Results of an Innovative 100kW Induction Heater Prototype Testing

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ABSTRACT

Industrial induction heating processes can contribute to the European Union (EU) energy saving goal of 20 percent before 2020. Induction manufacturers already propose many efficient solutions available at industrial scale. To improve induction devices for better energy efficiency, EDF R&D set up a French collaborative project called Innovative Solutions for Induction Systems (ISIS) with the financial support of the French National Research Agency (ANR).

The objective of ISIS is to promote induction heating as a best available technology (BAT) and to develop innovative solutions to increase its efficiency. This paper reports the ISIS project innovations. The paper also discusses about the efficient heat conversion from the induction heating devices through the use of new auto-adaptive multi-coil power supply with low losses coils. An important aspect of this project is the recovery of fatally lost heat energy (cooling of the inductors).

During the prototype testing, first the control algorithms of the multi-coil technology were successfully tested on a 100 kW 3-coils power supply. A homogenization technique is proposed to model a multi-strand coil and to use it in industrial setting. The multi-strand coils are now used only in low power residential applications such as induction cooking. A heat recovery test bench is built and equipped with a predictable function control (PFC) loop to fit with the production fluctuations. This paper also presents an analysis of the U.S. potential market for these new induction heating approaches and their applications in industries.

Induction Heating: Background

Induction heating is a method of providing fast and consistent heat for manufacturing applications that involve bonding or changing the properties of metals or other electrically-conductive materials. Induction heating may be used to replace a wide variety of conventional process heating methods, such as fossil/electric furnace heating, salt/lead bath heating, flame heating, and a variety of specialized brazing processes. All of these processes heat the outer surface of the workpiece. In contrast, induction heating heats deep inside the workpiece.

The induction heating process relies on induced electrical currents within the material to produce heat. The electromagnetic field is produced by applying current with a frequency of 60 Hz to 800 kHz to an inductor coil in proximity to the workpiece. Where the magnetic field intersects a workpiece made from any electrically conducting material, it generates a circulating current, which generates heat. The lower the frequency, the deeper the current penetrates into the workpiece. The basic components of an induction heating system are an AC power supply, induction coil, the workpiece (material to be heated or treated), and the cooling system.

Industrial induction heating power supplies cover a wide size range from approximately 1 to 3,000 kW of electric power. The size of the power supply depends on several variables, including the workpiece mass, the required temperature elevation, the specific heat and electrical properties of the workpiece, and the coupling efficiency of the coil design. In addition, thermal losses due to conduction, convection, and radiation must also be considered.

The AC power supplies utilize insulated-gate bipolar transistor (IGBT) or metal oxide semiconductor field-effect transistor (MOSFET) technologies. Advances in technology include the use of multiple microprocessors, rapid tuning, advanced controls, and an intuitive user interface. Depending upon the process and the workpiece, the power supply provides current to the coil only when heat is needed. Contrast that to batch ovens that operate continuously for hours at a time and heat more than just the workpiece.

The coil designs are carefully tailored for each workpiece. Figure 1 shows a circular coil design being used for induction hardening (EPRI 2007). In a sense, coil design for induction heating is built upon a large store of empirical data whose development springs from several simple inductor geometries such as solenoid, helical, pancake, and channel coils. Because of this, coil design is generally based on experience.

Figure 1. Copper Brazing of High-Pressure Steel Fitting Using Induction Heating—an Application That Is Often Done in a Batch Oven

The inductor is similar to a transformer primary, and the workpiece is equivalent to the transformer secondary. Therefore, several of the characteristics of transformers are useful in the development of guidelines for coil design. One of the most important features of transformers is the fact that the efficiency of coupling between the windings is inversely proportional to the square of the distance between them. In addition, the current in the primary of the transformer, multiplied by the number of primary turns, is equal to the current in the secondary, multiplied by the number of secondary turns.

