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Article

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Protecting power factor correction capacitors from overvoltage generated by non linear drives using parallel resonance filter

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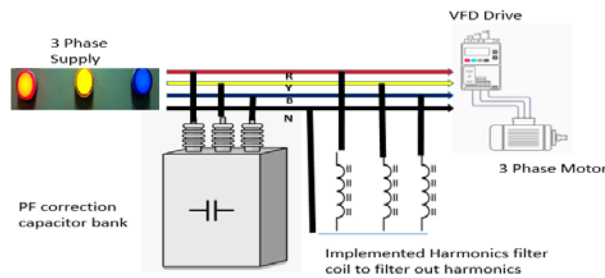
ABSTRACT



The speed of an AC motor primarily depends on the frequency of the AC supply. To control the speed of an AC motor, Variable Frequency Drives (VFDs) are widely used. VFDs offer energy efficiency, smooth start and stop functions, and many other advantages. However, when these drives are used at higher ratings, typically above 10 KVA, they generate harmonics that are introduced into the line supply. These harmonics distort the sine wave of the AC supply, effectively increasing the line voltage, and sometimes causing it to exceed the load's sustaining voltage. The voltage of the generated harmonics depends on the drive pulses used in VFDs. In 6-pulse VFDs, the 5th harmonic is particularly prominent. This research article presents a practical solution to these problems. The RMS voltages of the lower odd harmonics are detected by the circuit. Parallel resonance for higher harmonics is provided by a high-quality factor coil. Due to this parallel resonance, harmonic currents do not enter the power factor correction capacitor but remain in the line voltage, thus protecting the power factor correction capacitor from overvoltage generated by VFDs. The RMS voltages of the harmonics are detected by a PIC microcontroller and displayed on an LCD, with resonance provided specifically for the 5th harmonic.

Keywords: Odd harmonics, Total harmonics distortion, Parallel resonance, Overvoltage protection.

INTRODUCTION

Harmonics are multiples of the fundamental frequency. The amplitudes of even harmonics cancel each other out in each cycle, but the amplitudes of odd harmonics do not, which distorts the waveform of the fundamental component. Figure 1 illustrates the fundamental frequency component, along with the 3rd, 5th, and 7th harmonics. The blue line represents the fundamental component of the sine wave. As other harmonic components are introduced, the resultant waveform, shown in black, becomes distorted and random. This harmonic generation affects both the load and the distribution network. Harmonics are generated by non-linear drives and enter the line voltage, resulting in a voltage waveform that deviates from the original sine wave. This can create instantaneous high voltages. When the motor coil receives such voltage, it becomes saturated, leading to bearing damage due to sudden mechanical jerks. Overall, harmonics negatively impact the power distribution network and connected loads, causing the Total Harmonic Distortion (THD) level to rise.

To mitigate the effects of harmonics, we explored ways to protect certain loads. A power factor correction capacitor bank is used for this purpose. For the prototype, a three-phase 0.5 HP motor is employed. When the motor runs at full load, it operates with a lagging power factor of 0.75. To improve this, a 10-microfarad capacitor is connected between each phase and neutral. Additionally, a 1.5 kW Siemens VFD drive is used to control the motor speed. Figure 2 and equation 1 presents an equivalent circuit diagram, where Vs represents the 230V phase-to-neutral supply from the transformer's secondary. The transformer's internal resistance is denoted by Rs, and Ls represents the inductance of the secondary winding.

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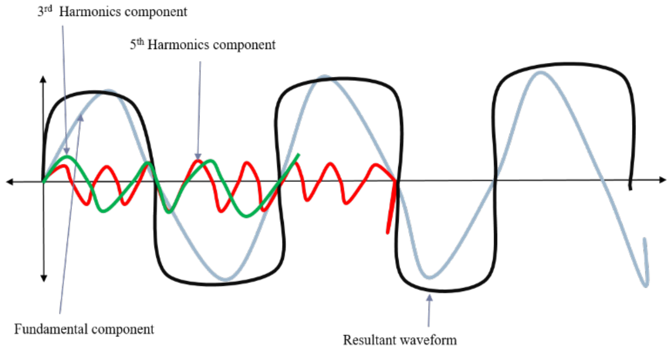


