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Study on Starting Characteristic of Synchronized Dual Frequency Gear Quenching Power Supply

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***Abstract*—Synchronized dual-frequency induction hardening machine tool is widely used in gear surface heat treatment because of its characters such as saving energy, no pollution in environment, high processing efficiency, small deformation of workpiece and so on. In view of the poor load adaptability of the dual frequency induction heating power supply; the high frequency and intermediate frequency connected to the same transformer, the crosstalk current will bring interference to the stable start of the power supply and so on, the high frequency and intermediate frequency in the synchronous dual frequency topology are modeled and simulated respectively. Based on the resonance points of medium and high frequency circuits, the phase difference angle of the inverting side current is studied at different frequencies, and the effect of crosstalk current is analyzed and verified by experiments. The results show that setting the start-up parameters near the resonance point and setting the phase difference angle threshold can ensure the efficient and stable start-up of dual-frequency power supply.**

Keywords-Synchronous Dual Frequency; Model Reconstruction; Phase Difference Angle; Crosstalk Current

I. INTRODUCTION

With the development of induction heating technology, parts such as gears and rails can eventually obtain uniform quenching layer by dual-frequency induction heating [1]. Synchronized dual-frequency induction heating is widely used in heat treatment of special-shaped workpieces because of its high efficiency, good processing quality and wide application range [2].

During the start-up of the induction heating power supply, the circuit changes from transient oscillation to steady-state oscillation. The instability of the zero-crossing point of the channel current is mainly caused by the charging process of capacitors and inductance energy storage elements in the circuit. Phase difference angle refers to the difference between voltage zero-crossing time and current zero-crossing time at both ends of the inverter side. When it is negative, it will affect the reliability of equipment and even lead to system collapse [3]. Therefore, it is important to study the starting characteristics of power supply for the performance of the whole system and the reliability of equipment.

In order to improve the quality of gear surface quenching, synchronous dual-frequency quenching is generally used, in which the high frequency (HF) is mainly used to heat the tooth tip and the medium frequency (MF) is mainly used to heat the tooth root [4,5]. The topology of synchronous dual-frequency power supply is shown in Fig. 1. Its working principle is that two sets of induction heating power supply superimpose HF and MF resonant current through transformer at load end, so that high-frequency current is superimposed at load end on medium-frequency current [6].

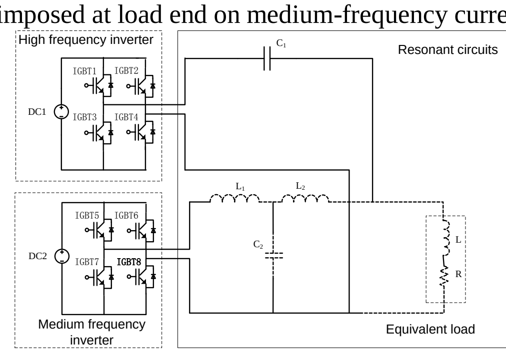

Figure 1. A Synchronous Dual-Frequency Resonant Inverter

The induction heating load is the induction coil and the heated workpiece, which can be equivalent to a series of inductors and resistors, and the load is inductive [7]. Its equivalent impedance will be enlarged by the load transformer due to the error of processing and positioning in the coil, and the resonant frequency of the load circuit will change accordingly. Therefore, the induction power supply must have good frequency tracking ability [8]. At the same time, because two power supplies are connected to the same inductor, it is necessary to consider the interference of series current on stable start-up of power supply [8,9].

II. SYSTEM MODELING

Dual-frequency topology is the core of synchronous dual-frequency quenching system. Fig. 2 shows how to reduce the complexity of the control circuit and reduce the order of the whole circuit. The HF and MF resonant grooves are taken as two independent circuits in Fig. 2 (a), (b).

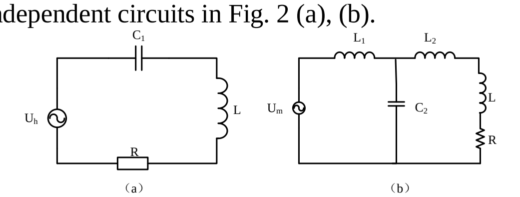

Figure 2. Equivalent circuit of proposed HFand MF inverter

A. Inverter Side Modeling

At present, the induction heating power supply controls the output voltage of the inverter by triggering IGBT or thyristor by PWM wave, so the working frequency of the inverter is the same as that of IGBT or thyristor. It can be considered that the voltage at both ends of the HF and MF inverters remains unchanged, and the voltage direction changes with the on-off of the switching elements, which ultimately makes the inverters output different frequencies.

