Next Generation High Efficiency Non-Ferrous Electric Induction Billet Heater

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Introduction

When consistency, repeatability, and accuracy are essential to ongoing process control and efficiency, electric induction heating is the clear and logical choice. Recent progressive developments for this equipment include innovative, 60Hz or 50Hz line frequency electric induction billet heaters. By utilizing breakthrough developments in winding design, these new heaters can save extruders 23% or more over a conventional induction heater's average electricity cost. Over a 25-year equipment lifetime, this operational cost reduction could add up to an estimated $1.4 million in savings. Utilizing solid-state power control, these units have no moving power control parts or expendable vacuum bottles and do not generate harmonics. Based on simplicity, durability, and reliability to minimize downtime, these units offer a clear and logical choice when electric induction heating for process consistency, repeatability, and accuracy are required.

This paper will briefly review the history and evolution of the line frequency electric induction billet heater, the challenges and development of next generation high efficiency line frequency heaters, and the results of a high efficiency heater in operation. Application of the high efficiency unit as a single heating source and as a hybrid gas and electric combination will also be discussed.

History & Evolution

Electric induction heating of non-ferrous materials utilizing 60Hz or 50Hz, with one- or three-phase power became commercially common beginning in the late 1940s. The units were simple, reliable, and durable—with some of the original units still in operation. Conventional style units built in the late 1950s have recently been updated, refurbished, and shipped as far as Eastern Europe.

Although the original units definitely were durable, materials and technology have evolved. When this equipment was originally supplied, electricity was cheap by today's standards, and utility companies did not aggressively monitor demand and power factors. Designed power factors were also poor by today's standards, and materials that were commonplace then are considered hazardous today.

One of the inherent advantages that has become apparent over the decades is the utilization of three-phase power in these induction heating units. During extrusion, heat builds up in aluminum billets due to friction. Introducing three-phase power allows for a precisely controlled temperature reduction in the tail of the billet to accommodate for the inherent extrusion process heat buildup, providing repeatability and quality. In other words, it provides variable taper heating along the length of the billet, while maintaining simplicity and reliability.

New conventional-style, three-phase, line frequency billet heaters utilizing advanced materials and technology are still being supplied today. High maintenance items, such as electromechanical contactors, have been eliminated. Early units in a time of low energy costs corrected to a 0.85 lag power factor. This has since evolved to 0.98 lag or better. Simple, basic tuning at startup should be followed to confirm this. Improper tuning can result in poor power factor correction, causing high current surges at the beginning of the heat cycle, and can cause excessive utility demand and reactive demand charges. In addition, vacuum contactors are frequently utilized to replace electromechanical contactor units in these conventional style units in both new and retrofit applications.

Figure 1. Example of a modern induction billet heater. (Photo: Induction Professionals.)

New, modern units operate at a nominal 50% system efficiency (Figure 1). As with any system, proper initial setup and operating procedures are important for optimizing system efficiency. Since these new units do not generate harmonics, there is no power distortion, no potential ancillary equipment damage, and no risk of harmonics being introduced into the plant or utility power distribution networks.

Challenges

Induction heating involves the production of an electromagnetic field in a coil in order to create thermal energy to heat a billet. The coils in induction heaters can be wound in single or multiple layers.

The coil currents in a classic, single layer winding required to meet press production rates can be 4,000–6,000 amps. The design of the coil must include sufficient and proper water cooling to dissipate the heat generated from energy losses at these current levels. This cooling capacity requirement is an important indirect cost. In addition, the durability and longevity of these units requires repairs, which are often attempted by inexpert entities. High current densities, improper materials, and sub-standard workmanship can lead to major failures (Figure 2).

Figure 2. Conventional coil winding failure after improper repair.