Coil designs are based on the heating-pattern requirements of the application, the frequency, and the power-density requirements. In addition, the material-handling techniques to be used for production determine, to a large extent, the coil to be used. If a part is to be inserted in a coil, moved on a conveyor, or pushed end to end, or if the coil/heat station combination is to move onto the part, the coil design must take the appropriate handling requirements into consideration. Accordingly, a variety of specialty coil designs have evolved for specific applications.

Because of its low resistivity, fully annealed, high-conductivity copper is most commonly used in the fabrication of induction heating coils. The copper is typically in a tubular form, with a minimum outer diameter of 0.125 inch (0.32 cm) to allow for water cooling. Material of this kind is available in a wide range of cross sections (round, square, and rectangular) and sizes.

Cooling is normally required for the AC power supply and the coils to remove heat generated by the equipment. Due to the close proximity to the hot workpiece, the coils are manufactured from hollow tubes, and cooling water is circulated through the coils. The type of cooling equipment depends on the induction heating power level, the surrounding environment, and the temperature of the waste heat. The cooling equipment choices are water-to-air heat exchangers, water-to-water heat exchangers, and chillers.

Table 1 shows as example a typical power distribution in the case of a billet heating up to 1,200 °C (2,192 °F) using a 500 Hz thyristor inverter. Losses can be divided into two main categories: the electrical losses and the thermal losses. The column "Where" indicates in which cooling circuit the losses are collected. The two right columns give solutions to improve efficiency and their corresponding drawbacks. Solutions written *in italics* are the innovative solutions developed in the frame of ISIS project described below.

Table 1. Typical Power Distribution. Billet Heating up to 1,200°C, 500Hz Inverter

Origin		**How much**	**Where**	**How to improve**	**Drawback**
Electrical losses	Inverter losses	7 %	Inverter cooling circuit	Resonant inverter	
				Heat recovery	Low temperature requested
	Coil losses	19 %	Coil cooling circuit	Air-gap reduction	Thermal insulation reduced
				Multi-layer or *multi-strand configuration*	Cooling difficulties More expensive
				Adaptation to workpiece size (multi-coil)	Magnetic interaction between coils
Thermal losses	Workpiece radiative losses	4 %	Coil cooling circuit	Thermal insulation increase	Electrical efficiency reduced
				Heat recovery	Safety degraded
	Workpiece conductive losses	6 %	Mechanical support cooling circuit	*Heat recovery*	Safety degraded
	Useful energy	**64 %**	**Billet**		

In this paper an innovative auto-adaptive control strategy is discussed along with a prototype development and implementation at EDF laboratories. The prototype is a 100 kW 3-coil induction heater with auto-adaptive control algorithm. Expanding the coil structure to be a multi-stranded construction as opposed to the traditional single solid coil is also explained with successful test results. Finally the wasted heat recovery of this induction heating system that is currently in operation at EDF laboratory is explained in detail.

Innovative Solution for Induction Systems (ISIS)

EDF R&D is a key-player in the development of induction heating in France and in Europe for several decades and is working on energy saving solutions using induction (Paya, Pateau & Neau 2010). It set up a French project called ISIS (Innovative Solution for Induction Systems) together with French academic partners – SIMAP (Grenoble), LAPLACE (Toulouse), ARMINES (Paris) and CRISMAT (Caen) – and industrial partners – FIVES CELES (Mulhouse) and ATYS CONSULTANTS (Grenoble) – and supported by French Research National Agency (ANR).

Its primary objective is to favor the induction penetration in industrial sectors where it could be especially efficient. For that purpose, work was approached from three complementary points of view:

- The techno-economical research of induction heating penetration potentialities (EDF, ATYS). This analysis aims to identify processes where induction solution turns out relevant regarding energy efficiency. In particular it looks for implementation possibilities of ISIS innovative solutions.
- The improvement of electroheat conversion of induction heating devices. On the converter side, the project implements a flexible multi-coil supply, adapting itself to a wide variety of heated parts (LAPLACE, CELES, and EDF). On the inductor side, it develops multi-strand conductors with better energy performance than conventional coils (SIMAP, CELES, and EDF).
- The recovering of the fatally lost heat energy and its reuse, preferably in the process line (ARMINES, ATYS). This energy comes either from inductor cooling circuits (low or medium temperature energy) (EDF) or from already treated hot parts (high temperature energy) (CRISMAT, LAPLACE). The various temperature levels lead to different recovery strategies.

