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Research Article

POWER FACTOR CORRECTION IN INDUCTION HEATING SYSTEM USING PFC BOOST CONVERTER

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Today, with the increased energy needs, carbon emission caused by energy production affects the environment negatively. This situation has made it necessary that electrical energy should be used efficiently. In order to achieve this, institutions such as IEEE and IEC have established some electrical energy standards to be complied with, by the consumers. In order to increase energy efficiency following these standards, current and voltage harmonics in the system must be eliminated or kept at the required limit. Otherwise, these harmonics will cause deterioration of receivers fed from the distribution network or decrease in operating performance. For this reason, power factor correction (PFC) processes are applied in power systems. Induction heating systems, which have found a wide area of use in recent years, require PFC process due to their structure consisting power electronics elements and inductive heating crucible. This study aims to eliminate the network harmonics and harmonics distortions and to bring the power factor (PF) closer to '1' by using AC-DC converter with PFC in induction heating system. Induction heating system designed in the study has three phases and has a full bridge parallel resonance inverter operating at a frequency of 20 kHz and power of 17 kW. The system uses full wave uncontrolled rectifier and boost type DC-DC converter. Voltage control is provided through the PID controller. Designed system is simulated in MATLAB. Current and voltage graphics measured from network and load were evaluated, PF and THD values were analyzed.

Key words*: Harmonics Standards, Power Factor Correction, Induction heating, Resonance circuits, Total Harmonics Distortion*

1. Introduction

In electric networks, deviation of load voltage -which has power electronic components- and current waveform from their ideal shapes cause harmonics distortion which causes distortion of the waveform. These distortions affect the operating performance of all the receivers fed form the AC network, negatively. They also cause power dissipation in the form of heat. All of these factors reduce

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energy efficiency. In order to achieve energy efficiency, institutions such as IEEE and IEC have established basic harmonics standards indicating the limits of current and voltage harmonics [1]. To meet the standards, current and voltage harmonics must be kept at the required limit. With the advancing technology, different methods are used in order to eliminate harmonics and improve power factor. In addition to parallel capacitor connection, passive filters, active filters, general purpose flexible alternating current transmission systems (FACTS) devices and AC-DC converter with power factor correction are used for correction of power factor [2].

Induction heating is a non-contact heating method used to heat metal workpieces up to the indicated temperature and for the stated period of time. The general principal of induction heating is based on conversion of electrical energy to heat energy, utilizing electromagnetism effect of electrical energy. When an electrically conducting object is placed in the alternating magnetic field, voltage is induced on the material. This voltage undergoes short circuit through the material and generates heat on it. This process is defined as induction heating, due to the fact that induction current generates the heat [3].

In induction heating principle, the coil through which the alternating current will flow, circles around the piece to be heated, but doesn’t touch it. While the needed heat for the temperature to rise is provided to the material from the outer surface in classical methods, needed heat is produced within the material itself with induction heating [4].

In this study, firstly, induction heating system will be introduced. Later on, existing harmonics standards will be specified; forming of harmonics, their effects and methods used to correct the power factor in harmonic networks will be emphasized. Therefore, parallel capacitors, passive filter, active filter, FACTS devices and AC/DC converter with power factor correction will be analyzed. MATLAB simulation of induction heating system -that is lately the modern method- which is designed by means of AC-DC converter with power factor correction, will be carried out. PF and THD values will be analyzed with the obtained data from the simulation

2. Analysis of the System

2.1. Induction Heating System

The basis of induction heating system -as a result of alternating magnetic field- is built on eddy currents generated by voltage induced on the object, caused by electromagnetic induction; immersion depth effect caused by these currents and heat transfer theories concerning distribution of the generated heat on the subject [5].

Induction heating system could be built by using transformer theory and transformer equivalent circuit. According to transformer principle, alternating magnetic field will be produced as current direction flowing through the primary winding will change when alternating voltage is applied on the primary winding. This way, voltage will be induced on the secondary winding and short circuit current will flow through it when the secondary winding is short circuited using two terminals of the secondary winding. This current, according to Lenz Law, will produce a flux which opposes the original flux and is directly changeable via frequency. This opposite direction flux will cause the high density eddy currents to flow in the single layer wound secondary winding. Metal piece to be heated inside the heating coil represents this single wound secondary winding in the application. These currents cause the heat loss defined as power loss transferred to the workpiece during the application.