It is also common knowledge that increasing the number of mechanical turns in the same area of the coil will decrease the current density per turn. When this principle is applied to induction heating coils in the form of multi-layer coil windings, other challenges are faced. In multi-layer windings, the challenge of high currents is replaced by higher voltages, as well as the need to maintain water flow and quality in long runs with small openings. The payback is in lower winding and transmission losses at 1,000–1,500 amp winding currents. Additionally, these lower coil currents generate lower energy losses, and therefore heat, than single layer windings and as a result require less cooling.

Although less than the total required for single-layer windings, the design of the multi-layer coil must still include sufficient and proper water cooling. The inherent mechanical requirements of the multi-layer coil winding create small water passages. These small water passages place a premium on maintaining proper water quality. When this quality is not maintained, major failures can occur (Figure 3).

Temperature control options historically have involved adjusting the timing of the heating cycle and contact thermocouples, which either connect directly to a temperature control device or a PLC T/C card, or feed back to a PLC temperature control program. Controlling the timing of the heating cycle alone does not account for variations in line supply voltage and is inexact. Contact T/Cs have ongoing maintenance requirements, as well as presenting additional considerations. The coil openings for the contact T/Cs actually weaken the magnetic field at the areas of the openings, adding complexity to control requirements and increasing coil manufacturing complexity. Alternatively, taper heating requirements, repeatability, quality considerations, and not overheating more sensitive alloys can be addressed by measuring coil section energy inputs.

Figure 3. Multi-layer coil failure.

Modern High Efficiency Heaters

Maximum efficient utilization of resources is a major challenge faced by aluminum manufacturers today. In turn, providing extruders with the tools to maximize billet per month output at minimum energy input is a challenge for billet heating equipment suppliers. Quality, repeatability, uptime, and maintenance costs are also important considerations.

Recent progressive induction heating equipment addresses these challenges with innovative high efficiency, cost saving, simple, durable heaters. Utilizing state-of-the-art materials and manufacturing processes for maximum durability, the coils feature innovative winding designs that offer increased electrical efficiency compared to other existing designs. The conductor utilized in the winding is configured to return what is normally waste flux (energy) back into the winding and, therefore, the billet.

These winding designs provide significantly reduced coil currents—1,000–1,500 coil amps vs. 4,000–6000 coil amps in a conventional three-phase line frequency billet heater. Lower coil currents equate to less winding stress, longer coil life, and less waste energy. Because less energy is wasted, the high efficiency coil generates less heating of the water, and as a result less cooling capacity is required. This yields a more than 23% reduction in energy used for the same production as a conventional induction billet heater. These high efficiency induction heater systems typically bump system efficiency at the power company's meter from 50% to 65%.

Solid-state power control is used for modern induction heaters. These switches have no moving parts or expendable vacuum bottles, and they introduce no harmonics into plant and utility power distribution networks. Reliability is increased because electromechanical contactors and vacuum contactors cannot control the timing required to deal with transformer and capacitor inrush currents. These inrush currents cause failures of these types of contactors. Solid-state power control switches are designed for these requirements.

These modern induction heating units and savings are not complicated—less energy is used for the same production, less components in the system equates to higher efficiency, lower installed cost, smaller installed footprint, and lower spare parts costs.

Production Application

After extensive development testing and field trials, a prototype induction heating unit was commissioned in December 2015 (Figure 4). Full production began immediately after completion of mechanical and electrical assembly. Prior to startup, a minimum 23% reduction in system efficiency energy usage was guaranteed. Actual results, depending on alloy, were up to 27%.

Subsequent to initial de-bugging, the prototype coil operated 24 hours a day, 350+ days per year for three years. There was no coil failure. Cleaning and preventive maintenance were done during the opportunity of a press maintenance shutdown after three years.

