# INVESTIGATION OF SUPRA-HARMONICS EMISSION DUE TO SOLAR PV INVERTERS

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Degree of Master of Science

Department of Electrical Engineering

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science in Electrical Engineering

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## DECLARATION

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Dr. J. V. U. P. Jayatunga

## ABSTRACT

The number and rating of power electronic systems interfaced to electricity distribution networks have been rising at residential, commercial, industrial and utility environments over the last few decades. Domestic roof top solar photovoltaic (PV) systems, utility level solar generating systems and modern lighting systems can be taken as examples of such systems from the more recent years.

This trend has caused an increasing concern on the associated power quality problems. High frequency harmonics in the frequency range between 2 and 150 kHz (referred to as Supra-harmonics) has become a topic of growing interest due to higher amount poor power electronic switching interfaces. Amongst the possible repercussions of High Frequency emissions, malfunctioning of equipment, interference with Power Line Carrier communication and lifetime degradation of other connected equipment are prominent. Alongside with the power electronic systems, generation of unwanted harmonics have received considerable attention over the years, where much of the focus has been on the low frequency harmonics below 2 kHz. With these efforts, standards have evolved to ensure electromagnetic compatibility and many engineering solutions now exist to control their magnitudes. However, the knowledge associated with HF emissions is still in the premature level.

An increasingly prominent grid connected devices, which can contribute to these HF emissions are the photovoltaic (PV) systems. Thus, this research is focused on investigating supra-harmonic emission in the low voltage distribution system due to photovoltaic inverters. The thesis presents the analysis on HF emission of PV inverters under different configurations and their propagation is also studied. The study results are based on the detailed simulations carried out in MATLAB/SIMULINK environment and they provide further research thoughts for laboratory controlled experiments.

Key words: High Frequency, photovoltaic, inverter, Supra-harmonics, distribution system

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## LIST OF ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| APFC | Active Power Factor Correction |
| BJT | Bipolar Junction Transistor |
| CFL | Compact Fluorescent Lamps |
| ECM | Electrically Commutated Motor |
| EV | Electric Vehicle |
| HF | High Frequency |
| HFH | High Frequency Harmonics |
| HVAC | Heating, Ventilation and Air Conditioning |
| IGBT | Insulated Gate Bipolar Transistor |
| LED | Light Emitted Diode |
| LF | Low Frequency |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| PFC | Power Factor Correction |
| PLC | Power Line Communication |
| PV | Photovoltaic |
| PWM | Pulse Width Modulation |
| SIT | Static Induction Transistor |
| SMPS | Switch Mode Power Supply |
| TL | Transformer Less |

# LIST OF APPENDICES

# CHAPTER 1

## Introduction

### 1.1 Background

Ideally, the power system is expected to handle perfectly sinusoidal currents and voltages, which have only one frequency. But, due to the non-linear operation of power system equipment, in reality, the practical voltages and currents differ from an ideal sine wave. That means, they contain frequencies other than the power frequency which are generally called as "harmonics". Harmonics in power systems has been a very popular research area over many years since the advent of grid connected power electronic systems. Over the past few decades, different types of power electronic devices are introduced to the power distribution system and electricity grid has undergone dramatic changes.

Other than the loads, due to the shortage of fossil fuels and the soaring oil prices in countries with climate change, the share of renewable energies in electricity generation is growing steadily. Other than that, renewable energy concept is highly considered to reach a greener world in the future where renewable energy sources are driven by power electronic systems. Furthermore, usage of plug-in hybrid electrical vehicles has been rapidly increased with the fuel efficiency.

The smart grid concept has become a new trend in the world; it intends to increase the energy efficiency, reduce the energy cost, and simultaneously to achieve a sustainable balance between production and consumption, increasing the reliability and the power quality of power system. Almost all these new technologies, as integrated with advanced communication system, and metering infrastructure are occupied with power electronic systems.

### 1.2 Problem Statement

Operation of power electronic systems is generally based on the high frequency switching which leads to distort the voltage and current waveforms. This distortion can give rise to range of frequencies, a higher amount of distortion at low order harmonics. However, higher the penetration of HF switching based devices, a considerable amount of HF harmonics in the range of 2 to 150 kHz range is present in the system.

The origin, spread and impact of waveform distortion up to 2 kHz is well studied and effective mitigation techniques are already in use. Other than that, developed standards are available, and due to that lower order harmonics can be avoided by referring to those standards.  Lower order harmonics up to 2 kHz can be called as lower frequency harmonics (LF). Above 150 kHz frequency range is also well studied and effective mitigation methods are implemented. In addition, complete set of standards based on electromagnetic interference are available. This range of frequencies is called as Radio Frequencies.

In between 2 kHz to 150 kHz frequency range harmonics are named as High Frequency harmonics (HF) or supra-harmonics. Recently, this frequency range has received more attention by researches and standard setting organizations like IEC, CENELEC and IEEE.

The typical classification of harmonics as in Low frequencies, High frequencies and Radio frequencies are shown in Figure 1.1.

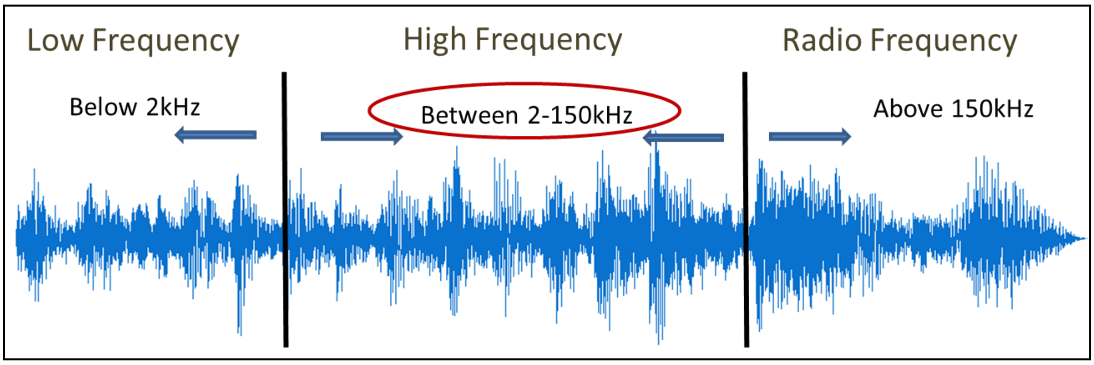



Figure 1.1: Frequency ranges of LF, HF and Radio frequencies

### 1.3 High frequency harmonics or supra harmonics

High frequency harmonic (HF) or supra-harmonic emission is a major concern due to power quality problems in low voltage electrical distribution system in the world. The presence of waveform distortion in frequency range of 2 kHz to 150 kHz range is called supra-harmonics. These harmonics are originating from power electronic devices and power line carrier (PLC) communication.

Just like other harmonics, High frequency harmonics also generate unnecessary heat in loads. As a result of this, equipment lifetime can be reduced with insulation degradation over time, causing temperature rise of equipment. Furthermore, Capacitor impedance goes to a very low value with the high frequencies, and due to that, equipment with capacitors can be more vulnerable to lifetime degradation. Moreover, sensitive equipment has more risk of damage with the rising excessive levels of voltages or currents under electricity network resonance conditions and measuring devices may exhibit measuring errors.

Increasing emission due to increasing number of electronics equipment with high switching frequency, increase of interference although equipment is marked with CE sign and gap in standardization can be found as import factors to study in the high frequency harmonics.

High frequency harmonics have to be studied relevant to the harmonic sources. Modern television, Power supply, Induction cooker, Photovoltaic inverter, Fluorescent lights and LED lamps can be identified as harmonic sources. Among these harmonic sources, Photovoltaic inverters are highly used nowadays due to most famous renewable energy generating methods as solar energy generation including most of the roof top installed solar power systems.

With this condition, this research is focused to analyze the impact of high frequency harmonics due to photovoltaic inverters to power distribution system.

### 1.4 Research goals and objective

The aim of this research is to analyze the high frequency harmonics in low voltage distribution system due to photovoltaic inverters.

The proposed work is focused on the impact of the level of solar penetration, type of inverter and different inverter configurations on HF harmonics emission and analysis of harmonic propagation.

## 1.5 Thesis overview

Second chapter of this paper gives a comprehensive literature review on the origin of Low frequency harmonics and high frequency harmonics in power system. Moreover, it gives an idea about two factors; primary and secondary emission. Other than that, it gives an overview about the high frequency harmonic sources and the relevant existing standard, where the shortcomings of the overall standards framework are highlighted.

Third chapter focuses on how to model photovoltaic inverter under device modeling and how to model distribution system under low voltage distribution system modeling.

Fourth chapter focuses on analyzing high frequency harmonics of photovoltaic inverter. Here, Single-phase and three-phase inverters are considered for analysis of high frequency harmonics. Fifth chapter describes high frequency harmonics propagation in power distribution system. In this chapter, impact of the level of inverter penetration, inverter configuration and analysis of harmonic propagation are discussed.

# Literature Review

## 2.1 Origin of HF harmonics

Power electronic devices generate Low frequency (LF) harmonics and High frequency (HF) harmonics. Passive power-electronic converters, active power electronic converters, grid-commutated converters are mainly emitted LF harmonics and high frequency (HF) harmonics [1]. It is identified that HF harmonics of 2 - 150 kHz are generated because of the switching operation of power electronic interfaces.

A passive Power Factor Correction (PFC) is often an inductor before the storage capacitor which softens the charge current of the capacitor. An active PFC uses a switching element together with an inductor, a switched-mode boost converter, before the storage capacitor to force the current, as in a resistor, to follow the shape of the voltage. The switching frequency and its harmonics in the PFC are generated independently, that is, not correlated, to the frequencies and their harmonics generated in other switching units like dc/ac converters, dc/dc converters or other PFC, connected to the same electrical network. The origin for the PFC switching frequency is also generated independent of the fundamental frequency of 50/60 Hz and its harmonic. But, as long as the origin of the frequency is not the same, two identical converters will differ in switching frequency. These harmonics of the switching frequency are called high-frequency harmonics (HF - harmonics), in distinction from the fundamental frequency harmonics. In the case there is a summation of lots of switching frequencies and their harmonics the expression, high-frequency noise, HF- noise is also used.

Two types of HF harmonics can be distinguished as synchronized behavior and random behavior. The synchronized behavior is present in the current as a “zero crossing distortion” or “crossover distortions” close to the current zero crossing. Random behavior is a “non-damped oscillation” present in between the zero-crossing oscillations (i.e., with the current maximum or minimum). This oscillation is associated with the power-electronic switching used in the active PFC circuits [1] [12].

Differences can be identified between LF harmonics and HF harmonics by using some basic investigations carried out in this research area. Most of the LF harmonics are appeared as narrowband components in the spectra and HF harmonics are appeared as broadband components. Another considerable difference is the pattern of aggregation of the harmonic patterns of HF and LF [13].

**2.2 Primary and secondary emission**

Two factors are associated with HF harmonics, as compared to the case of LF harmonics. Those are named as primary and secondary emission. Primary emission originates from the equipment itself. The secondary emission is the disturbance that flows to the equipment from the external equipment, usually from the neighboring equipment. Secondary emission also plays equally important role and is often dominant contribution as the primary emission for HF harmonics.

