Research on the Modeling Method of Microwave Power Module Cascade Converter

Zhang Guodong
Zhengzhou University of Aeronautics, Zhengzhou 450002, China

Abstract. It is difficult to obtain the accurate small signal modeling by traditional modeling method especially for the complex converter. System identification is a new method to construct the high voltage cascade converter small signal modeling. The first-stage and the second-stage can be analyzed on the whole. The improved least-square parameter estimation is used to analyze the sampling data of input and output. Furthermore, the system parameter and accurate system modeling can be acquired. Comparing the step response of system model with the Pspice stimulating result, the validity of the method is verified.

1. Introduction
Microwave power module (MPM) is one of the most important electronic devices in the fields of radar, communication, navigation and electronic countermeasures. MPM is a highly integrated amplifier, which consists of solid-state amplifier, miniaturized traveling wave tube and integrated power supply. Compared with traditional traveling wave tube amplifier, MPM has the characteristics of small volume, light weight, high power, high efficiency, low noise, high reliability and wide frequency band. Because MPM has been widely used in many military fields, especially in weapons and equipment, it has become an important electronic device in the world[1,2]. As the key component of MPM, the stability and reliability of integrated high-voltage power supply is the key to ensure the normal operation of MPM, and it is also the focus of MPM development[3,4].

Because of its special application background, MPM high voltage power supply needs to consider more complex problems in design. Under the premise of small volume and light weight, stability and reliability become the goal of engineers[5]. The accurate mathematical model of high voltage converter is an important guarantee for the design of high stability and reliability power supply. Without accurate mathematical model, stable and reliable power supply is impossible. The modeling method of MPM internal high voltage power converter is studied, focusing on solving the problem that the mathematical model of MPM high voltage power converter is difficult to establish. This method is also applicable to other vacuum electronic devices high voltage power converter and complex switching converter related fields.

2. Modeling of switching converter
As the core of switching power supply, switching power converter has high-order, nonlinear, time-varying characteristics, so its accurate mathematical model is very difficult to establish. At present, there are many typical modeling methods for switching converters, such as state space average method[6,7], circuit average method[8,9,10,11,12], equivalent small parameter method[13,14,15] and description function method[16,17,18]. These methods start from the circuit working mechanism to establish the equivalent circuit model of the switch converter. The establishment of the system model needs to carry on the analysis to the circuit structure, control sequence and each internal working
mechanism. These methods can solve the related problems in the simple converter such as Buck, boost and so on. In the case of complex switching converter or complex internal circuit structure, these methods are powerless, and the mathematical model established by them has no reference value.

In recent years, the modeling of switching converters with system identification method has gradually appeared [19, 20, 21]. The modeling of converters with system identification has its unique advantages. This method provides a good idea for the modeling of complex switching converters and makes the modeling of complex converters easy to solve.

### 2.1 System identification method

The essence of system identification is to determine a model equivalent to the tested system from a set of given model classes based on the input and output data. Therefore, the system model structure and model parameters can be determined by applying some test signals to the system whose mechanism is not clear or whose mechanism is too complex, and recording its output response or its input and output data in normal operation [22].

From the nature of system identification method, it can be seen that this method has obvious advantages in building system model with complex structure and unclear internal mechanism, and has completely replaced the traditional analysis method in some research fields. The typical system identification is based on the purpose of identification, using the prior knowledge to preliminarily determine the model structure, collect the input and output data, and carry out relevant processing, then carry out the model structure identification and model parameter identification, and finally obtain the final model after verification.

### 2.2 Recursive least square method for parameter identification

The improved recursive least square method is used to identify the system parameters in the paper. Input and output data in existing L group \{y(k), u(k), k = 1, 2, ..., K\}, using the basic least square method, the least square estimation of the system parameters is as follows:

\[
\hat{\theta} = (\Phi^\top \Phi)^{-1} \Phi^\top Y
\]

The basic algorithm of the least square method is to process all the input and output data at one time. With the increase of the parameters and data to be estimated, the amount of calculation will increase greatly. The way to solve this problem is to transform it into recurrence method, and its basic idea can be summarized as follows:

New estimates \( \hat{\theta}(k) = \text{Old estimate} \ (k-1) + \text{Correction item} \)

By changing the least square solution to recursive form, it is called recursive least square parameter estimation algorithm. The improved recursive form is as follows:

\[
K(k) = P(k)\phi(k)
\]

Through matrix inversion lemma, the recurrence formula of least square parameter estimation of system parameters is obtained as follows:

\[
\begin{align*}
\hat{\theta}(k) &= \hat{\theta}(k-1) + K(k)[y(k) - \phi^\top(k)\hat{\theta}(k-1)] \\
K(k) &= \frac{P(k-1)\phi(k)}{1 + \phi^\top(k)P(k-1)\phi(k)} \\
P(k) &= [1 - K(k)\phi^\top(k)]P(k-1)
\end{align*}
\]

By setting the initial value \( \hat{\theta}(0) \), \( P(0) \) and collecting the input and output data, using the above formula to calculate \( K(k) \), \( \hat{\theta}(k) \) and \( P(k) \), the system model parameters are finally obtained.