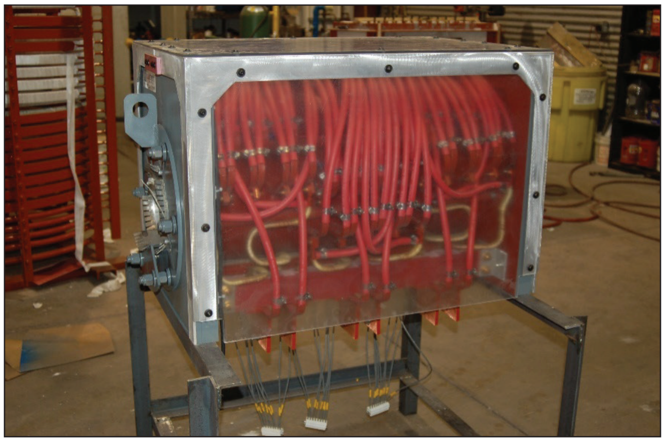

Figure 4. Prototype high efficiency coil.

Heat Time	73 seconds
Total Measured kW Seconds (at heater input)	29,415.51
kW Seconds per Pound	179.044
Average kW Paid for at Heater Input (based on kW seconds/heat time)	402.95
kW Seconds Required to Heat Billet (based on kW seconds per pound x billet weight)	20,411.02
Efficiency (based on kW seconds to heat billet/ average kW paid for at heater input)	0.694

Table I. Efficiency calculation method used for the high efficiency heater, evaluating a 114 lb billet heated from ambient temperature to a mean temperature of 775°F at the discharge end of the billet.

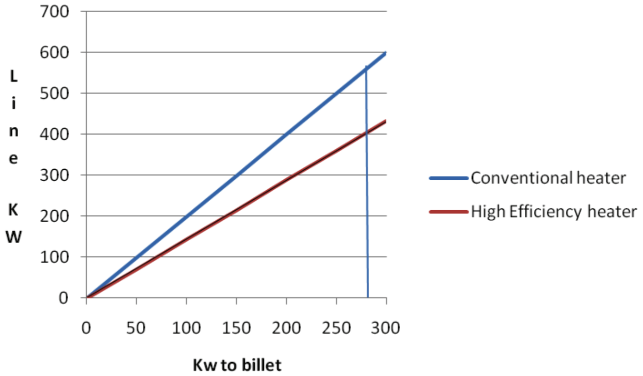

Figure 5. Comparison of kW used for the processing of billet using a conventional versus high efficiency induction heater with same final billet temperature.

Measuring Efficiency

It is common for OEM induction heating equipment suppliers to provide system efficiency ratings based on the induction heating coil. These ratings ignore the losses in frequency conversion solid-state power supplies. They also ignore losses in specially designed, costly, high impedance input transformers that need to be installed ahead of the power supply connection to the main incoming power to minimize power distortion and harmonics.

The efficiency ratings of the modern induction heaters previously described are based on system efficiencies. They are measured at the system input—the power company meter. Electricity is purchased based on the power consumed by the entire system, not just at the coil. This is an extremely important point, directly relevant to the bottom line of any extruder that should not be overlooked.

The calculation method used to determine the efficiency ratings for the prototype induction heating system was based on how much energy is required to heat a specific size billet from a specific starting temperature to the final desired temperature (Table I). The energy required (in kilowatt seconds) to heat the billet is always the same, whether the coil is a conventional design or high efficiency. To review briefly, the starting point is a 114 lb billet (1235LO alloy, with 99.35% Al, 0.3% Fe, and 0.1% Zn), heated from ambient to a mean temperature (not surface temperature) of 775°F at the discharge end of the billet. The billet temperature was measured by the heater's contact thermocouple for both the conventional and high efficiency coil. The high efficiency coil used more than 132 less kW at the heater input for the same results, more than 23% less kW than the conventional coil.

Using the data presented in Table I, the prototype high efficiency heater can be compared to a conventional system. The data from the conventional system, considering the same billet parameters, showed 535 kW paid for at the heater input, with approximately a 50% efficiency equivalent to 268 kW used to heat the billet. In comparison, the prototype heater showed 402.95 kW at heater input, with approximately a 69.4% efficiency equivalent to 279.7 kW to heat the billet. This means that for the same alloy and the same mean temperature at the discharge end of billet, the high efficiency heater will use 132.05 less kW at the heater input to do the same level of heating (Figure 5).