This project begun in December 2009 will last almost four years and aims to reach the industrial prototype level of the innovations.

Project Description

The scientific program is organized in five main tasks, each other independent, involving at least two or three partners and lasting the all duration of the project.

The first task “analysis of induction potential diffusion” aims to identify processes for which an induction solution may be relevant in term of energy efficiency. Diffusion of innovative solutions developed in the other project tasks is also analyzed.

The next two tasks study technical developments of induction heating solution regarding the improvement of energy consumption. In that way, the task “realization of an auto-adaptive multi-coils power supply” aims to design a flexible power supply able to energize many coils in mutual interaction and driving the coils’ current to adapt the heater to a large range of heated pieces. Preliminary works were done before, both on the inverter technology (Manot 2013; Souley et al. 2009; Souley et al. 2010 a) and on a multi-coil configuration (Forzan et al. 2010). The aim of this task is to reach a semi-industrial scale. The task “development of low losses inductors” develops multi-strands solutions having better performance than conventional coils. This work aims to extend the relevance of the CELINE™ concept to higher frequency range (up to 400 kHz).

The last two tasks deal with heat recovery on and around induction process. The task “heat recovery on induction heating losses” studies the pieces of equipment to be added on existing cooling systems to recover the fatal coil losses. Preliminary studies (Paya 2008; Paya, Gheorghe & Tudorache 2009) show that it is possible to use high fluid temperature (above 90

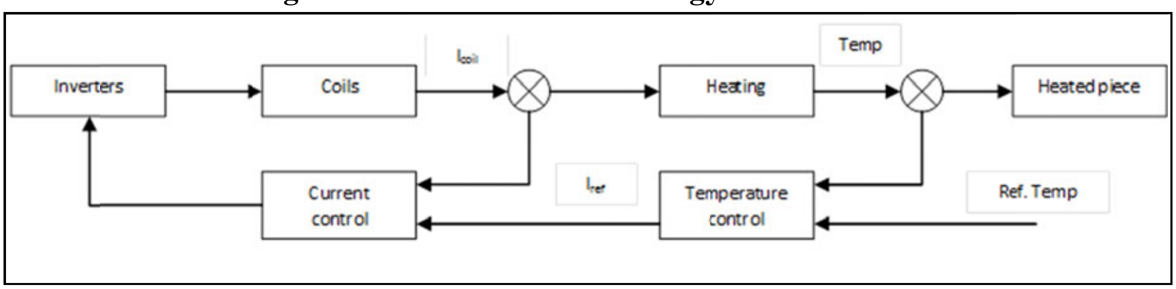
°C) without damaging the energy efficiency. The task "heat recovery on already treated hot parts" aims to recycle the energy collected by the piece during its heat treatment for other uses such as semi-product preheating before induction heating. This may be particularly relevant on induction heating lines due to high parts temperature at the end of the line (typically 600 to 800 °C).

Laboratory Testing: Description and Results

Auto-adaptive multi-coil power supply prototype description. To control the current injected, each coil is energized by a specific inverter. All the inverters work at the same frequency, but current amplitude and phase may vary. The control of the multi-coil system is organized in two interlinked loops (see Figure 2).

The outer loop controls the temperature profile and determines the reference current value for each coil. The inner loop controls the current injected in each coil by comparison with a reference value given by the outer loop. To achieve that, a full electromagnetic, thermal and power electronic modeling was developed by LAPLACE (Souley et al.2010 b).

