Analysis of harmonic behavior in power grids with induction melting furnaces

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Abstract. This research paper investigates the impact of an 800 kW induction furnace on power quality within a connected power grid. The performance and lifespan of induction furnaces can be negatively affected by harmonic voltages and currents. The degree of harmonic distortion in an induction furnace is influenced by the melting load, and excessive distortion can result in the generation of higher frequencies in the power distribution system. This phenomenon poses significant challenges to power systems, including power quality issues and equipment failures. Therefore, it is crucial to closely monitor and control the level of harmonic distortion to ensure optimal system performance and longevity. In this study, power quality and its parameters are assessed following the Mongolian MNS 1778:2007 standard, which outlines twelve parameters for evaluating single-phase or three-phase 50 Hz AC power systems. However, particular emphasis is placed on the analysis of total harmonic distribution (THD) as a key parameter impacting power quality. Our analysis demonstrates that substantial distortion in the furnace current waveform can lead to THD voltages in 6/10 kV transmission lines and substations, resulting in energy efficiency losses.

Keywords: Energy efficiency, Power quality, Distortion, Frequency, Total harmonic distribution

1 Introduction

Mongolia's energy sector has been the backbone of the country's growth since 1922. The groundwork for the power systems was established in 1932, and the first thermal power plant was constructed in the same year, creating a complex fuel and power system. Today, the energy sector operates 15 sources of renewable and convenient energy with a total installed capacity of 1277 MW, which supplies approximately 80% of the total consumption.

The mining industry is heavily reliant on the energy sector, as the former uses advanced, high-capacity equipment based on microprocessor and logic-controlled, fully automated, semiconductor-based techniques and devices. However, even a small change in the steady state or transient state of the power grid system can negatively affect the operation of these technical devices and, consequently, the production process.

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Concentrators, which are heavily used in the mining processing industry, rely on induction melting furnaces to process metals and produce key components, such as steel balls. With its efficiency and accuracy, the induction melting furnace has become a staple in the manufacturing of high-quality steel balls for concentrators. This furnace operates by utilizing electromagnetic induction to heat and melt metals, allowing for precise control over the melting process. The resulting molten metal can then be poured into molds to create steel balls of varying sizes and shapes.

However, the properties of induction melting furnaces and step-down transformers can create harmonic pollution and cause resonance in the power grid systems, which can degrade power quality. This can lead to a decrease in productivity and quality of the end products, as well as an increase in maintenance costs. Therefore, to ensure optimal productivity and quality of the end products, it is essential to maintain high power quality in the mining industry. This can be achieved through the use of advanced power quality solutions, such as harmonic filters and active power filters. These solutions can mitigate harmonic pollution and resonance in the power grid systems, ensuring smooth operation of technological processes and equipment, It is imperative for the energy sector to uphold high power quality standards to ensure peak productivity, product quality, and the uninterrupted functionality of technological processes and equipment.

2 Power quality and its standards

Power quality is a critical aspect that determines the efficient functioning of electrical equipment and power systems. In Mongolia, the evaluation of energy quality and its parameters is based on the Mongolian Standard MNS 1778:2007. This Standard provides comprehensive guidelines for assessing power quality and sets acceptable operating values for single-phase or three-phase AC power supply systems at a frequency of 50 Hz. Although the Standard's norms must be followed in all operational modes of electricity and power supply systems, there are exceptions in specific working modes, under certain conditions. These conditions include:

- Extreme weather conditions and force majeure events such as strong wind storms, floods, earthquakes, etc.
- Unforeseeable events that occur independent of the service provider and user, such as fires, explosions, military operations, etc.
- Situations related to the recovery and restoration efforts following disasters caused by weather and other unforeseen conditions

The norms specified in this Standard should be incorporated into the technical requirements for general electricity connections between consumers and the grid. Additionally, these norms should be included in the electricity consumption contracts between consumers and supplier organizations. They play a vital role in assessing the tolerance level for electromagnetic side effects experienced by electricity consumers. Moreover, they help identify any inductive electromagnetic side effects that may arise within the consumer's grid during power line operation and design.

