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Research on DC/DC phase-shifted full-bridge converter system identification

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Abstract: As a power electronic converter, DC/DC converter plays a pivotal role in power electronic system. By measuring *G*-parameter frequency data, people can extract information to identify the converter, building two-port 'black-box' model, thereby improving system-level simulation and analysis. Paper takes the 270–28 V DC/DC phase-shifted full-bridge converter of multi-electric aircraft distributed power supply system as study object, implements hardware design of the converter with high performance of loop and respond, and verificating the design by Saber simulation. Paper analysis ways of measuring converter's frequency response, considering injection strength of disturbance signal and interaction of subsystem, paper gives advices that experimenter should add input filter and use constant current source load. Base on Levy method, paper calculates corresponding *G*-parameter transfer function of converter by Matlab, builds 'black-box' model, then verifies the result by Matlab time domain simulation. Paper's research results will have great impact on the integration and optimisation of power electronic systems.

1 Research background

To improve the performance of DC/DC converter, engineers usually use 'top-down' design method which contains the effect of on/off time of switch, on/off loss, and parasitic parameters of power devices, modelling the DC/DC converter to study the specific phenomenon of the converter, such as dynamic characteristics at switch moment, ripple voltage and current. In the power electronics industry, people use the ideal switch model to study filter, using average model to study static characteristics of converter, using small signal model to design the control system. All model mentioned above are based on that designer which completely clears the structure of converter, we call it 'White-Box' model, however, when designing a power electronic system, limited by progress, reliability, environmental adaptability and safety, we usually consider buying mature products from different companies, a reality is that manufacturers generally do not provide internal structure and parameters. We know that the two-port network model can reflect the transmission relationship between the input voltage (or current) and the output current (or voltage), ignoring internal topology and control method, thereby the converter can be expressed as a 'black box' [1] with special properties. By obtaining the converter's input and output voltage current time domain or frequency domain data, the model information for system identification was extracted to build two-port 'black-box' model of the converter. System identification will accelerate the building of power electronic system, and also improve the system simulation level.

2 Current research situation

DC/DC converter can be equivalent to a *G*-parameter two-port network, the network has four parameters, input impedance, output impedance, reverse current gain and audio attenuation rate. The reverse current gain and audio attenuation rate reflect the transfer relationship between the input voltage (or current) and the output current (or voltage). The input and output impedance reflect its coupling relationship with other cascaded systems [2]. Therefore, the analysis based on impedance characteristics can reflect some of the essential problems of the system [3]. Fig. 1 shows that the DC/DC converter dual-port network model described by the *G* parameters. The input terminal is represented by the Norton equivalent circuit. The output terminal can be expressed as the Davidon equivalent circuit.

G_{11} for the voltage audio attenuation rate, G_{12} for the output impedance, G_{21} for the input admittance, G_{22} for the reverse current gain. By measuring the frequency response of the port, we obtain the *G*-parameter transfer function which can be used to describe the DC/DC converter. Formula (1) describes the relationship between converter's input and output variable

$$\begin{bmatrix} v_2 \\ i_1 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ i_2 \end{bmatrix} \quad (1)$$

The DC/DC converter running at the linear operating point belongs to a linear steady-state continuous system. The classical identification method includes step response identification method, impulse response identification method, frequency response identification method, correlation analysis identification method, spectral analysis identification method. For the scheme is a frequency response measurement, paper uses the Levy method, this method simplifies the index function, and makes use of least squares method to solve the problem. The algorithm has good convergence. The principles of the Levy law are as follows:

Define the transfer function:

$$G(s) = \frac{b_0 + b_1 s + b_2 s^2 + \cdots + b_m s^m}{1 + a_1 s + a_2 s^2 + \cdots + a_m s^n}, \quad (n > m) \quad (2)$$

Corresponding frequency response:

$$\begin{aligned} G(\mathrm{j}w) &= \frac{(b_0 - b_2 w^2 + b_4 w^4 - \cdots) + \mathrm{j}w(b_1 - b_3 w^2 + b_5 w^4 - \cdots)}{(1 - a_2 w^2 + a_4 w^4 - \cdots) + \mathrm{j}w(a_1 - a_3 w^2 + a_5 w^4 - \cdots)} \\ &= \frac{\alpha(w) + \mathrm{j}w\beta(w)}{(\delta w) + \mathrm{j}w(rw)} = \frac{N(\mathrm{j}w)}{D(\mathrm{j}w)} \end{aligned} \quad (3)$$

