RESEARCH ARTICLE OPEN ACCESS

Experimental Analysis of Total Harmonic Distortion in Induction Melting Furnace during Iron Scrap Charging Melting in Steel Industry

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ABSTRACT
The widespread adoption of Induction Melting Furnaces (IMF) worldwide in the past decade has raised concerns about power quality. Power quality is becoming a significant issue for both electric utilities and consumers due to the prevalent use of non-linear loads like IMF in steel plants. In steel industry, the IMF's melting cycle involves stages like scrap charging, melting, refining, alloy addition, and molten metal holding before casting. These processes cause fluctuations in the electrical parameters of the IMF's power converter system, impacting grid supply power quality. This paper explores the impact of harmonics generated by the Induction Melting Furnace (IMF) system on grid supply power quality. The analysis focuses on line current during various stages of the melting process, with particular attention to the iron scrap charging phase. Load patterns during this stage are investigated using a combination of simulations and real-world field data. The simulated results are validated against experiments conducted on an operational IMF system in a steel plant, demonstrating a close match between the two. This alignment between simulation and experimentation underscores the significance of this research for those designing harmonic mitigation systems and offers valuable insights into improving power quality in such industrial sceneries.
Keywords - Grid, Harmonics, Induction melting furnace, Inverters, Power Converters, Power quality

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I. INTRODUCTION

The IMF systems are gaining popularity in the steel industry due to cost-efficiency, rapid Returns on investment, and added benefits like surface stirring and alloy incorporation. The power supply unit consists of AC-DC-AC converters, often configured as 12 Pulse, with current source inverters in high-power setups. A capacitor bank maintains parallel resonance, supplying reactive current to the furnace coil. While IMF systems enhance steel plant productivity, they negatively impact the power grid's quality. Fluctuating operational impedance leads to varying resonance frequencies, causing harmonic distortion in the supply current, degrading the power grid's quality. Despite these drawbacks, IMF systems offer significant advantages in steel production [1-3]. Coreless induction furnaces are versatile, efficient tools for melting and alloying various metals, including copper and aluminium, with minimal melt losses. They are also employed for melting all grades of steel and iron. These furnaces offer rapid heating, excellent electrical efficiency, minimal melting loss, and simple operation and maintenance [4-6]. During the scrap charging stage of melting process, there is a change in the inductance value of the furnace coil. Since the furnace coil is a part of LC tank circuit, the change in the furnace coil inductance changes the resonance frequency of the inverter. This gives rise to the inter-harmonic distortion in the supply line current of the distribution grid. Hence, the correction on both sides of CSI-SCR based converter distorts the quality of the distribution grid's power [7]. Contemporary electronically-controlled coreless induction furnaces, functioning within the medium frequency range, present a unique challenge as nonlinear and time-varying loads. They possess the capability to generate a diverse spectrum of conducted electromagnetic disturbances, which can potentially lead to significant issues within electric power distribution systems [8-9]. The study delves into the characteristics of IMF systems and their impact through harmonics injection, extensively discussed in [10-11], resulting in voltage distortions within the grid and utility systems, as comprehensively detailed in [12-13]. The dynamic generation of unusual harmonics stems from cross modulation within the AC-DC-AC system of IMF within steel plants. Multiple melting cycles provide extensive field data, corroborating simulated results with real-world IMF operations. Investigative efforts target the root causes of harmonics and inter-harmonics originating from IMF systems. Field measurements employ a Fluke power quality analyzer, adhering to IEC 61000-4-30 standards for power quality parameter analysis [14]. This paper sequentially explores IMF system configurations, Scrap charging and its effect on refractory erosion in Section II. Real-time field data and simulations model with system parameters are presented in section III. Section IV compares the results and the detail discussion on results is done in Section V. Section VI concludes the paper.

II. ELECTRICAL CONFIGURATION OF IMF AND LOAD PATTERN

As illustrated in Fig. 1, the IMF installation in the steel plant consists of an induction furnace unit supplied by a power transformer and another similar transformer on the same grid that supplies power to the steel plant's auxiliaries.

