Feasible Evaluation of Shunt Active Filter for Harmonics Mitigation in Induction Heating System

Rahul Raman [a, b], Subrata Kumar Dutta [a], Priya Sarmah [a*], Mrigakshi Das [a], Amarjit Saikia [a], Pradip Kumar Sadhu [b]

[a] Department of Electrical Engineering, Jorhat Engineering College, Jorhat, 785007, India.

[b] Department of Electrical Engineering, Indian Institute of Technology (ISM), Dhanbad, 826004, India.

Abstract

This paper propounds the incorporation of a three-level inverter based Shunt Active Filter (SAF) in the Induction Heating (IH) system to eradicate the problems due to Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI). The IH system generates a considerable amount of high-frequency harmonics because of a myriad of causes, the predominant one being the high-frequency switching in the resonant inverter. The former has an immanent propensity to flow towards the supply side and results in the enfeeblement of power quality. Moreover, in the present work, attention has been paid off to develop a proper control strategy for a three level inverter based SAF for EMI and RFI suppression. A new modeling approach for three-level inverter based SAF is proposed, and the efficacy and viability of the proposed controllers for SAF in the IH system are validated via simulations in PSIM. A comparative analysis of THD in the input current waveform has been done to advocate the necessity of SAF as an imperative part of the IH system. Results obtained by simulations show that the proposed approach is more effective than the reviewed approaches at compensating the harmonic currents, and thus, the filtering action of SAF is able to achieve the THD of input current within the limit specified by the IEEE-519 standard.

Keywords: EMI; RFI; Induction Heating; Shunt Active Filter; PSIM.

1. Introduction

Technological demands in industries change rapidly due to changes in energy requirements, the need for loss minimization, and changes in the market. Hence, existing technologies need upgrading very often to enhance the outcome of the production and ensure smooth operation of the appliances. One such evolving technology is the Induction Heating Equipment (IHE). It is a compact, highly efficient, and easily controllable heating technique used for industrial as well as domestic heating purposes.

In IHE, electric energy is converted to heat energy by the application of Joule's law of heating. The heating workpiece is energized by high-frequency power generators like current source inverters, which are in turn fed by ac-to-dc three-phase rectifiers. Utilization of various kinds of power converters and non-linear loads used for this purpose in industries deteriorates the power quality, voltage and current waveforms. High-frequency switching operation of the inverter circuits also produces a large number of current harmonics, which tend to move back towards the input of the circuit, deteriorating the input current waveform [1-4] and reducing system stability. Current harmonics can also cause

interference problems in communication systems and lead to operational failures of electronic equipment. The grid voltage, however, remains almost unchanged.

Various passive and active filter circuit topologies have been explored in the past in order to suppress or compensate for the harmonic influx in the power supply within permissible limits. The passive filtering technique using LC filters and capacitor banks is a very old technique of harmonic mitigation and reactive power compensation. Though this technique is very simple and easy to implement, they have certain disadvantages like poor dynamic response, large inductor or capacitor size, etc. Moreover, passive filtering techniques are mainly suitable for the radio frequency range of operations. The use of Vienna rectifiers can reduce the problems related to electromagnetic and radiofrequency interference up to a great extent. However, the generation of reactive power is strictly restricted in Vienna rectifiers as it functions only in the rectifier mode. The direct control method of controlling Vienna rectifiers is imperfect as it allows unbalanced control sequences to appear. The voltage space vector control also has certain limitations, as demonstrated by Radomski et al. [3]. Due to these limitations, active power filter circuits are preferred, which can be conveniently used for reactive power compensation, reduction of total harmonic distortion rate, and suppression of harmonic currents of nonlinear loads, flowing back to the power supply [5-7].

The work reported by Akagi et al. (1983) [5], dealing with the calculation of reference compensation current signal employing instantaneous reactive power theory (p-q theory) has inspired many researchers to work on the development of better active power filter control strategies. In p-q theory, the input voltages and load currents are altered from the a-b-c frame of reference to the α-β reference frame, followed by determination of the p-q theory instantaneous power components. The reference compensation currents can then be calculated. Po-Ngam (2014) [6] identified the load currents and modified it to dq0 variables. The d-axis harmonic currents, q-axis and 0 axis currents are controlled by pi controller with feedforward supply voltage via space vector inverter such that the THD of the three phase source currents are decreased to 4.36, 4.46 and 4.51%. Chang et al. [7] proposed a new compensation strategy wherein the reference compensation currents are determined in the a-b-c frame of reference, thus decreasing the complexity in realization of the Active filter strategy. This approach requires a balanced source current, in phase with the positive sequence input voltage. The Induction heating system proposed by Bojoi et al. [8] comprised a SAF with a DSP controller. Current is controlled by Proportional-Sinusoidal Signal Integrators (P-SSI) and the controllers operate on the principle of selective harmonic compensation and can be tuned for different harmonics [9, 10].