Figure 2. Schematics and Strategy of the Multi-coil Control



The current control requires the knowledge of the impedance matrix of the multi-coil system that can be evaluated either by measurement or by a 2D or 3D electromagnetic numerical model. This impedance matrix is introduced into the power electronic model which gives in return the driving sequences of switches or gate control signals. These sequences have been successfully implemented into a 100 kW induction heater. Figure 3 shows the picture of the 100 kW 3 coil power supply prototype built and operational at the EDF laboratory that implements the auto-adaptive multi-coil control strategy.

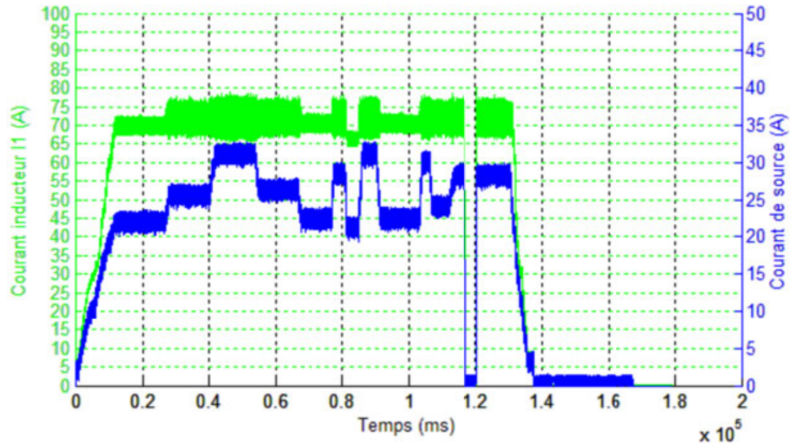
Figure 3. Model of Multi-coil Power Supply and Inductors with Three Associated Coils

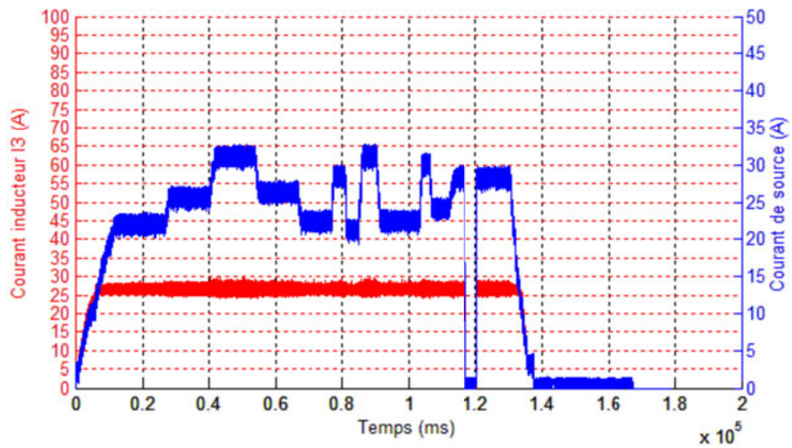
Figure 4 shows the experimental results of the auto-adaptive multi-coil control power supply testing. The x-axis represents the time in milli-seconds while the y-axis represents the magnitude of current going through each coil. The source current, phase – 1 and phase – 3 current magnitudes are shown in Figure 4. Key highlight of the waveforms shown in Figure 4 is that the current magnitude in each of the pairs of phases are varied to meet the specific heat requirements of the object to be heated which is not obtained in traditional control strategies.

The temperature control requires the knowledge of the normalized induced currents generated by each coil separately and evaluated by a 2D or 3D electromagnetic model; the global induced current distribution is then determined by superimposition of the elementary induced current's distribution. The thermal problem is modeled directly inside the power electronic model and gives in return the values of the reference currents to be put into each coil. The temperature control loop has been already tested numerically.

Experimental validation in a large setting is in progress since January 2013 on a 600 kW facility implemented at Fives Celes premises. For that purpose, Fives Celes has developed a new driving card able to control the inverter bridges. Numerical capacities (memory, fast calculations) have been increased to host the control loops software. Each slave card dedicated to an inverter hosts the corresponding current loop and the master card hosts the temperature loop. Fast communication busses at basket bottom allow data transfer between the cards.