Power quality standards for electricity and power systems within a customer's property must adhere to industry standards and other normative documents. These standards should not exceed the power quality standards established by the Standard MNS 1778:2007 at the general junction of electricity connections.

In cases where relevant normative documents are not available, the norms outlined in the MNS 1778:2007 are mandatory for electric energy consumers. These guidelines ensure efficient and effective operation of the power grid while minimizing potential negative impacts on consumers.

Every country develops and implements its own standards and norms suitable for controlling the quality of electricity. For example, European countries have adopted the IEC 61000-4-30 and EN 50160 standards approved by the International Electrotechnical Commission, while Russia has GOST 10913-2003, and Mongolia has MNS1778:2007. The Mongolian National Standard 1778:2007 serves as the official document for regulating electric energy and ensuring the electromagnetic compatibility of technical equipment. It plays a crucial role in maintaining the safety and efficiency of electrical systems and devices in Mongolia. This standard provides essential criteria and directions for manufacturers, providers, and users of electrical equipment to ensure compliance with the required standards for secure and reliable operation. Adherence to this standard is vital for enterprises and individuals relying on electrical equipment for efficient and effective operation.

The MNS 1778:2007 Standard specifies detailed conditions for voltage quality and stability requirements in the power grid and electricity supply. The central frequency stability and its deviation from the integrated grid should be continuously recorded with a fluctuation of 50±0.2 Hz for 10 minutes according to the rules of technical operation. Temporary operation with a frequency variation of 50±0.4 Hz is allowed. However, these Standards do not address high-frequency exposure, its harmful effects, or its limitations.

The Mongolian National Standard 1778:2007 outlines twelve parameters, which include:

1. Nominal voltage and acceptable voltage values ($\mathrm{U_y}$)
2. Steady-state voltage variation ($\delta \mathrm{U_y}$)
3. Voltage amplitude variation ($\delta \mathrm{U_t}$)
4. Flicker (voltage)
5. Total harmonic distortion THD ($\mathrm{K_U}$)
6. Individual harmonic order coefficient ($\mathrm{K_U}(n)$)
7. Supply voltage asymmetry inverse order ($\mathrm{K_{2U}}$)
8. Supply voltage asymmetry zero order ($\mathrm{K_{0U}}$)
9. Frequency deviation or variation ($\Delta \mathrm{f}$)

10. Voltage dip or sag (Δf_{vd})
11. Impulse voltage (U_{imp})
12. Transient overvoltage (K_{to})

However, it has been observed that distribution organizations in our country do not always prioritize the quality, reliability, and continuity of electrical energy, and may not strictly adhere to the provisions of this standard [1].

3 Measurements and analysis

The main problem is that, within a few seconds, voltage increases when the furnace starts operating. So, the relay protections at the communication station are detect over-voltage, greater than the setpoint, when the induction melting furnace used for steel ball production is in operation. As a result, the relay protections disconnect the communication station from supplying electricity. Additionally, the relay protections at the substation are also activated, disconnecting all customers connected to the power grid distributed by that substation. This issue requires immediate attention and resolution as per the request from the general substation. To address this problem, the root cause of the over-voltage and higher current readings needs to be identified. It could be due to a faulty relay, or a malfunctioning induction melting furnace. Once the cause is determined, appropriate measures can be taken to rectify the issue and prevent future occurrences. Therefore, research work was done to identify and resolve the issue, ensuring that the communication station and substation operate smoothly and efficiently. It is crucial to resolve this problem promptly to avoid any disruptions to the power supply and ensure the safety of the equipment and personnel.

The block layout of the problem description of the induction melting furnace is shown in Figure 1. The measurement of the induction furnace of 600 W was taken. The nominal parameters are given in Table 1.