Sharma et al. (2020) proposed a control strategy that enabled the working of the SAPF with reduced number of sensors. The unit vector voltages are estimated using PLL, without sensing actual source voltage. The THD for nonlinear load was found to be between 1.41 and 4.41% [11]. Colak et al. also proposed a sensorless DC voltage control based on the calculation of filter power losses in a single-phase SAPF. The THD for the power system after the installation of the SAPF was recorded in *MATLAB* at 2.85 and 1.64% respectively for two different non-linear loads. Although sensorless techniques and parameter robustness is helpful in fault-tolerant control operation in case of sensor failure, they require extensive PI controller tuning and high computational burden [12].

This paper highlights the use of a three-phase voltage source multilevel inverter, which is shunt connected through inductors to a high frequency resonant inverter, used as power supply for induction heating. This shunt connected filter circuit is mainly controlled for harmonic and reactive power compensation. The compensation currents are determined by employing direct current control technique. The multilevel inverter uses multiple lower or medium level DC voltage sources as input. They are very useful for industrial applications requiring high power and high voltage applications. Moreover, the introduction of LCL filter in the active power filter circuitry helps achieve better filtering effect, resulting in reduced THD, as proposed by Pan et al. (2019) and Park et al. (2017) respectively [13, 14]. The aim is to make the main currents practically sinusoidal and in phase with respective phase voltages. The shunt active filter achieves this by producing harmonics, equal in magnitude but in phase opposition to the harmonic components introduced by the switching devices and nonlinear loads [6-9]. Simulations are carried out in the PSIM software to verify the outcome of the proposed model.

1.1. Shunt Active Filter for the Elimination of RFI and EMI

The non-linear load comprises of odd harmonics, which are odd multiples of the fundamental frequency. These harmonic currents are incapable of contributing to the active power and leads to problems related to EMI and RFI. Thus, harmonic currents need to be eliminated in accordance with the harmonic standards [1-6]. The high frequency harmonics in the induction heating system (IHS) can be detected and eliminated efficiently using active filters. Active filters are usually of two types – Series Active filter and Shunt Active filter. Series filters compensate for distortion in the power line voltages [15-17] while Shunt Active filters (SAF) can compensate for both current harmonics and power factor. The latter does not compensate load for load compensation load current harmonics though it provides high impedance to the harmonics coming from the supply side.

The performance of a SAF depends upon many factors; the predominant ones being the reference signal generation technique, quality of the current controller, modulation technique employed, etc. Hysteresis band and PWM control methods have got wide popularity in the modulation techniques commonly used in SAFs. The former forces the inverter output to stick to the reference signal [18-20]. And for this purpose, a pair of switches is turned on and off when the error in the current exceeds a certain magnitude.

In the proposed model, a three phase- three wire voltage source PWM multilevel inverter is used. This inverter circuit is shunt connected at PCC to a nonlinear load comprising the IHE, through three input inductors. A low-cost switching filter is used in order to get rid of the lower order harmonic currents and high-switching ripple currents generated due to the combined effect of the input inductance and the main line inductance. The SAF will operate as a current source, injecting the compensation current which is equal to the harmonic current but phase shifted by 180˚. Thus, the THD of the system is reduced to give an optimized solution of the total system. Figure 1 shows the research methodology of the proposed method.
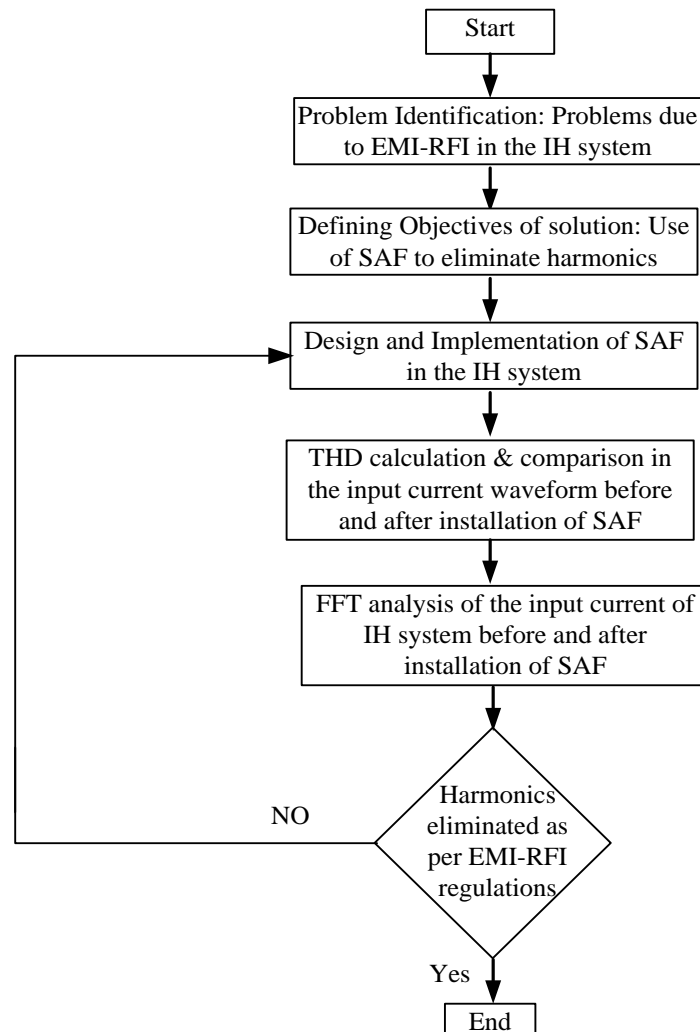