To identify the primary and secondary emission, the simplified model for two similar devices connected to the grid is shown in Figure 2.1 [5] [6]. It is assumed that two devices have the same capacitor C on the EMC filter and all the inductance and capacitance in to the gird is negligible. $I_{em}$ is the total emission of the first device. $I_{L1}$ and $I_{L2}$ are internal emission of first device and second device respectively.

$$I_{em} = \frac{1+j\alpha}{1+j\alpha} I_{L1} - \frac{j\alpha}{1+2j\alpha} I_{L2} \text{ where } \alpha = \omega RC$$

The current flowing into the grid is given by the summation of the emission from first device and the emission from second device.

$$I_{grid} = \frac{1}{2j\alpha} I_{L1} + \frac{1}{2j\alpha} I_{L2} \text{ where } \alpha = \omega RC$$

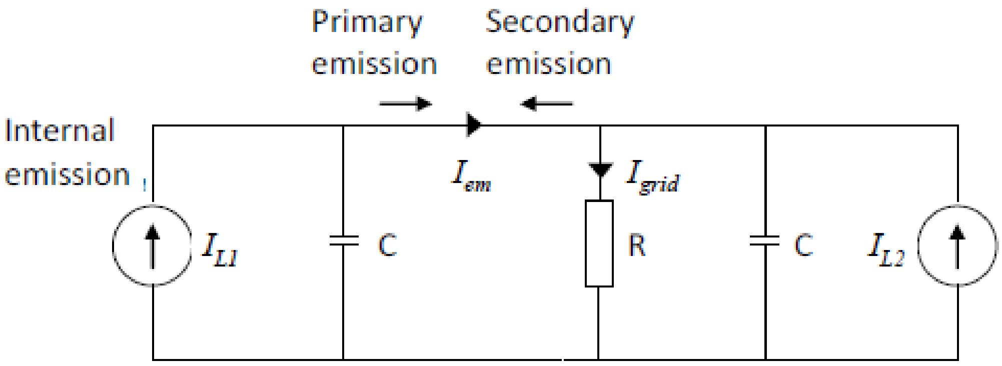



Figure 2.1: Simplified model for grid connected two similar type of devices

With reference to the Figure 2.2, the primary emission is directed by J1 for both voltage and current. And, the secondary emission is directed by E2. The measured current at the interface between the device and the grid can be equaled to the sum of primary emission given by $I_1$ and secondary emission given by $I_2$. [3][2]

$$I_1 = \frac{Z_1}{Z_1+Z_2} J_1 \text{ --------------------------------- Eq (01)}$$

$$I_2 = -\frac{E_2}{Z_1+Z_2} \text{ ---------------------------------Eq (02)}$$

$$I = I_1 + I_2 = \frac{Z_1.J1-E_2}{Z_1+Z_2} \text{ ---------------------------------Eq (03)}$$

Similar expressions can be obtained for the voltages. According to equation 01, 02 and 03, impedance of source ($Z_1$) and impedance of device ($Z_2$) can be affected to the changes of primary emission and secondary emission. The model in Figure 2.2 is aimed only to illustrating the concept, not the detailed design.

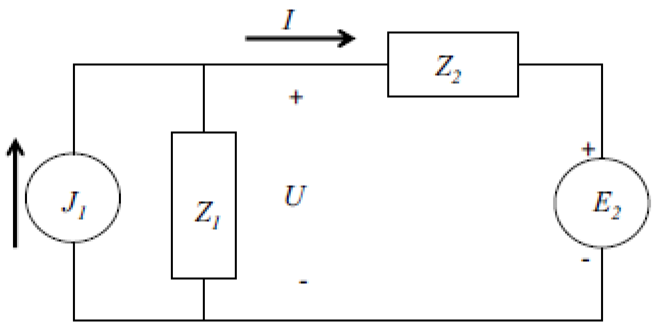
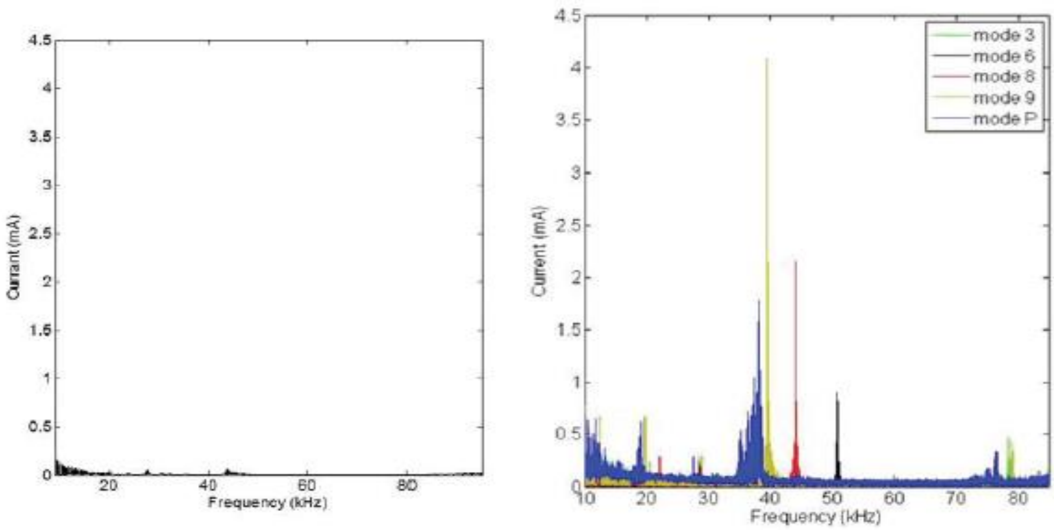



Figure 2.2: Primary and secondary emission

Measured primary emission of a Compact Fluorescent Lamp (CFL) is shown in Figure 2.3 [10]. Primary emission of the lamp connected to the system without any other load is shown in figure 2.3(a). And, the secondary emission of the induction cooker absorbed by the same CFL is shown in figure 2.3(b). Here, different settings of the induction cooker are used to identify the secondary emission with the different types of second device. In figure 2.3(b), different colors are used to identify that.




(a) (b)

Figure 2.3: (a) Measured primary emission of a CFL (b) Measured secondary emission of an induction cooker [10]

## 2.3 HF Harmonic sources

HF distortion has been introduced to the power system by the newly developed power electronic equipment. With that, new harmonic distortions are added to the system. Modern lighting technologies like compact fluorescent lamps (CFLs) and Light Emitted Diode (LEDs), Modern entertainment systems like televisions, radios and video players, electrical vehicle charges (EV), photovoltaic (PV) inverters, electrically commutated motor (ECM) based heating, ventilation and air conditioning (HVAC) units, adjustable speed drive-based home appliances, lots of energy efficient appliances with switch mode power supply (SMPS), Variable speed motor drives like an elevator, medical equipment like a dialysis machine, etc. can be identified as harmonic sources.

Measured current waveform for induction cooker and high frequency spectrum for induction cooker with range 2 kHz to 150 kHz is shown in figure 2.4. And, measured current waveform for power supply and high frequency harmonic spectrum for power supply is shown in figure 2.5. The magnitude of the harmonic part of the greatest high frequency harmonics is shown in Table 2.1. These high frequency harmonics components can be observed to be smaller than low frequency distortions, typically reaching several hundred or even thousands of mA. This is primarily happened due to the effect of the low-pass filter in high frequency harmonics generating devices. It can be identified as the key component to prevent the majority of high frequency harmonics distortions from being introduced into the network. [9].

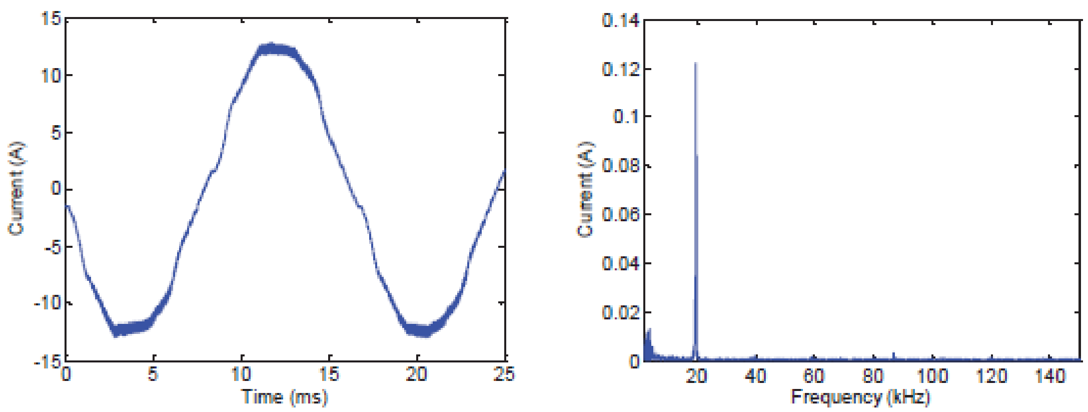



Figure 2.4: Current waveform and HF spectra of Induction cooker (1000 W) [9]

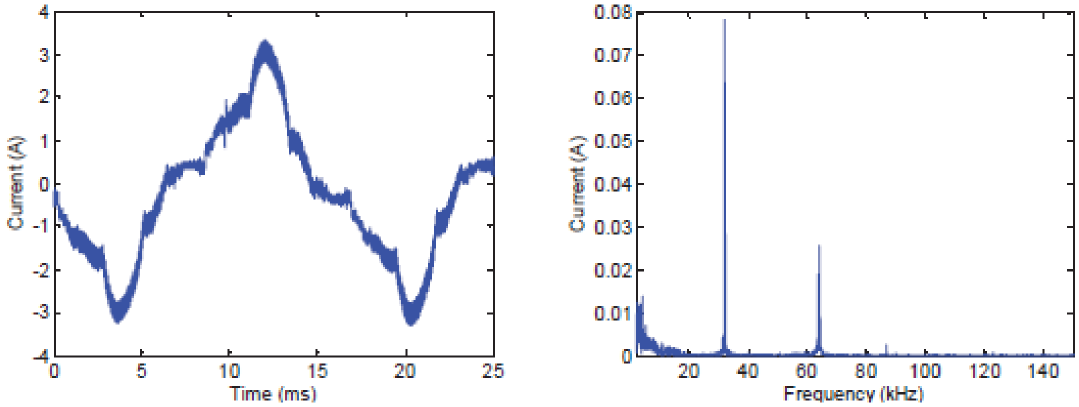



Figure 2.5: Current waveform and HF spectra of Power supply (180 W) [9]

Table 2.1: Dominant High Frequency Harmonics in power supply and Induction cooker

| Device Name | Current (A) | 60 Hz current (%) |
|---|---|---|
| Power supply | 0.0784 | 5.21 |
| Induction cooker | 0.1222 | 1.39 |

Incandescent lamps are no longer the preferred source of lighting; it is replaced with more efficient lighting technologies like Light Emitted Diode (LEDs) and Compact Fluorescent Lamps (CFLs). As example, experiment result taken by reputed research group in middle level Sweden hotel is shown in Figure 2.6. Figure red curve represents current in the frequency range 9 to 70 kHz with incandescent lamps and black curve represents same frequency range with energy efficient lamps.