Table 1. Parameters of the Induction Furnace

Parameters	**Induction Furnace**
Type	HTGP Aluminum Furnaces
Capacity, tons	1.5
Power, kW	600
Current, A	1200
Frequency, Hz	1000
Voltage, V	660

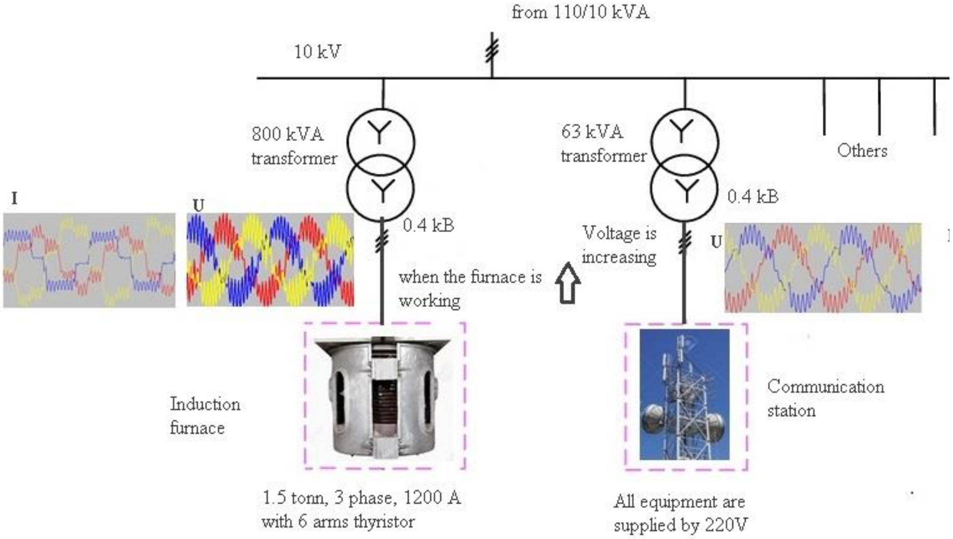


Figure 1.Power grid connection of both of the furnace and communication station in Nalaikh, Ulaanbaatar

An induction melting furnace is a type of industrial furnace used for melting various metals and alloys. It utilizes the principle of electromagnetic induction to generate heat within a conductive material, such as a metal charge, by applying a high-frequency alternating current (AC) to a coil surrounding the material. An induction melting furnace is shown in Figure 2 and its principle is shown in Figure 3.

Figure 2. Induction melting furnace at Pelletizing Plant in Nalaikh, Mongolia

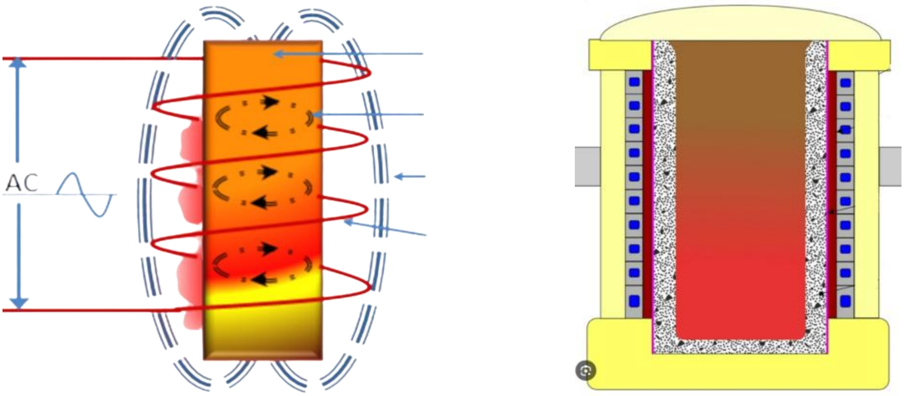


Figure 3. Working principle of induction melting furnace [3]

The power quality measurements were taken at both the induction melting furnace and the communication station locations. Field data were collected on the 1.5 ton, 600kW system for several melting cycles. Inputs from the power grid from the general power station were measured, using a custom- designed power quality measurement system which is programmed to collect raw data. The measurement points (MP1 and MP2) were measured by the Explorer 4000 Baker power quality device [4]. The voltage and current quantity were sampled at each point, at a rate of 0.1650 s, with time synchronization. The location of these measurements is shown in Figure 4 and Figure .