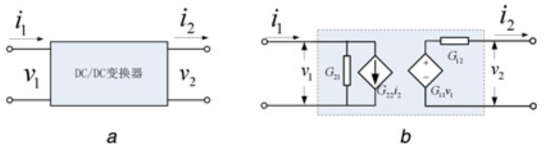

Fig. 1 *DC/DC converter 'black-box' network*

At the w_i frequency point, define the deviation between estimated frequency response and actual frequency response:

$$\varepsilon(\mathrm{j}w_i) = [\mathrm{Re}(w_i) + \mathrm{j}\mathrm{Im}(w_i)] - \frac{N(\mathrm{j}w_i)}{D(\mathrm{j}w_i)} \tag{4}$$

deviation criterion:

$$J = \sum_{i=1}^{L} ||\varepsilon(\mathrm{j}w_i)||^2 \tag{5}$$

deviation criterion corrected by levy:

$$J = \sum_{i=1}^{L} ||D(\mathrm{j}w_i)\varepsilon(\mathrm{j}w_i)||^2 \tag{6}$$

The model parameters equation estimated by the Levy method are as follows:

$$\begin{bmatrix} V_0 & 0 & -V_2 & & T_3 & S_2 & -T_3 & \\ 0 & V_2 & 0 & \cdots & -S_2 & T_3 & S_4 & \cdots \\ V_2 & 0 & -V_4 & & T_3 & S_4 & -T_5 & \\ & \vdots & & & & \vdots & & \\ T_1 & -S_2 & -T_3 & & U_2 & 0 & -U_4 & \\ S_2 & T_3 & -S_4 & \cdots & 0 & U_4 & 0 & \cdots \\ T_3 & -S_4 & -T_5 & & U_4 & 0 & -U_6 & \\ & \vdots & & & & \vdots & & \end{bmatrix} \begin{bmatrix} \hat{b}_o \\ \hat{b}_1 \\ \hat{b}_2 \\ \vdots \\ \hat{a}_1 \\ \hat{a}_2 \\ \hat{a}_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} S_0 \\ T_1 \\ S_2 \\ \vdots \\ 0 \\ U_2 \\ 0 \\ \vdots \end{bmatrix} \tag{7}$$

Among them

$$V_j = \sum_{i=0}^{L} w_i^j, \quad S_j = \sum_{i=0}^{L} w_i^j \mathrm{Re}(w_i),$$

$$T_j = \sum_{i=0}^{L} w_i^j \mathrm{Im}(w_i), \quad U_j = \sum_{i=0}^{L} w_i^j [\mathrm{Re}^2(w_i) + \mathrm{Im}^2(w_i)]$$

3 Hardware design

As shown in Fig. 2 (left), 270–28 V DC/DC phase-shifted full-bridge converter's main circuit consists of four parts, low-frequency filter circuit composed of C_0 and full-bridge inverter circuit composed of VT_1–VT_4, VD_1–VD_4, C_1–C_4, frequency transformer and full-bridge high-frequency rectifier and high-frequency filter circuit. Compared with the hard-switching full-bridge circuit, the phase-shifted full-bridge circuit does not increase any auxiliary switch and other components, but only adding the resonant inductance so that the four switching devices in the circuit are turned on in zero voltage condition. In Fig. 2, U_i is the input voltage of the converter, U_o is the output voltage; VT_1–VT_4 is the switch, VD_1–VD_4 is the rectifier diode; K is the transformer variable ratio, L_lk is the transformer leakage inductance; L_e is the output filter inductance, R_e is the output filter inductance parasitic resistance; C_e is the output filter capacitor, R_c is the output filter capacitor's equivalent series resistance, R is the load resistance.

Fig. 2 (right) is the phase-shifted full-bridge converter's equivalent circuit. In this figure, L_lk is leakage inductance of the transformer, $n^2{\cdot}L_\mathrm{f}$ is the equivalent filter inductance converted from the secondary side to the primary side, $n{\cdot}U_0$ is the equivalent to voltage converted from the secondary side to the primary side. According to the stability and response speed requirement of the DC/DC converter, considering hysteresis loss, voltage and current ripple, the parameters of power devices and control circuit were calculated. The parameters of the circuit are as follows, input voltage $V_1 = 270$ V, output voltage $V_2 = 28$ V, transformer ratio $K = 7$, output filter inductance $L_\mathrm{e} = 50\,\mu$H, output filter capacitor $C_\mathrm{e} = 1100\,\mu$F, load resistance $R_\mathrm{L} = 4.76\,\Omega$, partial voltage coefficient $H(\mathrm{s}) = 0.13$, switching frequency $f_\mathrm{s} = 20$ kHz. PWM modulator saw tooth amplitude $V_\mathrm{m} = 3.5$ V, reference voltage $V_\mathrm{ref} = 3.65$ V.