B. HF Topology Modeling

The high frequency topology is shown in Fig. 2 (a). By taking the voltage of capacitor C_1 as a variable, the equivalent equation of the HF topology is as follows.

$$\begin{cases} LC_1 \dfrac{d^2 u_{c1}(t)}{dt^2} + RC_1 \dfrac{du_{c1}(t)}{dt} + u_{c1}(t) = U_{\mathrm{h}} \\ U_{\mathrm{h}} = 514/\mathrm{n}_1 \times \mathrm{sgn}(t) \\ u_{c_1}(0) = 0 \\ i_L(0) = 0 \end{cases} \tag{1}$$

Where n_1 is the turn ratio of high frequency matched transformer, U_h is the output voltage of high frequency inverter and the *sgn(t)* in the formula satisfies the following relationship:

$$\mathrm{sgn}(t) = \begin{cases} 1 \quad , 2\pi k_1 T_1 \le t \le 2\pi(k_1+1)T_1 \\ -1, (2k_1+1)\pi T_1 \le t \le 2(k_1+1)\pi T_1 \end{cases} \tag{2}$$

Where T_1 is the voltage period at both ends of high frequency inverters.

C. MF Topology Modeling

The MF topology is modeled in complex domain as shown in Fig. 3 (a). The relationship between the input voltage Um at both ends of the inverter and the U_0 at both ends of the load is solved, and then the U_0 obtained is modeled discretely, as shown in Fig. 3 (b).

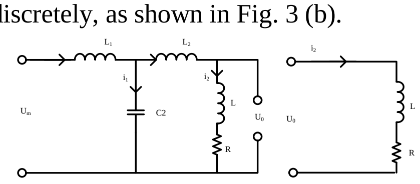

Figure 3. Complex Domain and Discrete Modeling of MF Topology

The output voltage (U_m) of high frequency inverters can be approximated as DC voltage changing its direction through switching devices. Voltage signals can be equivalent to periodic signals. Within (*t-T*, *t*) periods, the voltage signals can be expanded to the following Fourier series approximation.

$$x(\mathrm{x}\text{-}t\text{+s}) = \sum \langle x \rangle_k (t) e^{jk\omega_s(\mathrm{t\text{-}T\text{+}s})} \tag{3}$$

K-order Fourier series $\langle x \rangle_k (t) e^{jk\omega t}$ represents the magnitude of the harmonic component of order *K*.

$$U_m(t) = K_1 \bullet \sum \langle x \rangle_k (t) e^{jk\omega t} = K_1 \bullet \sum [x]_k \tag{4}$$

Where $K_1 = (4 \times 514)/\pi \bullet T_2$ .Pull-type transformation of U_m.

$$L(U_{\mathrm{m}}) = K_1 \sum L[x]_k \tag{5}$$

Solving Transfer Function(*T(s)*) by Complex Impedance Method.

$$T(\mathrm{s}) = \frac{Z_0(\mathrm{s})}{Z_{\mathrm{i}}(\mathrm{s})} \tag{6}$$

The equivalent impedance at the end of the intermediate frequency slot is $Z_o(j\omega)$. $Z_i(j\omega)$ is the impedance of both sides of the inverter.

$$\begin{cases} Z_o(j\omega) = j\omega L_3 + R \\ Z_i(\mathrm{j}\omega) = j\omega L_1 + \dfrac{1}{\dfrac{1}{j\omega(L_2+L_3)+R} + j\omega c} \end{cases} \tag{7}$$

By solving the transfer functions of each voltage component separately, the computation is reduced and the order of Laplace transform is reduced.

$$\begin{bmatrix} [U_1] \\ [U_2] \\ \vdots \\ [U_n] \end{bmatrix} = (K_1) \bullet \begin{bmatrix} T(\mathrm{s}) & 0 & \cdots & 0 \\ 0 & T(\mathrm{s}) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & T(\mathrm{s}) \end{bmatrix}_{\mathrm{n}} \bullet \begin{bmatrix} [x]_1 \\ [x]_2 \\ \vdots \\ [x]_{\mathrm{n}} \end{bmatrix} \tag{8}$$

The time domain function is solved by MATLAB software, and the sum of each component is superimposed.

$$U_0 = \sum_1^{\mathrm{n}} L^{-1}[U_n] \tag{9}$$

As shown in Fig. 3 (b), the equivalent equation of thecircuit is obtained by outputting U_0 to the load circuit.

$$\begin{cases} L \dfrac{di_{\mathrm{L}}(t)}{dt} + Ri_{\mathrm{L}}(t) = \mathrm{U_0(t)} \\ i_{\mathrm{L}}(0) = 0 \end{cases} \tag{10}$$

In MATLAB, the program is programmed according to the initial value. Finally, the numerical solution of the intermediate frequency and high frequency topological model is completed through the data processing ability of MATLAB and the visual calculation results.