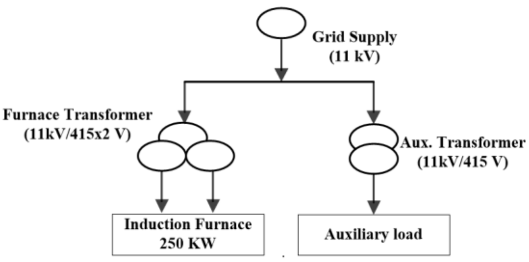


Figure 1. Single line diagram of IMF installation in steel plant.

2.1 Electrical Configuration of IMF

The essential elements of the IMF system are shown in Fig 2. It includes an H-bridge SCR inverter, a DC smoothing inductor, a three-phase SCR-based completely regulated rectifier, and a capacitor bank coupled in parallel with the furnace coil to form an LC tank circuit. A significant job is performed by the DC smoothing inductor (Ldc), which reduces short-circuit currents during SCR commutation and in situations when the inverter circuit or the resonant tank circuit might have problems. The completet sytem is powered by a transformer having 11 kV as a primary and two secondaries of 415 volts forming a configuartion of 12 pulse system. The electrical network, as depicted in Fig. 2, consists of various components, with Cmf representing the total capacitance value of all capacitors connected in parallel, Lf representing the inductance provided by the furnace coil, and R denoting the total resistance of the furnace coil, including the scrap material intended for melting. Notably, both R and Lmf are dynamic and subject to change throughout the IMF's melting cycle.

2.2 Iron Scrap Charging and refractory erosion in IMF

In the metal and steel industries, scrap charging in an induction furnace is a standard procedure for melting and converting scrap metal into molten metal for subsequent casting as shown ion Fig.3.

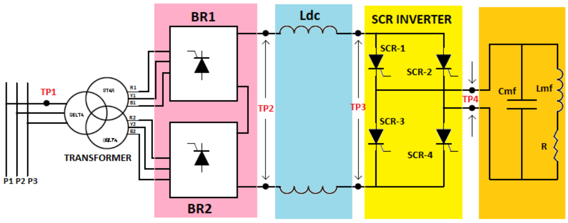


Figure 2. Block schematic of IMF System

The scrap material can be in the form of bundles as shown in Fig. 4 and are charged into the furnace. The scrap charging process can have a number of consequences, including refractory erosion. Over time, the high-temperature environment and the presence of contaminants in scrap can cause refractory erosion as shown in Fig. 5.

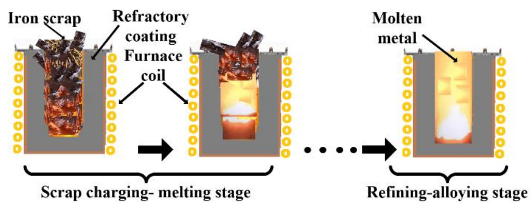


Figure 3. Iron scrap charging during melting cycle

Figure 4. Iron scrap bundles and charging into furnace (source: Steel plant site)

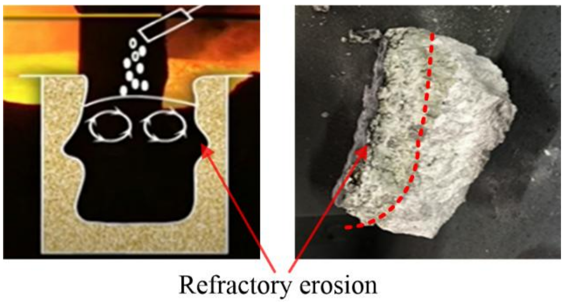


Figure 5. Refractory erosion due to iron scrap charging (source: Internet open acces)

Factors Contributing to Refractory Erosion are,

- High Temperatures: Induction furnaces run at extremely high temperatures, which can cause slow wear and tear of refractory materials.
- Chemical Reactions: When molten metal, slag, and refractory materials mix, chemical reactions occur that wear down the refractory lining.
- Thermo cycling: Repeated heating and cooling cycles can cause refractory materials to expand and contract, resulting in cracking and erosion.
- Iron Splash: Metal splash can occur during the charging process, affecting the refractory lining and causing erosion.