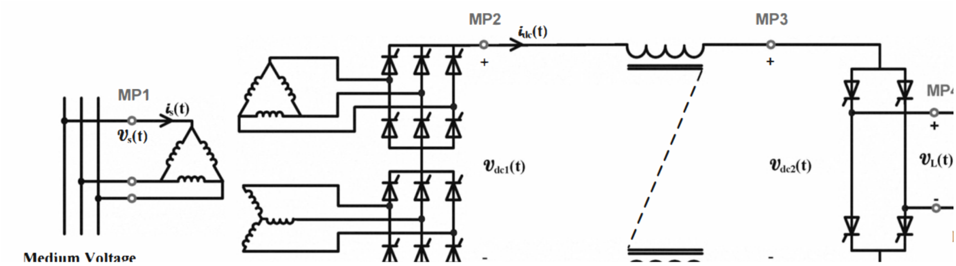


Figure 4. Measurments at the induction melting furnace

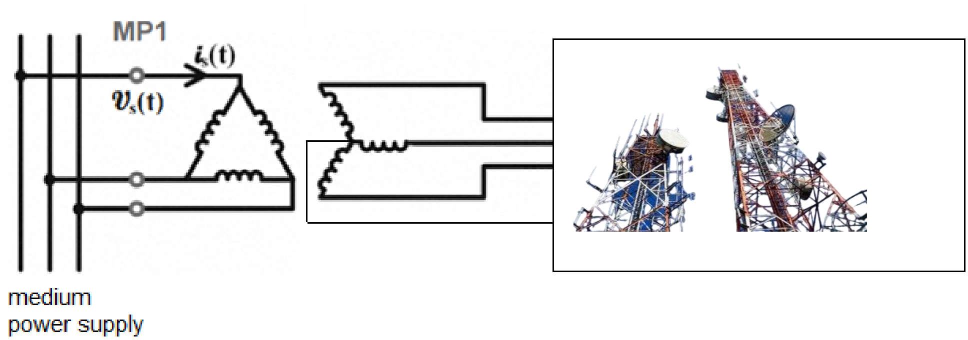


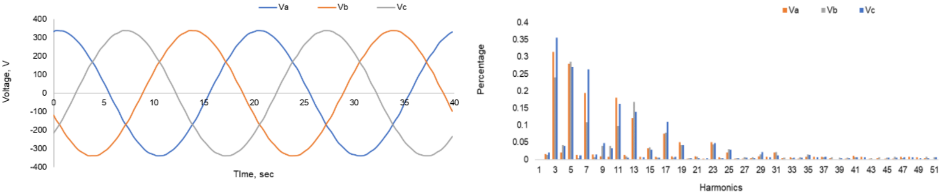
Figure 5. Measurements at the communication station

Measurement on voltage is increasing in two minutes seconds at the communication station shown in Figure 6.

Figure 6. Rapid voltage increase within the two seconds

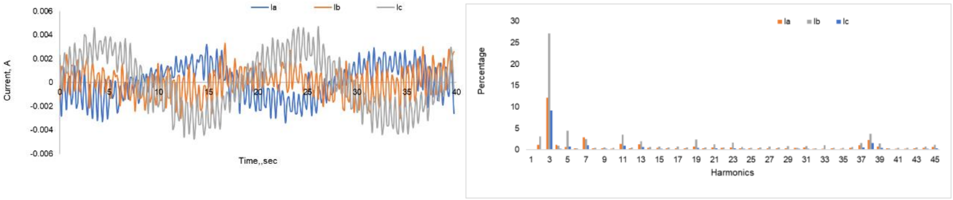
4 Measurement results

The waveform and harmonic measurements were performed on the induction furnace without a compensator when it was at 0% load or unloaded, as illustrated in Figure 7 and Figure 8 [5].



a) voltage sine waveform b) voltage harmonics

Figure 7 Voltage measurement without load



a) voltage sine waveform b) voltage harmonics

Figure 8. Current measurement without load

Based on Figure 7-Figure 8, the voltage sine waveform appears to be normal, and the specific harmonics (3, 5, 11, 13, 17, 23, 25, and 29) are within the limits specified by the MNS1778:2007 Standards. However, the current sine waveform is severely distorted, and the 3rd harmonic of the current accounts for 27.18%. This value exceeds the threshold set by the IEEE STD 519-1992 Standard, indicating that it is excessively high and does not meet the required criteria. Following the standards, individual harmonic distortions are divided by into three types of harmonics such us divided by three, not divided by three and even harmonics.