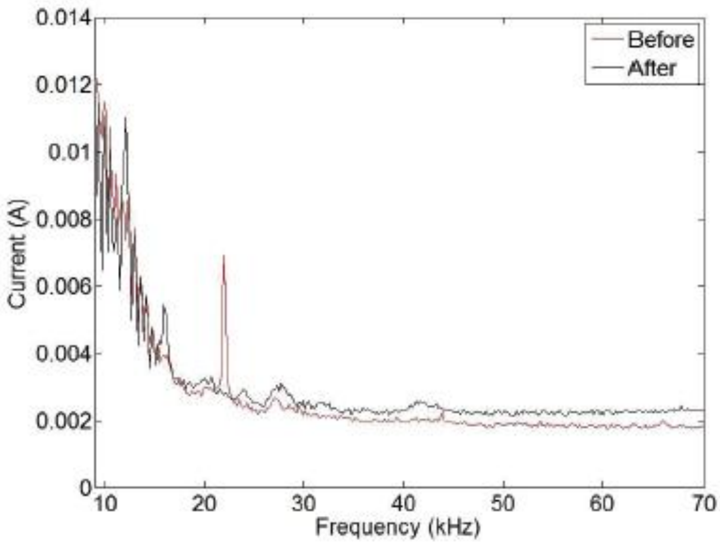



Figure 2.6: Current in the frequency range 9 to 70 kHz before (red curve) and after (black curve) the change from incandescent lamps to energy efficient lamps [9]

Electric vehicles have gained increasing attention during last few years as an alternative for conventional transportation systems. However, they act as unusual loads to the power grid. Frequency spectra for different types of electrical vehicle chargers with charging maximum current is shown in Figure 2.7 [14].

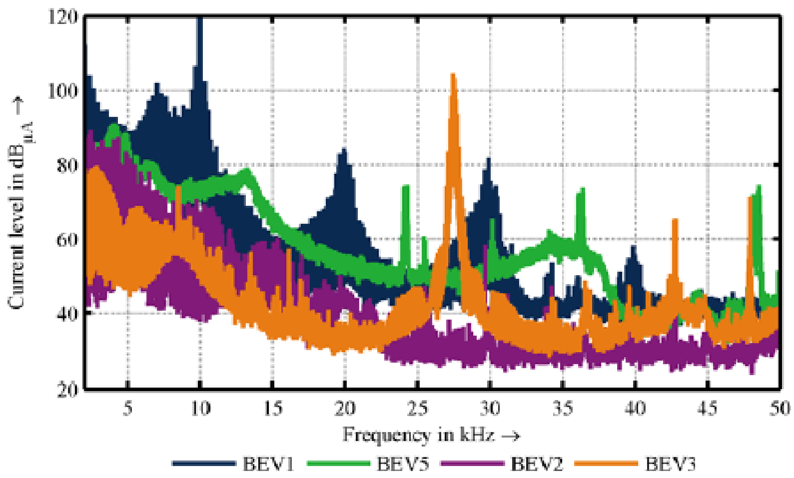



Figure 2.7: HF spectra of different types of Electrical chargers

Because of the shortage of fossil fuels and the rising oil prices in climate-change countries, energy-efficient methods and the renewable energy generation in electricity generation are increasing steadily, especially in the world. Other than that, the concept of renewable energy is highly regarded as achieving a greener world in the future.

Sources of renewable energy such as sun and wind are used for generating power. When using most of the renewable energy methods, energy converters are important part of the system.

PV inverters area major HF emission source in low voltage distribution system due to pulse width modulation (PWM) of the inverter. In Equation 4, the theoretical single-phase inverter output using neutral, unipolar pulse width modulation is displayed without using low pass filter.

$$V_{out} = V_{dc}.M.\cos(2\pi ft) + \frac{2.V_{dc}}{\pi}\sum_{m=1}^{\alpha}\sum_{n=-\infty}^{\alpha}\frac{J_{2n-1}(mM\pi)}{m} \times \cos((m+n-1)\pi) \times \cos(4\pi m f_s t + (2n-1).2\pi ft)$$

-------------------------- Eq (04)

Where; $M \approx \frac{\sqrt{2}\,V_{grid}}{V_{dc}}$

$V_{out} = Output\ voltage$ $V_{dc} = DC\ link\ voltage$

$V_{grid} = Grid\ voltage$ $M- = Modulation\ index$

$f = Grid\ frequency$ $t = Time$

$J_{2n} = Jacobian\ function\ of\ order\ 2$ $f_s = Switching\ frequency$

Three types of inverter topologies are commonly used as small-scale inverters less than 5 kW. These types of inverters are PV inverters with transformers of low frequency, PV inverters with transformers of high frequency and PV inverters without transformers. Inverter topology without transformer, PV inverter topology with a Low Frequency Transformer and PV inverter topology with a High Frequency Transformer are shown in Figure 2.8, Figure 2.9 and Figure 2.10 respectively.

When consider about the inverters with transformers, Both low frequency and high frequency inverter have transformers and it provides isolation for the circuit. Furthermore, TL inverters are used to minimize the ground leakage current without using galvanic isolation. Most of the commercially available inverters are transformer-less inverters.

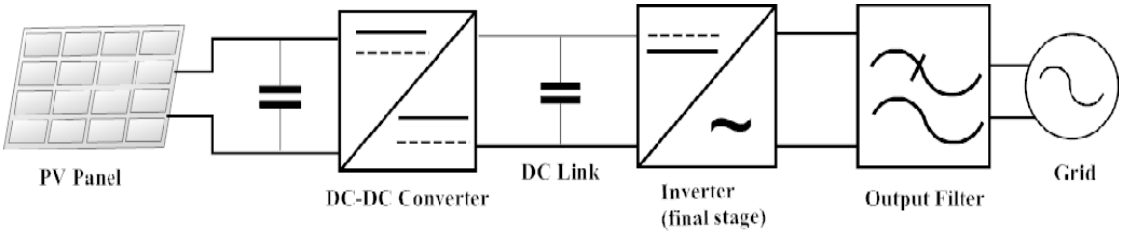



Figure 2.8: PV inverter topology without transformer

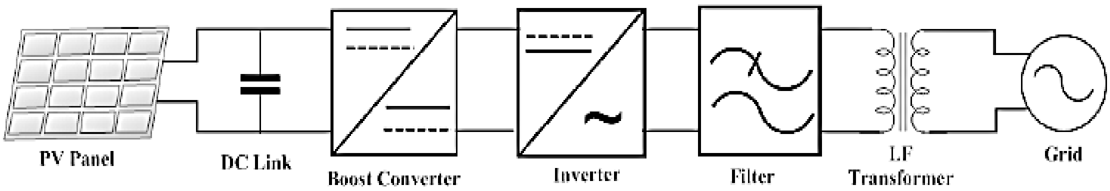



Figure 2.9: PV inverter topology with a Low Frequency Transformer

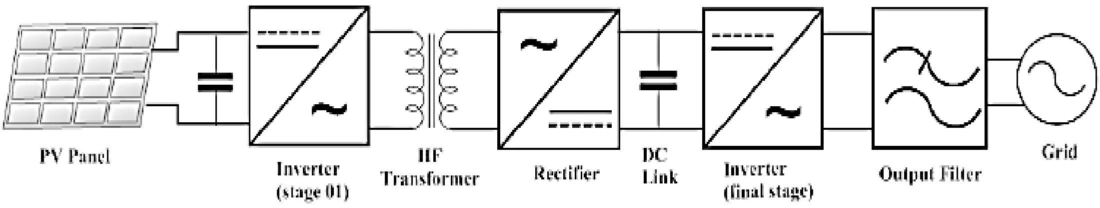
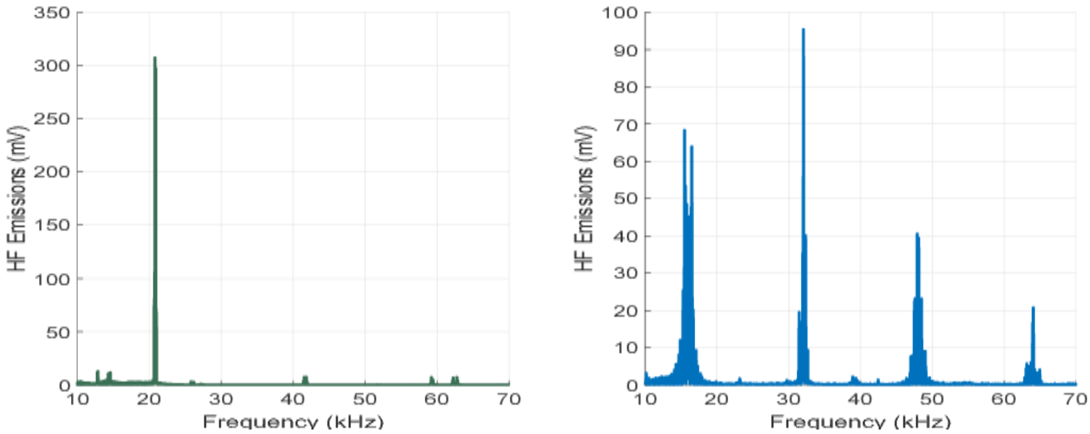



Figure 2.10: PV inverter topology with a High Frequency Transformer

Single-phase PV inverter and three-phase PV inverter high frequency harmonic emissions are shown in Figure 2.11. [16]




(a) (b)

Figure 2.11: (a) single-phase PV inverter high frequency harmonic emission (b) three phase PV inverter high frequency harmonic emission

## 2.4 Existing Standards and limits for high frequency emission

In IEEE EMC society, the term "low frequency emission" is basically used to refer to frequencies below 150 kHz. Furthermore, the term "low frequency" is used to refer to frequencies below 9.0 kHz in IEC standards [2]. The European standards of IEC counterpart given by IEC 61000-3-8 and power-line communication protocol given by EN 50065 are discussed the range of frequency from 9.0 to 148.50 kHz. EN 56061-1 is recently issued to for use in low voltage networks on power line communication devices covers the range of frequency from 1.6 MHz to 30.0 MHz. And, it is intended to cover frequencies down to 9.0 kHz. When consider about the available international standards relative to the frequencies, the high frequency range (2-150 kHz) is not covered enough in those standards.

Existing emission limits for conducted normal disturbances cover the spectrum from 50 Hz to 2 kHz (low frequency) and from 150 kHz to 30 MHz (Electro-magnetic Interreference). Different standards use different upper limits for LF harmonics, ranging from 2 to 3 kHz. In some cases, emission limits also exist between 9 kHz and 30 MHz, for example for lighting equipment. However, frequencies between 2 and 9 kHz, which are commonly referred to as HF, there are no emission limits developed. When the standards for conducted disturbances were set, the aim was to protect radio communication in the frequency range 150 kHz through 30 MHz against interference from currents in this frequency range in the power grid due to equipment connected to the grid [1].

Some examples for the limits of the frequencies can be summarized as follows. Considering the standards EN50065 and IEC61000-3-8, The frequency emission and safety limit for 3 kHz to 9 kHz is nearly 134 dBV (it is 2 percent of 230V).

In the frequency of 100 kHz, the emission and protection limits are approximately (120dBV) or (0.5 percent of 230V) according to standard EN50065. The immunity and safety range is given as the frequency range of 3 kHz to 95 kHz for power line communication (PLC) equipment according to EN50065-2-3. A part of unique PLC tests conducted within 9.0 kHz to 148.5 kHz range according to EN50065-2-2 [11].

# Modeling and Simulation for HF harmonics emission

This section describes about the details of modeling and simulation of high frequency harmonics sources in particular PV inverters. When considering the supra harmonics frequency range, modeling of the grid is well developed, particularly for overhead lines and medium and high voltage cables. However, the knowledge relevant to the low voltage distribution system is limited. Furthermore, Device modeling has not yet been studied well for high frequency range [2]. This section provides details about the model of the device and model of low voltage distribution system, in the range of 2 to 150 kHz.

