Mixed Inverter Regulation Method for Induction Heating

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Abstract. One of the commonly used methods of voltage source inverter regulation for induction heating is a frequency method of regulating the output power of the inverter, based on the frequency selectivity of the resonance load circuit. With frequency regulation at low values of the Q-factor of the resonance circuit, deep regulation of the output power is impossible. As a result, other methods of regulation are desirable. The article discusses the issue of using a mixed pulse and frequency phase or latitude regulation method under the obligatory conditions of the soft switching mode.

1. Introduction

Transistor resonance voltage source inverters are widely used as power supply sources for induction heating installations. The most common method for regulating power in these devices is frequency regulation method with inductive misalignment of the inverter, as a result of which the soft commutation mode of semiconductor power devices is achieved. Using this method is not suitable for deep adjustment of the output power - the operating frequency must vary over a wide range, which is not always possible at low values of the Q-factor of the load circuit, as the operating frequency range of the inverter is limited and the heating technology requirements are specific [1]. In order to expand the regulating range of inverter output power, it is possible to use other regulation methods: amplitude, phase, pulse and width, pulse and code and their combinations, including frequency [2]...[5]. As a general principle, the use of these methods significantly reduces the inverter efficiency due to the deterioration of the switching modes of the power keys resulting in the decrease in reliability and added complexity of the converter circuit, which in turn affects the reliability and cost. Thus, this article provides a study on the efficiency in terms of the depth of adjustment, use of frequency and phase and frequency and latitude methods for regulating the inverter output power under the obligatory and sufficient conditions for ensuring the soft switching mode [6] of power keys and without complicating power part of the circuit.

2. Problem

To study the operation of the voltage source inverter in the LtSpice package, a computer model shown in Figure 1 was developed. The model consists of: constant voltage source V5, the output characteristics of which simulate the output characteristics of a 3-phase rectifier with a low-pass filter; bridge inverter on field-effect transistors VT1-VT4, controlled from pulsed voltage sources with adjustable time and amplitude parameters Vg1-Vg4 with gate resistances R1-R4; resonance load circuit consisting of series-connected effective resistance of inductor R5 and the inductance of inductor L1, as well as the compensation capacitance of inductor C1.
Based on the calculations, a dependence (Figure 2) for minimum permissible relative pulse duration $D$ with pulse and latitude regulation and the maximum permissible phase shift $\phi$ with phase and pulse regulation depending on phase $\phi$ between output current and output voltage on the first harmonic of the inverter, the output phase $\phi_{u1}$ is in turn regulated by the operating frequency of the inverter, with the invariant parameters of the resonance load circuit, was developed. This dependence is easily confirmed analytically based on the calculation of the resulting time interval between the output current and voltage on the first harmonic when the frequency changes, within which the switching of the semiconductor power keys should occur (in the limit to the left of the current zero point), and, based on this, it becomes clear that this dependence remains unchanged at different $Q$-factors of the load circuit. It should be noted that the presented dependence is achievable provided that the reactive power of the circuit is localized in the inverter. This condition is achieved automatically when using phase and frequency dependence, and when using the latitude and frequency regulation, oscillations in the circuit are damped and therefore the soft switching condition ceases to be met, due to a change in the relative pulse duration of the control pulses of transistors of the same level (upper or lower) only or one half-bridge (arm) of the inverter, if this condition is not met in the dead time interval with narrowing time (relative pulse duration) of the control pulses of the transistors because of the counter emf effect on the circuit through the bypass transistor diodes. Also, the dependence shown in Figure 3 does not take into account the switching time of transistors and the dead time between control pulses of opposite diagonals. In actual implementation, for example, when adjusting a product or simulating using models of the corresponding transistors, the dependence shown in Figure 2 can be reconstructed several percent higher from the indicated one (for both ordinates) taking into account the dead time of control pulses, transistors switching delay, as well as the fulfillment of the conditions of the soft switching mode.

To illustrate, at point $\phi_{u1} = 44.289^\circ$, a calculation with the following parameters of the load circuit: $L_u = 200 \ \mu\text{H}; \ C_1 = 50 \ \text{nF}; \ R_u = 6.325 \ \text{Ohm}$ - was carried out. To establish the selected value of the phase deviation, the operating frequency of the inverter based on the calculation of the first

![Figure 1. The computer model](image-url)
harmonic should be approximately (excluding current harmonic distortion) equal to 52.846 kHz. Figure 3 shows timing diagrams explaining the operation of the inverter (Figure 1) at the specified operating point with the set parameters of the load circuit: Figure 3a – transistor control pulses VT2 (Vg2) and VT4 (Vg4), corresponding to curves 1 and 2; Figure 3b – transistor current VT2 (ID(VT2)); Figure 3c – transistor current T4 (ID(VT4)); Figure 3d - output current (I(Ru)) and voltage (Vout) of the inverter corresponding to curves 2 and 1.