Heating process is achieved by utilizing the created heat loss. The heat produced on the metal piece will cause the piece to melt [6].

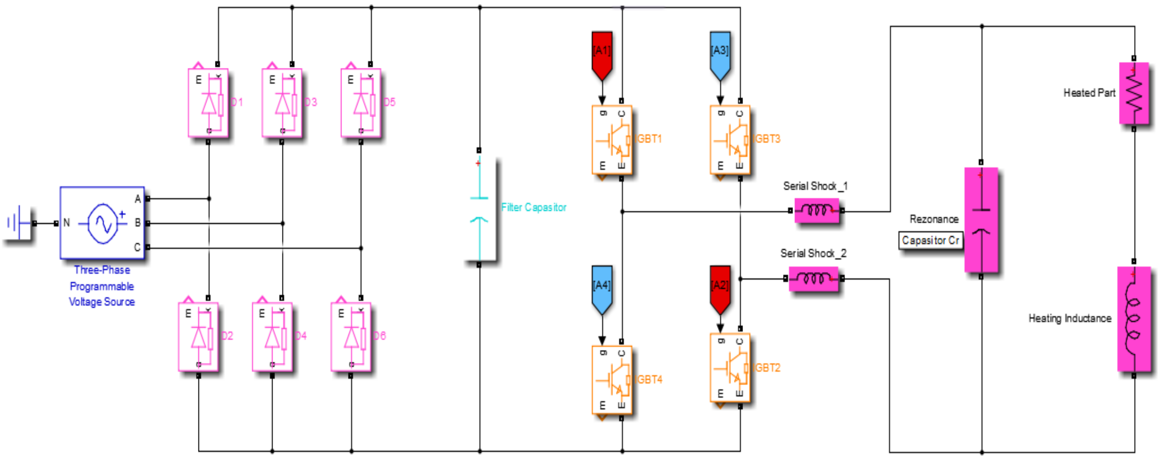

Figure. 1. Parallel resonance induction heating circuit

In Figure 1 an induction heating system with three-phase parallel resonant inverter is shown. With the help of inverter, directed network voltage is transferred to the load by being transformed into alternating voltage at the desired frequency. Low voltage and high current is created on the load. Resonance elements L-C are connected in parallel in application. Differently from series resonance circuit where L-C elements are connected in series, in this system, choke coils connected in series to the resonance circuit, regulate the load current. Choke coil feeds the resonance circuit with a regulated constant current and prevents instantaneous current pulses from flowing to resonance capacitor. This circuit type is preferred at higher power and frequencies compared to applications with series resonant inverter [7].

Induction heating system contains power electronics elements and active inductive circuit elements. For this reason, it causes harmonic occurrence in the network, low power factor and increased harmonic distortions. This leads to the malfunction of induction heating system or reduced operating performance. It also causes all the receivers fed from the network to draw harmonic current. Considering the harmonics standards to be complied with, using the system with a power factor corrector circuit will both increase the machine performance and prevent the network voltage from distortion [8].

2.2. Power Factor Correction

2.2.1. Harmonics Standards

IEEE 512-1992 and IEC 60001 are basic standards for harmonic circuits. Voltage harmonic limits regarding IEEE 512-1992 standards are shown in Table 1 and current harmonic limits are shown in Table 2.

Table 1. IEEE 512-1992 Voltage harmonic limits

Busbar Voltage(Vn)	Odd Harmonic (%)	THD (%)
Vn≤69kV	3.0	5.0
69kV<Vn≤161kV	1.5	2.5
Vn>161k	1.0	1.5

Table 2. IEEE 512-1992 Current harmonic limits

Vn≤ 69kV						
IK”/IL	**n<11**	**11<n<17**	**17<n<23**	**23<n<35**	**n>35**	**TDD(%)**
<20	4	2	1.5	0.6	0.3	5
20-50	7	3.5	2.5	1	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20
69kV<Vn ≤161kV						
<20	2	1	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4
50-100	5	2.25	2	0.75	0.35	6
100-1000	6	2.75	2.5	1	0.5	7.5
>1000	7.5	3.5	3	1.25	0.7	10
Vn>161kV						
<50	2	1	0.75	0.3	0.15	2.5
50	3	1.5	1.15	0.5	0.22	4