Crossing frequency at 3.22 kHz by − 20 dB/dec. Slope is made, the phase margin $PM = 60.5°$, the gain margin $GM = 21.6$ dB, the specific calculation process will not be repeated. Figs. 3 and 4 show the loop frequency characteristics and time domain characteristics of output voltage, Saber simulation results and Matlab calculation results are highly consistent, Saber simulation results show that DC/DC converter loop has good frequency-domain characteristics and time-domain characteristics [4].

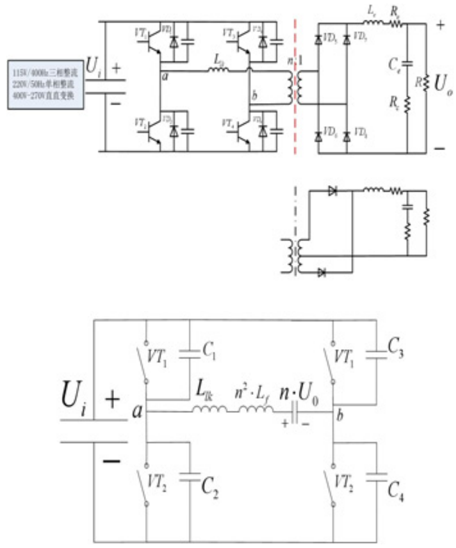

Fig. 2 *Main circuit (up) and its equivalent circuit (down) of converter*

4 Frequency response measurement

In the concept of power quality, the frequency response of DC/DC converter refers to the variety port characteristic along with the frequency change, its principle is injecting a scanning frequency signal at a specified point of the system, we measured the response of system's out-port, then derived the port characteristics. Actually, the frequency response measurement consists of four elements, the network analyser, the perturbation signal injection circuit, measuring probe, the linear amplifier and the insulating transformer, the network analyser is used to produce adjustable sine drive signal

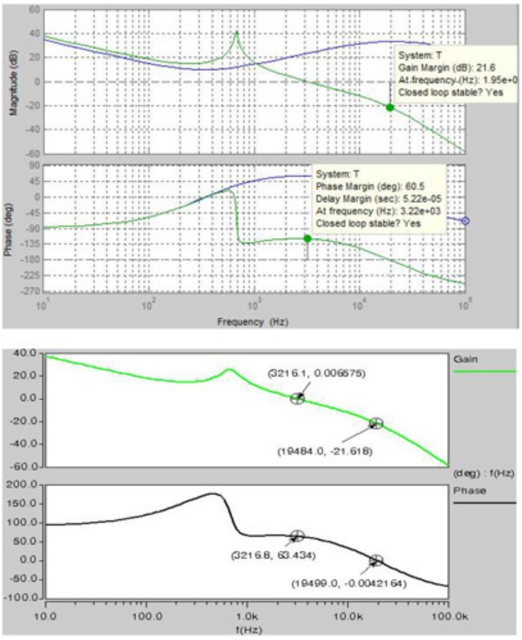

Fig. 3 *Matlab calculation result (up) and Saber simulation result (down) of loop*

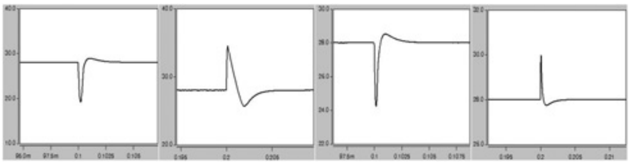

Fig. 4 *Light-full load, full-light load, half-full load, full-half load output voltage response*

with broadband, the power linear amplifier is used to enlarge the perturbation signal in order to inject the corresponding perturbation into power electric circuit, the isolation transformer realises the electrical isolation between the network analyser and the power circuit. In this section, the DC/DC converter frequency response measurement is analysed from two aspects, respectively, the perturbation signal injection circuit and subsystem interaction [5].

4.1 Perturbation signal injection

Fig. 5 shows three practical kinds of disturbance signal injection circuit, a programme injects disturbance signal through an isolation transformer in series with power supply. B programme introduces an *MOSFET* working in the amplification zone, by injecting the disturbance signal at the gate source, resulting in a drain-source voltage disturbance in series with the power supply. Based on the concept of b, Yuri Panov proposed a linear regulator perturbation current injection method, as shown in Fig. 5*c*.