Figure 1. Research methodology of the proposed method

1.2. Use of Multilevel Inverter

Most of the existing topologies of SAFs employ two-level Voltage Source Inverter (VSI). However, a better approach is to use three-level VSI. In the present paper, a three-level neutral point diode clamped PWM inverter topology has been used in the shunt active filter. Moreover, attention has been paid off to design a proper control strategy for the proposed NPC based multi-level inverter. It has several distinct advantages over the traditionally used two level inverters. They require only one common voltage source and consist of high frequency clamping diodes which limit the voltage stress on power devices. Multilevel inverters have high power capability with minimum switching losses and output distortion [21-23]. However, these advantages come at the cost of a more complex control strategy.

2. Proposed Model of IHE with Shunt Active Filter

Figure 2 shows the basic circuit diagram of IHE using the Shunt Active Filter. A diode bridge rectifier converts the sinusoidal ac voltage from the three-phase supply to a pulsating dc voltage, which is fed to a high frequency resonant inverter. The output of the inverter is fed to the induction heating load which generates heat energy by Joule's law of heating. The control circuit comprises a current control unit and a voltage control unit.
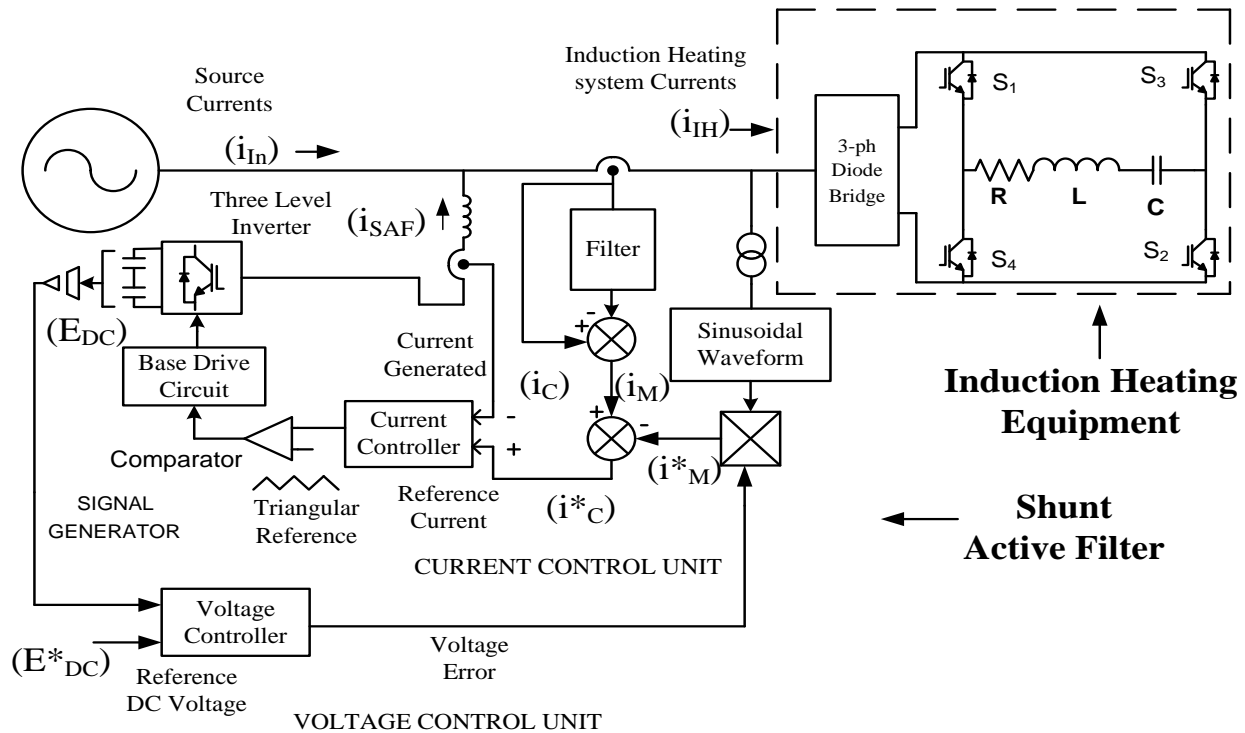

Figure 2. Basic circuit diagram of IHE using Shunt Active Filter

Current sensors are used in all three phases to measure the instantaneous value of currents flowing in the supply line. It is then passed through a second order band-pass filter (notch filter) whose centre frequency and stopping band are set at 50 Hz and 20 Hz respectively. The choice of 50 Hz centre frequency ensures infinite impedance to the fundamental component of current by the band stop filter. This in turn ensures blocking of the fundamental component of current while allowing the smooth passage of all other frequency components. The band-stop filter is well tuned to block the fundamental frequency component while allowing other harmonic components of current. Thus, the output of the band-stop filter compromises the harmonic currents only. Finally, it is subtracted from the current obtained by the current sensors from the main line.