### 3.1 Device modeling

Photovoltaic inverters (PV inverters), Uninterrupted Power Supply (UPS), Electrical vehicle charges (EV chargers) and LEDs can be taken as some examples for the devices connected to the low voltage power distribution system according to the requirement of people. The most challenging part of the modeling effort is connecting devices to the power distribution system, in this frequency range. At the considered frequency, characteristic of the device connected to the power distribution system depends on the ratio between source impedance of the device and network impedance, which imitates that of a current source and voltage source. Also, at some instance the same device can behave like a voltage source and at some instance it can behave like a current source.

To model the device completely, interaction between other devices also need to be considered. Behavior of a device can be seen as an impedance by other devices. Also, the emission of the device is changed due to the voltage distortion caused by emission from other grid-connected devices. This can be partly addressed by "harmonic finger-printing" as introduced for low-frequency harmonics [19]. Still, the interactions between signals at different frequencies will ot be covered by this. For the devices such as PV panel inverters, wind turbine inverters, adjustable-speed drives, equipment used for computing and televisions, existing models can be found.

Even though the devices can be modeled as an emitting source, it should be noted that every device may have an impact to the propagation of the emission from other sources.

Most of the renewable energy sources produce DC power, as the output power includes solar, wind, geothermal, etc. The inverters are used to convert direct current (DC) to alternating current (AC). With the current requirement of renewable energy sources such as solar and wind energy, DC to AC inverters have become very important. Considering about the environment impact with energy generation, most countries are focused to improve solar energy generation by using photovoltaic technology in recent decades with different scales of solar power plants. With this condition, photovoltaic inverters are highly installed including solar power sources in the roof in low voltage power distribution system.

In this research, Photovoltaic inverters are modeled to identify the generated high frequency harmonics. MATLAB/ Simulink is used to model photovoltaic inverters to simulate high frequency harmonics. MOSFET and IGBT are highly used in inverters. Usually, power MOSFET can operate at somewhat higher frequencies with power ratings of 1000V and 50A. When the voltage requirement increases, Insulated-gate bipolar transistor (IGBT) is used, which is a voltage-controlled power transistor. IGBT also provides better speed than BJTs, but not as fast as a power MOSFET. For higher switching frequencies, performance of MOSFET is superior to IGBT. Anyway, higher switching operation of IGBT is possible by employing soft switching power conversion. According to those details, MOSFET is chosen as semiconductor device to model the PV inverter.

The Sinusoidal Pulse Width Modulation (SPWM) is one of the most popular PWM techniques used for low frequency harmonic reduction of inverters. According to the sine functions, it can directly control the inverter output voltage and output frequency. SPWM is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches. Because of its circuit simplicity and rugged control scheme, The PWM (Pulse Width Modulation) inverter has been the main choice in power electronic for a very long period. Sinusoidal

Pulse Width Modulation switching technique is commonly used in industrial applications as well as photovoltaic inverters.

In this model, the SPWM technique has been used for controlling the inverter. To verify the model, a comparison is made between a detailed Simulink model and the emission measured by reputed research group.

### 3.2 Low voltage distribution system modeling

Grid modeling is well-developed for overhead lines and for medium-voltage and high-voltage cables. But the knowledge relevant to the low voltage distribution system is limited. Furthermore, Device modeling is not still studied well [2]. This section gives model and simulation of the device and low voltage distribution system.

Existing modelling for overhead lines, cables and transformers are mainly concentrated towards the transmission system and that of the distribution system is not very common. Models for overhead lines and cables remain valid for lower voltage levels. But it is not be practical to perform measurements on each distribution transformer. In low voltage installations, all the components, connected equipment and wires also have to be considered. Wiring inside a certain building is not symmetrical, not structured properly as overhead lines and currents are not balanced as well.

Low voltage power distribution system is taken to simulate the propagation of high frequency emission in power distribution system. For selecting the parameters to low voltage distribution system, actual parameters of the low voltage distribution system were studied. After that, system was simplified to modulate from MATLAB/ Simulink software. 40 kVA, 50 Hz step down transformer was selected with one feeder. That feeder supplies power to 18 houses with 0.8 kVA after diversity maximum demand per house (ADMD) and 0.85 power factor. It was assumed that the connected loads were uniformly distributed in three phases in power distribution system.

Furthermore, Arial Bundle Conductor (ABC) ABC 50 cables are used as cable type for low voltage distribution system. Cable inductance, impedance and voltage drop are 0.27 mH/ km, 0.50 mΩ/ km and 1.27 mV/ A/ m respectively. The distance between two poles is taken as 15 m to 40 m and total length is 200 m for feeder. Distribution line power loss and Voltage variation of distribution line are taken as 5% and 4 % respectively.

Base voltage of the gird is taken as 11 kV with 50 Hz frequency. Source resistance and source impedance of the grid are taken as 1 mΩ and 0.1 mH respectively. Photovoltaic inverter effect to the low voltage system is analyzed based on this simplified low voltage power distribution system.

# Analysis on HF harmonics of solar inverter (PV)

The MATLAB / Simulink software platform is used to model photovoltaic inverters to simulate the emission of high frequency harmonics as discussed in Chapter 3.

## 4.1 HF harmonics of Single phase-inverter

The single-phase inverter is modeled to analyze the high frequency harmonics generated by the single-phase inverter. Parameters of modeled single-phase inverter are shown in Table 4.1.

Table 4.1: Parameters of modeled single-phase inverter

| Components | Items | Value |
|---|---|---|
| Inverter | Type | Single phase. PWM Unipolar |
| | capacity | 2 kW |
| | output frequency | 50 Hz |
| | switching frequency | 16 kHz |
| | amplitude modulation ratio (ma) | 0.8 |
| MOSFET | Type | IRF840 |
| | Internal resistance | 0.01 Ω |
| | FET on resistance | 0.1 Ω |

In addition, the LCL filter (third order passive filter) is used as a low pass filter to reduce the harmonics generated by the inverter. The LCL filter is modeled with two inductors and a capacitor. The inductors and capacitors are selected as 3.6 mH, 0.9 mH, 40 μF respectively for the LCL filter.

To simplify the results, the DC output of the solar panel is assumed as constant DC output. With this assumption, the DC source is chosen as a constant source of 400 V, when modeling solar inverters in this investigation. In addition, the single-phase inverter is connected with a load of 1000 W to study the generated high-frequency harmonics.

As a result, frequency spectrum of the single-phase inverter with and without using the LCL filter are shown in Figure 4.1 and Figure 4.2, respectively. When considering Figure 4.1, harmonics can be identified in the frequency range of 2 to 150 kHz. The generated high frequency harmonics are considerable compared to the fundamental component. The first harmonic emission can be identified around 16 kHz and it is more than 20% of the fundamental frequency. When comparing Figure 4.1 and Figure 4.2, the emission percentage of the first harmonic is reduced to 6% of the fundamental frequency after applying the LCL filter to the system. Apart from that, the harmonics generated around 32 kHz is represented more than 10% of the fundamental frequency without LCL filter and it is approximately 3.5% of the fundamental frequency when applying LCL filter. According to these two figures, the generated high frequency harmonics are considerably reduced after connecting LCL filter to the inverter output.

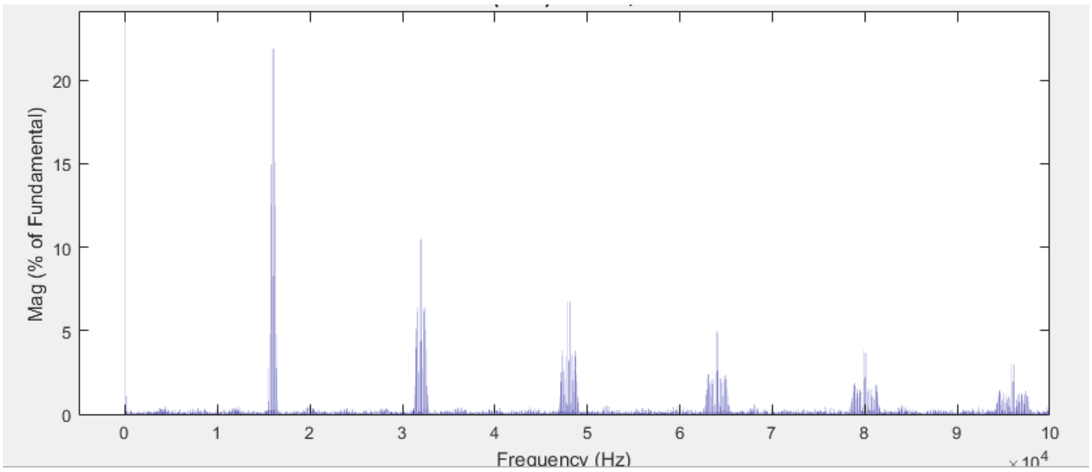



Figure 4.1: Frequency spectrum of single-phase inverter without using LCL filter

When considering the result of the waveforms, the high frequency harmonics are concentrated in the frequency range from 2 kHz to 150 kHz due to the single-phase inverter. However, these high frequency harmonics are concentrated around the switching frequency and around multiple integers of switching frequency. The switching frequency of the modeled single-phase inverter is 16 kHz. For this inverter, the harmonics are concentrated around 16 kHz and 32 kHz, 48 kHz, 64 kHz according to the result of simulated single-phase inverter waveforms. Here, 16 kHz is a switching frequency of the inverter and 32 kHz, 48 kHz, 64 kHz are integer multiples of 16 kHz. Concentrated harmonics around those frequencies are shown in Table 4.2.

Furthermore, Total harmonic distortion (THD) is reduced from 57.67 % to 18.93 % after applying LCL filter to single-phase inverter.

Table 4.2: Comparison of concentrated harmonics with and without LCL filter

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency (Without LCL filter) | Harmonic percentage from fundamental frequency (With LCL filter) |
|---|---|---|---|
| 16 kHz | 16 kHz | 20% | 6% |
| | 32 kHz | 10% | 3.5% |
| | 48 kHz | 7.4% | 2.8% |
| | 64 kHz | 5.2% | 2.1% |
| | 80 kHz | 4% | 1.8% |

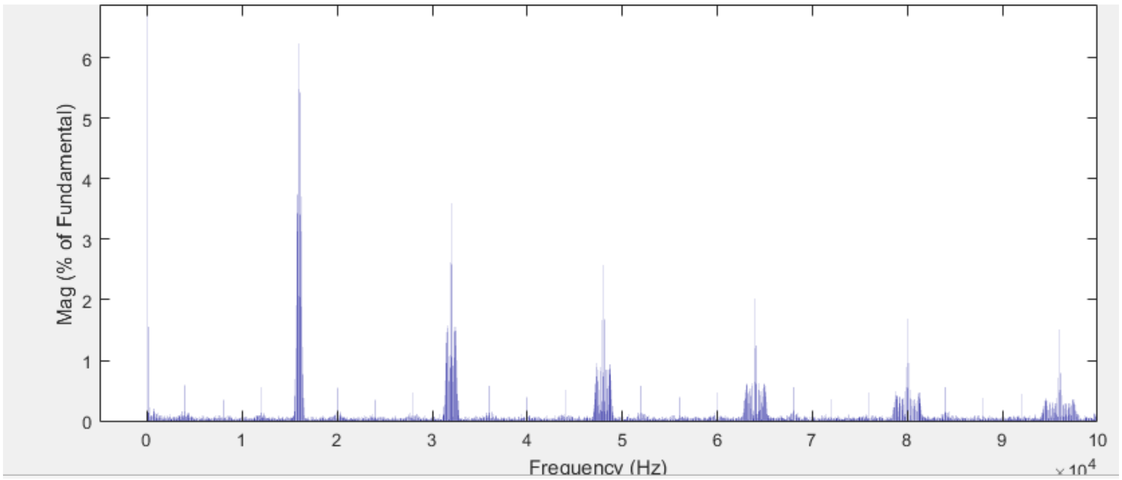



Figure 4.2: Frequency spectrum of single-phase inverter using LCL filter

In addition, the single-phase inverters are modeled with different switching frequencies of 20 kHz and 25 kHz to identify the harmonics generated with different switching frequencies. When modeling these single-phase inverters, all other parameters are similar to previously discussed single-phase inverter with 16 kHz switching frequency. Frequency spectrum of the single-phase inverter with 20 kHz and 25 kHz different switching frequencies are shown in Figure 4.3 and Figure 4.4 respectively. According to these waveforms, the generated harmonics can be identified for the single-phase inverter with different switching frequencies. In Figure 4.3, the harmonics are concentrated around 20 kHz, 40 kHz, 60 kHz and 80 kHz. Here, 20 kHz is the switching frequency of the inverter and 40 kHz, 60 kHz, 80 kHz are integer multiples of 20 kHz. The magnitude of the harmonics concentrated around 20 kHz can be identified as 6.5% of the fundamental frequency.