The melting process in the furnace involves initially charging it with loose and unsized scrap material, which occupies a considerable space within the furnace coil. Over the typical 110-minute melting cycle, the scrap material gradually transforms into molten metal, altering the volume of metal inside the coil. As the lining refractory starts eroding, the vollume of the molten metal increases, which is graphically represented in Fig.6 across multiple melt cycles. It has been noticed that as the quantity of molten metal inside the furnace coil rises, the operational inductance of the coil undergoes fluctuations throughout a single melting cycle, spanning from the initial scrap charging phase to the refining stage. Moreover, with each successive melting cycle, this inductance continues to decrease. This change in inductance is primarily attributed to the erosion of the refractory lining, which progressively diminishes in thickness and consequently affects the coil's inductance value.

The changing parameters of the LC tank circuit, encompassing Ct and Lf, from the scrap charging phase to the melting and refining stages, directly impact the resonance frequency of the CSI (Current Source Inverter). Moreover, during the initial scrap charging phase, where the resistance offered by the scrap material is low, the firing angles of SCRs in the front-end rectifier circuit must be adjusted to maintain the active power of the furnace coil. This continuous modulation of SCR firing angles in the rectifier circuit further contributes to the generation of harmonics in the supply current.

Hence, the supply current consists of two distinct harmonic components: the first stemming from the CSI inverter, and the second resulting from the switching actions of SCRs in the front-end rectifier circuit. Field results presented in subsequent sections illustrates the percentage change in harmonics from the scrap charging stage to the refining stage, highlighting the evolving nature of harmonic content throughout the IMF's operation.

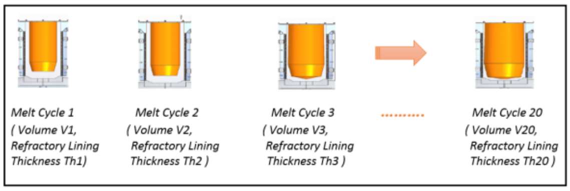


Figure 6. Refractory thickness variation due to erosion

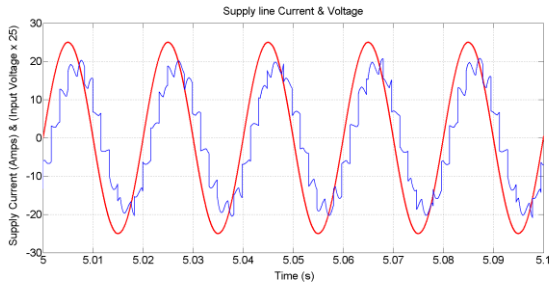
III. FIELD DATA AND SIMULATION MODEL

In this section of the paper, we established a simulation model using the specifications outlined in Table I.

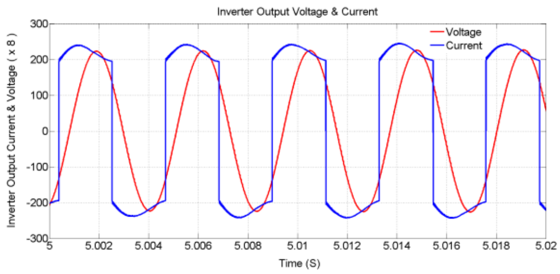
TABLE . I FIELD PARAMETERS USED IN MATLAB SIMULATION

Parameters	***Values***	***Unit***
Input AC voltage - Primary	11KV	Volts
Transformer Secondary Voltage	415X2	Volts
AC mains Frequncy	50	Hertz
CSI Invereter - output	1500	Volts
Inverter Power -output	250	kW
Switching Frequency - Inverter	155 to 235	Hertz
Output Current (Inverter)	225	Amps
D C Filter inductor	4.5	mHenry
Output LC Tank capacitor	5000	µFarad
Furnance coil Inductance	80-110	µHenry
Current Limiting Reactor	13	µHenry

MATLAB simulations produced waveforms representing the inverter's output voltage and currents, input voltage to the inverter, supply voltage, and line current, all of which are visualized in Fig. 7. Furthermore, we conducted MATLAB simulations along with Fast Fourier Transform (FFT) analyses on the supply line current, examining different operational phases, including scrap charging, melting, refining, and alloying stages. These results are presented in Fig. 8(a) and (b). The field results for the line side various electrical parameters and harmonic measurements are shown in Fig.9 and Fig. 10 respectively.