In the present work, attention has also been paid off to maintain a constant dc voltage at the input capacitor of the multi-level inverter. The latter is sensed and subtracted from a reference value and then fed to a low pass filter and PI controller. Then, it is synchronized with the three-phase input and multiplied with the output obtained from the difference of sensed current and output of band-stop filter (i_{IH})$_h$. The aforementioned technique is employed in all three phases. From the present value, the output of the multi-level inverter obtained by the current sensor is subtracted. Then, it is fed to a PI controller and limiter. Finally, it is fed to a hysteresis comparator to generate switching signal for the multi-level inverter. Thus, the SAF produces harmonic currents (i_{SAF}) which are applied at the point of common coupling (PCC). This compensating current mitigates the harmonic currents generated by the nonlinear loads and switching devices. Accurate generation of the reference current signal and proper control of the gate firing pulses of the filter is thus necessary for effective compensation.

Instantaneous current in the input is given by;

$$i_{IN}(t) = i_{IH}(t) - i_{SAF}(t) \tag{1}$$

The instantaneous voltage at the source is given by

$$E_{IN}(t) = E_{max} \sin \omega t \tag{2}$$

When high frequency IH system is fed by the supply, then the current at the input of the IH system comprises of fundamental & harmonic components and may be showed as follows:

$$i_{IH}(t) = \sum_{m=1}^{\infty} (I_{IH})_m \sin(m\omega t + \phi_m) \tag{3}$$

$$i_{IH}(t) = (I_{IH})_1 \sin(\omega t + \phi_1) + \sum_{m=2}^{\infty} (I_{IH})_m \sin(m\omega t + \phi_m) \tag{4}$$

The instantaneous power fed to the IH system is given by:

$$P_{IH}(t) = E_{\max} \sin \omega t (I_{IH})_1 \sin \omega t \cos \phi_1 + E_{\max} (I_{IH})_1 \sin \omega t . \cos \omega t . \sin \phi_1 + E_{\max} \sin \omega t \sum_{m=2}^{\infty} (I_{IH})_m \sin(m\omega t + \phi_m) \tag{5}$$

$$P_{IH}(t) = P_{IH,f}(t) + P_{IH,r}(t) + P_{IH,h}(t) \tag{6}$$

$$P_{IH}(t) = E_{\max} \sin^2 \omega t \cos \phi_1 + E_{\max} (I_{IH})_1 \sin \omega t . \cos \omega t . \sin \phi_1 + E_{\max} \sin \omega t \sum_{m=2}^{\infty} (I_{IH})_m \sin(m\omega t + \phi_m) \tag{7}$$

After compensation of current harmonics by the current supplied by SAF, the source current is given by:

$$i_{IN}(t) = \frac{P_{IH,f}(t)}{E_{IN}(t)} \tag{8}$$

$$i_{IN}(t) = (I_{IH})_1 \sin wt \cos \phi_1 \tag{9}$$

$$(I_{IN})_m = (I_{IH})_1 \cos \phi \tag{10}$$

Then,

$$i_{IN}(t) = (I_{IH})_m \sin wt \tag{11}$$

The source needs to supply some extra power along with the real power required in the IH system to maintain a constant capacitor voltage at the input of SAF and also to meet the converter losses.

Thus, total peak input current is given by;

$$(I_{IN})_{peak} = (I_{IN})_m + I_{CL} \tag{12}$$

The shunt active filter (SAF) produces current harmonics that compensates the harmonics in the current i_{IH} because the former & latter are 180° out of phase.

Thus, the compensating current supplied by the SAF is given by;

$$i_{SAF}(t) = i_{IH}(t) - i_{IN}(t) \tag{13}$$

So, it is important to accurately compensate the instantaneous reactive & harmonic power. And for this purpose, it is necessary to calculate the fundamental component of current fed to the IH system as the reference current.

