Numerical Modelling of Resonant Inverter Stability in Electromagnetic Processing of Different Materials

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Abstract

Some trends of modern electromagnetic processing of different materials are pointed out. The role of high frequency inverters for treatment of materials is shown. Results of resonant inverter scheme stability without control system are discussed. Classification of inverter stability is done. Different modes of resonance inverter operation are presented with the use of theory of catastrophe.

Introduction

In modern high-frequency (HF) electrotechnology for processing of different materials the following fast developing directions should be noted:
- receiving and processing of new materials
- processing of different materials with gas purification
- processing of different materials in vacuum with controlled gas ambience
- pulse processing of different materials
- induction treatment of the workpiece of complex form
- processing of materials in cold crucibles.

This list of modern electrotechnologies is not complete and it is specified from bibliography analysis and requirements from industry or scientific centres in Russia.

Of course, the development of new effective electrotechnology is impossible without mathematical simulation. There are different known successes in this field but also there are different problems in numerical simulation and these problems will be solved.

Power supply is one of the basic parts of HF electrotechnology installation as well as HF inverter is the main part of power supply. For one electrotechnology the requirements to power supply are not rigid, but for other one the role of power supply can be very important. There are special requirements for HF inverter from the side of electromagnetic system, for example, stability at the fast change of load parameters, special low of power transferred to electromagnetic system, existence of current source characteristic etc. All these requirements can be satisfied due to study of inverter behaviour at different load parameters. Numerical simulation of electromagnetic processes in inverter at wide range of change of load parameters as well as own parameters permits to develop a reliable and stable HF inverter.

1. General Information

The modern HF electrotechnological processes require the development of inverter, which able to operate with fluctuation of load parameters from short current mode till disconnection mode. The development of these inverters demands the creation of the theory of their stability at loading parameter fluctuations. The circuits of inverters are described by
systems of the equations with high order with non-linear coefficients. These researches can be made only at wide use of numerical modelling of electrical circuits.

The semiconductor power supplies for induction heating usually operate in a range frequency from one till to several hundreds kHz. The analysis of the circuit configurations, used in inverter, shows that for the purposes of induction heating, where the short current mode of inductor is possible, the application of resonant inverter [1] should be done. As shows experience of some researches during last 10-12 years, the use of classical parallel and series inverters of a current and voltage with any algorithms and computer control systems does not guarantee safety of transistors at failure mode. Only power scheme of inverter can overcome short circuit mode without troubles.

2. Resonant inverters

There is a class of HF inverters - resonant inverter with double frequency and subclass of resonant inverter with double frequency and backward diodes [2]. The main features of resonant inverters with double frequency and backward diodes are:

- application of transistors in definite frequency range permit do not use the backward diodes;
- transistor switch off process is realised always at zero current - commutation losses approximately equals to zero;
- simple control system of inverter is done due to only the requirements of technology, but not to the requirements of transistor operation mode;
- increase of output power of inverter by simple connection in parallel that give for the application both frequency control mode or/and phase control mode of power in workpiece.

One configuration of the resonant inverter scheme with double frequency and backward diodes can have four commutation inductances \( L_C \) in each leg of bridge or two \( L_C \) in different diagonals of bridge (Fig. 1). In any case the inverter frequency is defined by \( C_C \) and \( C_D \), \( L_C \) elements and these elements define resonant frequency of a commutation circuit.

Simpler scheme of the above inverter can be received if the whole bridge of inverter Fig.1 will be replaced on only one transistor – Fig. 2. For this inverter commutation inductance can be connected in series with the transistor or in series with \( C_D \) condenser. The name of the inverter is current-fed chopper or quarter-bridge.

![Fig. 1. Resonant inverter with double frequency and backward diodes](image1)

![Fig. 2. Resonant current-fed chopper](image2)

Standard operation modes of these inverters are known and described in some publications, for example, [4]. The articles devoted to the study of stability of the resonant inverters.
2.1. Practical stability of high frequency inverters

Stability of HF inverter for electromagnetic processing means trouble-free mode of operation at the fluctuation of load parameters from short circuit mode to disconnected mode. The stability can be classified on

- stability of electrical circuit of inverter
- stability of control system of inverter
- common stability of electrical circuit and control system of inverter

Specialists in the field of control system study the stability of control system of different objects. There are great achievements in this field.