Figure 4. Experimental Result of the Multi-coil Current Control (Source Current (Blue), Phase 1 (Green), Phase 3 (Red))





Low losses multi-strand coils. The multi-strand configuration of coil conductor, commonly called Litz wire, is widely used in small power devices such as domestic induction cooking systems.

Its extrapolation to high power industrial applications requires paying attention to the coil cooling. Thus, it is necessary to have a good evaluation of the Joule losses in the windings. Finite elements numerical models quickly reach their limits if several thousands of strands are finely meshed.

First simulations were realized by SIMAP with a small number of strands. 2D modeling (see Figure 5 and Figure 6) shows a current distribution among the conductors looking like a global skin effect. In the Figures 5 and 6 the colors correspond to the temperature of the coils, blue representing cold and red representing hot.

Figure 5. Joule Losses in the Multi-strands Wire – 49 Strands Wire

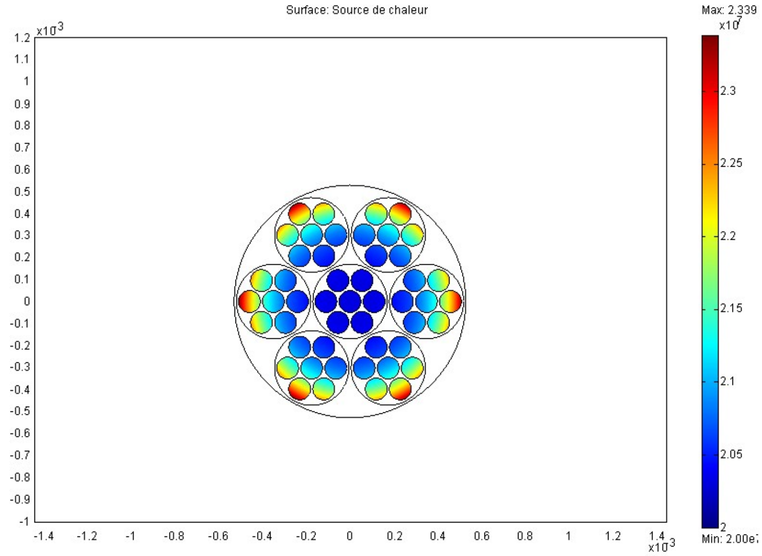
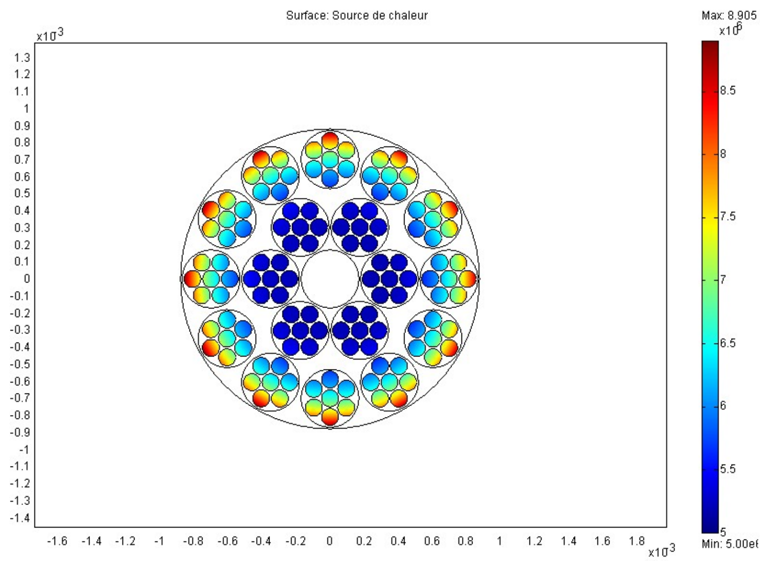
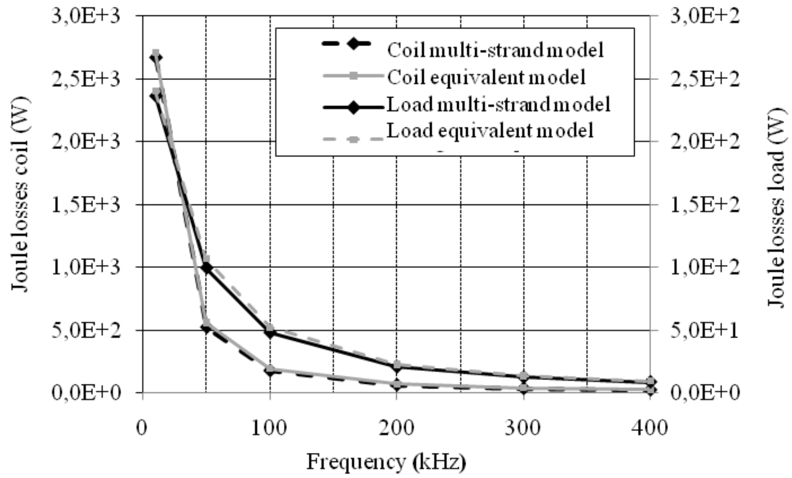