A programme achieves disturbance signal of high amplitude through power amplifier, but the measurement requires input DC current to flow through the input transformer, so the transformer core should have enough air gap to prevent the saturation and poor stability; B programme prevents the saturation by the isolation capacitor, the voltage across the DC blocking capacitor provides DC bias for *MOSFET* which is working in the linear amplification zone, the turn-on voltage and transconductance are heavily dependent on the device's temperature, thermal stability is poor; C circuit is a linear voltage regulator device, the output sinusoidal AC signal of FRA superpose on the reference voltage, so that the cathode voltage disturbs, causing that the power transistor base current disturbs, the resulted power transistor emitter current is directly injected into the measured module, this scheme solves the problem of thermal stability by introducing a power transistor. However, since the measuring device is a negative feedback system, the measuring device interacts with the module under test, experimenter should pay attention to the bandwidth of the linear regulator, and the method consists of more components, the circuit is too much complex to measure. Through the analysis of the series injection method, the above three methods cannot guarantee stability and accuracy; moreover, Virginia Tech's Luis Arnedo confirmed that the series injection method increases the power output impedance, which has a negative impact on the measurement. Based on the various factors, parallel disturbing injection method is proposed. Fig. 6 shows two typical parallel disturbing injection circuits, the former one injects the sinusoidal swept AC signal directly into the measured module through the blocking capacitor, the latter one makes *MOSFET* work in the saturation amplification area, through the amplification of the gate drive voltage AC disturbance, the current disturbance signal of adjustable intensity is injected into the module under test.

A program's injection circuit is simple and stable, the disturbance signal strength is weak, but it can be improved by the power amplifier r; However the b program, in order to ensure *MOSFET* to work in the saturation zone, people must ensure $V_{ds} > V_{gs}$, when the output voltage is too small or large, it is necessary to adjust the sampling resistor, the characteristic parameters are easily affected by the temperature, so the thermal stability of the measuring circuit is poor. In summary, a program is chosen as the final choice of DC/DC full-bridge phase-shift converter frequency response measurement circuit.

People should obtain the mature measurement skill through the practice, once the test circuit establishes, next work is to inject the perturbation signal with correct level, small signals are easily disturbed, large signals can affect system stability, therefore in the test process, it is better to use oscilloscope observing the injected signal and the input and output of the converter, to avoid distortion and instability. Taking the measurement of loop at medium- to low-frequency ranges, we introduce that how the strength of the injected signal affects the measurement results as well as some advices.

Fig. 7 shows the measurement results of the loop gain, respectively, at the condition of 50 m–100 m–200 mV injection signal strength, we can visually see the relationship between the measurement results and the Saber mean model predictions. At 50 m injection signal strength, below 800 HZ, there is no enough signal to solve the system's high gain problem, and due to insufficient signal-to-noise ratio, the *n* closer to the Saber average model

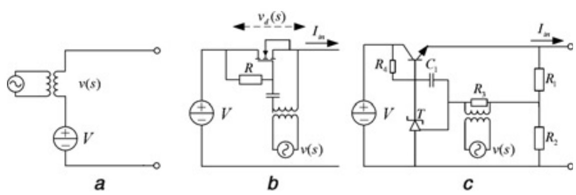

Fig. 5 *Series disturbing signal injection circuit*

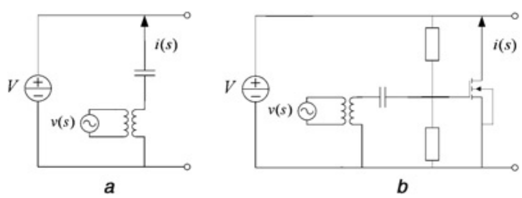

Fig. 6 *Typical parallel disturbing injection circuit*

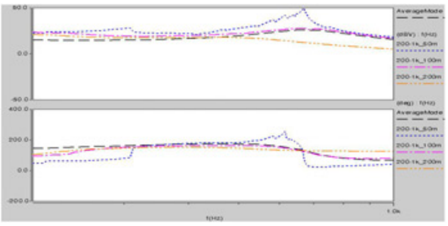

Fig. 7 *50–100–200 m injection signal strength measurement result (200–1 kHz)*

prediction results than 50 m's, 400−1000 Hz, measurement results are generated by the circuit will produce measurement spikes, the curve is relatively smooth, at 100 m injection signal strength, <400 Hz, the high gain problem is not resolved, but which has been improved, in the figure, we can clearly see that results at 100 m injection signal strength are and predictions have been basically consistent; at 200 m injection signal strength, the low-band high gain problem is further improved, but over 400 Hz, the system measurement results deviate significantly from the Saber average model prediction results, which indicates that the system has now been over driven, from 400 Hz, measurement error starts until the end of the measurement.