Figure 1. Waveform of fundamental, odd component and the resultant waveform.

$$fn = \frac{1}{2\pi}\sqrt{\frac{1}{LfCf} - \frac{Rs^2}{Ls^2}} \text{------------- (1)}$$

Ih is the harmonics current that is generated by the VFD drive. The inductance coil has internal resistance which is denoted by Rf. Lf is the inductance of the resonated coil. Cf is a 10 microfarad phase to neutral capacitor used for power factor correction. The resonated frequency is given by equation number 1. Equivalent L = Ls parallel Lf. As the value of Ls is higher, effective L remains Lf. Parallel resonance for the 5th harmonics component, the value of Lf is given by equation number 2.

$$Lf = \frac{1}{w^2 h * cf} \text{----------------- (2)}$$

Background

G. Sarowar et.al[1] used SEPIC topology for enhancing the power factor. It is essential for optimizing energy efficiency, reducing electricity costs, and enhancing the reliability of electrical systems. Industrial facilities often have a mix of resistive and inductive loads, such as motors, transformers, and welding equipment, which can lead to a low power factor. M. M. Islam et.al[2] worked on Protecting PFC Capacitors from Overvoltage Caused by Harmonics and reactors where they deeply studied the relation power factor improvements and economic savings. G. Mailsamy et. al[3] worked on Constrained maximum power extraction in pmvg wind turbine system with predictive rotor position bias-based current angle control for power factor improvement which offers valuable insights into optimizing power factor and improving energy efficiency in electrical networks. ERACS, a widely used simulation tool, facilitates the analysis and design of power systems by modeling various components such as transformers, capacitors, and loads. In this study, capacitor banks are strategically placed within the network to decrease reactive power.

The harmonics has the dominant effect on Ferro resonance. It has a major impact on the system's stability and reliability, was studied by Junhong Lai et al[4] When the resonant frequency of the system and the natural frequency of the ferromagnetic core in transformers or other inductive devices coincide, a nonlinear phenomenon known as Ferro resonance takes place. Harmonics, which are non-linear distortions of the fundamental frequency, can exacerbate this phenomenon by altering the resonance conditions within the system. In power factor correction systems, where capacitors are often used to compensate for reactive power, harmonics can arise from non-linear loads such as variable frequency drives or electronic equipment. These harmonics can disrupt the voltage and current waveforms, leading to an increased risk of Ferro resonance events. N. Oshimoto et.al[5] worked on wireless power transfer, an analysis was conducted to address the challenges associated with low power factor in rural areas. Typically, village loads consist of a mix of residential, agricultural, and small commercial consumers, often characterized by a high proportion of inductive loads such as motors and transformers. These loads contribute to a low power factor, leading to inefficiencies in the distribution system and increased energy consumption. The case study involves implementing power factor correction measures such as the installation of capacitor banks at strategic locations within the distribution network. G. Zhang et.al[6] worked on the Self-Protected Single-Stage LLC Resonant Rectifier. The work represents a significant advancement in power electronics, offering a streamlined solution for converting alternating current (AC) to direct current (DC) with remarkable efficiency and reliability. This rectifier integrates both rectification and voltage conversion into a single stage, simplifying the circuitry while boosting overall efficiency. At its core lies the LLC resonant converter, known for its high efficiency and soft-switching characteristics, which helps reduce switching losses. V. M. López-Martín et.al[7] worked on Power quality enhancement in residential smart grids. They offer an efficient solution for industries with variable inductive loads to maintain optimal power factor levels, thereby improving energy efficiency and reducing electricity costs. Industries with fluctuating load profiles often face challenges in managing reactive power, leading to inefficient power usage and penalties from utilities. Automatic power factor correction systems utilize control algorithms and capacitive banks to dynamically adjust reactive power compensation based on real-time load conditions. W. Qi et.al[8] worked on a solar plant that is used as a source of reactive power in an inventive power factor correction method. Y. Kabir et. al[9] worked on decreasing the reactive power in the electrical grid, traditional power factor correction methods often depend on passive parts like capacitors. On the other hand, incorporating a solar power plant into the power system offers the chance to dynamically modify the reactive power output in response to current grid conditions. Through the utilization of the solar plant's inverters, which are already equipped with the ability to regulate both active and reactive power output, the plant can actively introduce or absorb reactive power to maximize the grid's power factor.

