FEM modeling of a continuous induction heating process of steel wire hardening

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Abstract: Hardening of steel wires requires heating the wires above their Curie temperature, temperature at which the material becomes nonmagnetic causing a sudden change in the load. This change affects to the induction heating converters and is difficult to be evaluated due to the complexity of the problem and the interdependence of the parameters. In this paper a continuous Post-Curie wire heating model using commercial FEM software is presented and evaluated for two cases.

1 Introduction

Induction Heating (IH) is a method of heating electrically conductive materials used in many domestic and industrial applications because it has many advantages to other heating systems (e.g. gas- and oil-fired furnaces) such as quicker heating, faster start-up, more energy savings and higher production rates [1, pp.7].

One application of IH systems is the continuous hardening and tempering of steel wires which involves the austenitizing, quenching and tempering of the wire. At the austenitizing stage the wires have to be heated above their Curie temperature [1, pp.109] and at this temperature the relative permeability decreases to one becoming a nonmagnetic material. In case of steels the magnetic permeability value depends not only on the temperature but also on the composition of the material, with values of high carbon steels that triple the values of low-carbon steels [2, pp.107]. When crossing the Curie point the heat intensity at the surface decreases because the magnetic permeability starts to decrease and also because near the Curie point there is a maximum in the specific heat, [2, pp.146]. These parameters determine the whole process and make it difficult to study the dynamics of the equipment.

Due to this change of characteristics and above all due to the change in the permeability, that leads to an increase of the penetration depth and a decrease of efficiency in the transference, it is recommended to use two converters during the austenitizing process and specially in a continuous process, [2, pp.531]. The first of these converters has to have a lower frequency and is used for heating the wire before the Curie point and the second, with a higher frequency, is used for heating the cable above the Curie point, Figure 1. In this case the Post-Curie system has to be able to pass from the Pre-Curie temperature to the Post-Curie temperature, having to deal with the steel's properties change. From an electrical point of view the equivalent circuit of the load is modeled by a resistor and an inductance, [3, pp.231], and these changes in the material's properties affect their values. In case of steel wires this phenomenon causes a sudden change in the inductance value arriving to a decrease of 20%. However, the parameter which affects the most to the converter is the drop in the equivalent resistance value that could be superior to the 70%, [4] [5], and generates an increase in the current. This change in the load's behavior takes

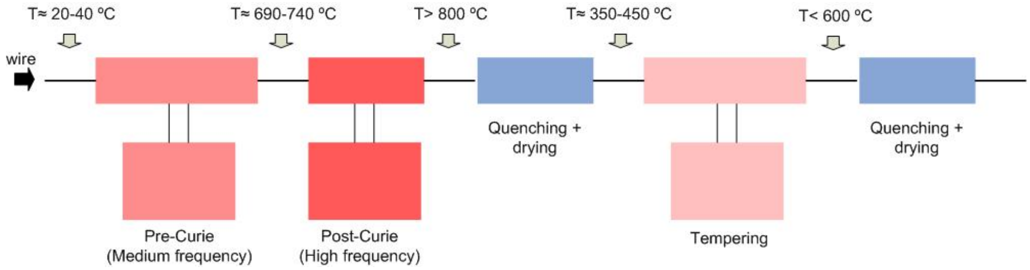

Figure 1: Schematic of a typical installation for continuous induction hardening of steel wire.

place just during the startup of the process being stabilized afterwards. Nevertheless, in order to enter in the Post-curie zone and start working, the converter has to be able to give enough power with high resistance values when the temperature of the whole wire is below the Curie point.

In this paper a 177kHz and 15kW Post-Curie system will be modeled in order to assess the converter's behavior during this start-up process by using the Finite Element Method (FEM) with the commercial software FLUX2D ©.

2 Theoretical basis

2.1 Electrical problem

Generally in IH systems the coil-workpiece is connected with a capacitor in order to resonate. There are many different tanks with their associated inverters which could resonate with the coil, but in this article a voltage-fed series resonant inverter (VFSRI) has been chosen for the simulation, Figure 2.