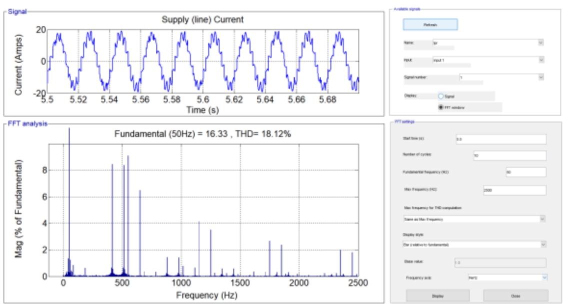


(a)

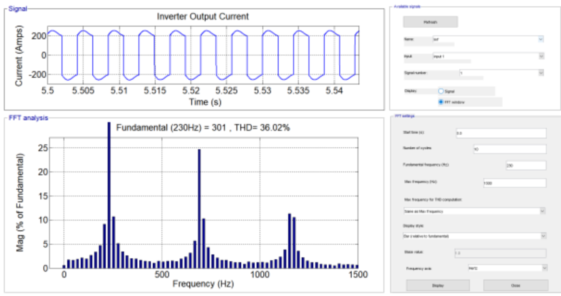


(b)

Figure 7. MATLAB Simulation Results (a) Line Voltage and Current (b) Inverter Output Voltage and Current



(a)



(b)

Figure 8. MATLAB Simulation FFT during Iron Scrap Charging and Melting (a) Line Current (b) Inverter Current

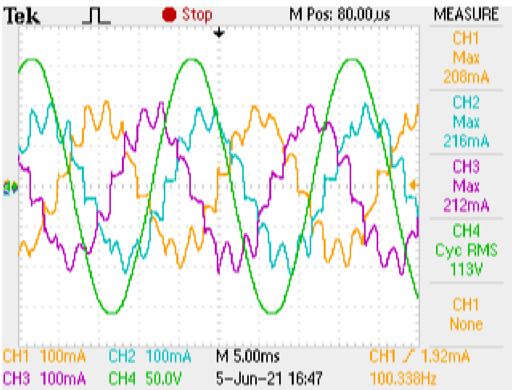
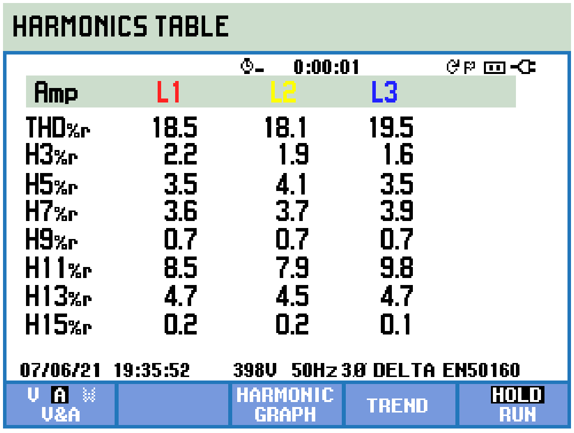


Figure 9. Line Voltage (CH4) and Currents (CH 1 to 3)