The work by A. Kouchaki et. al[10] focused on implementing power factor correction (PFC) stages to improve the power quality within residential smart grids. Residential smart grids integrate various renewable energy sources, energy storage systems, and smart appliances, leading to a complex power network with diverse loads. The paper proposes the use of PFC stages to enhance power quality by improving the power factor, reducing harmonic distortion, and minimizing voltage fluctuations. By strategically placing PFC stages throughout the grid and utilizing adaptive control algorithms, the system can dynamically adjust capacitor banks to compensate for reactive power variations and maintain a balanced power factor. This method maximizes energy efficiency while simultaneously improving the home smart grid's stability and dependability, preventing interruptions and guaranteeing seamless operation. Yue Zhang et.al[11] worked on the Adaptive Constant Power Control of MHz GaN-Based AC/DC Converters for Low Power Applications which presents a novel approach to power factor correction (PFC) rectification without relying on traditional electrolytic capacitors. By employing a three-level flying-capacitor topology, this rectifier architecture offers several advantages, including improved efficiency, reduced size, and enhanced reliability. An analytical approach to designing passive LCL filters for three-phase two-level power factor correction rectifiers is presented in the work Analytical design of passive lcl filter for three-phase two-level power factor correction rectifiers by A. Y. Yav et al.[12] These rectifiers are widely used in various applications to convert AC power to DC while correcting power factors. However, they often generate harmonic distortions that can affect power quality. The paper addresses this challenge by proposing the integration of LCL filters, which effectively attenuate harmonic currents and mitigate voltage ripple.

Yongheng Yang[13] worked on a methods which are essential for optimizing the efficiency and performance of electrical systems by ensuring a balanced relationship between real power (kW) and apparent power (kVA). These techniques encompass various methods aimed at minimizing reactive power consumption and improving power factor, thereby enhancing overall energy efficiency and reducing electricity costs. Passive power factor correction involves the addition of capacitors to the system, which counteract the inductive effects of loads. Young-Jin Kim et.al[14] worked in the context Development and Analysis of a Sensitivity Matrix of a Three-Phase Voltage Unbalance Factor, the implementation of Automatic Power Factor Compensation (APFC) devices offers significant benefits for power factor improvement. The study investigates the impact of the low power factor on energy consumption, electricity bills, and overall operational costs. By employing power factor correction technologies such as capacitor banks or active power factor correction devices, the aim is to improve the power factor, thereby reducing reactive power demand and minimizing losses in the electrical system.

SYSTEM ARCHITECTURE

System Working

To determine the RMS voltages of fundamental components, third, fifth, and seventh harmonics, a PIC microcontroller-based system is developed. The secondary inductance of the transformer is used in conjunction with additional capacitance (C) and inductance (L) values to detect each component. It is determined that the third, fifth, and seventh harmonics have parallel resonance. The basic part is rectified using a rectifier circuit, and the output is then connected to a filter capacitor. A scaled potentiometer receives this filtered output next, and 1/4 of the signal is then sent to the microcontroller via it. Readings are calibrated while programming is going on. The third, fifth, and seventh harmonics' parallel resonance is calculated using equation 2. Initially, a standard capacitor value of 1 μf is considered, and the corresponding inductance (L) is then calculated. The calculations are as follows:

For the 3rd harmonic (150Hz), a capacitance (C) of 5 μf and an inductance (L) of 198 mh are utilized.

For the 5th harmonic (250Hz), a capacitance (C) of 4 μf and an inductance (L) of 99 mh is employed.

For the 7th harmonic (350Hz), a capacitance (C) of 3 μf and an inductance (L) of 66 mh is applied.