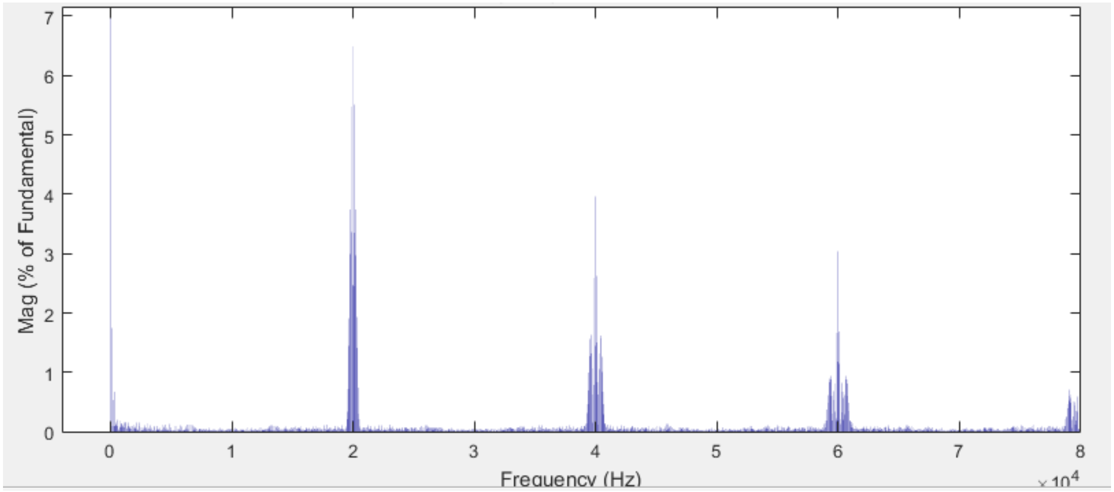



Figure 4.3: Frequency spectrum of single-phase inverter with 20 kHz switching frequencies

Although, the concentrated harmonics for the single-phase inverter with 25 kHz switching frequency shown in Figure 4.4. Like two inverters described above, harmonics are generated around 25 kHz (switching frequency) and 50 kHz, 75 kHz are integer multiples of 25 kHz. Generated harmonics around 25 kHz is shown as 6.5% of the fundamental frequency in Figure 4.4. Other than that, 4.2% and 3.2% of fundamental frequency can be identified around 50 kHz and 75 kHz respectively. Concentrated harmonic percentages around switching frequencies and it’s integer multiples with different switching frequencies are shown in Table 4.3.

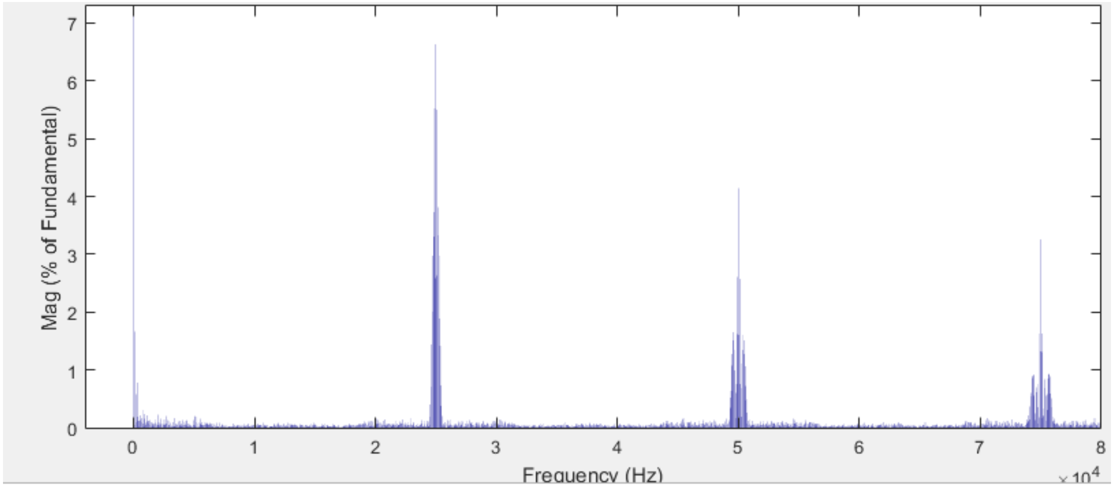



Figure 4.4: Frequency spectrum of single-phase inverter with 25 kHz switching frequencies

Table 4.3: Concentrated harmonic percentages around switching frequency and it's integer multiples

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Concentrated harmonic percentage from fundamental frequency (With LCL filter) |
|---|---|---|
| 16 kHz | 16 kHz | 6% |
| | 32 kHz | 3.5% |
| | 48 kHz | 2.8% |
| 20 kHz | 20 kHz | 6.5% |
| | 40 kHz | 4% |
| | 80 kHz | 3.1% |
| 25 kHz | 25 kHz | 6% |
| | 50 kHz | 4.2% |
| | 75 kHz | 3.2% |

According to the result of the waveforms of different single-phase inverters, the high-frequency harmonics are concentrated around the switching frequency and the integer multiples of the switching frequency, for that installed capacity is not affected.

### 4.2 HF harmonics of three phase-inverter

In this part, three-phase inverter is modeled to analyze the emission of high frequency harmonics. For that, sinusoidal PWM technology is used to switch a unipolar three-phase inverter with 20 kW capacity. Parameters of modeled three-phase inverter are shown in Table 4.4.

Table 4.4: Parameters of modeled three-phase inverter

| Components | Items | Value |
|---|---|---|
| Inverter | Type | Three phase. PWM |
| | capacity | 20 kW |
| | output frequency | 50 Hz |
| | switching frequency | 4 kHz |
| | amplitude modulation ratio (ma) | 0.8 |
| MOSFET | Type | IRF840 |
| | Internal resistance | 0.01 Ω |
| | FET on resistance | 0.1 Ω |

The LCL filter (3$^{rd}$ order passive filter) is chosen as a low pass filter to reduce the generated harmonics from three-phase inverter. 3.6 mH, 0.9 mH inductors and a 40 μF capacitor are used to model the LCL filter for a three-phase inverter.

Similar to the single-phase inverter, the DC source is chosen as a constant source with 400 V. The output of the solar panel is assumed as constant DC output to simplify the result. In addition, the 1000 W load is connected to the three-phase inverter to identify the generated high frequency harmonics.

The frequency spectrum for three-phase inverter with and without using the LCL filter are shown in Figure 4.5 and Figure 4.6, respectively. High frequency harmonics can be identified in Figure 4.5; it is considerable compared to the fundamental component. The first harmonic emission of high frequency around 4 kHz is more than 20% of the fundamental frequency without using LCL filter. When applying the LCL filter to the output of the three-phase inverter, the emission percentage of the first harmonic generated is reduced to 0.5% of the fundamental frequency. Concentrated harmonics around those frequencies with and without LCL filter are shown in Table 4.5.

Table 4.5: Comparison of concentrated harmonics with and without LCL filter

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency (Without LCL filter) | Harmonic percentage from fundamental frequency (With LCL filter) |
|---|---|---|---|
| 4 kHz | 4 kHz | 20% | 0.5% |
| | 8 kHz | 10% | 0.1% |

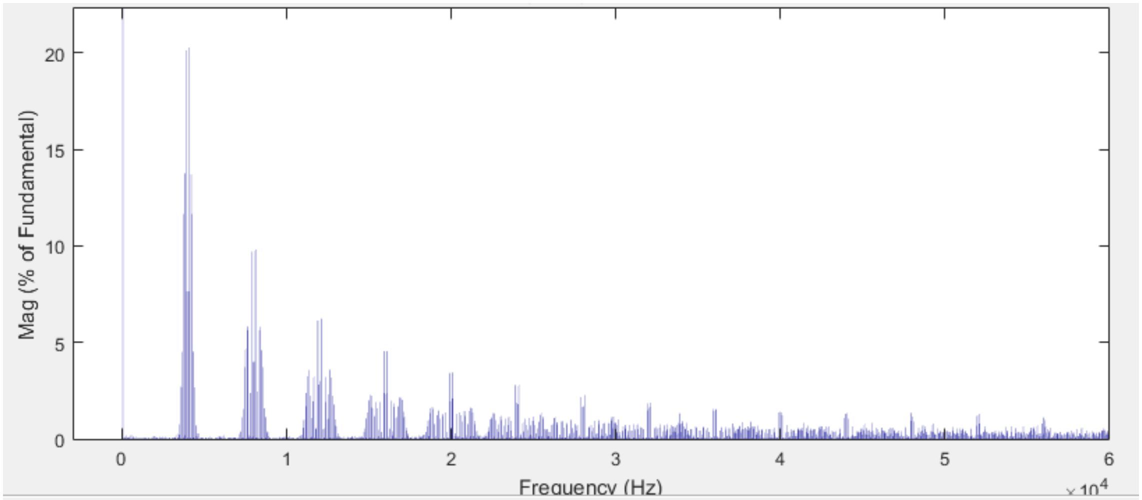



Figure 4.5: Frequency spectrum of three phase-inverter without using LCL filter

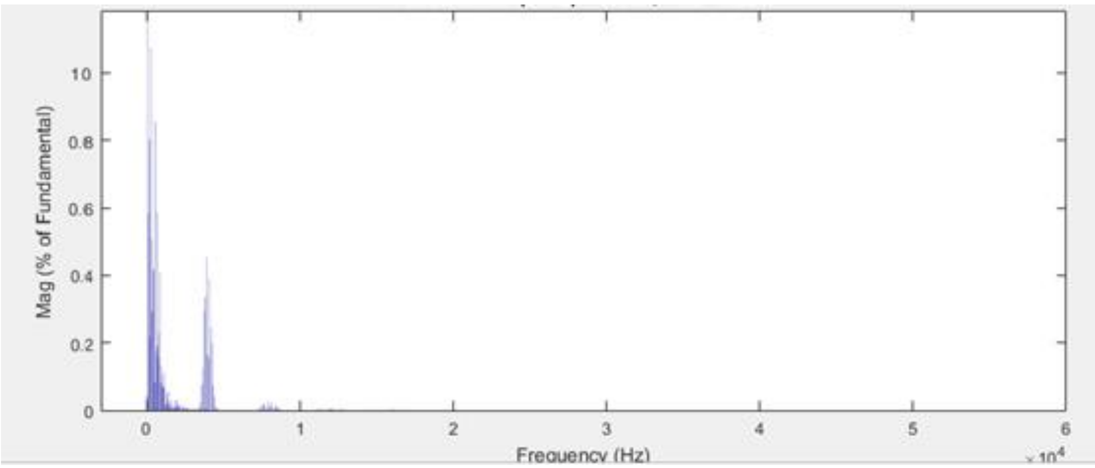



Figure 4.6: Frequency spectrum waveform of three phase-inverter using LCL filter

According to the current waveform of the three-phase inverter, the harmonics are generated in high-frequency range of 2 to 150 kHz. Relevant to the three-phase inverters, the harmonics are concentrated around the switching frequency and around multiple integers of switching frequency according to the resultant waveforms. The switching frequency of the modeled three-phase inverter is selected as 4 kHz in Figure 4.5. When consider about waveforms, harmonics are concentrated around 4 kHz and 8 kHz. Here, 8 kHz is an integer multiple of the switching frequency of 4 kHz.

