Research on Modeling for Combined Three-level DC-DC Converter

Liu Shulin
Xi'an University of Science & Technology
Xi'an, China
lsigma@163.com

Yin Xiaohu
Xi'an University of Science & Technology
Xi'an, China
dmszcld@126.com

Song Yaya
Xi'an University of Science & Technology
Xi'an, China
symnyd@163.com

Qi Lili
Xi'an University of Science & Technology
Xi'an, China
qiyubianli@163.com

Abstract—The zero-voltage-switching combined DC/DC three-level converter, just has six switches, and the voltage stress of all switches is ensured to be only the half of the input voltage, especially suitable for high-voltage input situations, and the converter can reduce the output filter significantly at the mode of three-level and two-level. The small-signal transfer function is obtained by modeling analysis based on small signal of the converter. According to the proposed block diagram of closed-loop system, the closed-loop transfer function of the converter is deduced. The established closed-loop system model is simulated through Matlab, the experiment and simulation results are in positive to the analysis showing the feasibility of the established model.

Keywords- three-level DC-DC converter; combined; small signal model; Matlab simulation;transfer function

I. INTRODUCTION

The development of three-level DC/DC converter (TL converter) is based on the three-level inverter, in 1992, after the concept of three-level DC/DC converter is proposed by Pinheiro J R and Barbi I in the conferences of IEEE industrial electronics, control, instruments and automation (IECON), three-level DC/DC converter is greatly developed, and a variety of circuit topologies are proposed by many scholars to achieve the soft switch of switching tube [1]. In 2005, a kind of combined three-level DC/DC converter is put forward by the third literature, compared with full-bridge three-level DC/DC converter, the converter reduce two switches, which can change operating mode between three-level and two-level, especially suitable for the situations of middling or high power, high input voltage and a wide range of input voltage.

The best advantage of TL converter is that it can decrease the voltage stress of the switch, thus, it is being widely used in the situation of high input voltage and output voltage. The value of energy store element such as inductor and capacitor can be decreased in TL converters, for example, Buck converter, Boost converter, Buck-Boost converter, Cuk converter, Sepic converter and Zeta converter, thus, the dynamic performance of converter can be improved, and the volume weight can be reduced. The three-level DC/DC converter (TL converter) is being widely used in the following aspects [2-4]:

(1) It is being used in communication supply. TL converter is used as the topology to decrease the kinds of elements and reduce cost.

(2) It is being used in the situation of power-factor correction. The voltage stress of the switch can be decreased by TL converter in the condition of the fixed inductor current pulse, and the input current zero-crossing distortion can be decreased highly.

(3) It is being used in the situation of high voltage.

(4) It is being used in the situation of low voltage and large current, TL converter is being widely used in the Voltage Regulator module especially, and power loss and cost can also be reduced because of its advantage of decreasing the size of filter.

Thus, the control technology of TL converter has also become a focused issue in the industry [5-7], and novel three-level DC/DC converter has become the research orientation for converters [8-11].

In this paper small signal mathematical mode of the converter is established and analyzed the performance which will utilize the averaging method of state space, and verified by MATLAB simulation.

II. WORKING PRINCIPLE AND MODELING

The main circuit topology of combined three-level DC/DC converter is shown in Fig .1, the main waveform of the converter at the mode of three-level and two-level is shown in Fig .2.

When the input voltage is low, phase-shift angle of Q1, Q2, Q3 and Q4 is zero, the part of half-bridge three-level converter work at full duty cycle, and the primary voltage VAB of transformer T1 is an alternating positive and negative square wave. When Q1, Q3, Q5 and Q6 are in the phase-shift condition, by way of changing the phase-shift angle between them to adjust output voltage, in this case the primary voltage VAC of transformer T2 is a pulse width modulation (PWM) waveform, and its waveform is shown in Fig .2 (a). As can be seen from Fig .2(a), rectified voltage exists two levels: one level ((k1+k2)Vin/2) and middle level (k1Vin/2), if considering the loss of duty cycle, there will be a brief zero level in this waveform, and now converter work at the three-level mode.

With the increasing of input voltage, the phase-shift angle of full-bridge converter increase gradually, along with pulse width narrow. When input voltage increase to a certain value, this phase-shift angle reaches to the maximum value 180°, the pulse width from full-bridge is zero, and output voltage is not provided. At this moment half-bridge TL converter start to proceed phase-shift control, by adjusting phase-shift angle among Q1, Q4, Q2 and Q3 to change output voltage. In this mode, the secondary voltage is a voltage waveform of two-level (middle level and zero level), its waveform is shown in Fig .2 (b), and now the converter work at two-level mode.