2.2.2 Power Factor Correction in Curcuits Where Harmonics Are Present

Because of the effects of non-linear load used in industry, or the characteristics of semiconductor elements, distortions called ‘harmonics’ occur in the current and voltage waveforms drawn from the network. This way, sinusoidal waveforms whose frequencies are multiples of the fundamental frequency and whose amplitude decreases gradually; except for the fundamental wave. Devices such as transformers, DC voltage sources, static VAR generators, interrupted power supplies and electronic ballasts cause the occurrences of harmonics [9].

Harmonics cause problems such as power losses transformed into heat in power systems, additional voltage projections, resonance occurrences, lowering of power factor and malfunctions in fragile devices. Non-linear receivers cause drawing of current harmonics from the network. This leads to distortion of network current by producing voltage harmonics because of network impedance [10]. Network voltage must be brought closer to sinusoid during the AC voltage generating stage, with the help of necessary improving precautions made in the alternator. However, negative effect on the network caused by non-linear receivers could affect the linear receivers connected to the same network [11].

Power factor correction (PFC) in circuits where harmonics are present could be made via several methods. It can be achieved by the use of capacitor connected to the load in parallel, passive filters, active filters, FACTS devices and AC/DCconverter with power factor correction.

In parallel capacitor method, high voltage fluctuations and charge current pulses of the capacitor is formed in the power system. High values of radioactive power and harmonic current are drawn from the network. In this case, network voltage and and power factor (PF) of the network current is rather low and the total harmonic distortion is pretty high [12].

Filters are designed to correct the voltage waveform of a load fed from a harmonic network, filter unwanted harmonics that can be incorporated to the alternating current system by the load and prevent electromagnetic interferences. In general, filters are designed for the harmonic values that are thought to be more active.

Passive filters are based on the principal that the desired harmonic could be eliminated by picking the proper values of capacitance and inductance that will enter resonance, at the frequency value of the harmonics that are wanted to be eliminated. This procedure must be done separately for each harmonic. Considering the values of inductance and capacitors and the current that will flow over them, selected elements' sizes are expected to be quite large. When taken into consideration that these filters need to be designed separately for each harmonic compound, power density of the system is reduced by this situation. All these reasons cause the passive filters to be highly expensive and bulky, in addition to their low performance [13].

Active power filters were developed in order to eliminate the disadvantages of passive filters and find dynamic solutions to power quality problems. Active power filters can be used for reactive power compensation, elimination of instabilities in current and voltage, and neutral current compensations in addition to compensating current and voltage harmonics. Basic working principal of active power filter is to produce opposite amplitude harmonic compounds using power electronics techniques in order to eliminate harmonics produced by non-linear load. They eliminate harmonics by monitoring harmonic current or voltage waveforms transiently and injecting the needed current or voltage to the system in moments when distortions are occurred. In active filters, levels of harmonics is detected, and is aimed to achieve harmonic improvement by applying a signal to eliminate this harmonic.

Active filters composed of electronic circuit elements have advantages such as filtering all harmonics and not needing separate control circuits, having high efficiency, being able to be used in non-linear loads. Purpose of active filters is to provide the content of the harmonic that is drawn by non-linear load, and thus correct the network current. Active filters' performance in eliminating harmonics is higher compared to passive filters.