Based on a standard 1 μf capacitor and 22 mh inductor, these calculations are made. All of these resonated parts are then fed into circuits for rectifiers. Schottky diodes are used in the rectifier circuit to reduce forward voltage drop; Schottky diode has forward voltage drop of 0.2 volts. After rectifying, the output is fed into a 100 μf filter capacitor, which filters out AC components by converting them to DC voltage. A scaled potentiometer is used to feed the microcontroller with a quarter of this output.

The logic used in programming is where calibration happens. The presence of two Schottky diodes in the bridge rectifier accounts for an extra 0.4 volts if the potentiometer reading registers at 0.4 volts. Following that, the transformer turns ratio of 12 is multiplied by this value. As a result, the LCD board shows a 4.8-volt RMS value through programming. Calculations, both theoretical and practical, have a 95% accuracy rate. This technique makes it easier to find and show each harmonic's RMS value on the LCD board. The setup becomes a parallel resonance configuration, as shown in Figure 2 if any harmonic surpasses the critical limit. To do this, the precalculated parallel resonance coil is connected in series with the PFC capacitor. This method successfully stops line voltage-affecting harmonics with high RMS values. Using a high-Q (2000) filter coil limits the amount of current that can flow through the capacitor and protects the power factor correction capacitor from harmonics produced by nonlinear drives, like VFD drives. An analogous circuit diagram showing the insertion of harmonic current by a nonlinear drive is shown in Figure 2. In this case, Rs denotes the transformer secondary's internal resistance, and Rf denotes the inductance coil's internal resistance, which is used for filtration.

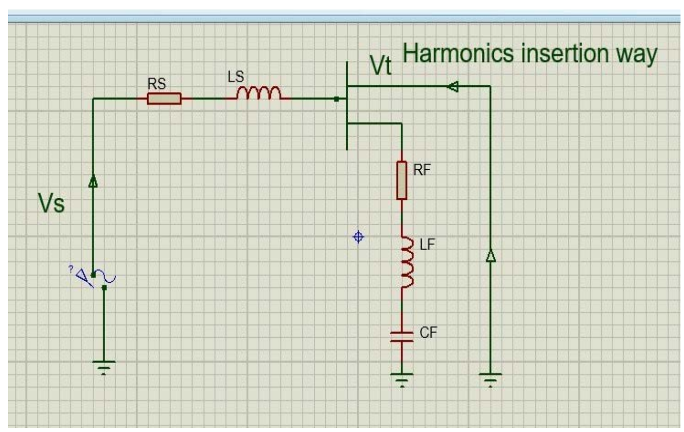


Figure 2. Shows the harmonics insertion equivalent diagram.

Equivalent inductance (L) is calculated using the formula:

$$L\ (equivalent) = \frac{Ls * Lf}{Ls + Lf}$$

Where:

Ls represents the secondary inductance value of the transformer.

Lf represents the inductance of the resonated coil to be connected.

Cf represents the capacitance value of the phase-to-neutral power factor correction (PFC) capacitor.

A unit shows the reading for basic components (230 volts). A unit displaying the third harmonic reading with an RMS value of 6.9 volts is shown in Figure 3. A unit with a reading for the fifth harmonic and an RMS value of 2.3 volts. A unit with a 7th harmonic reading and an RMS value of 0 volts. Moreover, the total harmonic distortion (THD) level is shown.

$$\mathrm{THD} = \frac{\sqrt{(V3)2 + (V5)2 + (V7)2}}{V1} \text{ ------------------------ (3)}$$

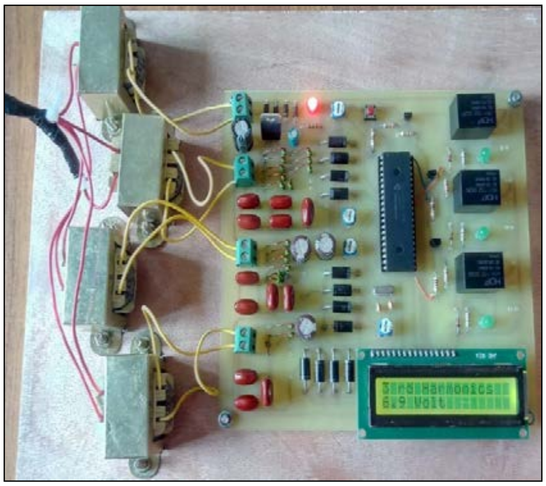


Figure 3. Shows RMS value of 3rd harmonics.