The measurements of individual harmonic distortions without being divided by three, were conducted when the induction furnace was unloaded, as presented in Table 2 and Table 3. Similarly, the measurements of individual harmonic distortions, divided by three were taken when the induction furnace was unloaded, as indicated in Table 4 and Table 5.

Table 2. Comparing individual harmonic distortion not divided by three at no load (voltage measurements) and without compensators

Harmonics	MNS 1778:2007	Total Harmonic Distortion			Comparisons		
		A phase	B phase	C phase	A phase	B phase	C phase
5	6	0.28	4.41	0.71	1	1	1
7	5	0.19	2.49	1.09	1	1	1
11	3.5	0.18	3.48	0.93	1	1	1
13	3	0.12	1.95	0.68	1	1	1
17	2	0.08	0.71	0.16	1	1	1
19	1.5	0.05	2.35	0.49	1	1	1
23	1.5	0.05	1.66	0.38	1	1	1
25	1.5	0.02	0.41	0.12	1	1	1
29	1.3	0.01	0.90	0.17	1	1	1

(1)-Satisfied; (0) – Unsatisfied

Table 3. Comparing individual harmonic distortion not divided by three at no load (current measurements) and without compensators

Harmonics	IEEE STD 519:2014	Total Harmonic Distortion			Comparisons		
		A	B	C	A	C	B
5	4	0.66	4.41	0.71	1	(0)	1
7	4	2.87	2.49	1.09	1	1	1
11	2	1.34	3.48	0.93	1	(0)	1
13	2	1.23	1.95	0.68	1	1	1
17	1.5	0.31	0.71	0.16	1	1	1
19	1.5	0.80	2.35	0.49	1	(0)	1
23	0.6	0.51	1.66	0.38	1	(0)	1
25	0.6	0.31	0.41	0.12	1	1	1
29	0.6	0.30	0.90	0.17	1	(0)	1

(1)-Satisfied; (0) – Unsatisfied

Table 4. Comparing individual harmonic distortion divided by three at no load (voltage measurements) and without compensators

Harmonics	MNS 1778:2007	Total Harmonic Distortion			Comparisons		
		A	B	C	A	C	B
3	6	0.31	27.18	9.20	1	1	1
9	5	0.01	0.52	0.26	1	1	1
15	3.5	0.03	0.71	0.23	1	1	1
21	3	0.01	1.26	0.38	1	1	1
27	2	0.00	0.72	0.15	1	1	1
33	1.5	0.01	1.11	0.18	1	1	1
39	1.5	0.00	1.46	0.45	1	1	1
45	1.5	0.00	1.18	0.37	1	1	1

51	1.3	0.00	0.87	0.17	1	1	1

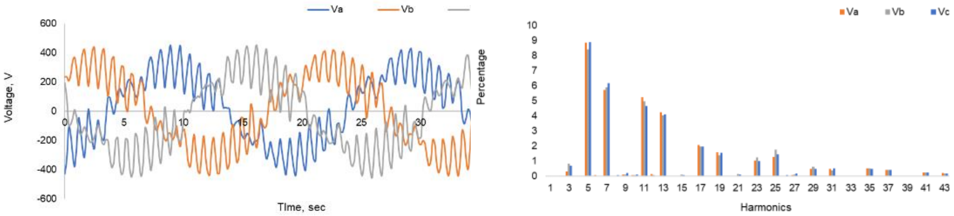
(1)-Satisfied; (0) – Unsatisfied.

