factor (EF) and researched the relations between EF and the mathematical modeling for power electronics converter[21]. This theory is available for complex structure converters. But it's also not successful to describe the dynamical property of power electronics converters well.

III. TRADITIONAL CONTROL STRATEGIES

The traditional control strategies are based on duty controlling. The switch frequency is set and the duty is controlled. In this place, constant duty control and PID control are discussed simply to show the characteristic of traditional control strategies.

A. Constant Duty

Base on the equation (4), when the D is a constant value between 0 to 1, 0 < D < 1, equation (5) can be gained.

$$\begin{cases}
I_{L2} = \frac{1}{D} I_{L1} \\
U_{C1} = U_{S} \\
I_{O} = I_{L2} \\
U_{O} = U_{C2} = DU_{C1} = DU_{S}
\end{cases}$$
(5)

This is the most fundamental direct AC-AC converter. The Figure 7 is shown the model of Simulink.



Figure 7. The Simulink Circuit about Constant Duty Control Strategy

The control pulses of D1~D4 is shown in Figure 8. When the $U_S>=0$, D1 and D3 was closing alternately, D2 and D4 kept closing. On the contrary, when the $U_S<0$, D2 and D3 was closing alternately, D1 and D3 kept closing.



The Figure 9 is the result of the simulation for constant duty.

According to the equation (5), the relation between U_S and U_O is linear. But from the Figure 9(b), it is can be seen

that there is a phase difference between U_O and U_S . Because the trace in Figure 9(b) is moved anticlockwise, the phase of U_O lagged the phase of U_S .

This phase shift can be explained by equation (1)(2) (3). In each switch period, the instantaneous value of U_S can only decided the next switch period value of I_{L1} , so the I_{L1} changed behind the U_S . And so on, the U_{C1} changed behind the I_{L2} and the U_O changed behind the I_{L2} .

In another word, the U_0 needs a response time to follow the changing of U_s .



Figure 9. The Result of Simulation about Constant Duty

At the same time, when the Duty is a constant value, the amplification factor between U_S and U_O is also a constant value. It means that, when the U_S is unstable, the U_O would be unstable too, just like the simulation results in figure 10.



From the Figure 10, the input source U_s contains a 11order harmonic. This 11-order harmonic can transmit from the input port to the output port directly.

B. PID Control

Based on above analysis, the PID converter control the duty D dynamically instead the constant duty to get a better output wave. PI or PID control based on traditional control theory is used to control the D.

Since D is no longer a constant, the system is converted into a time-varying system.

The Figure 11 is the simulation model. The PWM1H is the control pulse of D1, the PWM2H is the control pulse of D2; the PWM1L is the control pulse of D3; the PWM2L is the control pulse of D4.



Figure 11. PID Controller

It can be seen from the equation (3) that the duty D and the input U_S decide the output U_O together. Even when the instantaneous value of U_S is closed to zero the PID controller can hardly reduce the error. So the error between U_{target} and U_O is divided by the absolute value of U_S to get a more reasonable error value.

The duty D is comprised of two main parts. One part is the ratio between U_S and U_O , the other part is the output of PID controller with error inputting. The first part is a constant value in conventional practice. The Figure 12 is shown the duty D.

In this control strategy, PID control is used to correct the Duty. The Figure 13 is the simulation results of U_s and U_0 .

In the Figure 13(b), it is clear that there is a oscillating process. And from the Figure 12, this oscillating process

needs about 0.01s. And then, the trace is almost a line with a small oscillation. The small oscillation can be seen more clearly from the wave of PID output which has been shown in Figure 12.

Compared to the constant duty, the PID controller can reduce the phase delay between U_S and U_O . But it needs a short cycle to wait for the integral part working. But the PID controller can regulate the Duty to reduce error in time, it can control the output voltage U_O as a ideal sine wave while the input U_S contains high order harmonic.



The Figure 14 is the simulation result about a input voltage with 11-order harmonic and the Figure 15 is the Duty controlled by PID controller.