Active filters can provide an AC voltage without harmonics on load terminals even if the network voltage has harmonics, and make it possible to draw complete sinusoidal current that is the same phase as the load's network voltage. They are superior to power electronics based PFC circuits in this way. PFC circuits make it possible for the current to be drawn from the network by the load, to be same as the network voltage waveform. It doesn't carry out a direct process to correct the voltage flowing to the receiver. It indirectly assists to correct the network voltage by getting the drawn current to have the same waveform as network voltage. Process of elimination of harmonics is different in active filters from PFC circuits. With series active filter, voltage waveform that the receiver sees can be corrected. With parallel active filter, sinusoidal current drawing from the network can be made. Hybrid power quality corrector, which is the combination of series and parallel active filters, can both filter the voltage harmonics reaching to the receiver terminals and get the load to draw sinusoidal current. However, controlling active filters is quite difficult and costly. That's why they are only suitable for special applications that are highly powerful and theyse filters are not practical. In one-phase active filters, harmonics are eliminated by monitoring the voltage or current waveforms tricentenary and injecting the system tricentenary with voltage or current; when waveform moves away from the sinus. In three-phase active filters system is interfered using d-q transformation and instantaneous reactive power theories [14].

Considering the disadvantages of series and parallel filters, power electronics based PFC circuits were started to be used with the increasing high frequency applications. Aspects such as easy control, low cost and high performance made these circuits become widespread.

FACTS(Flexible Alternating Current Transmission Systems) is a power electronics based alternating current transmission system allowing alternating current transmission systems to improve controllability, stability and power transfer ability. In power systems, FACTS devices can correct harmonic distortions and power factor considerably [15]. With the use of FACTS in the power system; power transfer control, transmission capacity enhancement, voltage control, reactive power compensation, stability improvement, power quality improvement and vibration decrement are possible [16].

Lately, increased high frequency applications have led to the use of AC-DC converter with power factor correction. They have been used widely because of their decreased size with increased operating frequency, low cost, simple control structure. AC-DC converters with power factor correction show performance close to perfection in power factor correction and reduction of THDs.

2.2.3. AC-DC Converters With Power Factor Correction

Vast majority of industrial receivers are connected to the AC network, using AC-DC converters. That’s why AC-DC converters with PFC have found a large field of application and gained importance. Also, because these converters operate in a high frequency, their sizes decrease, along with their costs [17].

With high frequency switching applications, power density can be enhanced. However, higher frequency switching causes switching losses and EMI noises. These problems can be avoided with soft switching (soft start) techniques[18]. Soft switching can be done by getting the current or voltage to zero on the switch; during the switching. For a perfect PFC, it is significant to choose a proper AC-DC converter ,and to apply a proper soft switching technique[19].

AC-DC converters with power factor correction, also known as improved power quality converters, can be designed interchangeably. They can be made in different topologies; including boost, buck, buck-boost, multi-stage or multi-pulse. Structure of three-phase boost type AC-DC converter studied in this article is shown on Figure 2. By operating the switched DC-DC converter at a high frequency, current drawn from the AC network is enabled to be at the same phase and follow the sinus form. With this method, reactive power drawn from the AC network and harmonic currents are brought closer to zero [20-24].

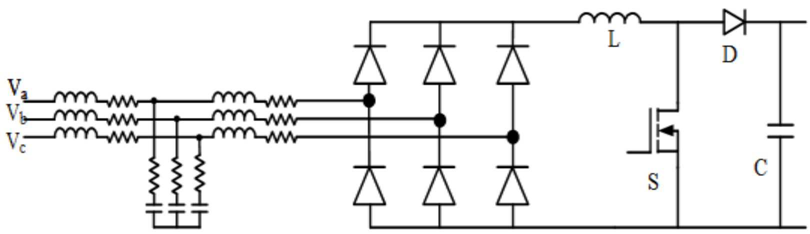

Figure. 2. Structure of three-phase boost type AC-DC converter with power factor correction

In this system the purpose is to control the current of the coil present in the converter. This current is controlled according to current reference signal that will be produced based on sinusoidal voltage reference of the network. With the control of these converters, network current harmonics can be eliminated and power factor value is brought closer to 1.

2.3. Simulation of the Study

Induction heating system with PFC three-phase full bridge parallel resonance inventor is shown on Figure 3. As seen on the figure, circuit consists of RLC filter on the input, three-phase full-wave uncontrolled rectifier consisting diodes, boost type DC-DC converter, PID controller circuit for voltage control, inverter circuit consisting four IGBT power switches, choke coil and parallel resonance circuit. After network voltage is rectified with uncontrolled rectifier, regulated DC voltage is obtained at the desired level with DC-DC converter. This voltage is controlled by PID controller. Voltage on the inverter input is converted to alternating voltage at the desired limit by applying proper switching. Resonance capacitor feeds the load with regulated voltage and carries out heating process. Measurement is done through the measuring tools connected to phases and load in the system.