RESULTS AND DISCUSSION

Figure 4 depicts the experimental setup for detecting harmonic readings when the VFD drive is bypassed, and a direct 3-phase supply is applied to the load (noting the MCB position). The figure 5 shows the multimeter displays a reading of 1.455 volts for the 3rd harmonic. A reading of 0.763 volts for the 5th harmonic on the multimeter. Additionally, a reading of 0.473 volts for the 7th harmonic on the multimeter. Figure 6 illustrates the experimental setup for detecting harmonic readings when the VFD drive is activated, and the supply is routed through the VFD drive to the load (again noting the MCB position). In Figure 7, the multimeter records a reading of 1.916 volts for the 3rd harmonic. A reading of 1.466 volts for the 5th harmonic on the multimeter. Furthermore, displays a reading of 1.312 volts for the 7th harmonic on the multimeter. All of these measurements show that the RMS value of harmonics rises with the activation of the VFD drive, influencing distortion at the THD level. Table No. 1 presents an overview of these readings. Furthermore, the Siemens 1.5 kW VFD graph below provides a graphical representation of these values.

Table 1: Harmonics level comparison when VFD drives are used.

Sr. No.	Harmonics Number	Direct in Power Supply	When VFD Activated	Remark
1	Third	1.455V	1.916V	RMS voltage of third harmonics comparatively increases
2	Fifth	0.763V	1.466V	RMS voltage of third harmonics comparatively increases
3	Seventh	0.473V	1.312V	RMS voltage of third harmonics comparatively increases

Figure 4. Shows unit settings for direct 3-phase readings.

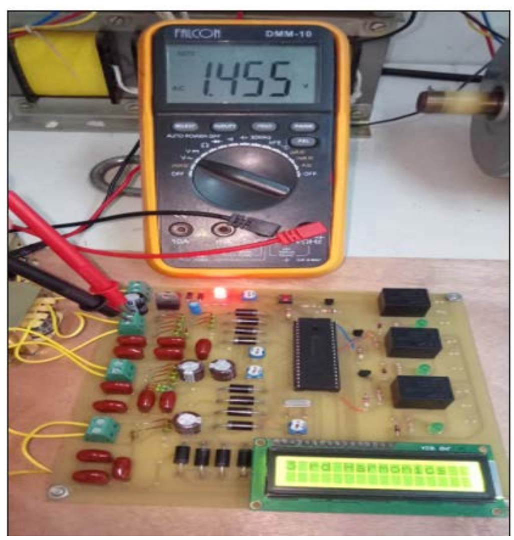


Figure 5. Shows the reading of 3rd harmonics in the power supply.

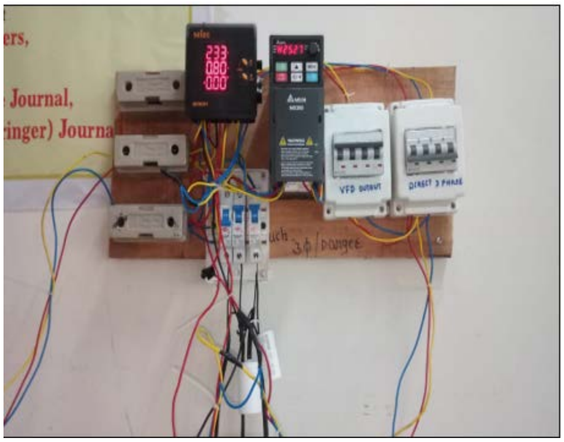


Figure 6. Shows unit settings for readings through VFD.