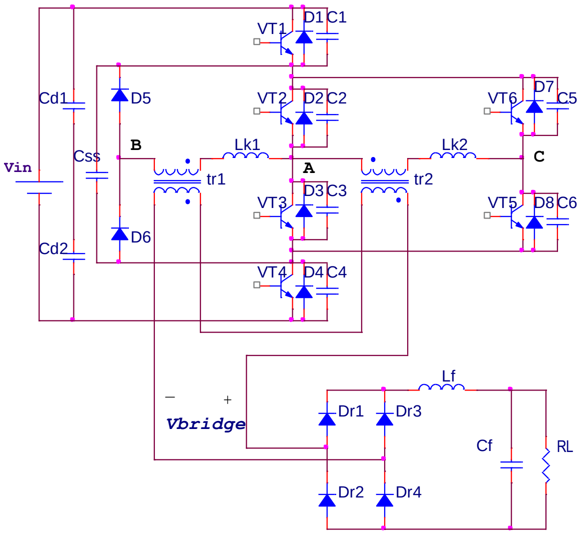
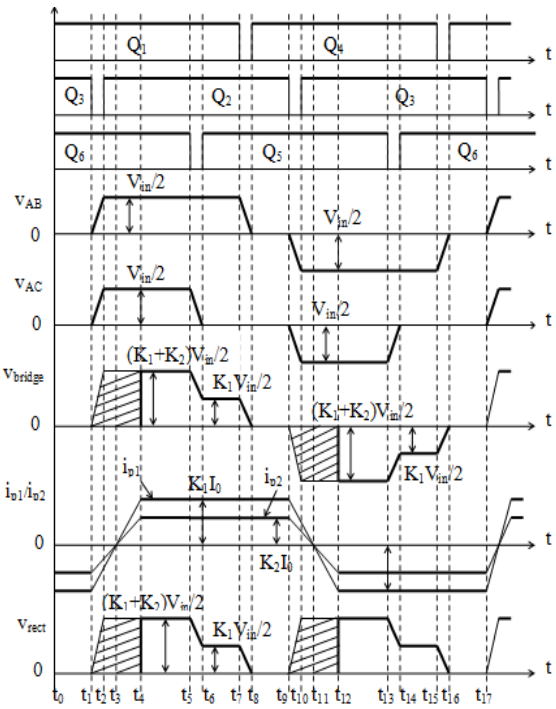
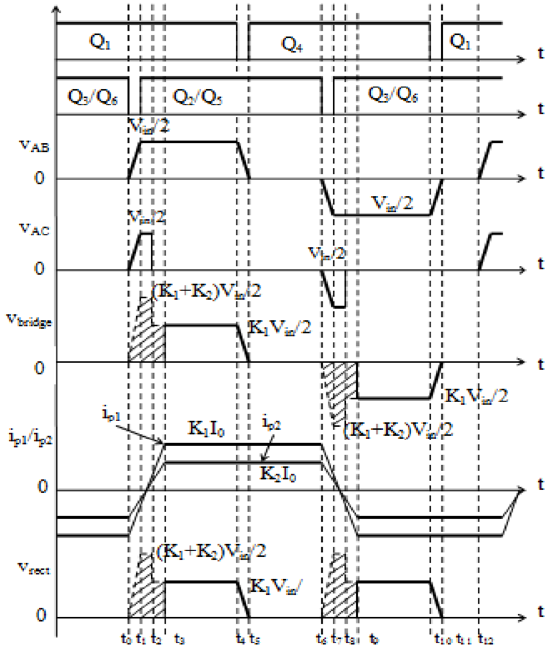


Figure1. Combined three-level DC/DC converter



(a) Three-level mode



(b) Two-level mode

Figure2. The main waveform of combined three-level DC/DC converter

Due to the combined three-level DC/DC converter has two transformers, it is difficult to model, and effective duty cycle is defined as Deff, then in 3L mode, there are time periods from t4 to t7 or between t12 and t15, because the primary current is not enough to provide load current, all rectifier diodes of secondary side are turned on, the secondary voltage is zero, that is to say secondary side lost the voltage of this part of time, it can be seen from the shaded area. The equivalent circuit of 3L mode from t4 to t7 time period is shown in Fig .3.