Figure 6. Joule Losses in the Multi-strands Wire – 126 Strands Wire



To evaluate the global Joule losses in the composite wire, SIMAP has proposed a homogenization technique (Scapolan, Gagnoud & Du Terrail 2012) the multi-stands coil is approximated by an equivalent electrical resistivity applied to the global cross section of the wire. Simulations of an aluminum bar heating with a homogeneous model and with the fine multi-strand coil models are in agreement in a wide frequency range (see Figure 7). The significant conclusion drawn from this simulation as see in Figure 7 is that the multi-stranded coils can be approximated to a solid metal coil with equal cross section area.

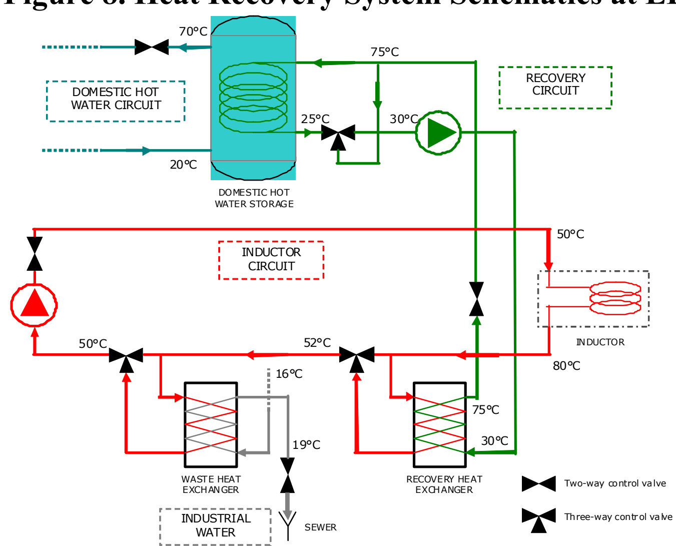
Figure 7. Comparison between the Homogeneous Model and the Multi-coil on Joule Losses in the Coil and the Load



Heat recovery. A heat energy recovering system using heat exchangers is in operation in EDF laboratory since 2010.

The main goal of the heat recovery test bench is to test and quantify in industrial conditions the heat energy to be recovered coming from the coil cooling circuit. Figure 8 shows the schematics of the test bench and provide the main functions of the bench. The test bench is made up of two heat exchangers which can be by-passed according to the control and regulation system. The "recovery heat exchanger" collects the heat to be recovered and transfers it to the reuse, the recovery circuit simulator. For our test bench, this simulator is a 300 liters (79 liquid gallons) water tank ("domestic hot water storage") which can store the collected energy.

Figure 8. Heat Recovery System Schematics at EDF



The "waste heat exchanger" evacuates the remained energy to ensure a safe use of the induction heating device. These two exchangers are designed for 100 kW. The water flow is obtained by two pumps and their associated valve, the smallest for the range 0.3 – 2 cubic meters per hour or m^3/h (equal to 1.32 – 8.81 gallons per minute or gpm) and the biggest for 1.5 – 9

m^3/h (equal to 6.61-39.6 gpm) water flow rate. Many temperature and flow-meter sensors are implemented in different locations to evaluate the energy balance or for driving the test bench.