III. ELECTRICAL SIMULATION

A. HF Topology Simulation

Series inverters have poor load adaptability. When the inverters fail, the short-circuit current can easily damage the related components. The main reason is that when the load is amplified by the load inverters according to the square of turn ratio, the error will be amplified, and the basic parameters of the circuit elements will change with the continuous start of the power supply. The resonant frequency is given by [10]:

$$f = \frac{1}{2\pi\sqrt{LC_1}} \tag{11}$$

When the load changes, the equivalent inductance L changes, and the high frequency capacitor C_1 is affected by temperature. The starting frequency can be set by formula (11).

TABLE I. HF TOPOLOGICAL PARAMETERS

Descriptions	Symbols	Values（Groups）			
		1	2	3	4
HF Resonant Capacitor	C1（nF）	38.4	36.4	38.4	38.4
Equivalent inductance	L（uH）	45.8	45.8	48.1	45.8
Equivalent resistance	R（Ω）	2.21	2.21	2.21	1.71
Resonance Point of HF	f（KHz）	120.0	123.2	117.1	120.0

In order to ensure that the induction heating power supply is always in the weak inductive region, the frequency of the inverter must be greater than the resonant frequency. By choosing 125K, 135K and 145K for these four parameters, the startup characteristics of different frequencies are studied. The simulation results are shown in Fig. 4.

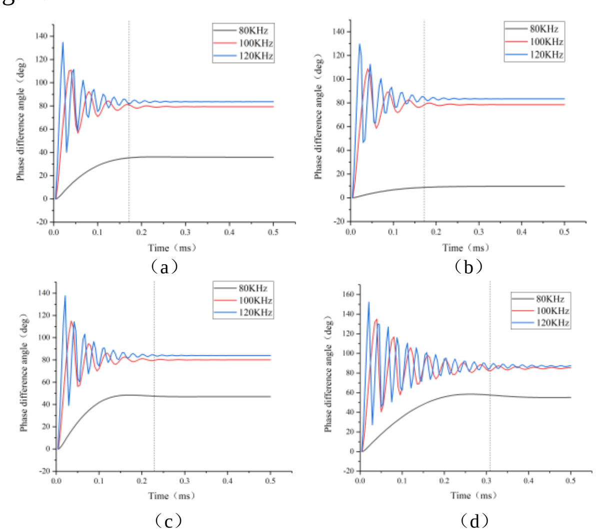

Figure 4. Phase Difference Angle Curves at Different Starting Frequencies under Four High Frequency Topological Parameters

By comparing the simulation results of Fig. 4 (a), (b), (c), (d), it can be observed that the high frequency topology is sensitive to the changes of high frequency capacitance and equivalent inductance, and may lead to the start of high frequency topology in the capacitive region. By comparing the distance between the operating frequency and the resonance point calculated in Table 1, it is found that the more close the starting frequency of the power supply is to the resonance frequency, the smoother the phase difference angle curve is, and the smaller the phase difference angle is when the circuit reaches the steady state. When the starting frequency is much higher than the resonant frequency, the higher the frequency, the larger the phase difference angle changes. The reason is that the voltage and current change violently before the capacitor is charged, which results in the sharp change of phase difference angle.

Fig. 4 (a) is compared with Fig. 4 (b). Fig. 4 (b) shows that the capacitance value decreases with the increase of temperature or charge times, which makes the circuit easy to enter the capacitance range. Fig. 4 (c) shows that when the error reaches 5% of the equivalent inductance, the resonant point changes about 3KHz, and the phase difference angle changes obviously. Fig. 4 (d) considers that the equivalent resistance "becomes lighter", while the change of resistance has little effect on the start-up of power supply. By cooling the relevant components, the circuit parameters can fluctuate within the allowable range. By adjusting the parameters, the operating frequency is set within the optimum starting frequency range. Real-time phase difference angle detection is carried out for high-frequency channel to dynamically adjust the operating frequency of power supply.