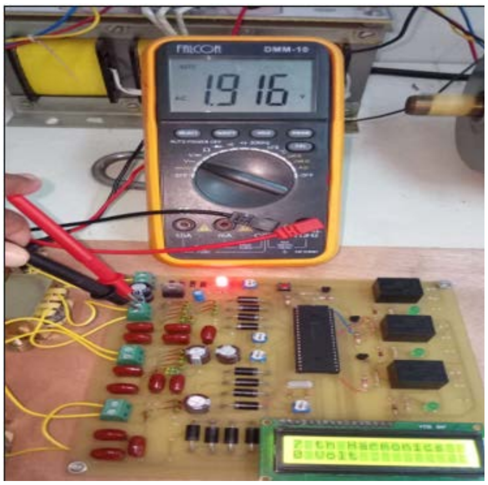


Figure 7. Shows the rms value of 3rd harmonics through VFD.

In a 6-pulse VFD drive, it is always a case that the 5th harmonics always become high. So figure 8 shows the connection of the designed coil to filter out 5th harmonics. Due to parrallel resonance to 5th harmonics, that harmonics current will not pass through capacitor bank.

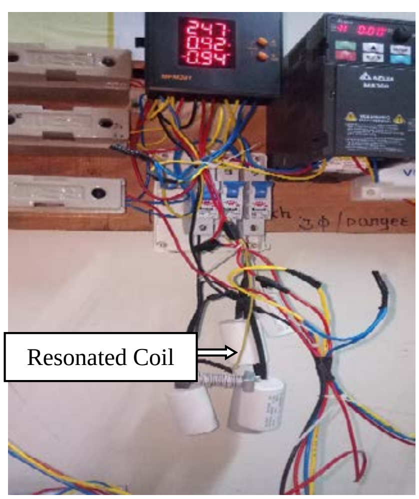


Figure 8. Parallel resonated coil connected for 5th harmonics filtration.

Ms. Lamkane (Executive Engineer) and the team from MSEDCL Solapur verified and validated the results of the research work, the results validation letter was provided by MSEDCL Solapur. Figure 9 shows the Proteus simulation diagram of the unit to prepare PCB. Figure 10 shows the PCB layout of the designed unit.

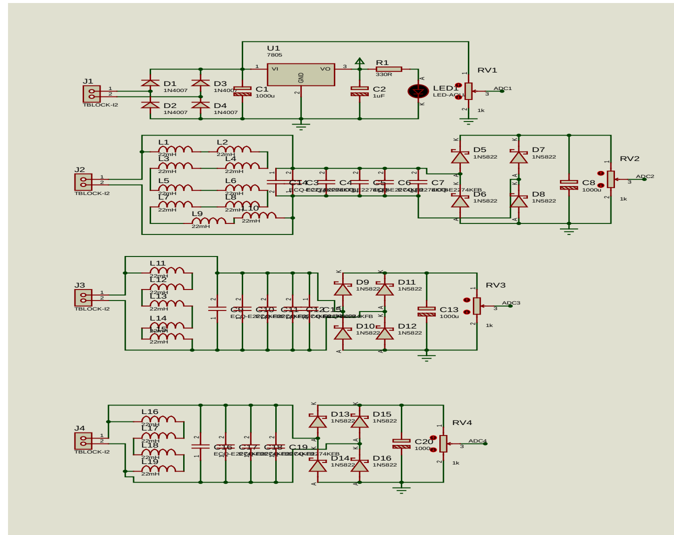


Figure 9. Proteus simulation diagram.