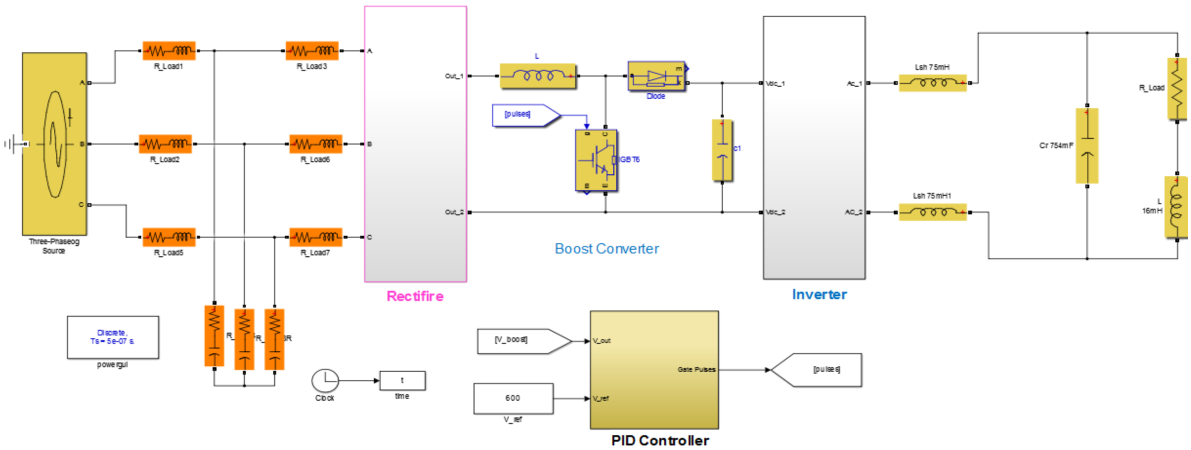

Figure. 3. Induction heating system with PFC three-phase full bridge parallel resonance inverter

In inverter, in accordance with the level of current or voltage, in the first period of switching, two switches of different branches are used on transmission while the other two are used in the second period. Switches perform switching alternately. For the period in which switches are on transmission, current flows to the positive direction across them. When they are in isolation, flow transmission to the negative direction is occurred only through the diode. Switches, at switching frequency, are driven by rectangular-wave voltages at certain values, in accordance with switch aspects.

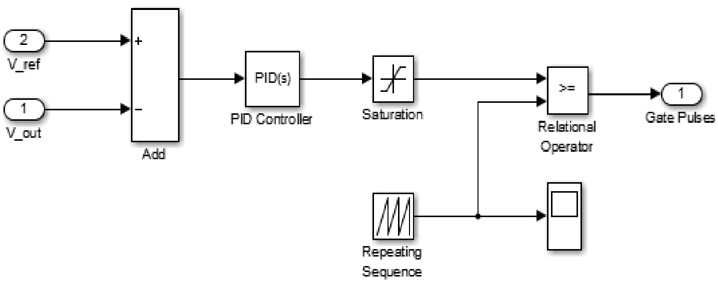

Figure. 4. PID control circuit

After input voltage is rectified with rectifier, desired amplitude can be achieved with DC-DC boost converter. In this study, voltage value was increased from the value of 540V to 640V. This voltage feeds the load by being transformed into alternating current at desired frequency, using resonance inverter. Power factor value is brought closer to 1 by PFC circuit designed for the system.

Voltage control is achieved in PFC circuit with PID controller. Boost converter control circuit is shown on Figure 4

Fluctuations of network voltage and network current is examined. Phase voltage graphic is shown in Figure 5, graphic of phase current is shown in Figure 6. It is seen that network voltages are presented fully sinus-shaped; network currents are presented sinus-shaped with minor distortions.