Regarding the converter's topology, a full-bridge structure has been chosen for the inverter. Although other topologies could be used to obtain an alternating voltage or current, in most applications above 5kW (that is the case of continuous wire heating) the full-bridge topology is the most common used one, [6]. Therefore, during the simulation it is considered that the inverter is commutating near the resonant frequency with a 50% of duty-cycle. Taking into consideration that the quality factor, which represents the ratio between the imaginary power (kVAR) and the real power (kW) of the tank, in the Post-Curie equipment is above 20 [5], it is supposed that the wave at the converter's output is sinusoidal and just the first harmonic of the square-wave will be considered, [7]. Moreover, in VFSRI all the current seen by the load crosses the inverter and in most applications it is necessary to connect a matching transformer between the tank and the inverter. In case of Post-Curie systems, where the equivalent resistance and the equivalent inductance are small, a transformer with a big transformation ratio ($1/i$) is necessary.

Taking this into consideration the voltage in the source used for the simulation is:

$$U_{tank2_{RMS}} \approx \frac{4 \cdot U_e}{\sqrt{2} \cdot \pi} \cdot \frac{1}{i} \approx \frac{0.9 \cdot U_e}{i} \tag{1}$$

Due to the small values of the resistance and the inductance in the coil-workpiece, the resonant frequency as well as many other parameters are pretty affected by any parasitic resistances and inductances such as the transformer's leakage inductances or the connections in the secondary. In this model these values will be incorporated in order to simulate a more realistic situation, Figure 2.

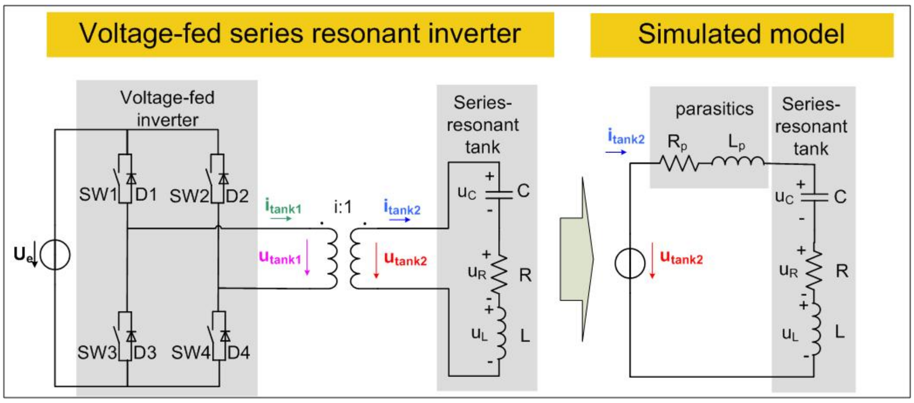

Figure 2: Series tank and equivalent electrical model.

2.2 Electromagnetic and thermal problem

Regarding the electromagnetic and thermal problem and due to its length and complexity, in this article just a brief enumeration of the physical and mathematical background is presented. However, the whole explanation could be found in many articles and reference books as for example in [2, pp.150].

FEM simulation of an induction heating system requires of a coupled magnetic and thermal model due to the temperature dependence of the materials. In case of the magnetic problem the equations have been solved regarding the magnetoquasistatic problem, in which the derivation with respect to the time of the displacement is equal to zero. Taking this into consideration, and using the definitions of the magnetic potential vector, the Maxwell-Ampere's law becomes:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) + \sigma \cdot \frac{\partial \mathbf{A}}{\partial t} = 0 \tag{2}$$

Where $\mathbf{A}$ is the magnetic vector potential, μ is the magnetic permeability of the material and σ its electrical conductivity.

Because of the symmetry of the problem, in cylindrical coordinates the complex vector $\mathbf{A}$ is independent of the angle (A(r,z)), and considering it is sinusoidal Equation 2 becomes:

$$\frac{\partial}{\partial z} \cdot \left(\frac{1}{\mu} \frac{\partial A}{\partial z} \right) + \frac{\partial}{\partial r} \cdot \left(\frac{1}{\mu \cdot r} \frac{\partial r \cdot A}{\partial r} \right) + i \cdot \varpi \cdot \sigma \cdot A = 0 \tag{3}$$

where ϖ is the angular frequency.

