Modeling and Design of Induction Heating Systems

Amaiur Mendi Altube[1,2], Irma Villar Iturbe[2], Claudio Carretero Chamarro[1], Jesús Acero Acero[1]

[1]Grupo de Electrónica de Potencia y Microelectrónica (GEPM)
Instituto de Investigación en Ingeniería de Aragón (I3A)
Universidad de Zaragoza, Mariano Esquillor s/n, 50018, Zaragoza, Spain.
[2]Ikerlan Technology Research Centre, Basque Research Technology Alliance (BRTA)
e-mail: amendi@ikerlan.es

Abstract

This thesis is based on a specific industrial application of induction heating technology: induction hardening. The main objective is to create a simulation model that predicts the whole heating process, combining the electrical simulation with the electromagnetic-thermal analysis, employing electrical simulation software and finite element tools, respectively. This proposed model will be called as dynamic model in the following lines.

Introduction

Each Induction Heating (IH) process is a challenging combination of three phenomena: electromagnetism, heat transfer, and metallurgy [1,2]. In other words, it is a multiphysical problem. Therefore, Finite Element Method (FEM) tools are employed to execute numerical computations that solve IH problems [3].

This work is focused on the power electronics involved in the heating process, so the final structural analysis will not be considered. Thus, electro-thermal simulations by FEM tools are employed to model IH loads, considering the material's non-linear properties [4]. In this way, accurate modeling is achieved under a wide range of operational conditions, so that the control of the supplying power electronics influenced by the variable behavior of the load can be properly designed.

The IH load under study is presented and detailed in Fig. 1 and Table 1, respectively. In Fig. 2, the general diagram of the power conversion stages together with the dynamic IH load model is presented. The power converter in this analysis consists basically of a 3-phase rectifier, an intermediate DC-DC buck topology to further control the power, and a high-frequency half-bridge inverter, whose aim is to excite the inductive coil with an AC current. For the sake of simplicity, in the dynamic simulation model, the first rectifying stage is replaced by a DC voltage source of 650 V.

Proposed Dynamic Model

The output load seen from the power converter is the coil-workpiece couple captured in Fig. 1. Its electrical equivalence is an impedance dependent on magnetic field's amplitude and frequency and temperature of the billet.

The proposed dynamic model [5] in this thesis is the one resumed in the last part of the Fig. 2, which consists of simulating the power electronics converter stages and their control dynamics during the whole heating process, while the load's electrical characteristics are being modified.

To obtain the variable equivalent impedance of the inductive load, COMSOL Multiphysics finite element tool is employed [6]. On the one hand, electromagnetic frequency domain simulations are realized to model the dependence of the magnetic field level and frequency. This simulation is coupled with a thermal transient study to obtain the temperature-dependent characteristics, especially critical after surpassing the Curie temperature. Then, this equivalent model is implemented in Matlab/Simulink electrical simulations tool to perform of the power conversion stages behavior.

Experimental Validation

All the simulation models are experimentally tested on the induction hardening test bench of the laboratory of Ikerlan. For example, in Fig. 3 some simulation results are compared with experiments.

Conclusions

This work proposes a dynamic model based on electro-thermal simulations data to completely simulate IH processes. Electro-thermal models by

FEM have again resulted advantageous to reflect the non-linear behavior of the load.

REFERENCES

[1]. RUDNEV, V., LOVELESS, D., and COOK, R. Handbook of Induction Heating. *CRC Press*. 2017.

[2]. LUCIA, O., MAUSSION, P., DEDE, E. J., and BURDIO, J. M. Induction heating technology and its applications: past developments, current technology, and future challenges. *IEEE Transactions on Industrial Electronics*. 2014, 61(5), 2509-2520.

[3]. FISK, M., LINDGREN, L.E., DATCHARY, W., and DESHMUKH, V. Modelling of induction hardening in low alloy steels. *Finite Elements in Analysis and Design*. 2018, 144, 61-75.