Figure 15. Duty Wave of PID controller All the traditional control strategies are based on controlling the duty D. The above two are just two fundamental control strategies. There are also many other derived control methods. But they can be analyzed through

IV. VARIABLE STRUCTURE CONTROL

the equation (3).

Whichever the constant duty control and the PID controller, their switch frequencies are all unchanged. But the variable structure control (VSC) and the first two control strategies are completely different.

The VSC controls the switches in a different way. The switch frequency and duty are ignored and a judge function $S(U_s, U_o, U_{target})$ is used to decide the state of switches.

The U_{target} is the voltage wave which the system wants to output. In another word, the U_{target} is the purpose of the U_{O} .

From the equation (1) and equation (2), it can be seen that the two states of switches stood for two different circuit structures. The equation (1) stands for the structure with voltage source input and the equation (2) stands for the structure without voltage source input.

The function $S(U_S, U_O, U_{target})$ is designed to help the controller to know whether the voltage source would be needed.

As the equation (6), it is the simplest VSC switching function S.

$$S = \left| U_{t \operatorname{arg} et} \right| - \left| U_O \right|. \tag{6}$$

And then, the switching plane is given by equation (7).

$$S = \left| U_{t \operatorname{arg} et} \right| - \left| U_O \right| = 0.$$
⁽⁷⁾

For D1~D4, defined:

$$D_{i} = \begin{cases} 1, & Di \text{ is closed;} \\ 0, & Di \text{ is opened;} \end{cases} (i = 1, 2, 3, 4;) .$$
(8)

The states of D1~D4 can be controlled by following strategy.

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

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

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

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

So, when S>0, the equivalent circuit is just like the Figure 16 and the state equations is the equation (1).



Figure 16. The Equivalent circuit of equation (1) And when S<0, the equivalent circuit is given in the Figure 17 and the state equations is the equation (2).



Figure 17. The Equivalent circuit of equation (2)

But, from the equation (1) and equation (2), the relation between is a four-order polynomial. There must be oscillations and the exchange of energy between L_{f1} , L_{f2} , C_{f1} and C_{f2} . In order to make the system more stabilized, some small buffer circuits are needed to be connected in parallel with the MOSFETs.

Figure 18 is the simulation system based on the Simulink platform.





A additional 1 Ω resistance is series connected with the C_{f1} to help the system more stabilized, too.

The figure19 is the VSC controller. The sample frequency and the values of L_{f1} , L_{f2} , C_{f1} and C_{f2} must be select carefully or the system would be unstable.



The result of simulation is given in the Figure 20. The Figure 20(a) is the waveform of Us and Uo and the Figure 20(b) is the relation between Us and Uo.

In the Figure 20 (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 21 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.

The Figure 22 is shown the waveform of switching function S. It is also the error between U_0 and U_{target} .

From the waveform of S, the VSC controller can control the system running near the switching plane almost all time but the small region closing the zero. The reason is the Us can be ignored when the input closing 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 22. The Waveform of S

The energy changing of Lf1, Lf2, Cf1 and Cf2 lags the changing of input Us. How to through the zero point smoothly is a main point of the VSC strategy which will need more research.

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 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.

The Figure 23 is the relation between US and UO of the other grout simulation parameters.



Figure 23. Data of the other Simulation

The Figure 24 is the error based on the second group simulation parameter.

Compared to the Figure 22, the VSC controller has no help for the errors while the input Us run through the zero point.

Same as the PID controller, the VSC controller can also work well while the input voltage containing 11order harmonic.

Furthermore, the VSC controller responds faster than the PID controller and the output voltage wave is smoother than the PID controller.



The Figure 25 is the voltage waves of U_0 and U_s on the condition of 11-order harmonic interference.



Figure 25. Voltage Waves for 11-Order harmonic Interference

V. CONCLUSION

The simulation results of different control strategies based on the Simulink platform for Buck-Type converter are given in this paper. The comparing and analysis of these results shows that 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. At the same time, the VSC controller can filter the high order harmonic contained in AC source effectively. But how to through the zero point smoothly is still a main point of the VSC strategy which need more research.

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