HARMONICS TABLE

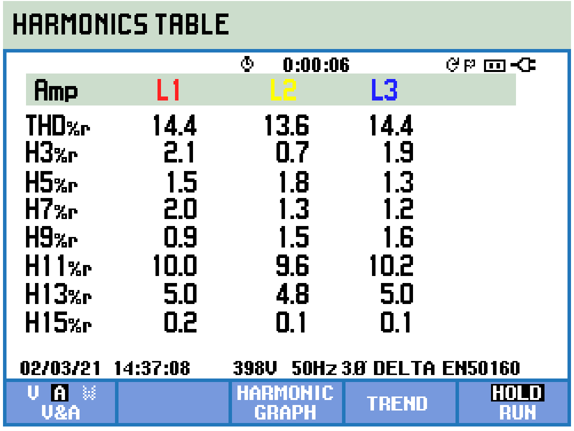
0:00:01

Amp	L1	L2	L3
THD%r	18.5	18.1	19.5
H3%r	2.2	1.9	1.6
H5%r	3.5	4.1	3.5
H7%r	3.6	3.7	3.9
H9%r	0.7	0.7	0.7
H11%r	8.5	7.9	9.8
H13%r	4.7	4.5	4.7
H15%r	0.2	0.2	0.1

07/06/21 19:35:52 398V 50Hz 3Ø DELTA EN50160

V&A | HARMONIC GRAPH | TREND | HOLD RUN

(a)



(b)

Figure 10. Supply Current Harmonics during (a) During scrap charging and melting (b) During refining and alloying

IV. COMPARISON OF SIMULATION VERSES FIELD DATA

The simulation results tabulated in Table II shows that the line current harmonic (I_{THD}) varies from 16.06 to 18.12 % during scrap charging operation IMF. Field data found to range from 14.4%, varying up to 18.5%.

TABLE II. COMPARISON OF I_{THD} : SIMULATION VERSES FIELD MEASUREMENTS

Conditions (Stage of Operation)	Simulated Results of I_{THD}	Field data Results of I_{THD}	Limit Value According to IEEE 519-2014 (%)
Scrap Charging and Melting Condition	18.12 %	18.5 %	< 12 %
Refining and Alloying Condition	16.06 %	14.4 %	

V. DISCUSSION ON POWER QUALITY ISSUE

In addition to the prominent harmonics of the 11th, 13th, 23rd, and 25th orders, other harmonics that are multiples of the inverter frequency have been observed during MATLAB simulations, as demonstrated in Fig. 8(a) and (b). Additionally, because furnace operation is dynamic, the order of these harmonics changes over time. As a result, the resonance frequency of the inverter is continuously changing. Unusual harmonics coming from the inverter side are consequently injected into the supply current. The quality of the power delivered to the grid is greatly impacted by the addition of these harmonics as well as those from the rectifier side, which raises the amount of total harmonic distortion. As illustrated in Fig. 8(b), MATLAB simulations of the inverter output current at two resonance frequencies, namely 150 Hz and 250 Hz corresponding to scrap charging conditions, reveal that the harmonics in the inverter current reflect back into the supply line current harmonics.

As shown in Fig. 8 to 10 and Table II, both simulated and real-world data demonstrate that the supply current harmonics on the grid side are greater than those permitted by the most recent IEEE standard 519-2014. This raises serious concerns about the grid's power quality declining as a result of induction furnace operation.

VI. CONCLUSION

- This paper focuses on studying harmonic and inter-harmonic characteristics.
- Simulated results are compared and validated with experimental findings.
- The paper investigates the impact of the load pattern of the IMF on the power system grid, particularly the time-varying harmonics and inter-harmonics.
- The electrical network circuit model discussed in the paper is derived from practical data collected from a functioning induction furnace in a steel plant.
- Different stages of the IMF operation cause shifts in the system's operating frequency, leading to continuous changes in the resonance point of the LC tank circuit.
- Continual adjustments of the firing angles of SCRs in the front-end rectifier circuits to maintain the desired power to the furnace coil contribute to harmonic distortion in the supply current.
- This distortion affects the total harmonic distortion (THD) on the supply side, increasing THD levels and degrading the quality of grid supply.
- Supply current harmonics are found to range from 14.4%, varying up to 18.5% during scrap charging operation IMF.

- The close alignment between field and simulated data underscores the potential for using experimental work to develop harmonics mitigation systems tailored to IMF applications in steel industries.

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