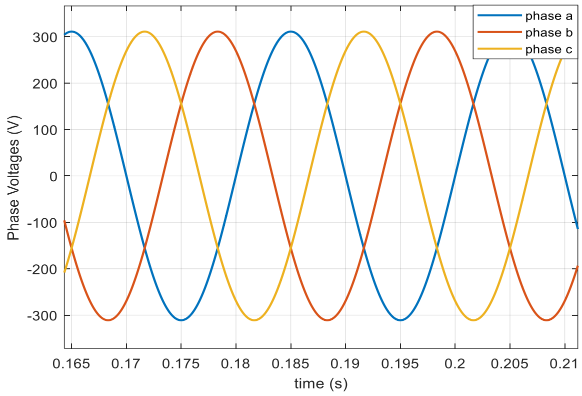

Figure. 5. Phase voltages

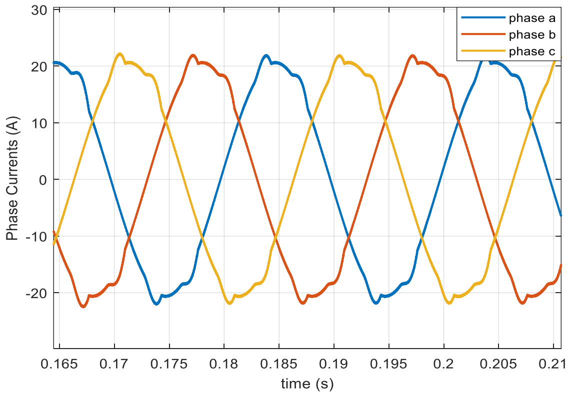

Figure. 6. Phase currents

In figure 7, it is seen that graphics obtained from one phase of the current do not have phase differences; which shows that the power factor is quite close to 1.

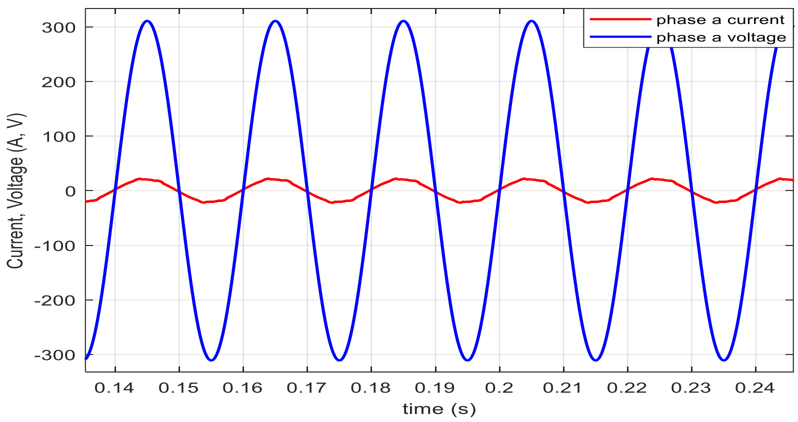

Figure. 7. Phase A current-voltage graphic

Ohmic resistance defined as the load in the parallel resonance circuit represents the metal workpiece placed inside the heating coil. Voltage graphic measured from the load is shown in Figure 8, current graphic is shown in Figure 9. Current and voltage on the load is generated in form of an almost complete sinus curve.