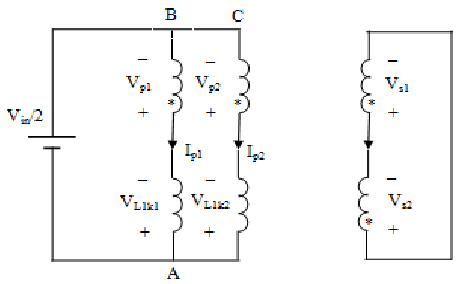


Figure3. Equivalent circuit of 3L mode from t4 to t7 time period

From Fig .3, we have:

$$v_{p1} + L_{1k1}\frac{di_{p1}}{dt} = v_{p1} + L_{1k1}K_1\frac{di_{\sec}}{dt} = -\frac{V_{in}}{2} \quad (1)$$

$$v_{p2} + L_{1k2}\frac{di_{p2}}{dt} = v_{p2} + L_{1k2}K_2\frac{di_{\sec}}{dt} = -\frac{V_{in}}{2} \quad (2)$$

Because the sum of secondary voltage of two transformers is zero, so we have:

$$v_{s1} + v_{s2} = K_1 v_{p1} + K_2 v_{p2} = 0 \tag{3}$$

Combining (1)-(3), we have:

$$\frac{di_{\sec}}{dt} = -\frac{(K_1 + K_2) \bullet V_{in}}{2L_{eq}} \tag{4}$$

Where, $L_{eq} = K_1^2 L_{1k1} + K_2^2 L_{1k2}$

Because the time period is short between t4 and t5, it can be ignored. Isec changed from I0 to -I0 between t5 and t7, according to (4), we have:

$$t_{57} = \frac{4L_{eq} I_0}{(K_1 + K_2) \bullet V_{in}} \tag{5}$$

Thus, the duty cycle loss at 3L mode can be expressed by:

$$D_{loss-3L} = \frac{t_{57}}{T_s/2} = \frac{8L_{eq} I_0}{(K_1 + K_2) \bullet V_{in} \bullet T_S} \tag{6}$$

So effective duty cycle is:

$$D_{eff} = D - D_{loss-3L} = D - \frac{8L_{eq} I_0}{(K_1 + K_2) \bullet V_{in} \bullet T_S} \tag{7}$$

From (7), the effective duty cycle D_{eff} is a function of primary duty cycle D, input voltage V_{in} and load current I_0. The disturbance of effective duty cycle will be produced by the disturbance of D, V_{in} and I_0. So for combined three-level DC/DC converter there are three different disturbances $\hat{i}_L$, $\hat{v}_{in}$ and $\hat{d}$, and the effective duty cycle D_{eff} will produce three correspond disturbances $\hat{d}_i$, $\hat{d}_v$ and $\hat{d}_d$ .The three disturbing variable of (7) are solved partial derivative, we can get:

$$\hat{d}_{eff} = \hat{d}_i + \hat{d}_v + \hat{d}_d = -\frac{8L_{eq}}{(K_1+K_2)\bullet V_{in} \cdot T_s}\hat{i}_L + \frac{8L_{eq} I_0}{(K_1+K_2)\bullet V_{in}^2 \cdot T_s}\hat{v}_{in} + \hat{d} \tag{8}$$

The small signal equivalent circuit mode of combined three-level DC/DC converter is shown in Fig .4.

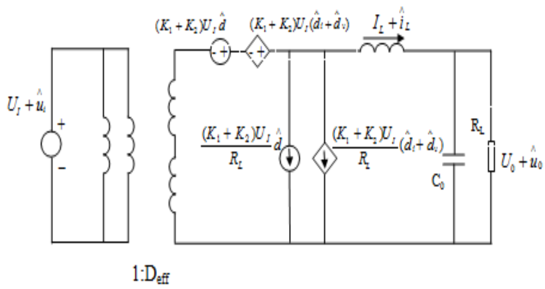


Figure4. The equivalent small signal mode of converter

According to small signal mode we can get the transfer function which is from input to output is:

$$\left.\frac{\hat{u}_0(s)}{\hat{u}_i(s)}\right|_{\hat{d}(s)=0} = \frac{4(k_1+k_2)L_{eq}D_{eff}}{T_s RLCs^2 + (4RCL_{eq} + T_s L)s + (4L_{eq} + TR)} \tag{9}$$

The transfer function from control to output is:

$$\left.\frac{\hat{u}_0(s)}{\hat{d}(s)}\right|_{\hat{u}_i(s)=0} = \frac{(k_1+k_2)TR \bullet V_{in}/2}{T_s RLCs^2 + (4RCL_{eq} + T_s L)s + 4L_{eq} + TR} \tag{10}$$

So the small signal mode system block diagram of converter is shown in Fig .5.