The authors note that energy costs vary widely in different areas. The dollar figures in this paper are illustrations only. The directly relevant point to the bottom line of any extruder is the percentage of savings. It is difficult to know the actual specific cost to heat a billet for every extruder. However, it is possible to know the actual specific cost to heat a billet will be over 23% less using the high efficiency heater, based on using less kW at the system input for the same results.

An illustration of cumulative savings of using a modern induction heater (such as the prototype mentioned) compared to a conventional heater is presented in Table II. The example is based on heating a 114 lb (7 x 30 inch) billet heated from 70°F to 850°F, with the billet sitting in the coil at power off. The illustration assumes a 50% efficiency for a conventional coil and a projected 65% efficiency for modern high efficiency coil.

Energy efficiency data is measured at the power input of the heater, with the data measured on a full coil basis. Overall electricity cost in Table II is estimated at 7.9 cents per kWh, with an electricity-only cost of $1.00 per billet for a conventional coil and a $0.77 per billet cost for the modern, high efficiency coil. As the table shows, the yearly savings of using a modern induction heater over a conventional heater (based on electricity cost per billet) is $57,408. Over a 25 year period of the equipment's operational lifespan, this would result in a savings of around $1.44 million.

Electricity Charges and Harmonics

The cost of energy demand charges and harmonics are often overlooked, even though both directly impact the energy cost bottom line. Either of these subjects could be a topic for a separate paper. Nonetheless, as previously noted, the high efficiency heater minimizes demand charges and generates no harmonics. Therefore, these costs savings will be briefly discussed.

Energy and Demand Charges: Electric bills have two components: energy charges and demand charges. Demand is the power draw from the utility at any one time, typically in kW. Energy is the accumulation of power over a period of time, typically measured in kWh. For example,

Conventional Induction Heater
40 billets/hour x $1.00/billet = $ 40.00/hour
$40.00/hour x 20 hours/day = $800.00/day
$800.00/day x 6 days/week = $4,800.00/week
$4,800.00/week x 52 weeks/year = $249,600.00/year

Modern High Efficiency Induction Heater
40 billets/hour x $0.77/billet = $30.80/hour
$30.80/hour x 20 hours/day = $616.00/day
$616.00/day x 6 days/week = $3,696.00/week
$3969.00/week x 52 weeks/year = $192,192.00/year

Yearly Cost Comparison	
Conventional Heater	$249,600
Modern Heater	$192,192
Savings (based on electricity cost per billet)	**$57,408**

Table II. Projected yearly cost for operating a conventional induction heater versus a modern high efficiency induction heater.

a load that draws 600 kW running for a half hour would accumulate 300 kWh, while a load that draws 300 kW running for a full hour would also draw 300 kWh. Both of these would incur the same energy charge of 300 kWh, but the first load would have a demand charge of 600 kW, while the second would only get charged for 300 kW.

An illustration of what might be paid in electric bills for a heater is presented here. To simplify the math, assume that a conventional heater draws 600 kW and takes one minute to deliver a billet. This then accumulates 600 kW x (1/60 hours) = 10 kWh. Assuming an energy charge of $0.07/kWh, the billet costs $0.70 to process.

In comparison, the high efficiency heater would only require 462 kW (23% less kW) to heat this same billet. The energy cost for this billet would then be 462 kW x (1/60 hours) x ($0.07/kWh) = $0.539 to process a billet.

Demand charges are a one-time charge each month based on the highest demand measured during a specific time interval defined by the utility that month. Again, to simplify the math, assume the conventional heater delivers 40 billets per hour, operates six hours per shift and 15 shifts per week. After one month, the conventional heater will have delivered 14,400 billets, with an energy charge of $10,080. On the other hand, the high efficiency heater would have a charge of $7,761.60 for the same amount of billet.