2.1. Estimation of Reference Current:

The dc capacitor at the input of SAF can be controlled for estimating the peak value of reference current $(I)_{peak}$ in the source side. The compensation of harmonic currents will be ideal when the input current is completely sinusoidal. Moreover, the latter should be in phase with the supply voltage irrespective of the harmonics present on the load side. After compensation, it is desirable to achieve the following current on the input side.

$$i_{IN,a}^* = (I_{IN})_{peak} \sin \omega t \tag{14}$$

$$i_{IN,b}^* = (I_{IN})_{peak} \sin(\omega t - 120°) \tag{15}$$

$$i_{IN,c}^* = (I_{IN})_{peak} \sin(\omega t + 120°) \tag{16}$$

Where;

$$(I_{IN})_{peak} = (I_{IH})_1 \cos \phi + I_{CL} \tag{17}$$

Equation 17 represents the amplitude of current desirable at the input side while the input voltage may be used for determining the phase angles. This in turn indicates that the waveform & shape of the input current is known & only the magnitude needs to be calculated.

As per the notations taken in Figure 2:

$$i_M^*(t) = [k_p(E_{DC}^* - E_{DC}) + k_i \int (E_{DC}^* - E_{DC})dt]\sin(wt) \tag{18}$$

Again, we know

$$i_C^* = i_M - i_M^* \tag{19}$$

Where;

$$i_M^* = i_{Mp} + i_{loss} \tag{20}$$

Where, i_{MP} is the real part of current and i_{loss} represents the losses in the filter circuit.

$$i_M = i_{Mp} + i_{Mq} + i_{Mh} \tag{21}$$

I_{Mq} and i_{Mh} are the reactive components and harmonic components of the current.

Therefore;

$$i_C^* = i_{loss} - i_{Mq} - i_{Mh} \tag{22}$$

The voltage of the dc capacitor at the input of SAF needs to be regulated for estimating the peak value of reference current. The former is compared with a dc reference value (400V in the present case) and error obtained is fed to a PI controller.

2.2. Use of the DC Capacitor

The capacitor installed at the dc side is used to assert a dc voltage with the allowance of minimum ripples in steady state. Ideally, during this period, the source supplies real power, which is equal to the load power demand. The former also supplies a small amount of power to compensate for the active filter losses. But, during the transient period, due to changes in the load demand, there is a difference in real power between the load and the source. The dc capacitor compensates for this real power difference. As a result, the dc capacitor voltage which was initially maintained at a reference value also changes. If the peak value of the reference current is regulated such that it changes in proportion to the real power drawn from the source, the active filter can be satisfactorily operated. In order to balance the real power demand between the source and the load, the dc capacitor voltage needs to be recovered and maintained at the reference voltage.

2.3. Use of the PI Controller

In the present paper, PI controllers have been employed to provide appropriate system control. In the voltage control unit, the PI controller is used to correct the error between the input DC capacitor voltage of the multilevel inverter and a reference value. The difference between the two is calculated and then some corrective measures are introduced to get a desired outcome.

The proportional response to the error value is regulated by multiplying the error with proportional gain k_p, while the integral mode helps to restore the desired DC voltage with minimum delay by calculating the accumulated proportional offset over time. The constants k_p and k_i of the PI controller can be obtained from the characteristics of the voltage control loop as:

$$1 + (k_P + \frac{k_i}{s})\frac{3[V_{in} - L_C I_{Co}s - 2I_{Co}R_C]}{C_{DC}V_{DCo}S} = 0 \tag{23}$$

Here, k_p determines the voltage response and k_i defines the damping factor of the voltage loop.

The amplitude of the current desired in the input side may be considered as the output of the aforesaid PI controller. For estimation of the reference currents, the unit sine vectors which are in phase with the input voltage are multiplied with the aforesaid peak value. The reference currents and actual currents from the multilevel inverter are fed to a hysteresis PWM controller which in turn generates the switching signals. These signals are properly segregated and

amplified, before applying to the switching devices. In view of the switching activities, current flows through the SAF inductor L_c and thus cancels out the harmonic currents in the system.