A "Predictable Function Control" (PFC) regulation has been implemented to drive the bench. This system is more efficient compared to a conventional PID controller. Because of the precise modeling of the bench parts and the induction device, it is possible to anticipate disturbances (such as induction power fluctuations) and adapt the heat recovery in order to always work in a safe way. As an example, we have simulated the load curve of a melting workshop. During the melting process, the crucible works at full power during the melting phase, at reduced power during the elaboration or temperature holding phases and is switched off during loading and casting phases.

Induction Heating: Applications and Market Study

Electric induction heating and melting can increase productivity and reduce energy use, depending on the baseline technology it replaces. Likewise, the simple payback period for this technology will vary according to the technology replaced, but it can be as short as one year when used instead of equipment such as fossil-fuel batch ovens. Applications of induction heating and melting have enabled energy cost savings of 20–30% by users, per examples cited below, and productivity has increased in example applications as well.

There are many applications of induction heating, which includes but not limited to the following:

- Brazing, bonding, soldering, and welding
- Curing of coatings
- Electromagnetic stirring and casting
- General purpose heating and preheating
- Heat treating (includes hardening, annealing, tempering, and stress relieving)
- Heating of non-conductive materials using a conductive susceptor (usually a metal interface)
- Levitation melting
- Melting
- Shrink fitting and press fitting

A new application of induction heating is a non-contact system for the heating barrels used with plastics molding and extrusion machines developed by Xaloy, Inc. (EPRI 2007). They have demonstrated that induction barrel heating with an interposed insulating layer increases barrel heating efficiency to around 95% from typically 40 to 60% with band-heaters. By virtually eliminating the thermal mass of the heating system, induction accelerates temperature response to seconds (versus minutes with band-heaters), which greatly improves control predictability and reduces the sensitivity of control performance to thermocouple depth. In addition, induction heaters are more reliable than band heaters, and can typically provide three times the heat flow into the barrel.

Depending upon the size and application, the capital cost of the induction heating systems can range from under $8,000 to over $1 million. The smallest systems generally cost around $8,000/kW while the largest systems are perhaps $1,000/kW (EPRI 2007). Maintenance costs are usually lower than the alternatives due to the reliability of solid-state electronics and minimal moving parts. The potential payback when replacing batch ovens burning fossil fuels is often about a year.

Ameritherm, Inc. was the first North American manufacturer to introduce all solid-state induction heating RF power supply technology in 1986. At least a dozen vendors now offer solid-state induction heating equipment for a wide variety of applications as shown in Table 2. Equipment specifically tailored to new applications is continuously under development.