In this case the heat is produced by the generated eddy currents with the following root mean square power density:

$$p_v = \frac{|\sigma \cdot j \cdot \varpi \cdot A|^2}{2 \cdot \sigma} \tag{4}$$

This will increase the temperature following the Fourier equation:

$$\rho \cdot c_p \cdot \frac{\partial T(r,z,t)}{\partial t} - \nabla \cdot (k \cdot \nabla \cdot T(r,z,t)) = p_v(r,z,t) \tag{5}$$

where T is the temperature value, k is the thermal conductivity, c_p is the specific heat and ρ is the mass density.

These equations are solved in the nodes thanks to the FEM with the following procedure. At the beginning the magnetic and electrical properties are evaluated for an initial temperature and the magnetic problem is solved obtaining the induced power. Then the new and first temperature

chart is calculated for the next time step and the new thermal properties of the material are found. After this, the thermal problem is solved and a new temperature chart is obtained. With this new temperature distribution, the new electric and magnetic properties of the material are evaluated and the magnetic problem is solved again. Following the same procedure a new temperature chart is obtained and then the thermal problem is obtained again with this second temperature profile.
If the difference between the first and the second temperature distribution is less than a certain error the solution is validated and the next time step computed, otherwise the iterations continue until the error diminishes.

3 Model description

The system modeled in this paper is composed of 6 inductors of 10 square-shape turns that are heating a 3 mm diameter wire of AISI 1080 steel, with the characteristics seen in Tables I and II. The coils are connected in pairs and series forming three tanks which are connected in parallel, and the capacitors, as well as the parasitic components, are connected in series. In Figure 3 the connections of the electrical circuit are shown, in this case every turn being modeled by a two terminal solid conductor.

The wire is moving at a constant velocity and due to this movement the model requires a huge dimension compared to the area of interest which is just the area near the coils. Though it is difficult to provide an accurate meshing in such an big area, the meshing is much more precise in the area of interest, Figure 4.

Table I: Parameters of the tank.

	Parameter	Value
Coil	Number of coils	6
	Number of turns	10
	Inner diameter	20 mm
	Outer diameter	32 mm
	turn's width	1 mm
	Space between turns	1 mm
	Space between coils	36 mm
Capacitor	Capacitance	1.6 μF
Parasitic Components	Resistance	10 $m\Omega$
	Inductance	150 nH
Wire	Diameter	3 mm

Table II: AISI 1080 characteristics.

Temperature °C	Resistivity $m\Omega \cdot mm$	Relative permeability	Specific heat $kJ/(m^3 \cdot °C)$	Thermal conductivity $W/(m \cdot °C)$
0	0.180	100	3790	47.8
20	0.180	100	3790	47.8
100	0.232	100	3850	48.1
200	0.308	100	4140	45.2
300	0.410	100	4400	41.3
400	0.505	40	4700	38.1
600	0.772	40	5470	32.7
700	0.932	30	5890	30.1
750	1.032	5	15900	30.1
800	1.129	1	4690	24.4
900	1.164	1	4690	24.4
951	1.164	1	4690	24.4
1100	1.164	1	4690	24.4

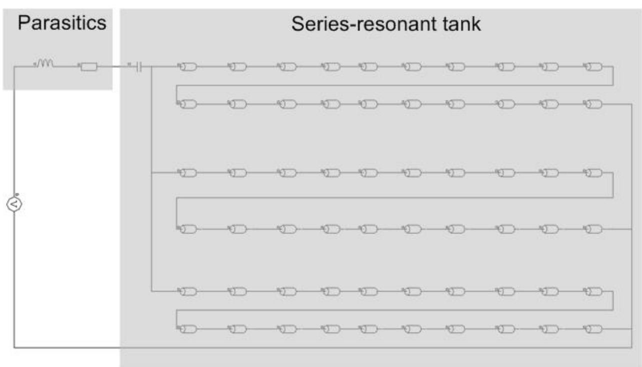

Figure 3: Electrical circuit simulated.

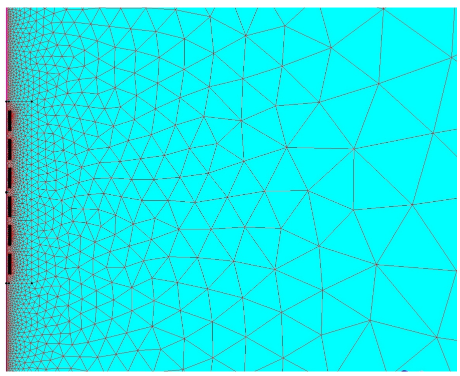
Figure 4: Interest's area meshing.