In addition, the three-phase inverter is modeled using similar parameters as taken for previous three-phase inverter, but with different switching frequencies. Here, 6 kHz and 8 kHz are used as switching frequency of three-phase inverter to identify the generated harmonics of the three-phase inverters. Frequency spectrum for 6 kHz switching frequency and 8 kHz switching frequency is shown in Figure 4.7 and Figure 4.8, respectively. According to the simulated waveforms, the harmonics are concentrated around 6 kHz. It is approximately 0.2% of the fundamental frequency in Figure 4.8. This 6 kHz is the switching frequency of the three-phase inverter. Moreover, 0.2% of the fundamental frequency can be found around 8 kHz in Figure 4.8.

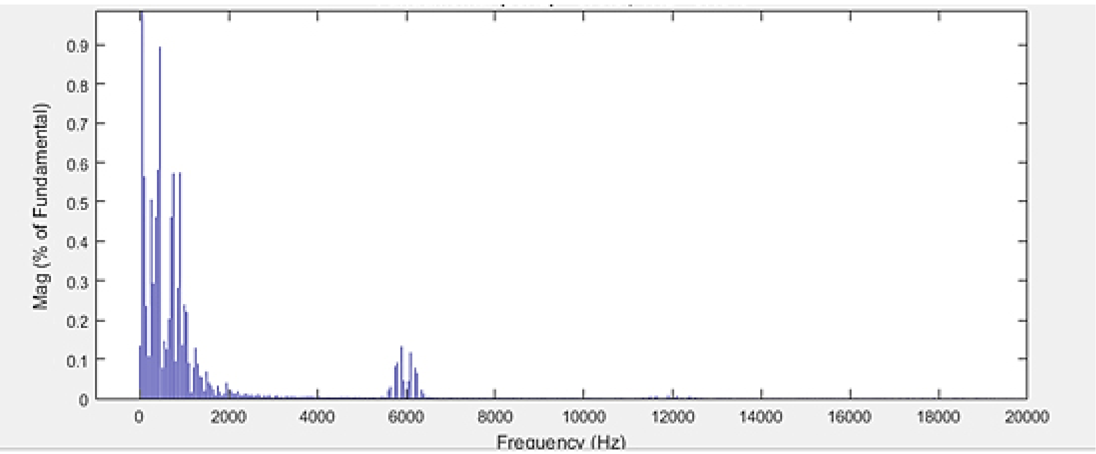



Figure 4.7: Frequency spectrum of three phase-inverter with 6 kHz switching frequencies

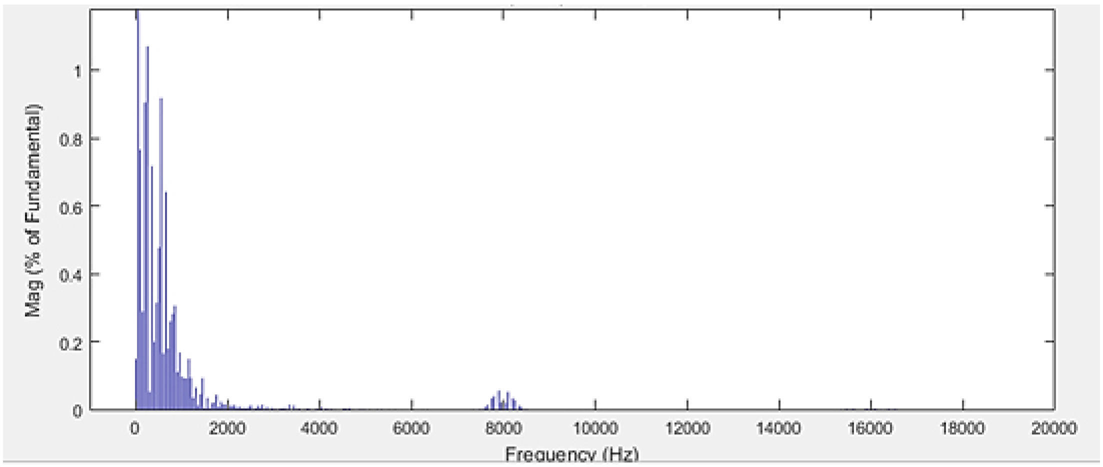



Figure 4.8: Frequency spectrum of three phase-inverter with 8 kHz switching frequencies

With these waveforms, the generated high frequency harmonics can be identified around the switching frequency and multiple integers of switching frequency, in three-phase inverter. Furthermore, the generated high frequency harmonics are concentrated due to the switching frequency of the three-phase inverter. For that, Inverter capacity is not effected.

### 4.3 Comparison of Model results with Experimental Result

There are certain controlled experiments that have been carried out by reputed research groups in the world, to identify the high frequency harmonics generated by the inverters. To clarify the modeled inverters, the simulated results were compared with the results of experiments. As an example, Figure 4.9 shows the spectrogram of a 5 kVA single-phase inverter with a switching frequency of 16 kHz [14]. In this spectrum, the background noise is shown in blue and the different emission levels due to other effects are shown in yellow and red colors. Solar photovoltaic inverters only work during the day time with sunrise. Because of solar systems are functioning with solar energy. Due to that reason, inverters are not working in night time duration. With this condition, there are two different operating states available in photovoltaic inverters. With the spectrogram, the inverter's emission can be clearly identified in daytime from 06:00 to 18:00 at frequencies of around 16 kHz and 32 kHz in Figure 4.9. Because of this, the first and second emission around 16 kHz and 32 kHz can be identified as harmonics generated by the effect of the photovoltaic inverter. The modeled single-phase inverter with the switching frequency of 16 kHz also receives a similar result in the simulation.

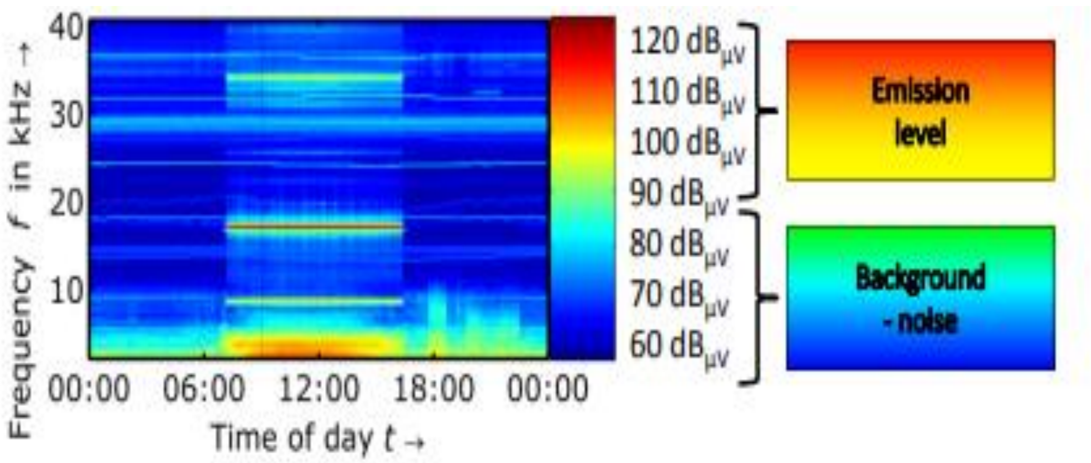



Figure 4.9: Spectrogram of a 5 kVA PV inverter [14]

As a second example, the laboratory measurement of the inverter with three different switching frequencies is shown in Figure 4.10 [14]. In that research, the frequencies of 16 kHz, 17 kHz and 20 kHz are used as switching frequencies for Type A (Blue), B (Green) and C (Brown), respectively. The waveform of the modeled single phase inverter with a switching frequency of 16 kHz and the waveform of the single-phase inverter type B have a similar pattern for harmonic emission. The waveform in the frequency domain for modeled single-phase inverter is shown in Figure 4.2. When considering these two waveforms, the high frequency harmonics are concentrated around 16 kHz and 32 kHz and 48 kHz.

When considering about type A inverter (Blue), harmonics are generated around 20 kHz and 40 kHz. Type B inverter (green), the harmonics are generated around 17 kHz and 34 kHz. Finally, the C-type inverter (brown) generates harmonics around 16 kHz, 32 kHz and 48 kHz. According to the experimental result of this research, high frequency harmonics are concentrated around the switching frequency of the inverter and multiple integers of switching frequency.

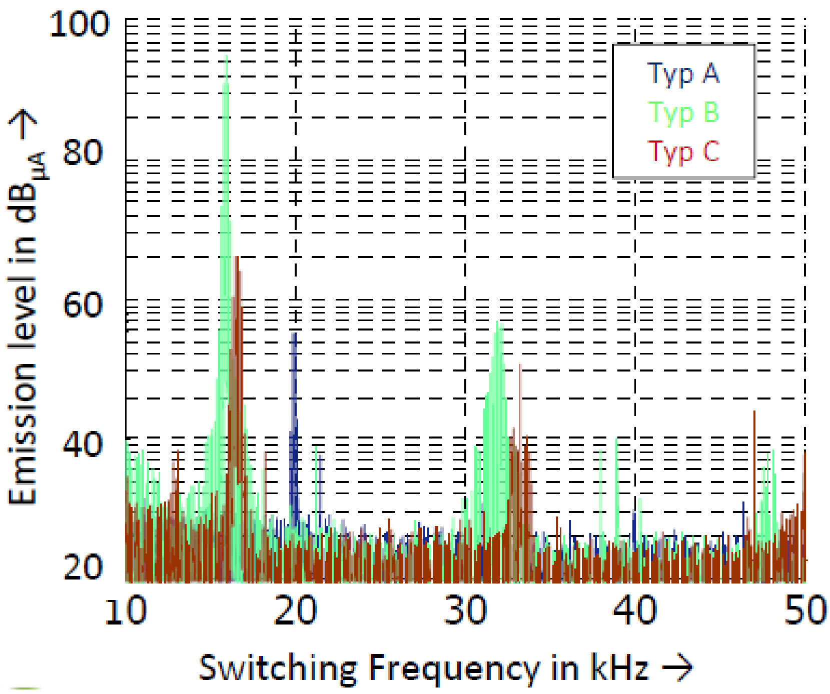



Figure 4.10: Spectra of three different PV inverters [14]

The modeled inverters relevant to the experimental results given by the reputed research group in the world for inverter can be identified as similar results. With this condition, the single-phase and three-phase inverter model can be taken as similar to the real inverter available in the world.