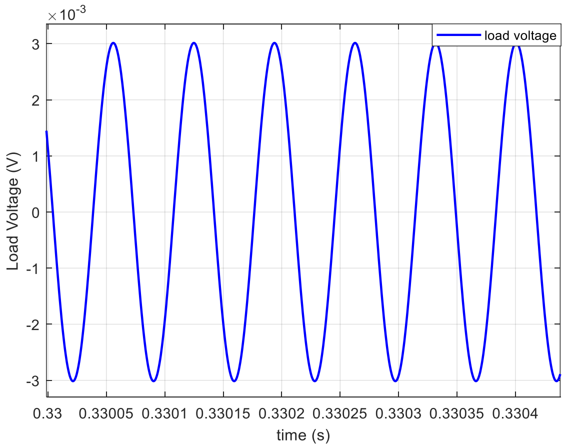

Figure. 8. Load voltage

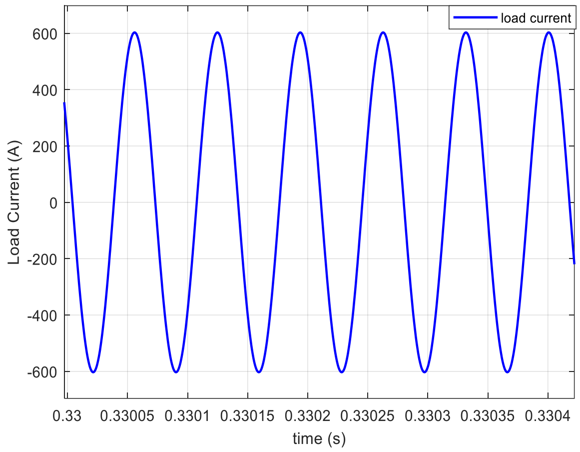

Figure. 9. Load current

As seen in Figure 10, power factor value of the system is measured to be 0,995. It can be said that a process of PFC is carried out, close to perfection

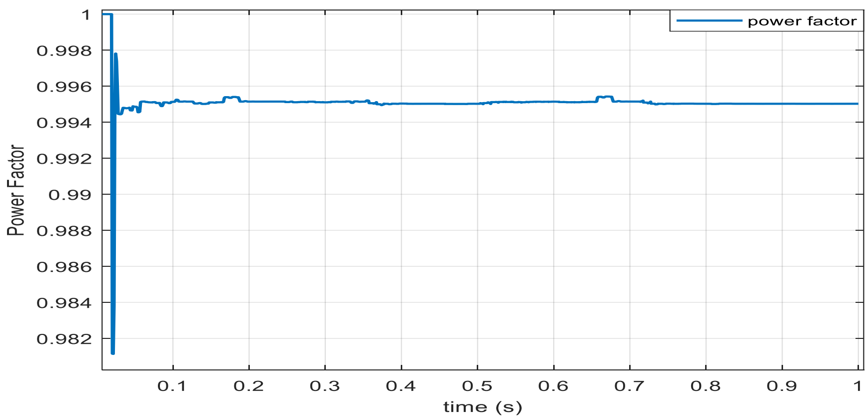

Figure. 10. Power factor of the system

Figure 11 shows total harmonic distortion (THD) measured from phase A of the network. THD value is measured to be 4,23%. THDs, which are the total distortion created by all active harmonic is seen to be at low levels; with the PFC process carried out.