Specialists in the field of HF inverters study the stability of electrical circuit of inverter as well as common stability of electrical circuit and control system of inverter. There are some publications on this item, for example, [5], but usually these articles devoted to mutual operation mode of control system and HF electrical part of inverter.

Stability of HF electrical circuit of inverter is also important particularity of general inverter stability. We can classified stability in steady-state and transient processes of electrical scheme of inverter.

Stability in steady-state modes means reliable operation with not so fast fluctuations of load parameters. This stability analysis permits to define the range of load parameters as well as own parameters of electrical elements of inverter. Usually engineers define preliminary parameters at the initial design of inverter and only after these values should be specified.

The stability in steady-state mode at the sudden change of load parameters should be also studied because this problem is very important [6] for reliability of inverter.

The big importance has stability of inverter in transient process and, first of all, initials start-up mode. Reliable start-up mode depends on algorithms of start-up, initial values of voltage on capacities, parameters of circuit. For some schemes of inverters special start-up devices is installed and after special algorithm for whole power supply realises reliable start-up mode. Special initial conditions, for example, definite voltage on capacities also can provide good start-up mode and we attempt to find these conditions because this mode has economical advantages.

2.2. Theoretical analysis of high frequency inverter stability

Different types of analysis of electrical circuit have been developed for linear and non-linear circuits. As known stability of electrical circuit can be estimated from system of differential equation which its describes. There are no problems when we have linear differential equation system, but inverter is described by non-linear system of differential equation and difficulties of its analysis are also known.

Today the theory of catastrophe [7] and theory of bifurcation are used for the analysis of different objects in building, in theory of vacuum-tube generators, mechanics etc. Unfortunately methods and approaches of these theories are not wide applied for non-linear electrical circuits due to their complexity. But the necessity of development reliable HF inverters compels to begin these researches. Moreover, inductor current and inductor voltage have differential low of relationship that simplifies the analysis of stability.

There is also other problem at the use of stability analysis – the definition of steady-state mode. Today the steady-state analysis gives voltage and current for each element of inverter through transient analysis. If steady-state mode is reached through transient processes the currents and voltages can be obtained for start-up process of power supplies. For this case also other question exists - what is it steady-state process or when we should stop calculation of transient process etc.
Let us show some examples of different processes in resonance inverters in steady-state and transient processes.

### 2.3. Numerical results of inverter modes

First of all, different modes for inverter fig.2 are presented. On fig.3 standard operation time-domain mode of inverter is shown as well as its steady-state process as current of inductor versus inductor voltage fig.4.

![Fig.3 Standard operation mode of inverter](image1)

![Fig.4 Steady-state process of inverter](image2)

The similar process is shown on fig.5 and fig.6. The doubling of period observes in the inverter at the negligible fluctuations of load parameters (not more than 10 %). Comparison of fig.3 and fig.5 shown the change of transistor mode.

![Fig.5 Operation mode of inverter with doubling of period](image3)

![Fig.6 Steady-state process of inverter](image4)

These two modes are stable and it seems they are not so critical for the material processing due to big inertia of thermal processes in comparison of double period of inverter.
The further fluctuation of load parameters gives the next mode - fig.7 and fig.8. Fig.7 demonstrates steady-state process with undefined period. Transient process with low frequency component is observed on fig.8. This process can not be classified as chaos because there is a repeatability of mode. This mode is also stable but low frequency modulation can influence on electromagnetic processing and these modes should be prevented. Fig.9 shows other mode with further fluctuation of load parameters and the mode is similar to previous one. Fig.10 demonstrates start-up process with non-zero initial conditions of inverter, i.e. capacity \( C_D \) has been charged up to definite voltage from rectifier.

Variation of initial charge of \( C_D \) capacity leads to different start-up conditions and the failure of inverter can be reached at definite values of voltage.

**Conclusions**

Some trends of modern electromagnetic processing of different materials are pointed out. The importance of high frequency inverters for treatment of different materials is proved. Stability of electrical scheme of resonant inverter without control system was discussed. Common classification of HF inverter stability was done. Different modes of resonance inverter operation are discussed on the example of resonant current-fed chopper.
Similar modes can be received in bridge resonant inverter as well as non-symmetrical mode. Non-symmetrical modes of resonant inverter is very interesting topic and researches in this field should be done.

References

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