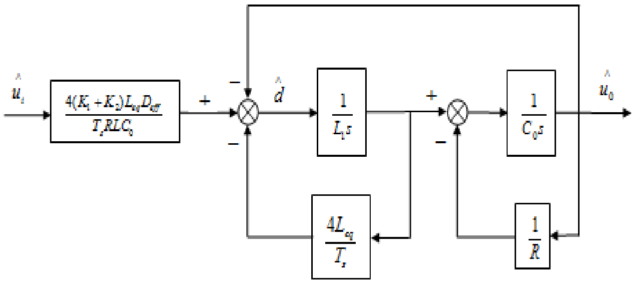


Figure5. The system block diagram of small signal mode

III. COMPENSATING CIRCUIT DESIGN

This converter use the control of voltage mode, in order to increase the stability of the circuit, type 2 error amplifier is used as a feedback loop. The block diagram of closed-loop feedback network is shown in Fig .6.

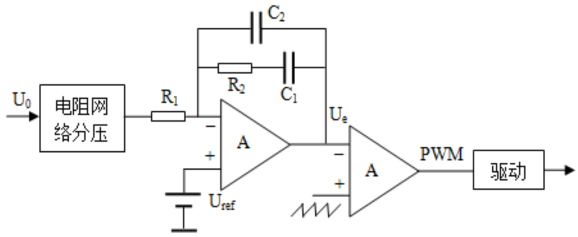


Figure6. The block diagram of closed-loop feedback network

The transfer function of error amplifier (ignore polarity) is:

$$G = \frac{dV_0}{dV_i} = \frac{(R_2 + 1/jwC_1)(1/jwC_2)}{R_1(R_2 + 1/jwC_1 + 1/jwC_2)} \tag{11}$$

The complex variable s=jw is introduced to transfer function G, we have:

$$G = \frac{(R_2 + 1/sC_1)(1/sC_2)}{R_1(R_2 + 1/sC_1 + 1/sC_2)} \tag{12}$$

Considering (11) and (12), we can obtain the transfer function is:

$$G = \frac{1 + sR_2C_1}{sR_1(C_1 + C_2)(1 + sR_2C_1C_2/(C_1 + C_2))} \tag{13}$$

Considering C1《C2 , we can obtain the transfer function of compensation network is:

$$G = \frac{1 + sR_2C_1}{sR_1(C_1 + C_2)(1 + sR_2C_2)} \tag{14}$$

IV. MATLAB SIMULATION VERIFICATION OF SMALL SIGNAL MODEL

Based on the analysis of above, in order to verify the validity of small signal model, it is simulated by MATLAB. And its simulation parameters are as follows: VI=600V, VO=400V, Lf=1100uH, Lr=16uH, T=10Us, RL=40Ω, IL=10A, CO=2200uF, RC=1.5Ω.

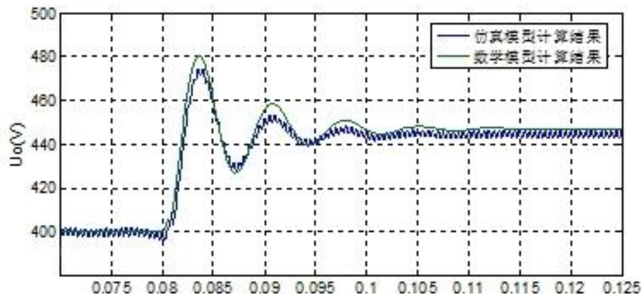


Figure7. The output voltage dynamic of dα sudden 10% disturbance

The circuit parameters are applied to simulation model and mathematical model, and its dynamic performance is shown in Fig .7. From Fig .7, when the time is 0.08s, we can see the phase-shift duty cycle dα sudden 10% disturbance, just as the Fig .7 shows, the change of output voltage uo reflect that dynamic response of small signal model and simulation model are roughly consistent. As we can see from the simulation waveform, it is similar to the simulation results, and the simulation result shows a certain rationality of mathematic modeling with the present method.

V. CONCLUSION

The zero-voltage switching combined three-level DC/DC converter is analyzed in this paper, three dynamic variables which influence the effective duty cycle are obtained, and the closed-loop system model is established by utilizing state-average method, then the corresponding transfer function is deduced, meanwhile, the feedback loop is designed and simulated in MATLAB according to the requirements of performance, the simulation results verify the accuracy and feasibility of the established model, a certain guiding significance for the modeling analysis and design of DC/DC converter can be offered.

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