ELECTRICAL MODELLING OF INDUCTION HEATING FURNACES USING PSPICE

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ABSTRACT. This paper proposes the use of PSpice, or a similar circuit simulation tool, to model and simulate induction heating systems. The model is used to simulate the effects of circuit changes, such as replacement of the output inductor or readjustments in the oscillator circuit. Furthermore, the simulation results provide useful information about the inductor current, the output frequency and power losses, and provide an estimation for the cooling requirements and efficiency of the circuit components. The synthesis of a representative model for the different circuit elements is discussed by means of a triode generator example circuit. Special emphasis is given to the practical measurements needed to set up the equivalent circuits.

I. INTRODUCTION

A typical induction heating system is based upon a coil or inductor, which is supplied with a high-frequency, high-amplitude current. Different power supply systems and topologies exist, of which the solid state generator and vacuum tube generator are of most interest. This paper proposes the use of electrical circuit simulation software, such as PSpice, to model and simulate induction heating systems. The PSpice model incorporates the entire system, starting from the high-voltage DC power supply to the inductor and workpiece, including oscillator circuits, coupling transformers, busbars and other circuit elements. The model is useful to simulate the effects resulting from circuit changes (e.g. installing a new inductor, adjusting capacitor banks,…) before, or even without, implementing the changes in reality. The PSpice simulations also provide useful parameters, such as the output current amplitude, output frequency and inductor power. Furthermore, it is possible to evaluate improvements or circuit changes, which are too expensive or too difficult to try in real-life.

In section II, the modelling of induction heating systems in PSpice is discussed, focusing on how to obtain the model. Section III gives some applications and examples, and focuses on how to use the model once it is available. Finally, section IV gives some general conclusions.

II. PSPICE MODELLING

Circuit components

Induction heating generators come in different types (e.g. triode-based or solid state generators) and different topologies, and therefore various generator circuits exist [1]. However, some critical circuit elements, such as busbars, inductors and air cored transformers, are commonly used in many generator systems. This section focuses on how to represent these components in PSpice, and how to model them.

As an example, Fig. 1 shows the PSpice model of a triode oscillator which drives the inductor through an air cored coupling transformer. From left to right, the following system components are observed: a triode colpitts-oscillator, a coupling transformer (L_{s1}, L_{s2}, L_H, R_{ts}) and a busbar (R_{busbar}, L_{busbar}) which couples the output inductor ($L_{inductor}$) with the generator. Each component is represented by its circuit equivalent. The more accurate the equivalent model for each component, the more precise the behaviour of the actual system is reproduced. The circuit from Fig. 1 is a simplified version of the real generator circuit, other models might be more complex depending on the required accuracy of the investigation.

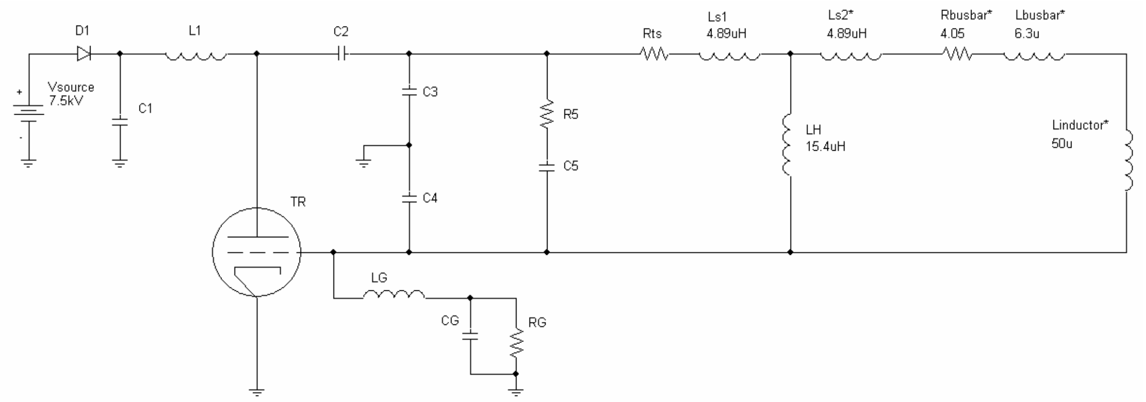


Fig. 1. PSpice schematic of a triode-based induction heating generator.