3. Simulation Diagram and Results

In the present paper, all the simulations have been executed in the PSIM platform. PSIM is simulation software particularly designed for power electronics and motor control. Simulation is performed on a high frequency induction heating system with and without the shunt active filter such that the effect of the Shunt APF on the IHE can be observed and compared. The simulation results hence acquired for the above cases are studied, the input currents are assimilated and their FFT analysis is carried out. Figure 3 shows the simulation circuit diagram of IHE before the installation of SAF and the corresponding input current waveform and its FFT analysis are shown in Figures 3(a) and 3(b) respectively. Figure 4 shows the simulation circuit diagram of IHE after the installation of SAF. The input current waveform followed by its FFT analysis are shown in Figures 4(a) and 4(b) respectively.
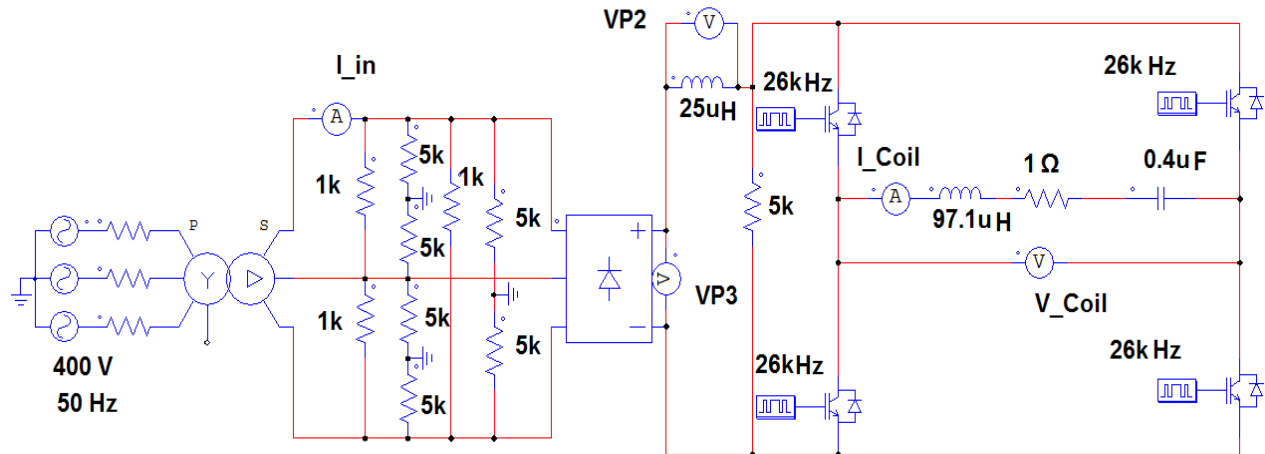
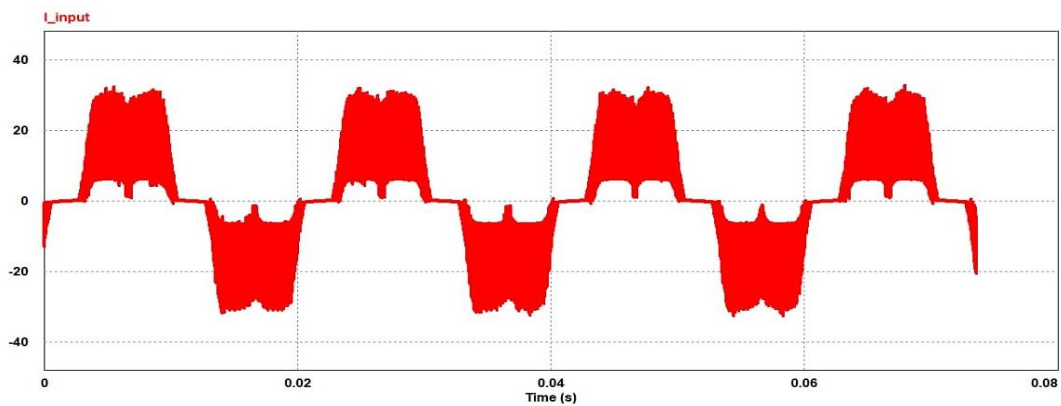**Figure 3. Simulation diagram of IHE before installation of SAF**

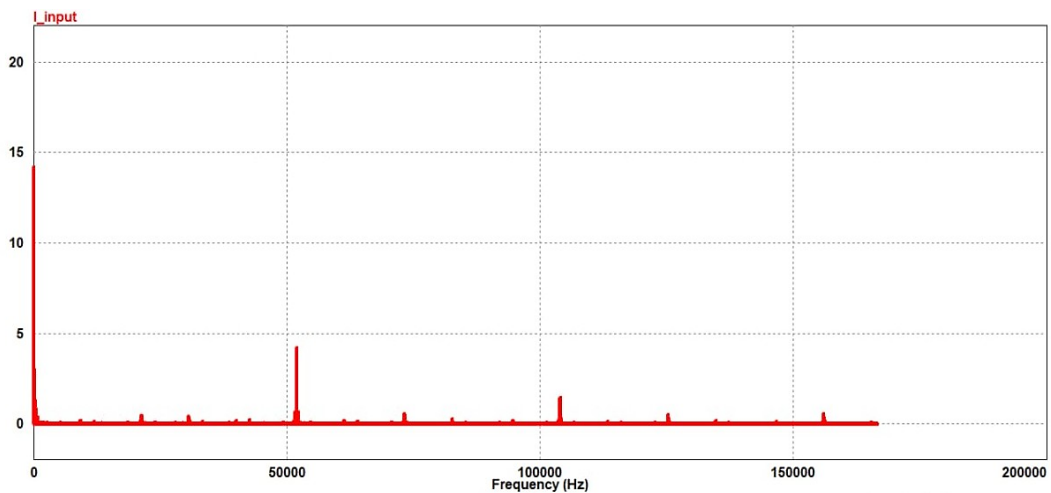**Figure 3(a). Input current waveform analysis of the IHE before installation of SAF**