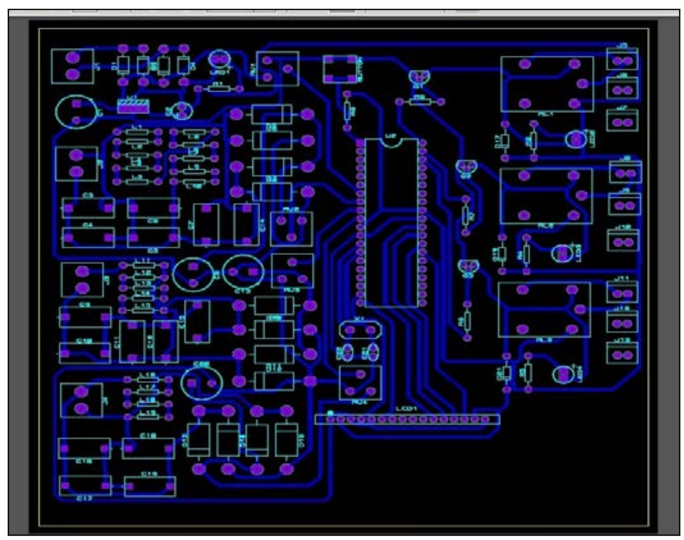
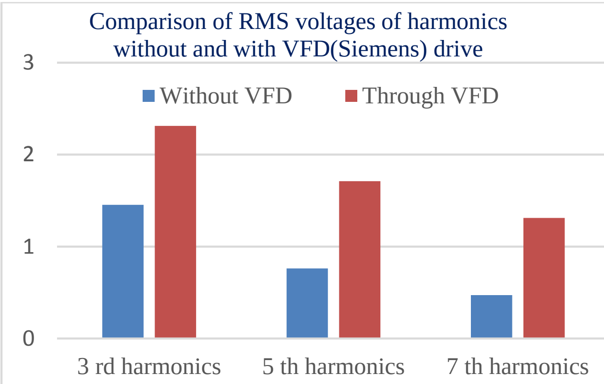
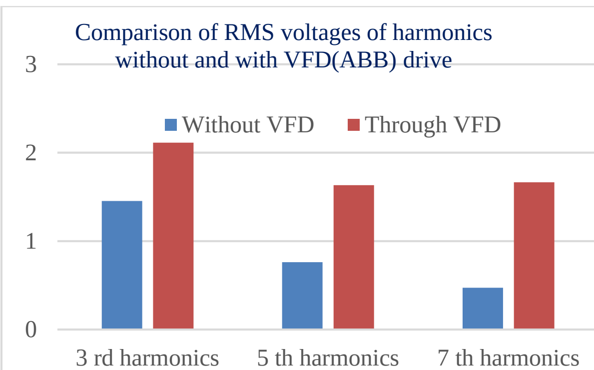
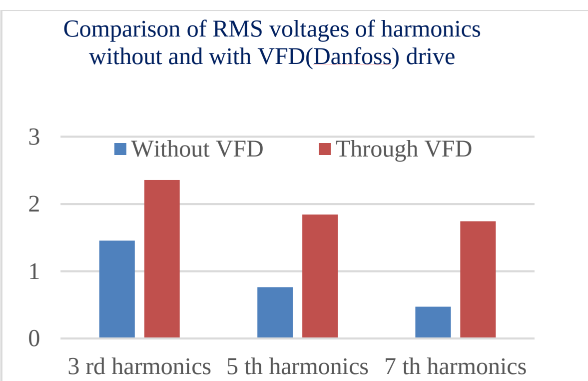


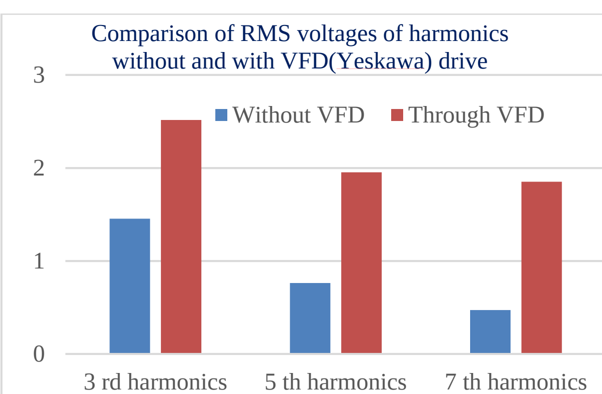
Figure 10. PCB layout of the unit.

Further another VFD of ABB company was taken and similar readings were taken. So, following are graphs of different companies' VFD drives of 1.5 kW ratings. Harmonics generation also depends on the quality of drives. High-quality drives have inbuilt best harmonics filter. As the quality of drives decreases, it increases the rms value of harmonics also. VFD of companies Siemens, ABB, Danfoss, Yeskawa, and Rockwell is the sequence of quality degradation. Cost is directly proportional to the quality of drives. As cost increases quality also increases. 1.5 kW 3 phase Siemens VFD cost is around 20,000 Inr., and the same VFD of ABB company cost is around 12,500 Inr. The below graphs indicate a change of rms values of harmonics increases sequentially as the cost of drives decreases. All these are indicated in figure 11.