[4]. SCHWENK, M., HOFFMEISTER, J., and SCHULZE, V. Experimental determination of process parameters and material data for numerical modeling of induction hardening. *Journal of Materials Engineering and Performance*. 2013, 22(7), 1861-1870.

[5]. MENDI-ALTUBE, A., VILLAR, I., CARRETERO, C., and ACERO, J. Dynamic DC-bus voltaje control of induction hardening system under load temperatures from ambient to beyond Curie point. *2024 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Long Beach: 2024, pp. 1669-1674.

[6]. MENDI-ALTUBE, A., VILLAR, I., CARRETERO, C., and ACERO, J. *Electro-thermal modeling of an induction heating process of 42CrMo4 steel probe.* International Journal of Applied Electromagnetics and Mechanics. 2024, 1-10, Preprint.

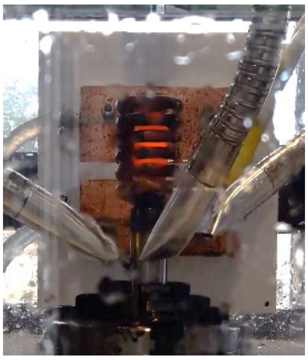

Figure 1. Inductive load's picture.

Table 1. Inductive load's geometry.

Parameter	Value	Unit.
Coil's turn number	6	
Coil's inner radius	15	mm
Turn inner diameter	4	mm
Turn outer diameter	6	mm
Distance between turns	9	mm
Billet radius	10	mm
Billet length	75	mm

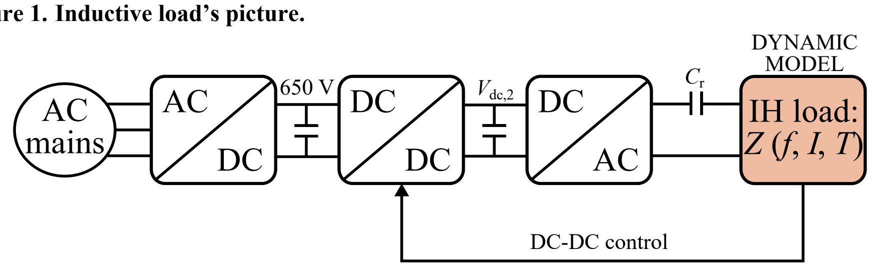

Figure 2. General diagram of the dynamic model.

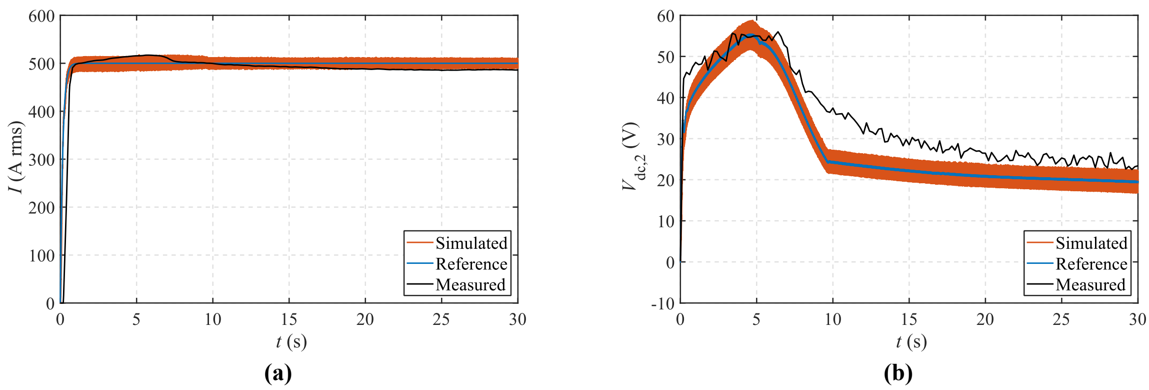

Figure 3. Simulation results vs experimental data: (a) rms current through the coil, and (b) regulated voltage in the second DC-bus.