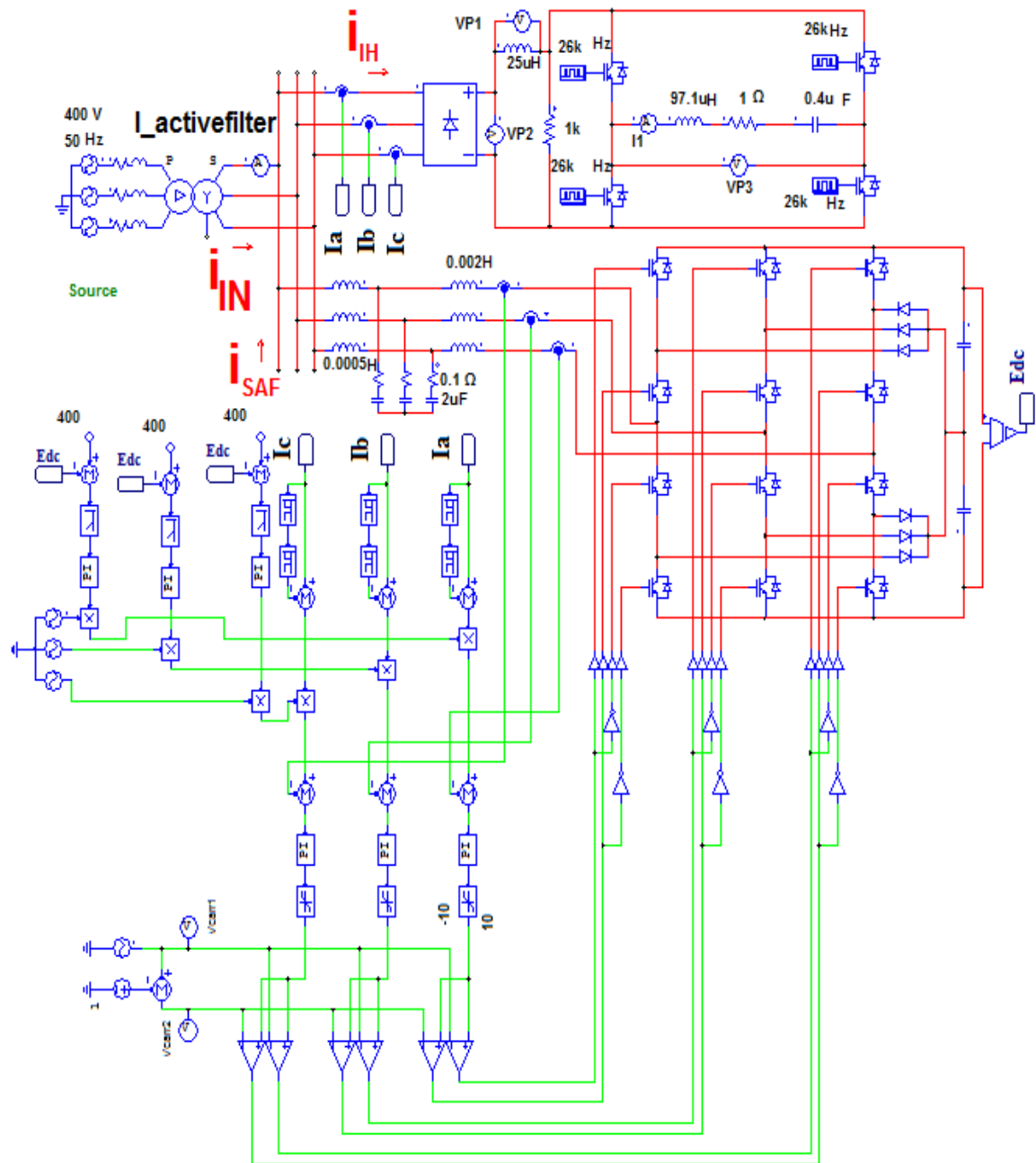**Figure 3(b). Input current FFT analysis of IHE before installation of SAF**