Table 5. Comparing individual harmonic distortion divided by three at no load (current measurements) and without compensators

Harmonics	IEEE STD 519:2014	Total Harmonic Distortion			Comparisons		
		A	B	C	A	C	B
3	4	12.16	27.18	9.20	(0)	(0)	(0)
9	4	0.37	0.52	0.26	1	1	1
15	2	0.41	0.71	0.23	1	1	1
21	2	0.53	1.26	0.38	1	1	1
27	1.5	0.34	0.72	0.15	1	1	1
33	1.5	0.28	1.11	0.18	1	1	1
39	0.6	0.78	1.46	0.45	(0)	(0)	1
45	0.6	0.62	1.18	0.37	(0)	(0)	1
51	0.6	0.48	0.87	0.17	1	(0)	1

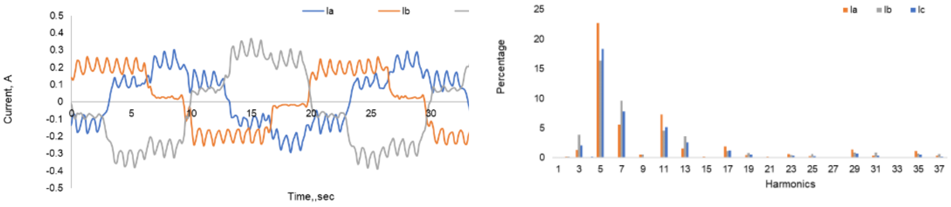
(1)-Satisfied; (0) – Unsatisfied

The waveform and harmonic measurements were performed on the induction furnace, without a compensator, when it was at 100% load or fully loaded, as illustrated in Figure 9 and Figure 10.



a) voltage sine waveform b) voltage harmonics

Figure 9. Voltage measurement at full load, and without compensator



a) current sine waveform b) current harmonics

Figure 10. Current measurement at full load, and without compensator

Based on Figure 9-Figure 10, the voltage sine waveform does not appear to be normal, and the specific harmonics (3, 5, 11, 13, 17, 23, 25, and 29) are more standard values specified by the MNS1778:2007 standards. This value exceeds the threshold set by the IEEE STD 519-1992 standard, indicating that it is excessively high and does not meet the required criteria.

The measurements of individual harmonic distortions, both without being divided by three, with and without a compensator, were conducted when the induction furnace was fully loaded, as presented in Table 6 and Table 7.

Table 6. Comparing individual harmonic distortion at full load (voltage measurements) without division by three and without compensators

Harmonics	MNS 1778:2007	Total Harmonic Distortion			Comparisons		
		A	B	C	A	C	B
5	6	5.52	4.79	5.83	1	1	1
7	5	5.03	5.60	5.44	(0)	(0)	(0)
11	3.5	2.16	1.97	2.40	1	1	1
13	3	0.75	0.89	0.75	1	1	1
17	2	0.46	0.40	0.47	1	1	1
19	1.5	0.24	0.29	0.22	1	1	1
23	1.5	0.18	0.14	0.17	1	1	1
25	1.5	0.10	0.13	0.09	1	1	1
29	1.3	0.08	0.05	0.07	1	1	1

(1)-Satisfied; (0) – Unsatisfied

Table 7. Comparing individual harmonic distortion at full load (current measurements) without division by three and without compensators

Harmonics	IEEE STD 519:2014	Total Harmonic Distortion			Comparisons		
		A	B	C	A	C	B
5	4	22.70	16.36	18.37	(0)	(0)	(0)
7	4	5.60	9.60	7.86	(0)	(0)	(0)
11	2	7.33	4.55	5.12	(0)	(0)	(0)
13	2	1.59	3.63	2.56	1	(0)	(0)
17	1.5	1.94	1.12	1.19	(0)	1	1
19	1.5	0.44	0.79	0.57	1	1	1
23	0.6	0.65	0.44	0.34	(0)	1	1
25	0.6	0.32	0.66	0.30	1	(0)	1
29	0.6	1.41	0.88	0.75	(0)	(0)	(0)

(1)-Satisfied; (0) – Unsatisfied

Similarly, the measurements of individual harmonic distortions, divided by three, without a compensator, were taken when the induction furnace was unloaded, as indicated in Table 8 and Table 9.