**Figure 2.** The dependence for minimum permissible relative pulse duration D with pulse and latitude regulation and the maximum permissible phase shift ϕ with phase and pulse regulation depending on phase ϕ between output current and output voltage on the first harmonic of the inverter

With the set misalignment of the inverter on the first harmonic ϕiu1 = 44.289 ° - the limiting minimum permissible relative pulse duration of the control pulses of the regulated part of the inverter, based on the dependence shown in Figure 2, is: D = 25.5%. However, because of the introduced dead time between the control pulses of opposite diagonals equal to 100 nS, which is more than enough for a confident switching of the opposite diagonals of the bridge on field-effect transistors in the absence of through currents through the inverter half-bridges (arms) - the limiting minimum relative pulse duration at which the soft switching mode is maintained slightly differs from that determined based on the dependence in Figure 2 and is equal to: D = 26.5%. Figure 4 shows timing diagrams explaining the operation of the inverter (Fig. 1) with a relative pulse duration of the control pulses of the regulated arm of the inverter D = 26.5% and a phase deviation on the first harmonic of the output current and voltage of the inverter ϕiu1 = 44.289 °: Figure 4a - control pulses with an unregulated relative pulse duration of transistor VT2 (Vg2) and transistor VT4 (Vg4) with an adjustable relative pulse duration corresponding to curves 1 and 2; Figure 4b – transistor current VT2 (ID(VT2)); Figure 4c – transistor current VT4 (ID(VT4)); Figure 4d - output current (I (Ru)) and voltage (Vout) of the inverter corresponding to curves 2 and 1. It should be noted that the pattern of the inverter operation, shown in Figure 4, will remain with the phase and frequency regulation, except for the type of control pulses, which will be deviated by ϕ = 88.5 °.

Comparing the operating modes of the inverter according as per the timing diagrams shown in Figures 3 and 4, the following points can be identified: the output current of the inverter dropped from 67.4 A to 51.4 A; the current switched by transistors from 48 A changed to 1 A for the pulse and latitude unregulated arm and up to 51.3 A for the regulated one; based on a linear approximation, the average current (area) of bypass transistor diodes during the conduction time changed from 51.4 μA to 11 nA for the pulse and latitude unregulated transistor and to 115.2 μA for an adjustable one; the
average current (area) of the forward conductance of the transistor during the open state changed from 356.3 μA to 309.6 μA for a pulse-width unregulated and to 167.1 μA for the regulated one.

Figure 3. The timing diagrams explaining the operation of the inverter at the specified operating point with the set parameters of the load circuit

Figure 4. The timing diagrams explaining the operation of the inverter with a relative pulse duration of the control pulses of the regulated arm of the inverter \( D = 26.5\% \) and a phase deviation on the first harmonic of the output current and voltage of the inverter \( \phi_{iu1} = 44.289^\circ \) It may be said that when an additional regulation channel is used together with a frequency (phase or latitude) channel, the switching losses of the additionally regulated transistors practically do not
change – of those unregulated are practically excluded, forward conduction losses for all transistors of the bridge are reduced, the conduction losses of the bypass diode increase for regulated transistors - unregulated ones are practically excluded, however, the total bypass conduction losses for the entire inverter remain the same as when using frequency regulation only.

Thus, we can conclude that the use of an additional regulation channel integrally reduces losses in the entire inverter. Thus, the possibility is confirmed and the limits of the mixed regulation of the output power of the resonance source voltage inverter are demonstrated, at which soft switching mode of the semiconductor power keys of the inverter is necessarily provided. The purpose of using the mixed regulation method is to reduce the frequency range of the regulating converter output power. Figure 5 shows the dependences of rated output power Pn on the operating rated frequency of the inverter relative to resonance circuit fn when using only a particular regulation method (Figure 5a) and mixed pulse-frequency-latitude or frequency-phase method (Figure 5b) ensuring the soft switching mode of power keys with different Q-factor values of the load circuit. Figure 5 shows that using the mixed method compared to the frequency method exclusively, the ratio of the maximum achievable narrowing of the operating frequency range is 1.41 times.

Figure 5. The dependences of rated output power Pn on the operating rated frequency of the inverter relative to resonance circuit fn

Thus, the article demonstrates the possibility of implementing a mixed regulation of the output power based on pulse latitude-frequency and phase-frequency methods. At the same time, implementation of these methods is based on the linear dependence of the maximum permissible relative pulse duration or phase deviation of control pulses from the output phase of the inverter on the first harmonic, at which the soft switching mode of the power keys of the inverter is maintained.
Using the output phase of the inverter as the main parameter is convenient because the dependence on the load parameters of the inverter, which also includes an inductor, is excluded, and the parameters of the inductor, in turn, can change by ten folds [7], and the mixed regulation based on the established linear relationship become possible to be implemented. Linear dependence can be implemented both programmatically on the process controller, and through feedback with a selected amplification factor based on the data of the output phase of the inverter.

3. Conclusions
Using an additional control channel together with a frequency channel allows to narrow the control frequency range by 1.41 times in the limit at which the soft switching mode of the power keys of the inverter with minimum output capacitances is still maintained, compared to exclusively frequency regulation. Narrowing of the frequency range provides the following advantages: expanding the regulation capabilities of converters with a limited operating frequency range with a low Q-factor value of the load circuit (or heating stage, when the Q-factor value of the inductor is minimal); reducing the cross impact of induction systems with magnetically coupled inductors and individual power supply by increasing the difference between the operating frequency of the inverter and the resonance frequency of the magnetically coupled inductor circuit [8]; complying with the special requirements of the induction heat treatment technology in terms of the frequency of currents induced in the part.

In the case of magnetically coupled induction systems with individual power supply - somewhat reducing their cross impact by increasing the difference between the operating frequency of the inverter and the resonance frequency of the magnetically coupled inductor circuit; also complying with the special requirements of induction processing technology.

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