Busbar and inductor model

A high-current, high-frequency busbar is often used to connect the generator with the remotely positioned inductor. The busbar inductance affects the resonance frequency of the generator, and causes a considerable voltage drop at the secondary side of the transformer, leading to higher losses. These effects are further explained in the next section. The equivalent circuit of both the inductor and the busbar consists of an inductance and a resistance in series. Because of the high frequencies (10-1000kHz) typically used, the inductance is the most significant parameter, since the reactance dominates the total impedance. The inductance is generally low (magnitude nH or µH), especially for inductors with only few windings. A first straightforward way of measuring the inductance of these components, is with a precision LCR meter. An alternative measurement method, proposed in [2], is specifically suited for very low inductances. A high frequency (1MHz or higher) sinusoidal voltage is applied to the component, and the resulting current is determined with differential measurements on two shunt resistors. The inductance is then calculated using the ratio between the voltage applied to the inductance, and the current flowing through it. The differential measurement technique and the averaging functions on modern digital oscilloscopes yield a stable measurement value with a high signal-to-noise ratio.

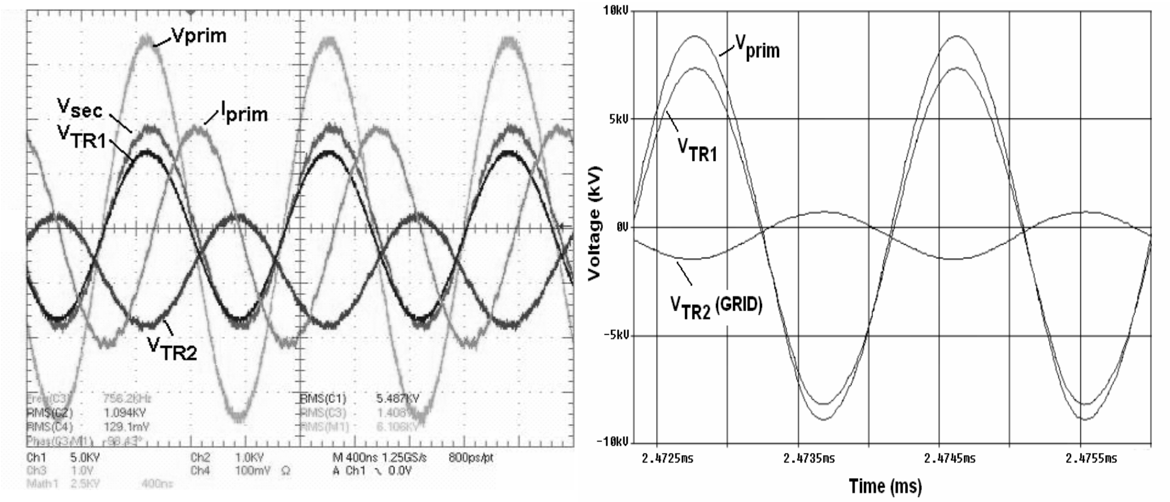
The previously described measurement methods require the component to be physically decoupled from the rest of the installation. On-line inductance measurements, without the need to disassemble the installation, are accomplished by measuring the current through the component (e.g. the busbar) and the resulting voltage drop. However, measuring the secondary current at the high frequencies and high current levels typically used in induction heating installations proves to be quite challenging. At high frequencies (>100kHz), shunt resistors have a high reactive voltage drop compared to the expected resistive voltage drop. Higher resistance values help to increase the R/L ratio, but introduce substantial power losses at these high current levels. Current measurement with a Rogowski coil is a more interesting alternative, but care must be taken not to influence the inductance of the component when the Rogowski coil is inserted into the air gap of the busbar or the inductor. A simple current pick-up coil, consisting of a few windings in the vicinity of the busbar, also produces a voltage proportional to the current flowing at that moment, and is a non-intrusive measurement technique [3]. Furthermore, after calibration, the pick-up coil lends itself for permanent current measurement and monitoring, and can be used as an indication for output power when combined with a voltage measurement [4].

Although smaller than the reactance of the busbar and the inductor, the resistive part of the equivalent circuit is important, since it determines the power losses and heat dissipation in these components. Direct DC resistance measurement is inaccurate, since the resistance changes at high frequencies because of the skin effect. However, the resistance can be calculated from the current and voltage waveforms recorded during the inductance measurements. The in-phase component of the total impedance gives the resistance, the out-of-phase component gives the inductance. For simple geometries of inductor and busbar, Finite Element (FE) simulations also provide an estimation for inductance and resistance.

Transformer model

The galvanically isolated transformer is represented in Fig. 1 by its T-equivalent circuit, consisting of the main inductance L_H, leakage inductances L_{s1} and L_{s2}, and series resistance R_{ts}. All component values on the secondary side of the transformer are referenced to the primary side, and therefore multiplied with the square of the winding ratio N.