### 3. MPM high voltage cascade converter

The MPM high-voltage power converter adopts the cascaded form. The cascaded converter is usually composed of the non-isolated converter and the isolated converter in different ways, which combines
the advantages of the two converter, so it has more excellent performance than the ordinary single-stage converter.

The basic structure of the main circuit of the converter is shown in Figure 1, which is mainly composed of three parts. \( L_b \) is the energy storage inductance of the former boost converter. \( S_b \) is the power switch. \( D_b \) is the rectifier diode. \( C_b \) is the filter capacitance. \( C_{h1} \) and \( C_{h2} \) are the bridge arm capacitance of the half bridge converter, the two capacitance values are equal. \( S_1 \) and \( S_2 \) are the main power switch of the half bridge arm, \( L_r \) is the sum of the leakage inductance and external inductance of the transformer, \( C_r \) is the sum of the parasitic capacitance on the primary side and the parasitic capacitance converted from the secondary side winding to the primary side of the transformer. Diodes \( D_1, D_2 \) and capacitors \( C_1, C_2 \) form a voltage doubling rectifier circuit structure [4].

![Figure 1: Basic Topology of MPM Cascaded High Voltage Converter](image1)

Converter is mainly composed of three parts in figure 1. Its internal structure is complex. If conventional modeling method is used, the workload is large, the analysis is tedious, and the accuracy of conventional modeling method is poor. At present, there is no effective method to establish the accurate model of complex switching converter. For this kind of complex converter, many modeling methods also lose reference value because of the poor accuracy and low accuracy.

The modeling problem of this kind of converter can be solved by using the system identification law, which perfectly solves this complex problem. System identification method is used to establish system model for figure 1. The front and back stages of the cascade converter are regarded as a whole. By sampling and analyzing the input and output signals of the system, the small signal model of the system is modeled at its steady-state working point.

### 4. Construction of high voltage switching converter system mode

The cascade converter is simulated and analyzed by PSpice, and the simulation circuit structure is shown in figure 2:

![Figure 2: Simulation circuit structure](image2)
The input voltage of the cascade converter is 270V, the power is 300W, the working frequency is 25kHz in the front stage and 80kHz in the rear stage, and the output voltage curve of the converter is shown in figure 3:

![Figure 3](image)

**Figure 3  Output voltage curve of converter**

Through the sampling analysis of the output voltage data in figure 3, the identification method is used to identify the system parameters, and the MATLAB is used to analyze the data. The discrete parameter model of the system can be obtained as follows:

\[
\theta = (-3.333, 4.092, -2.18, 0.4213, 1.201e6, -2.082e6, 1.755e6, -8.033e5)
\]  \hspace{1cm} (4)

Figure 4 shows the change curve of each parameter in the process of system parameter identification. From Figure 4, it can be seen that the value of each parameter after identification basically tends to be constant. Since the values of C, D, E and F parameters are small, they are completely coincident in this figure.

![Figure 4](image)

**Figure 4  system parameter estimation result curve**

According to the parameters of (4), the discrete transfer function of the converter is as follows:

\[
\frac{1.201e6z^3 - 2.082e6z^2 + 1.755e6z - 8.033e5}{z^4 - 3.333z^3 + 4.092z^2 - 2.18z + 0.4213}
\]  \hspace{1cm} (5)

The continuous transfer function of the system is as follows:

\[
\frac{6078s^3 + 1.186e7s^2 + 2.042e11s + 6.601e13}{s^4 + 4322s^3 + 3.234e6s^2 + 7.886e8s + 6.658e10}
\]  \hspace{1cm} (6)

In order to verify the effect of the identification model, the step response curve of the final transfer function is compared with the output curve of PSpice, as shown in figure 5.
In the figure 5, the real line part is the step response curve of the actual simulation output of the converter, and the dotted line part is the step response curve of the system transfer function obtained by the system identification method. In figure 5, it can be seen that the fitting effect of the two curves is very good. The system model obtained by the system identification method can truly reflect the internal working mechanism of the complex converter system.