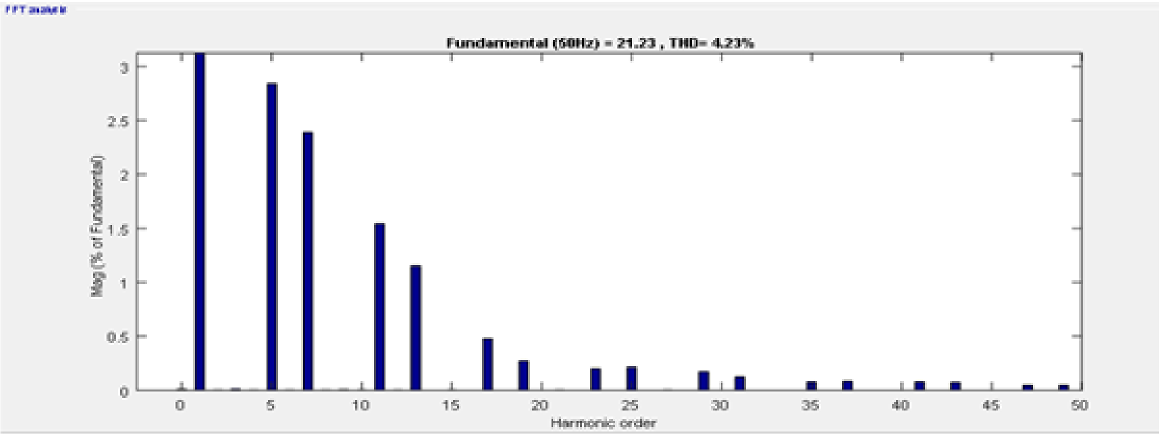

Figure. 11. Phase A THD graphic

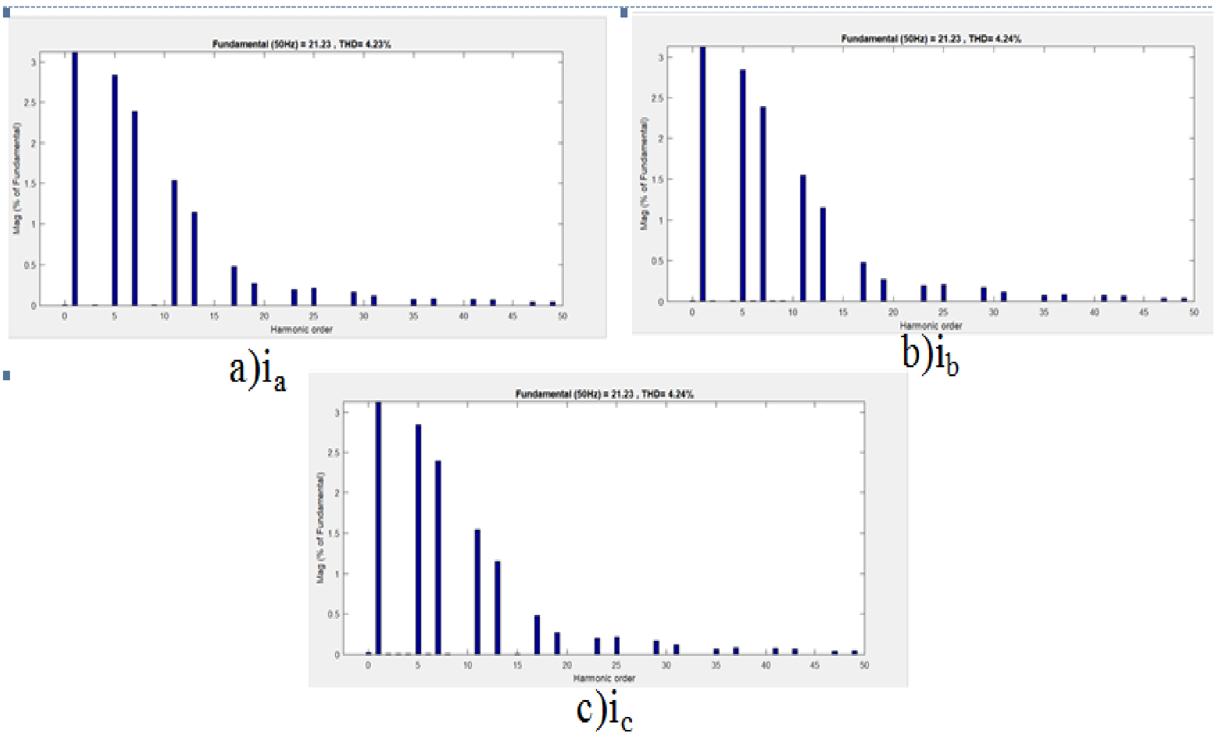

Figure. 12. Three-phase THD graphics

Figure 12 shows THD values obtained from all three phases. Considering that even harmonics and harmonics that are multiples of 3 have no impact on three-phased systems, THDs are created actively; especially on harmonic values of 5,7,11,13.

3. Conclusion

In this study, designed three-phase induction heating system with power factor correction is analyzed. Harmonics across the power system and and the network is examined. Analyses on power factor and total harmonic distortion were made. The use of AC-DC converter with power factor correction for PFC process in induction heating system was highly effective on elimination of network harmonics. Use of PFC circuit along with PID controller contributed to improvement of power factor. Power factor (PF) value of the system was measured to be 0,995 and seen to be quite close to 1. Total harmonic distortion (THD) value obtained was 4,23%. Considering that THD value was below the standard value of 5%, it was seen that harmonic distortions of the network was reduced and met the standards. With the use of AC-DC converter with power factor correction, PFC process was carried out efficiently, even on the most effective harmonic levels. All of these show that a PFC process close to perfection was achieved with this design. Considering its easy control, low cost and has high performance, AC-DC converter with power factor correction can be used efficiently in induction heating systems with the operating performance concluded in this study.

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