All elements from the equivalent circuit (L_H, L_{s1}, L_{s2} and R_{ts}) are calculated from voltage and current measurements at the primary and secondary side of the transformer, for different secondary load conditions. L_H, L_{s1} and R_{ts} are determined from an open circuit experiment, when the inductor is temporarily removed. A second experiment, with load (the inductor) applied, then gives L_{s2}. In situ measurements are desired here, because it is often difficult to isolate the transformer from the rest of the installation. Acquiring a good equivalent model for the coupling transformer is not trivial, since it involves measuring the high voltage (kV range) on the primary side of the transformer, and the high current (kA range) on the secondary side. The primary terminals of the transformer are both at a high potential with respect to ground, corresponding with the voltage across C_3 and the grid voltage of the triode. A differential high-voltage probe is thus required for these measurements.



a) **b)**

Fig. 2: a) Voltages V_{TR1} (5kV/DIV) and V_{TR2} (1kV/DIV), measured at the transformer terminals; transformer primary voltage V_{prim} (2.5kV/DIV); primary current I_{prim}; secondary voltage V_{sec} b) Simulation results for V_{TR1}, V_{TR2} and V_{prim}.

An alternative method is shown in Fig. 2a, where the voltages at both terminals are measured with two probes referenced to ground (V_{TR1} and V_{TR2}). The primary voltage V_{prim} is then calculated as $V_{TR1} - V_{TR2}$ on the digital oscilloscope. The PSpice simulation results in

Fig. 2b show the same voltage waveforms, and are helpful to confirm the accuracy of the transformer model, when compared with the measurement results.

Triode model

Stable operation of the simulated triode oscillator requires an accurate triode model. The model itself (the basic equations) has to be capable of describing the triode's behaviour with sufficient detail. Furthermore, the model has to include the real triode characteristics (using manufacturer's data or measurements), in order to get representative results.

III. APPLICATIONS AND SIMULATION RESULTS

Determination of the output power and efficiency of the system

Since the results of each simulation run include the voltages at every node in the circuit, as well as the currents flowing into each terminal, voltage or current stresses in critical components (e.g. the triode) are easily identified. Furthermore, the simulation results predict where power losses are to be expected. The busbar that connects the generator with the inductor, often shows high losses because of the high output current, and a relatively large voltage drop when the inductor inductance is low. A PSpice simulation then provides an estimation for the cooling requirements of the busbar, and other components in general.

The amplitude of the output inductor current is of particular interest here, since it determines the amount of power transferred to the workpiece at a certain generator setpoint and circuit configuration. When the electrical simulation results are used as a basis for further Finite Element (FE) simulations, thermal information about the heating process is obtained, e.g. the amount of power transferred to the load. Given the generator input power (the power supplied by V_{source} in Fig. 1), the global efficiency of the system is calculated with the useful output heating power from the FEM simulations.

Influence of the inductor and circuit components

Circuit components are often adjustable or can be exchanged for other components with different values. Such circuit changes affect both the output current and the operating frequency of the generator. For example, when multiple inductors are available for the same generator system (e.g. coils with a higher or lower number of windings to accommodate different heating processes), the output current and frequency depends on the coil installed.

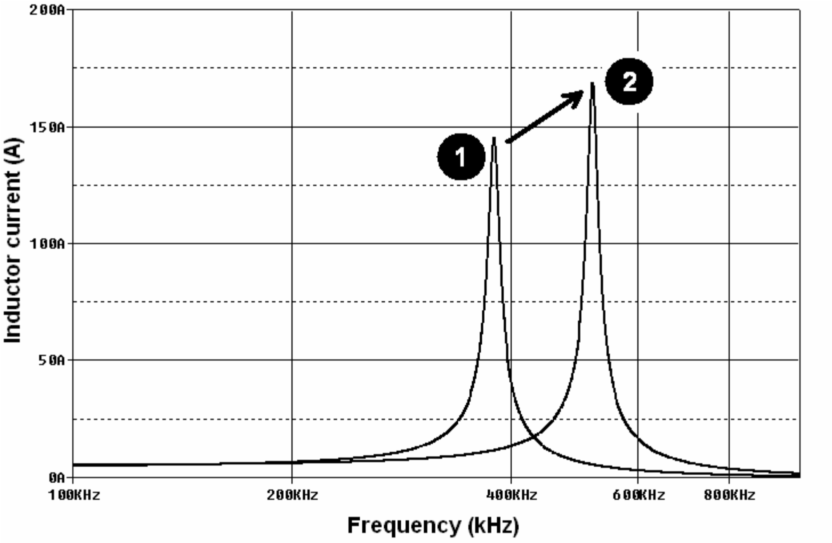


Fig. 3: Frequency analysis of the generator circuit, showing the inductor current as a function of frequency.