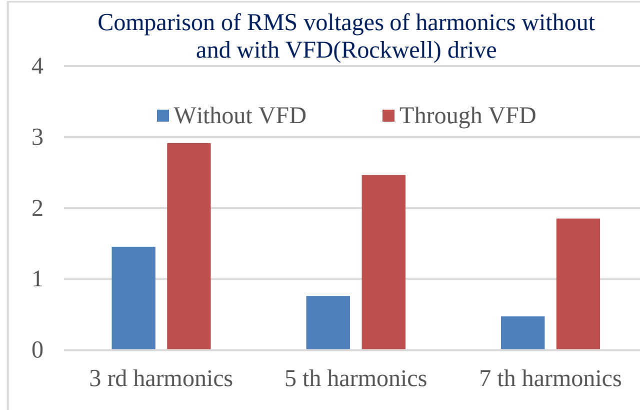


Figure 11. Harmonics level of different VFD drives.

The VFD and PFC capacitors are connected in a shunt. Its goal is to improve the power factor of the VFD system by lowering its reactive power requirement. A tuned passive filter is produced by connecting the PFC capacitor in series with the reactor (inductor). Because the filter is resonant at the fifth harmonic frequency, it can attenuate the source current's fifth harmonic component (Is). The fifth harmonic component of the source current that flows through the PFC capacitor is successfully reduced by the tuned filter. Important details regarding the efficiency and energy usage of the filters are provided by the evaluation of power loss in the filters. Let's review the outcomes.

Filter with Q = 2000, Power Loss: 0.0526 W, Equivalent Energy Loss per Year: 461.52 Wh.

Conclusion

When VFD drives are used in higher ratings it has the disadvantage of inserting harmonics in the power supply. When VFD drives are used with higher rating side effects should not be ignored, especially in situations where drives have ratings greater than 5 KW. MSEDCL has kept a higher limit of THD level 3%, when that limit crosses MSEDCL charges a heavy fine. Harmonics insertion affects entirely on the distribution network. So by considering all the above factors harmonics insertion should be below the critical limit. Inserted harmonics increase the line voltage. Increased line voltage can spoil the rated capacitor banks. In this situation, an appropriate way should be utilized in which a high-quality Q filter should be used which avoids passing harmonics current into the capacitor bank. All this will be possible by using resonated coils. The resistance of the coil used should be very low so the power loss will be very low. Resonated coil should be used in industrial load when the load is in MW. The Q factor of the coil used at that time should be above 2000 rather than greater than this. A prototype model is developed in the research lab, and it is scalable for MSCDCL customers. The generated results are validated by MSEDCL. Coil resistance 5 ohm and quality factor Q 3500 is coil under construction. The above research has shown that reactor coil has many advantages and it protects from the over-voltage of many loads. The data suggests that it is a promising solution for industrial applications where load magnitudes are substantially higher and use a high range of VFD drives. There are approximately 1.62 million customers of 100+ kva load in the state of Maharashtra. All these have a power factor correction capacitor bank. All these customers are affected by harmonics insertion. This study has shown that, when non-linear drives are present, parallel resonance filters are an effective safeguard for power factor correction capacitors. The longevity and dependability of power factor correction systems are seriously threatened by the growing integration of non-linear loads in industrial settings. Our findings highlight the following key findings. The incorporation of parallel resonance filters not only safeguards PFC capacitors but also contributes to enhanced overall system reliability. So, by knowing the challenges associated with non-linear drives, power factor correction systems operate more efficiently and with increased longevity. The practicality of implementing parallel resonance filters in real-world applications is underscored through a combination of experimental and simulation-based approaches.

In summary, the research outcomes affirm the viability of parallel resonance filters as a valuable tool. This work contributes to the broader goal of optimizing power quality in industrial environments, ensuring the stable and reliable operation of power systems. We made a effort to protect the capacitor bank of all these to some extent.

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CONFLICT OF INTEREST

The authors decleare that they do not have any conflict of interest regarding this research.

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