In summary, we know that in the low-frequency band, the loop gain is high, we need to inject a relatively large signal; however, in the high-frequency band, the loop gain is low, we need to inject a relatively small signal. The skill is that in a certain band, applying a large signal and a small signal, respectively, the signal is applied in a band to apply a large signal and a small signal, if the measurement results remain the same, it can be believed that the measurement is valid. When the measurement results in curve tend to be smooth and continuous, it indicates that the actual system response is more reasonable and effective.

4.2 Subsystem interaction

In practice, the measurement of the frequency response is closely coupled with the dynamic characteristics of the source and load, and the consequence is that the measurement results cannot 100% reflect the true internal characteristics of the converter. We should replace power resistor with the constant current source, so the affection of the load can be ignored. We only analysed the effect of source-level output impedance on frequency measurements. Fig. 8 shows the signal block diagram of converter considering the effect of the source stage output impedance. The variables are linked by *G*-parameters. The relationship between the variables can be seen intuitively.

When the input voltage of the converter is disturbed and the output current remain unchanged, the input admittance is not affected by the output impedance of the source stage; however, the output impedance is not only coupled with the source output

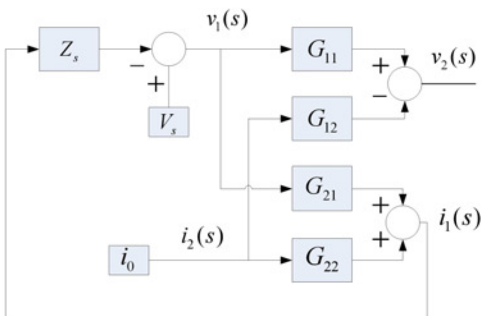

Fig. 8 *Signal block diagram of converter with constant current source load*

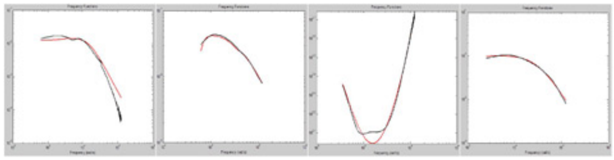

Fig. 9 *G_{11}, G_{12}, $1/G_{21}$, G_{22} measurement results(rough) and identification results (smooth)*

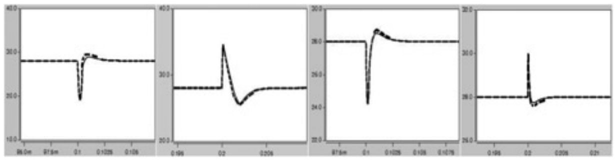

Fig. 10 *Light-full load, full-light load, half-full load, full-half load output voltage response (The dotted line is the identification model.)*

impedance but also with other *G* parameters. Details are as follows:

$$G_{12m} = \frac{v_2(s)}{i_2(s)} = G_{12} + \frac{G_{11} \cdot G_{22} \cdot Z_s}{1 + Z_s \cdot G_{21}} \qquad (8)$$

Based on the above analysis, in order to ensure the correctness of measurement, there's need to take the following measures: Using constant current source load to eliminate load's affection on the frequency response measurement; adding the input-level filter to improve the input voltage stability and educe the source-level output impedance.

5 Identification and verification

In the case of system identification [6], one of the indispensable steps is verification. If the model is not qualified, the model order or structure re-identification will be changed. However, there is no general method to follow, and it is closely related to the model structure. Fig. 9 shows the corresponding measurement data and identification results (smooth curve), due to space reasons, we will not list the result. Calculated by Matlab, the identification results and the actual are 95% coincidence, Fig. 10 shows that the time-domain response comparison of the identification model equivalent circuit and the actual circuit, basically the same.

6 Conclusion

This paper studies the system identification of 270–28 V DC/DC full-bridge phase-shifted converter in multi-electric aircraft distributed power supply system with the background of power electronic system integration. The paper first introduces the design of DC/DC converter, then, based on the frequency response Levy method, combined with the measured frequency response data, the system identification is carried out, and the 'black-box' model of the converter is established, and the identification model is verified by Matlab simulation. The research results of this paper have important guiding significance for the simulation and integration optimisation of power electronic system. Based on the research of the paper, it is necessary to study the characteristics of the converter under the large signal model so as to ensure the correctness of the non-linear state analysis of the power electronic system.

7 References

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