### 4.4 Input impedance for PV inverters

All circuits have one or more natural frequencies that contain both capacitances and inductances. It can be described as resonance if one of these frequencies is associated with a frequency that occurs in the power system that the voltage and current at that frequency still persists at very high values. This is the root of most problems in energy systems with a harmonic distortion.

There are two types of resonances; series resonance and parallel resonance. At the parallel resonance frequency, as seen from the harmonic current source, the apparent impedance of the parallel combination of the corresponding inductance and capacitance becomes very much higher. The series combination of the inductance and capacitance became very small value. It can be taken as theoretically zero. And, it is only limited to the inverter resistance. In this circuit the harmonic current corresponding to the resonant frequency will therefore flow freely.

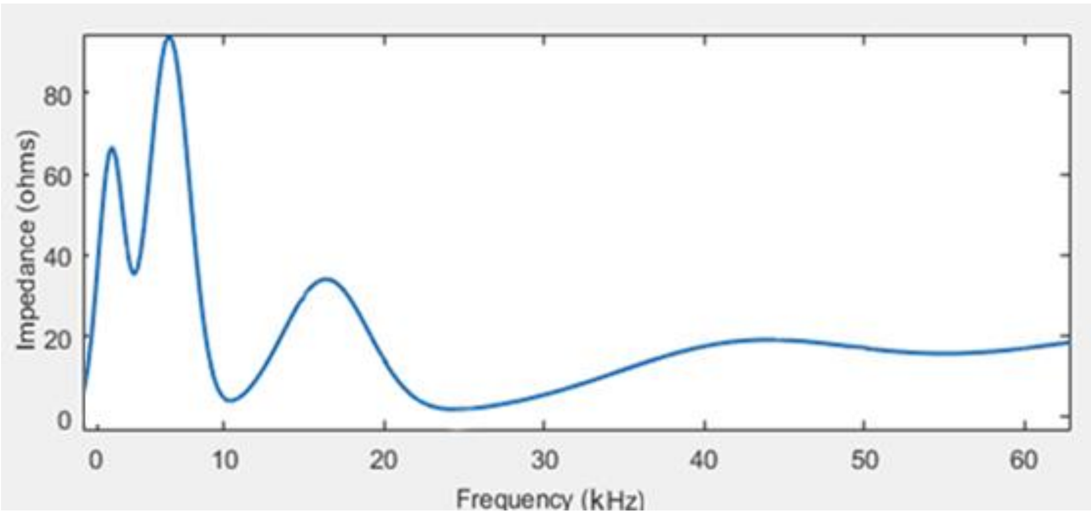



Figure 4.11: Impedance curve for Single-phase PV inverter

Modeled single-phase photovoltaic inverter and three-phase photovoltaic inverter impedance curve is taken by using MATLAB Simulink impedance tool. According to that, the input impedance curve for the single-phase photovoltaic inverter and the three-phase photovoltaic inverter are shown in Figure 4.11 and Figure 4.12 respectively. When considering these figures, the low impedance characteristic can be identified over a wide range of frequencies. In addition, multiple resonance points can be identified.

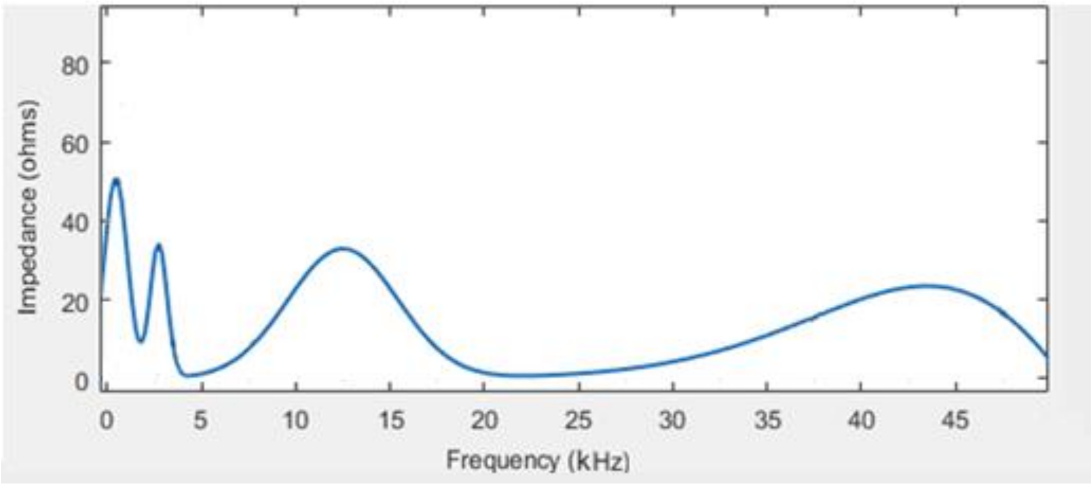



Figure 4.12: Impedance curve for three-phase PV inverter

The impedance curve for the photovoltaic farm with a different number of inverters is shown in Figure 4.13. It is the result of the experiment carried out by the reputed research group and the curve M1 receives the inverter's shutdown condition and the M6 curve receives the ignition condition of the inverter. By also considering this figure, low impedance characteristics can be identified by connecting the inverters to the distribution system. Apart from that, the impedance is significantly reduced with the increasing number of inverters connected to the distribution system.

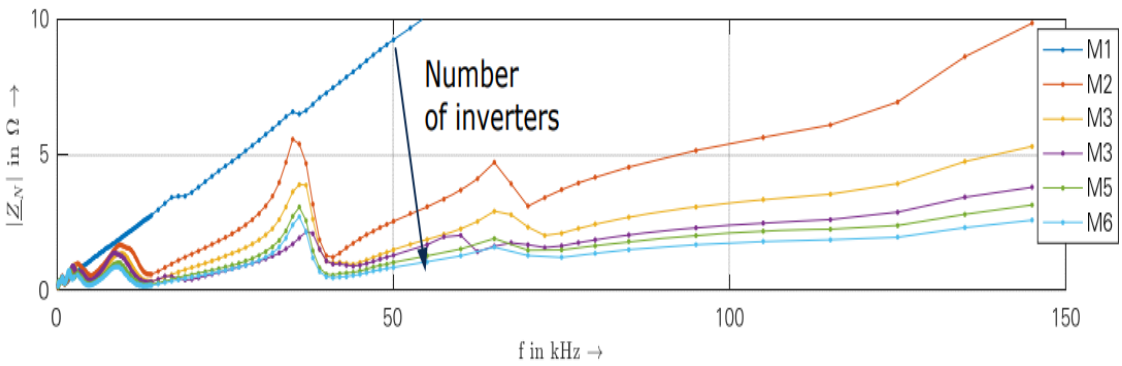



Figure 4.13: Impedance curve for PV farm with different number of inverters

The HF behaviour of single-phase inverter with 20 kHz switching frequency is modelled as a Thevenin's equivalent circuit. The voltage source becomes a short circuit and the inverter behaves as a HF sink in high frequency range. The relationship between resistance and output power is shown in figure 4.14. Furthermore, the relationship between impedance and output power is shown in figure 4.15.

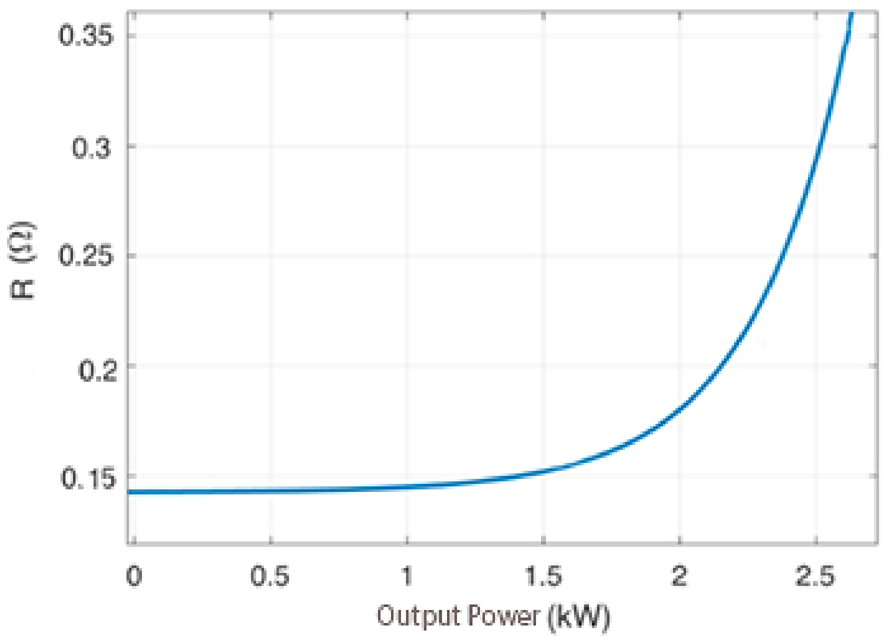



Figure 4.14: Inverter resistance with different power output of the inverter

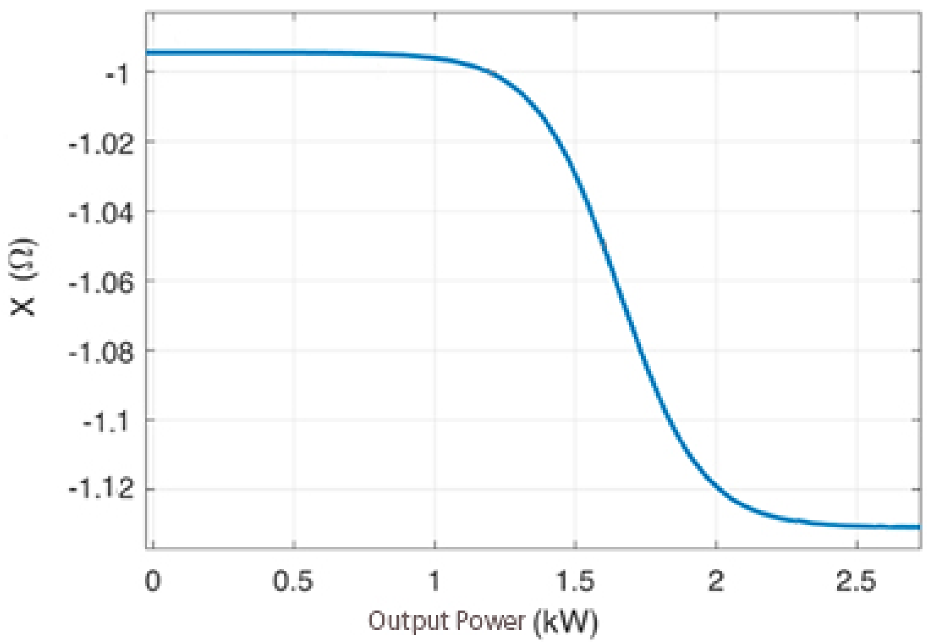



Figure 4.15: Inverter impedance with different power output of the inverter

## HF Harmonic propagation in distribution system

Generated high frequency harmonics due to different type of power electronic devices affect power distribution system as other harmonics. In this chapter, High frequency harmonics propagation in power distribution system is discussed. The low voltage power distribution system is taken to simulate the propagation of the high frequency emission in distribution system. The real parameters of the low voltage distribution system were studied to select the parameters of the low voltage distribution system and the low voltage distribution system was simplified to model the distribution system. MATLAB / Simulink software is used to model and simulate the low voltage power distribution system.