A convection boundary condition with an emissivity of 0.8 and a heat transfer coefficient of 30 $W/(m^2 \cdot ^\circ C)$ is imposed in the external diameter of the wire in order to have a more realistic approach. For the same reason the initial wire's temperature is set to ensure that the wire is entering at a certain temperature.

Regarding the resolution of the problem, FLUX2D © defines a *Steady State AC Magnetic coupled with Transient Thermal application* which uses FEM for solving the equations with the procedure explained in the previous section. It has to be noted that in this case the problem is Axisymmetric.

4 Simulation results

During the simulation the velocity of the wire is 5 m/min, the initial temperature at which the wire enters is at 720 °C and the temperature of the air is 40 °C.

Two simulations have been done in order to compare the results. The first case is a more common simulation where the voltage is constant during the whole process. The second case is a more realistic approach from the converter's point of view, where the voltage is considered by simulating a power control loop and changed manually according to a ramp of 100 V/s.
In both simulations the resonant frequency has been searched and set to 177kHz and a 1/17 transformer ratio has been considered. In the first case the voltage is fixed in order to obtain the same power as in the second case, and in the second case the simulation starts at 30 V.

In Figure 5 the results of the simulations are plotted according to Equation 1 and Figure 2. It could be observed how in the first simulation the steady-state condition is reached in half of the time than in the second simulation. Though in the transient period the results differ, in case of steady-state stage they are pretty similar, including the thermal analysis, Figure 6. However, to reach definitive conclusions more research should be done by varying the initial condition. One of the cases to study would be lowering the initial temperature in order to evaluate the changes in the properties in a more adverse scenario.

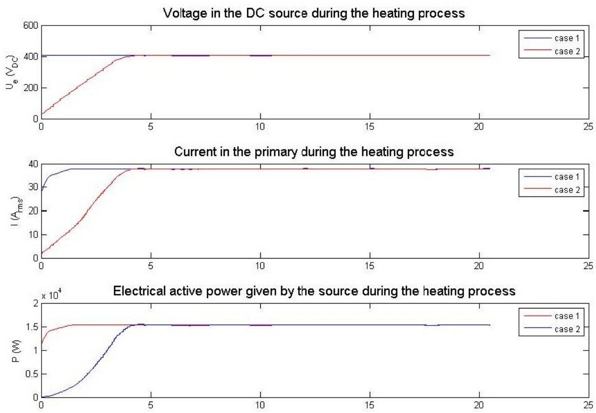

Figure 5: Voltage given by the DC source, current in the primary and power given by the DC source.

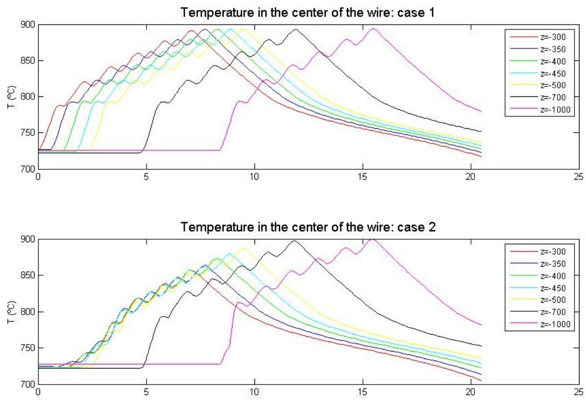

Figure 6: Temperature in the center of the wire in case 1 and 2.

5 Conclusions

In this paper a hardening process has been introduced, and a continuous Post-Curie wire heating converter's model using FEM analysis with a commercial software has been presented and evaluated for two cases. In the first case the voltage has been maintained constant and in the second case the voltage has been varied according to a power control loop. In both cases the

steady-state solutions are very similar but during the transient period the differences are significant, the second case taking longer to reach the steady state stage.
Though two cases have been presented with some expected results, more research should be done using the model and changing the parameters in order to correctly evaluate the behavior of the load and the converter during this process.

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