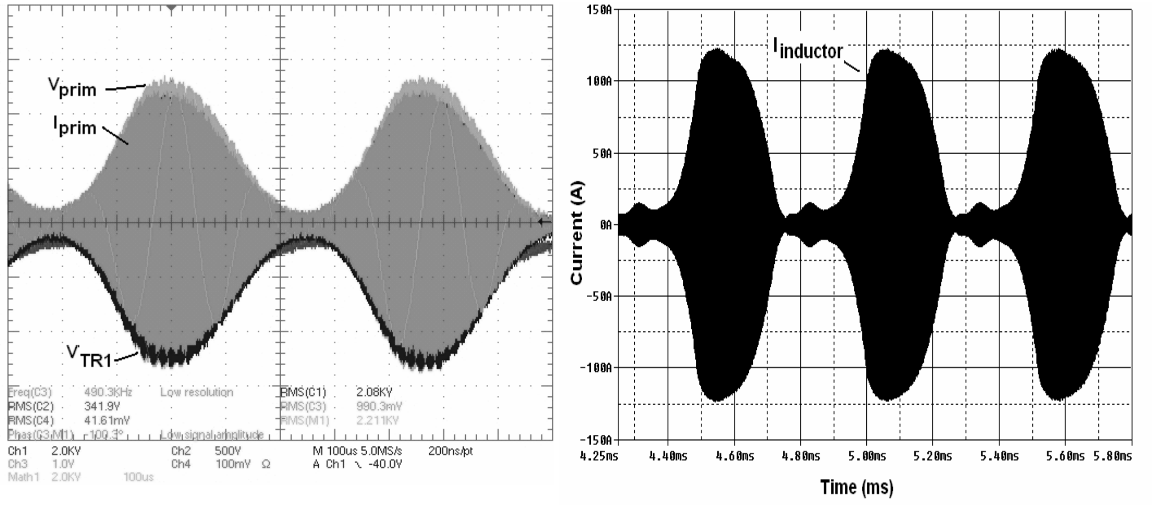
When the frequency changes, care must be taken not to exceed either the triode's maximum specifications or the imposed electromagnetic radiation restrictions.

Moreover, the inductance of the output inductor, with respect to the busbar inductance, determines the ratio between useful output power and busbar losses since both carry the same current. A PSpice simulation of the modified circuit helps to understand which parameters change, and how to tune the new circuit to the new coil with the other adjustable elements, e.g. with C_5.

Capacitor bank C_5 in Fig. 1 consists of several individual capacitors, of which a certain combination is connected in parallel to adapt the generator and the resonance frequency to the installed inductor. To study the effect of such circuit modifications on the frequency and the output current, a frequency sweep analysis is a helpful simulation tool. Fig. 3 shows the inductor current as a function of frequency for two different values of capacitor C_5: 10nF for curve (1) and 4nF for curve (2). When C_5 is changed, and the inductor remains the same, the resonance frequency of the triode oscillator shifts to the right.

Influence of the generator setpoint and triode quiescent point

The voltage and current measurements in Fig. 4a show a typical beating effect in the output current, due to triode biasing issues at low operating levels. Proper biasing of the triode grid is accomplished with the grid leak bias circuit based around L_G, C_G and R_G. At low generator setpoints, both the output current and the anode voltage oscillate with a fundamental frequency of 2kHz. The average current (and thus the transferred power) is smaller than the peak value. The real-life measurements from Fig. 4a correspond with the simulation results from Fig. 4b, where the same modulation effect, at the same modulation frequency, was obtained. By tweaking the bias circuit (e.g. changing R_G), stable operation is achieved even at low operation points. Experimentation with different component values in PSpice is less expensive and labour-intensive than making the same changes in the real generator circuit.



a) **b)**

Fig. 4: a) Measured beating effect in primary current I_{prim} and primary voltage V_{prim}
b) Simulation of the same beating effect

IV. CONCLUSIONS

The electrical modelling of induction heating generators has been discussed, using a simple triode oscillator circuit as an example. Special consideration has been given to the correct modelling of the different components, and their representation in an equivalent circuit. The high currents and high frequencies which are typical for induction heating applications, often make the necessary measurements difficult. Some alternative low inductance measurement techniques are presented, and several high current measurement methods are compared against each other. Examples and applications of the model are described, including the beating or modulation effect in triode oscillators, typical at low operating points.

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