B. MF Topology Simulation

Although LCL inverters have good load adaptability, the circuit is not easy to adjust due to the large number of circuit topology parameters [11]. The results of circuit analysis by series-parallel method deviate greatly from the actual results. The impedance expression of IF topology is as follows:

$$Z_2(\omega) = \frac{R}{(1-\omega^2 L_3 C_2)^2 + (\omega R C_2)^2} + jI \tag{12}$$

I is the imaginary part of the impedance, which is expressed as:

$$I = \frac{L_1C_2^2L_3^2\omega^5 + (-2L_1C_2L_3 + L_1C_2^2R^2 - C_2L_3^2)\omega^3 + (L_1 + L_3 - C_2R^2)\omega}{(1-\omega^2L_3C_2)^2 + (\omega RC_2)^2} \tag{13}$$

According to the analysis of MF topology, there are two resonance points. The parameter conditions for the existence of two resonance points are as follows:

$$\begin{cases} \frac{C_2}{L_3}R^2 - \frac{L_3}{L_1} < 2 \\ \frac{L_1}{C_2} + \frac{L_3}{C_2} > R^2 \end{cases} \tag{14}$$

The series resonant angle frequency is ω_0, the parallel resonant angle frequency is ω_1, and $\omega_0 > \omega_1$.

$$\omega_{0,1}=\sqrt{\frac{-\beta\pm\sqrt{\beta^2-4\alpha c}}{2\alpha}} \tag{15}$$

Among $\begin{cases}\alpha=L_1C_2^2L_3^2\\ \beta=(-2L_1L_3+L_1C_2R^2-L_3^2)C_2\\ c=L_1+L_3-C_2R^2\end{cases}$.

Because the dual-frequency power supply chooses voltage-source inverters, the inverters should work at the resonant angle frequency ω_0 in series and be in a weak inductive state.

TABLE II. MF TOPOLOGICAL PARAMETERS

Descriptions	Symbols	Values（Groups）		
		1	2	3
Equivalent resistance	R（Ω）	2.21	2.54	2.21
MF inductor	L_1（uH）	205	205	205
MF inductor	L_3（uH）	129.5	129.5	129.5
MF Resonant Capacitor	C_2（uF）	2.84	2.84	2.55
Series resonance point	F_1（KHz）	10.827	10.834	11.437

Because LCL structure has resonance peak at resonance point, which changes the amplitude-frequency characteristic near resonance point and is difficult to control output power, starting frequency is usually selected from the right side of series resonance point. Three sets of starting frequencies are selected for simulation, and the results are shown in Fig. 5.

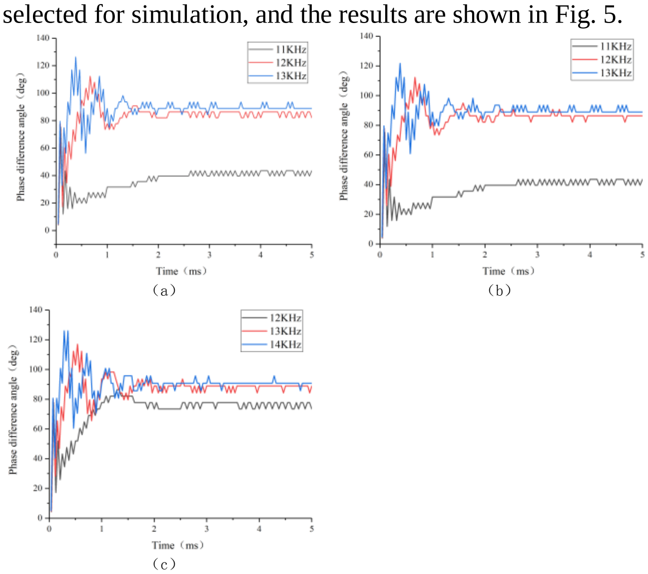

Figure 5. Phase Difference Angle Curves at Different Starting Frequencies under MF Topological Parameters

By comparing Fig. 5(a), 5(b) and 5(c), the closer the output frequency of the inverter is to the series resonant point, the smoother the change of phase difference angle curve is, the smaller the phase difference angle is in the steady state, and the start-up characteristic curve with the phase difference angle less than 75 degrees in the steady state makes the start-up process more stable. The reason is that energy storage elements such as capacitors and inductors achieve dynamic balance in the range of series resonance frequency, so the channel current conversion is relatively smooth.

Compared with Fig. 5(a) and Fig. 5(b), the change of load impedance has little effect on the start-up process, so the influence of the change of resistance value on the circuit characteristics can be weakened in the design of circuit parameters. Compared with Fig. 5(b) and 5(c), the resonant point moves backward and the series resonant point is changed due to the decrease of the capacitance value. Therefore, the operating frequency of the power supply can be set within the optimum starting frequency range by adjusting the capacitor terminal.