Assuming the demand charge (sometimes called capacity charge) is $12.00/kW, the conventional heater would have a monthly demand charge of $7,200. However, the monthly demand charge for the high efficiency heater would be only $5,544.

With all of this information in mind, it can be determined that the total electric bill per month would be $18,000 for the conventional heater and $13,305.60 for the high efficiency heater (Figure 6).

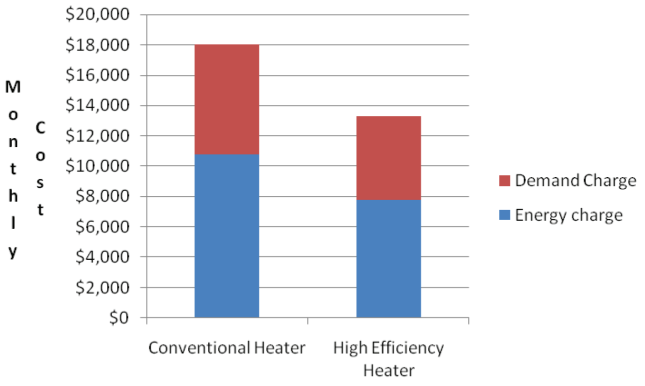

Figure 6. Comparison of illustrative monthly energy cost for a conventional versus high efficiency heater.

Harmonics: Electric utilities naturally supply voltage and current in a sinusoidal form. A billet heater in its simplest form (conventional or high efficiency) is comprised of a transformer, a heating coil, and probably capacitors. These are linear devices, which means they only draw sinusoidal currents. The heater is typically controlled by an electromechanical contactor, vacuum contactor, or solid-state contactor. These are essentially on-off switches that ensure the power is either off or on at full power when using sinusoidal currents.

Some heaters use a solid-state power supply. The advantages are that they can have soft start and very fine control of voltage and power in each section of the heating coil. These power supplies, however, will have a rectifier front end. This means that they will draw current from the utility in blocks of square wave current. Mathematically, these square wave currents can be represented as the sum of higher frequency sinusoidal currents. Essentially, a typical rectifier current is a sum of currents at the fundamental frequency (60 Hz), as well as at the 5th harmonic (300 Hz), 7th harmonic (420 Hz), 11th harmonic (660 Hz), 13th harmonic (780 Hz), and so on. Since these higher frequencies are always integer multiples of the fundamental frequency, they are termed "harmonics." Representing these square waves by sinusoids makes it easy for the utility to calculate where the higher frequency harmonic currents travel on their distribution system.

A power supply with a rectifier causes high frequency harmonic currents to flow on the utility's system. This is a problem for the utility because these harmonics cause extra heating or damage to their transformers and capacitors. This extra heating is wasted energy that they have to supply, increasing their costs. Also, harmonics can cause distortions in the system voltage, which creates problems for any other electronic equipment connected to the utility.

There is no direct charge for harmonics, since they measure this as a reduced power factor. However, the utility will have limits on the generation of harmonics (probably referenced to IEEE-519 standard).

A typical input power factor to a rectifier is 0.93 lag. The kilovolt-amp (kVA) that the utility measures then is kW/0.93. For example, a 600 kW system would have a kVA of 600/0.93, which is equivalent to 645 kVA. In general, demand charges are actually based on kVA not kW. Assuming a demand charge of $12/kVA, operating a power supply of 645 kVA would cost an extra $540 per month.

Summary

Modern high efficiency line frequency induction billet heaters offer a simple, durable, and economical method to precisely heat billet as dictated by the extruder's process. The heating pattern and cycle are continuously repeatable thereby also offering increased quality and process control. The design innovations now available offer significant electrical utility cost savings. These cost savings are achieved on every billet, every shift, every day, every week, and every year. Design simplicity and durability provide increased uptime and reduced maintenance costs. This technology is applicable both as a single heating source and as a hybrid gas and electric combination. ■