Table 2. Partial List of Induction Heating Manufacturers in USA

Manufacturer		Description
Ajax Tocco Magnethermic© Corporation	1745 Overland Avenue Warren, OH 44482 800.547.1527 www.ajaxtocco.com	Ajax Tocco designs and manufactures induction heating and melting equipment for various industries and applications. The equipment includes induction coils, ovens, and power supplies.
Ameritherm©	39 Main Street Scottsville, NY 14546 585.889.9000 www.ameritherm.com	Ameritherm© manufactures micro-processor based RF induction heating equipment. Ameritherm© offers free evaluation of customer parts to allow a precise recommendation of the proper induction heating system for the applications.
Eldec Induction U.S.A.	3355 Bald Mountain Rd., Unit 30 Auburn Hills, MI 48326 248.364.4750 www.eldec-usa.com	Eldec manufactures systems for induction heating used in various applications including hardening, brazing, annealing and tempering, shrink joining as well as removal, and many other areas.
Induction Atmospheres LLC	35 Industrial Park Circle Rochester, NY 14624 585.368.2120 www.inductionatmospheres.com	Induction Atmospheres designs and builds turnkey induction heating solutions for continuous flow manufacturing. They evaluate customer parts and process requirements in their laboratory to determine the optimum induction heating system that matches the process requirements.
Induction Systems, Inc.	209 Travis Lane Waukesha, WI 53189 888.856.2096 www.inductionsystemsinc.com	Induction Systems offers the latest technology in heat treating scanners, power supplies, billet heating, custom heat treating systems, water systems, and quality monitor systems, as well as servicing all types and makes of induction equipment.
Inductoheat, Inc.	32251 North Avis Dr. Madison Heights, MI 48071 800.624.6297 www.ihs-usa.com	Inductoheat builds induction heating equipment for case hardening, tempering, annealing, bonding, brazing, strip/slab heating, galvanic annealing, and other applications.
Inductotherm Corp.	10 Indel Ave. Rancocas, NJ 08073 888.463.8286 www.inductotherm.com	Inductotherm manufactures coreless and channel-type induction furnaces, and induction melting, holding, heating and pouring systems for virtually all metals. Furnace capabilities range from coffee cup size melting a few troy ounces of precious metals to furnaces holding hundreds of tons of iron. Induction power supply systems that accompany these furnaces range in size from 20 kW to 42,000 kW.

Manufacturer		Description
Pillar Induction Co.	21905 Gateway Road Brookfield, WI 53045 800.558.7733 www.pillar.com	Pillar products include solid state power supplies, prototype/production heat treating systems, and specialized total induction solutions. Applications of Pillar products range from induction annealing, hardening, tempering, drying, through heating, brazing, melting, and coating.
Radyne Corp.	211 West Boden St. Milwaukee, WI 53207 800.236.8360 www.radyne.com	Radyne designs, manufactures, and sells advanced induction power supplies, induction coils, heat stations, coils, scanning systems, brazing systems, wire, rod, and cable processing systems, pipe coating systems, and systems for process automation.
RDO Enterprises	50 East Johnston St. Washington, NJ 07882 908.835.7222 www.rdoent.com	ROD Induction offers induction systems for induction heating, induction casting equipment for dental, jewelry and industrial casting trades (titanium), induction melting systems with tilt-pour furnaces (from 5 to 200 kW in power) for all metal melting industries, stand-alone induction melting equipment for small lot melting (precious metal melting and industrial alloys), and micro-welding equipment for ferrous, non-ferrous and titanium alloys.
Taylor-Winfield Corp.	Hubbard-Thomas Road Brookfield, OH 44403 330.448.4464 www.taylor-winfield.com	Taylor-Winfield offers a variety of induction heating power supplies for various induction heating applications, process automation (work stations, scanners, automated systems), support services and a development laboratory.
Trithor GmbH and Bültmann GmbH represented in the U.S. by SC Power Systems	999 Baker Way, Suite 150 San Mateo, CA 94404 415.407.2366 www.scpowersystems.com	SC Power Systems specializes in high-temperature superconducting (HTS) products, including induction heaters using 1G and 2G HTS wires, current leads, and coils. Trithor's HTS induction heaters are available in standard sizes of 0.25 MW and 2 MW; they reduce energy use by almost half compared to conventional induction heating.
Xaloy	1399 County Line Road New Castle, Pennsylvania 16107 724.656.5600 www.xaloy.com	Xaloy is a manufacturer of high-performance machinery components and equipment for the plastics industry, such as injection molding, extrusion, and other processes. One such product line heats the barrel of injection molding machines by induction heating, which cuts energy costs and improves temperature control compared with conventional heater bands.

Conclusion

Technological innovations of efficient induction solutions are discussed in this paper, namely, flexible multi-coil power supply with current control for each coil, development of a multi-strand conductor for industrial induction heating, energy recovery on coil cooling water with "Predictable Function Control" (PFC). New numerical models are developed and adapted to the various needs: simplified multi-coil model for power electronic control, homogenization technique for multi-strand wire. Work is on going to reach industrial applications within 2014.

Acknowledgement

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