C. *Crosstalk Current Analysis*

As shown in Fig. 6, when the power supply is started, there are multiple zero crossing points in the first two cycles of the MF channel current. After observing the frequency domain diagram through FFT change, it is found that the MF channel current flows into the HF current. Although the MF topology has the characteristics of on-MF and HF resistance, the HF current affects the channel current at start-up due to the long time of the MF topology reaching steady state. In order to avoid the shutdown of dual-frequency power supply due to the abnormal phase difference angle detected, it is necessary to shield more than two zero-crossing points in the MF channel.

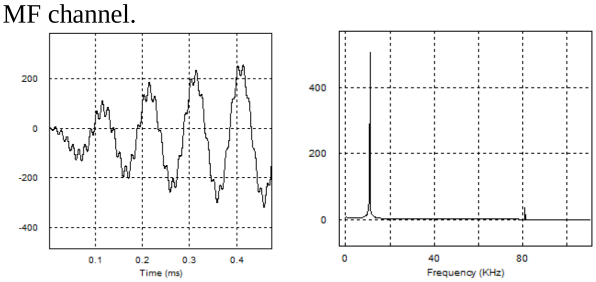

Figure 6. Output waveform of Mf Channel Current and FFT analyzed result

As shown in Fig. 7, at the start-up moment, the high-frequency waveform basically remains unchanged, and the envelope of high-frequency current fluctuates slightly. The reason is that the ratio between the HF topology start-up frequency and the MF topology's is about 8:1.By the time the first eight periodic currents rapidly reach the amplitude of high frequency topological resonance, the effect of intermediate frequency series current on high frequency topology can be neglected.

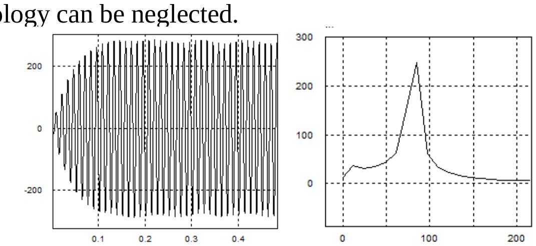

Figure 7. Output waveform of Hf Channel Current and FFT analyzed result

IV. Experiment Results

According to the theoretical circuit experimental parameters and considering the influence of parasitic parameters such as transformer on the circuit, a 120KW dual-frequency synchronous induction power supply experimental platform was built. *R*=2.02 and *L*=48.580 uH are measured on the original side of the inverter by bridge. Other component parameters L_1 = 204.752 uH, L_2 = 80.181 uH, C_1 = 38.41 nF, C_2 = 3.141 uF. The oscilloscope channel 1 measures the groove voltage at the inverting side through a high-voltage differential probe, and channel 2 measures the groove current through an AC transformer. The results are shown in Fig. 8.

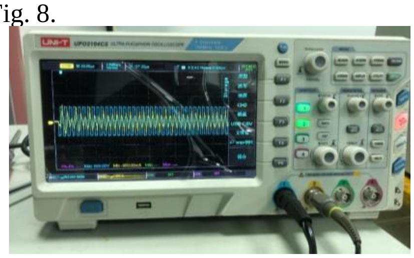

Figure 8. Oscilloscope Measurement of Channel Voltage and Current

The working frequency of the inverters is between 114KHz and 119KHz by solving with MATLAB software. At the same time, the slot current generates multiple zero-crossing points in the half cycle of equipment start-up. By setting a threshold, the first zero-crossing point is used to replace the other zero-crossing points in half a cycle to observe the sharp change of phase difference angle. As shown in Fig. 9, the actual phase difference angle curve is basically consistent with the theoretical phase difference angle curve.

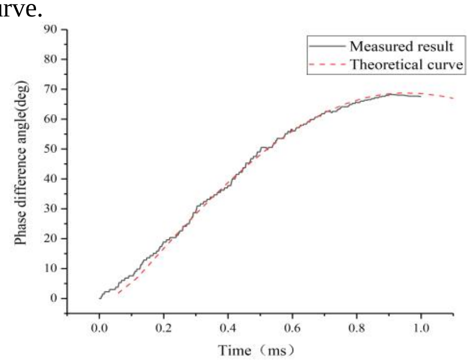

Figure 9. Phase Difference Angle Fitting and Contrast

V. Conclusion

The closer the starting frequency of the power supply is to the resonance point, the more stable the circuit is. Therefore, the actual working frequency of the circuit can be set near the resonance point by adjusting the circuit parameters.

The simulation results show that the channel current conversion is relatively smooth when the phase difference angle is less than 75 degrees. Setting the phase difference angle threshold and shielding the zero crossing points caused by crosstalk current can ensure the normal operation of the phase difference angle program.

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