5. Conclusions
In the paper, the system identification theory is introduced into the application of small signal model parameter identification of MPM high voltage complex switching converter. In the process of parameter identification, the improved least square method is used to identify the parameters, which solves the problem that the existing modeling method is difficult to accurately model the complex switching converter. Compared with the traditional small signal modeling method, this modeling method is more accurate, more convenient and faster, especially for the design of complex converter system.

References
[1] Wang Bin, Wang Fengyan, Zhou Xu, et al. Application and development trend of TWTs and MPMs [J]. Vacuum electronics, 2019(02):1-7.
[2] Li Jianbing, Lin Pengfei, Hao Baoliang, et al. Overview of development of microwave power amplifiers [J]. High Power Laser and Particle beams, 2020, 32(07): 70-77.
[3] Wang Xiaoqiao, Zhou Dongfang, Li Jianbing, et al. Thermal analysis and thermal optimized design of microwave power module electronic power conditioner [J]. Journal of Henan Polytechnic University (Natural Science), 2018, 37(06): 131-136.
[4] Zhang Guodong, Zhou Dongfang, Yang Linchuan. Development of Novel Type of Two-Stage High Voltage Converter [J]. Chinese Journal of Vacuum Science and Technology, 2013, 33(5): 419-425.
[5] Gao Yubo, Li Qun, Cheng Li, et al. AC Power Supplies with LCC Resonant Converter for Filaments of TWT in Array Transmitter [J]. Ship Electronic Engineering, 2020, 40(02): 74-77.
[6] Bi chao, Xiao fei, Xie Zhen. Modeling and design of DC-DC switching power supply [J]. Chinese Journal of Power Sources, 2014, 38(2): 359-362.
[7] Zhang Weiping. Modeling and control of switching converter [M]. Beijing: China Electric Power Press, 2020.
[8] Vorperian, V. Tymerski, R. Equivalent circuit model for resonant and PWM switches [J]. IEEE Transactions on Power Electronics, 1989, 4: 203-205.
[9] Al-Naseem, O., Erickson, R. W., Carlin, P. Prediction of switching loss variations by averaged switch modeling [C]. IEEE APEC, 2000: 242-248.

[10] A. Abrishamifar, A. Rahmati, S. M. khazraei. Small signal and large signal charge control models for a phase-shifted PWM converter [J]. IEEE International Conference on Industrial Technology, 2008: 1-6.

[11] Ammous, A., Ammous, K., Ayedi, M., et al. An advanced PWM-switch model including semiconductor device nonlinearities [J]. IEEE Transactions on Power Electronics, 2003, 18(5): 1230-1237.

[12] Femia, N., Tucci, V. On the modeling of PWM converters for large signal analysis in discontinuous conduction mode [J]. IEEE Transactions on Power Electronics, 1994, 9(5): 487-496.

[13] Ding Yuehua. Transient-state symbolic analysis for PWM DC-DC converters and synchronous algorithm for the paralleled-UPS [D]. South China University of Technology, 2009.

[14] Cao Wensi, Yang Yuxia. Modeling approach and simulation analysis of PWM dc-dc converter [J]. Science and Technology & Innovation, 2007, 23(32): 291-293.

[15] Yang Yaze. Modeling and Simulation of DC-DC switching converter based on equivalent small parameter method [D]. Changsha: Central South University, 2010.

[16] Martin P. Foster, Christopher R. Gould. Analysis of CLL voltage-output resonant converters using describing functions [J]. IEEE Transactions on Power Electronics, 2008, 23(4): 1772-1780.

[17] Manli Hu, Norbert Frohleke, Joachim Bocker. Modeling and control design for a very low-frequency high-voltage test system [J]. IEEE Transactions on Power Electronics, 2010, 25(4): 1068-1077.

[18] Zhijun Qian, Abdel-Rahman, O. Al-Atrash. Modeling and control of three-port DC/DC converter interface for satellite applications [J]. IEEE Transactions on Power Electronics, 2010, 637-649.

[19] Liu Xiaobao. Research and Realization of The Core Converter for TWT Power Supply with High Efficiency and High Power Density [D]. Zhengzhou: Information Engineering University, 2007.

[20] Wang Weiping. Research on Dynamic Modeling Method of Complex Switch Resonant Converter [D]. Zhengzhou: Information Engineering University, 2009.

[21] Yang Jie. Research on Dynamic Modeling Method of Switching Converter Based on System Identification [D]. Zhengzhou: Information Engineering University, 2012.

[22] Pang Zhonghua, Cui Hong. Matlab simulation of system identification and adaptive control [M]. Beijing: Beijing University of Aeronautics and Astronautics Press, 2017.