Table 8. Comparing individual harmonic distortion at full load (voltage measurements) with division by three and without compensators

Harmonics	MNS 1778:2007	Total Harmonic Distortion			Comparisons		
		A	B	C	A	C	B
3	6	0.32	3.91	2.11	1	1	1
9	5	0.13	0.52	0.13	1	1	1
15	3.5	0.05	0.11	0.07	1	1	1
21	3	0.05	0.10	0.05	1	1	1
27	2	0.08	0.13	0.06	1	1	1
33	1.5	0.03	0.05	0.04	1	1	1
39	1.5	0.00	0.01	0.00	1	1	1
45	1.5	0.01	0.05	0.02	1	1	1
51	1.3	0.03	0.07	0.03	1	1	1

(1)-Satisfied; (0) – Unsatisfied

Table 9. Comparing individual harmonic distortion at full load (current measurements) with division by three and without compensators

Harmonics	IEEE STD 519:2014	Total harmonic Distortion			Comparisons		
		A	B	C	A	C	B
3	4	1.32	3.91	2.11	1	1	1
9	4	0.51	0.52	0.13	1	1	1
15	2	0.21	0.11	0.07	1	1	1
21	2	0.16	0.10	0.05	1	1	1
27	1.5	0.05	0.13	0.06	1	1	1
33	1.5	0.05	0.05	0.04	1	1	1
39	0.6	0.01	0.01	0.00	1	1	1
45	0.6	0.03	0.05	0.02	1	1	1
51	0.6	0.08	0.07	0.03	1	1	1

(1)-Satisfied; (0) – Unsatisfied

5 Discussion

The analysis of the induction furnace data revealed the detrimental effects of non-linear loads on power quality. The presence of high harmonics in both voltage and current waveforms can lead to several issues, such as overcurrent protection triggers, harmonic resonance, damage to capacitor banks, transformer core overheating, cable insulation degradation, reduced equipment lifespan, motor stator winding burnout, overloaded neutrals, and generator damage.

The measurements demonstrated that introducing a compensator significantly improved power quality, reducing harmonic distortions and bringing the waveforms within acceptable limits. However, without a compensator, the induction furnace operation at full load resulted in higher harmonic distortions, indicating the need for mitigation measures. The comparison of individual harmonic distortions revealed that most harmonic components satisfied the relevant standards when a compensator was present. However, some harmonics exceeded the limits without a compensator, especially under full load conditions. These findings emphasize the importance of compensators or other corrective measures to mitigate harmonic distortions and ensure compliance with power quality standards.

It is crucial to note that the results obtained from dynamic simulations provide valuable insights into power system behavior and power quality issues. However, they should be complemented with real-world measurements and assessments to validate the simulation results and ensure practical implementation.

6 Conclusion

The power system dynamic simulation results focused on analyzing the harmonic behavior based on load measurements from two different sources: electric motors and an induction furnace. For the induction furnace without a load, it was observed that the voltage waveform appeared normal, while the current waveform exhibited severe distortion. The 3rd harmonic of the current exceeded the threshold specified by the IEEE STD 519-1992 Standard, indicating unsatisfactory performance. However, when introducing a compensator, the voltage and current waveforms improved, and all harmonics complied with the Standards.

Comparisons of individual harmonic distortions were conducted for unloaded and fully loaded conditions, considering harmonics divided and not divided by three. When a compensator was present, all harmonic distortions satisfied the Standards. Some harmonics exceeded the specified limits without a compensator, particularly at full load.

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References

[1] MNS 1778:2007 Electricity. Electromagnetic compatibility of electrical equipment. Norms of power quality in the general-purpose power system. Department of Standard Metrology, Mongolia, 2007, pp. 1–37.

[2] Wikipedia, Induction furnace, (2023, May 24). In Wikipedia. https://en.wikipedia.org/wiki/Induction_furnace (accessed Jun. 11, 2023).

[3] Induction Furnace Introduction, Pacific Crest Transformers, White City, Oregon, USA, 2013 (online source)

[4] “Baker EXP4000 Dynamic Electric Motor Analyzer,” Megger Baker Instruments 4812 McMurry Avenue, Fort Collins, CO 80525, USA, 2018. Available: www.megger.com (online source)

[5] Ankhbayar Vandandorj, “Power Systems Dynamic Simulation Developments for Power Quality Monitoring” Master’s Thesis.