Figure 4. Simulation Diagram of IHE after installation of SAF
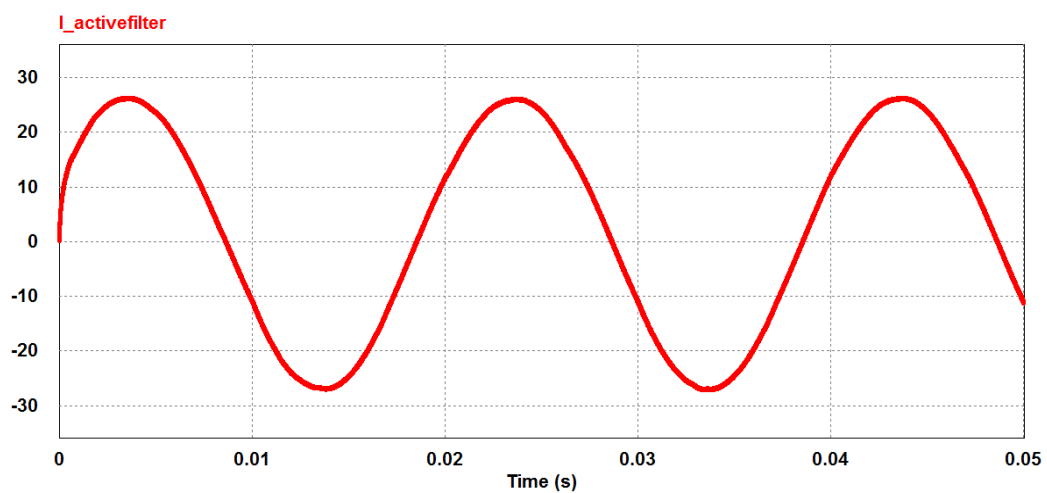
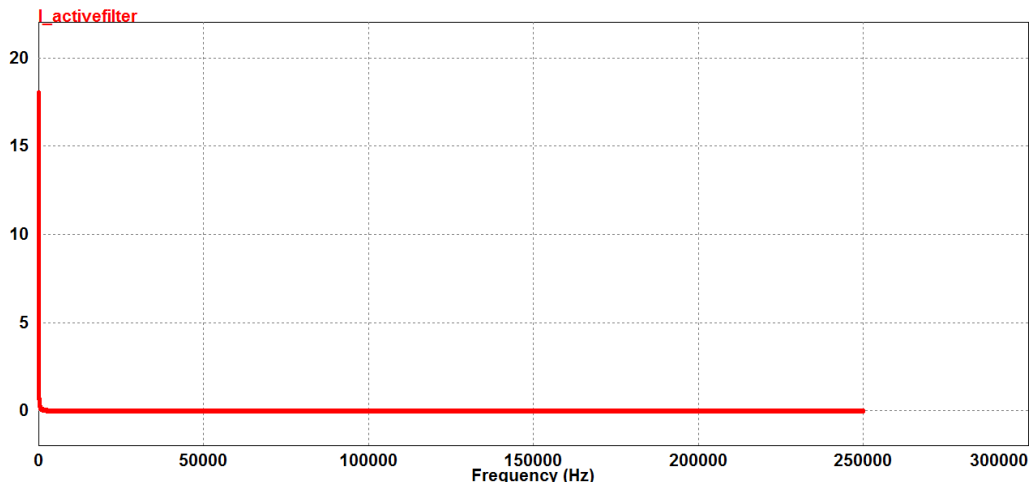**Figure 4(a). Input current waveform analysis of IHE after installation of SAF**

Figure 4(b). Input current FFT analysis of the IHE after installation of SAF

The FFT analysis of the input current waveform without the incorporation of shunt active filter shows the presence of some predominant harmonic components and as a result of that the total harmonic distortion was found to be 33.3%. With the incorporation of the shunt active filter, the harmonic spectrum is improved and the total harmonic distortion is reduced to 0%. All the components that have been used in PSIM are ideal in nature. Henceforth, the shunt active filter is able to successfully eliminate all the high frequency harmonic components that were causing a considerable amount of deterioration in the power quality. So, it justifies the necessity and importance of shunt active filter in an induction heating system.

4. Calculation of THD

From the simulation results and FFT analysis, the THD is calculated as follows:

4.1. Before SAF installation

The FFT analysis of the source current waveform in the absence of the SAF is observed to be non-sinusoidal in nature and contains three predominant and a few negligible harmonic components alongside the fundamental current component.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} (I_{line})_{n,rms}^2}}{I_{(line)1,rms}} \qquad THD = \frac{\sqrt{4.669^2 + 0.852^2 + 0.25^2}}{14.231} \times 100 = 33.3\%$$

4.2. After the installation of SAF

The FFT analysis is performed again after the installation of the SAF in the IHE. The analysis shows that the harmonics are eliminated completely. Practical implementation of this model may give rise to a very negligible value of THD due to small imperfections in the equipment used. Here we have used ideal components, so it shows nearly zero THD value.

5. Conclusion

The present work deals with the elimination of the high-frequency harmonics available on the supply line. Induction heating at a high frequency has a lot of advantages over traditional models. But operation at high frequency has got several disadvantages like electromagnetic and radio frequency interference and the production of harmonics, resulting in the deterioration of power quality.

Many techniques are available for the elimination of harmonics, but the total harmonic distortion is considerably higher in all the existing topologies. So, in the present work, attention has been paid to designing the controller for the shunt active filter that can attenuate the harmonic components present in the supply line in a very efficient way.

The THD of the current waveform at the input side of the Induction Heating Equipment before the installation of SAF was found to be 33.3%. However, after the installation of SAF, the harmonics, which were present are completely eliminated. Thus, it justifies that the SAF successfully performs harmonic damping in the Induction Heating Equipment resulting in increased power factor and lower THD.

6. Declarations

6.1. Author Contributions

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

6.4. Acknowledgements

6.5. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. References

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