Table 5.1: Parameters for power distribution system

| Components | Items | Value |
|---|---|---|
| Transformer | Type | Step down |
| | Capacity | 40 kVA |
| | Frequency | 50 Hz |
| Feeder | Number of Houses | 18 houses |
| | After diversity maximum demand per house (ADMD) | 0.8 kVA |
| | power factor | 0.85 |
| Cable | Type | Arial Bundle Conductor (ABC) |
| | Size | ABC 50 |
| | inductance | 0.27 mH / km |
| | impedance | 0.50 mΩ / km |
| | voltage drop | 1.27 mV / A / m |

The 40 kVA, 50 Hz step-down transformer was selected with a one feeder. As a matter of course, the connected loads are evenly distributed in three phases. Furthermore, Arial Bundle Conductor (ABC), cables are used as a cable type for low voltage distribution systems. Parameters for power distribution system are shown in Table 5.1.

Other than those parameters, the distance between two poles is taken from 15 m to 40 m and the total length is 200 m. The power loss of the distribution line and the voltage variation of the distribution line are taken as 5% and 4% respectively. The base voltage of the beam is taken as 11 kV with a frequency of 50 Hz. The resistance of the source and the impedance of the source of the network are 1 mΩ and 0.1 mH respectively.

The block diagram of the simplified low-voltage distribution system is shown in Figure 5.1. The effect of the photovoltaic inverter on the low-voltage system is analyzed based on this simplified low-voltage power distribution system.

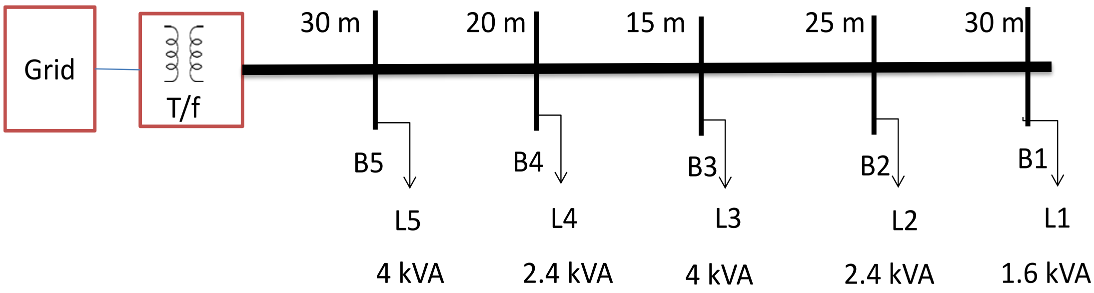



Figure 5.1: Block diagram of simplified low voltage distribution system

This section of thesis is mainly focused to discuss the impact of the level of inverter penetration, Impact of inverter configuration and analysis of the propagation of harmonics.

### 5.1 Impact of the level of inverter penetration

In this section, single-phase inverters and three phase inverters are used separately to identify the penetration level of inverters. As first part, the same types of single-phase inverters with the same switching frequencies are taken to analyze according to the parameters given in Table 5.2.

Table 5.2: Parameters for Single phase inverter

| Parameter | Value |
|---|---|
| Type of Inverter | Single Phase |
| Capacity | 2 kW |
| Output Frequency | 50 Hz |
| Switching Frequency | 16 kHz |

A single-phase inverter of 2 kW capacity with a switching frequency of 16 kHz is used to analyze the spread with an increasing number of inverters connected in the same location in a low voltage distribution system. Here, single-phase inverters are connected to the location B1 given in Figure 5.1. The results of the MATLAB simulation are given in below figures.

Frequency spectrum of the single-phase inverter, frequency spectrum of the same type of two single-phase inverters and frequency spectrum of the same type of three single-phase inverters connecting to the distribution system are shown in Figure 5.2, Figure 5.3 and Figure 5.4 respectively.

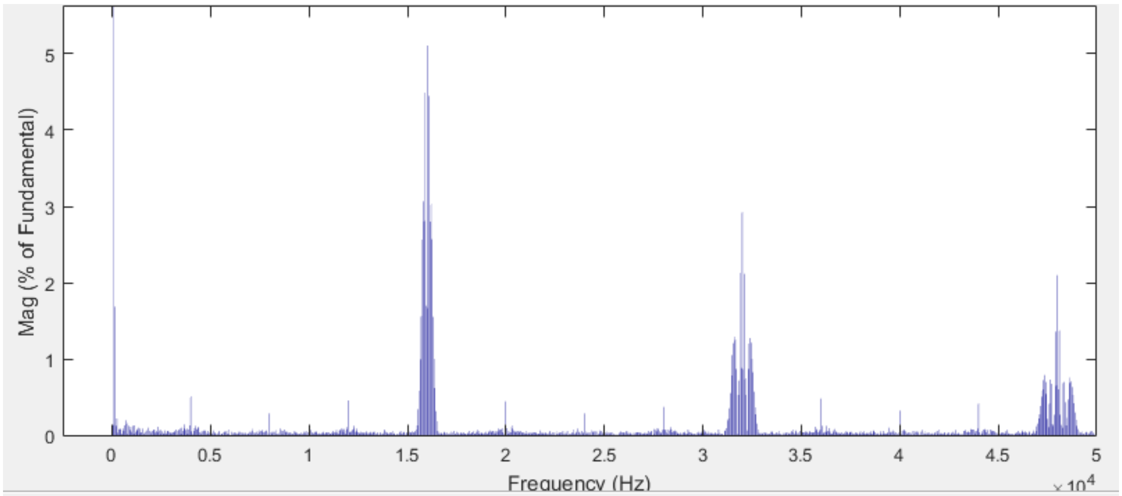



Figure 5.2: Frequency spectrum of single -phase inverter connecting to the distribution system

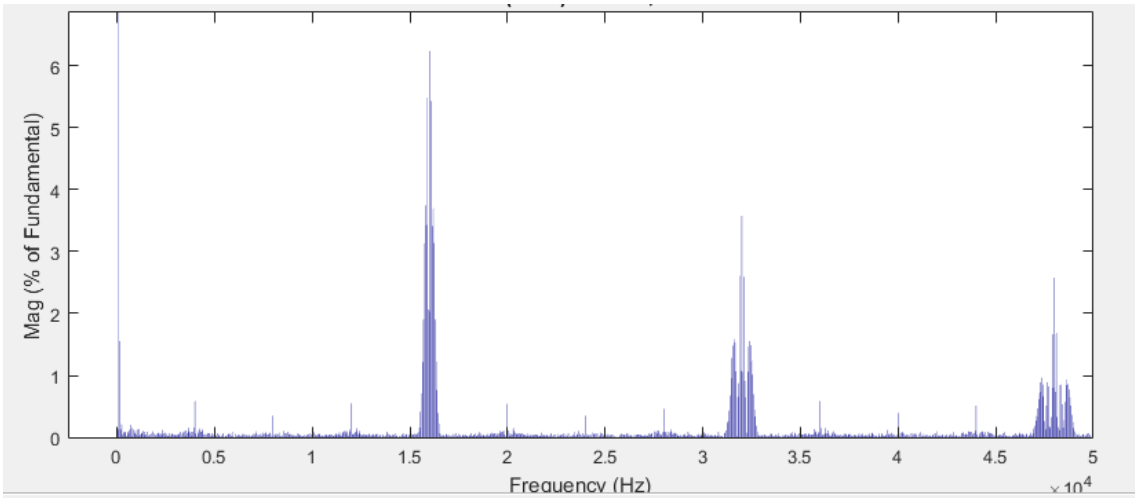



Figure 5.3: Frequency spectrum of same type of two single -phase inverters connecting to the distribution system

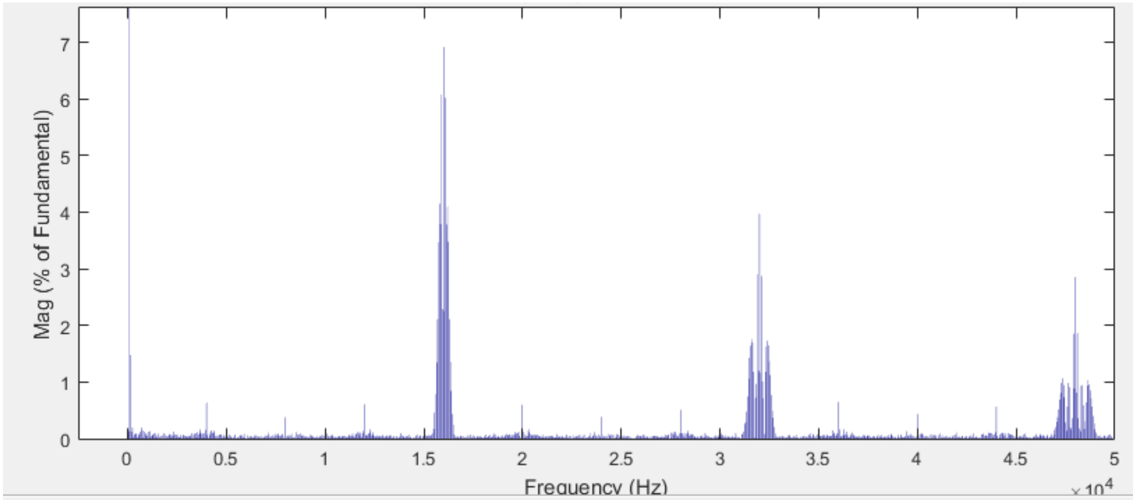



Figure 5.4: Frequency spectrum of same type of three single -phase inverter connecting to the distribution system

When comparing resultant three waveforms of different number of single-phase inverters, the harmonics generated around 16 kHz is increased with the number of connected inverters increases. Here, the magnitude of the generated harmonics is around 5% of the fundamental frequency when connecting one single-phase inverter to the distribution system according to the Figure 5.2. It increases up to 6.2% when connecting another same type of inverter and it can be identify referring Figure 5.3. According to Figure 5.4, it is shown as 7% of the fundamental frequency with connecting three same type of single-phase inverters. Apart from that, the harmonics generated around 32 kHz and 48 kHz are also increased with the increasing number of the inverter connected to the power distribution system. Here, 32 kHz and 48 kHz can be identified as multiple integers of 16 kHz. Comparison of concentrated harmonics after connecting different number of single-phase inverters to the same location in distribution system is shown in Table 5.3.

Table 5.3: Comparison of concentrated harmonics after connecting different number of single-phase inverters to the same location in distribution system

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency (No of inverters-one) | Harmonic percentage from fundamental frequency (No of inverters-two) | Harmonic percentage from fundamental frequency (No of inverters-three) |
|---|---|---|---|---|
| 16 kHz | 16 kHz | 5% | 6.2% | 7% |
| | 32 kHz | 2.9% | 3.7% | 4% |
| | 48 kHz | 2.1% | 2.7% | 2.9% |

As second part, the same types of three-phase inverters with the same switching frequencies are taken to analyze according to the parameters given in Table 5.4.

Table 5.4: Parameters for Three-phase inverter

| Parameter | Value |
|---|---|
| Type of Inverter | Three Phase |
| Capacity | 20 kW |
| Output Frequency | 50 Hz |
| Switching Frequency | 4 kHz |

In this part, a three-phase inverter of 20 kW capacity with a switching frequency of 4 kHz is used to analyze the spread with an increasing number of inverters to the same location in the low voltage power distribution system. Three-phase inverters are connected to the Location B1 according to the Figure 5.1. Resultant waveforms are shown in below figures.

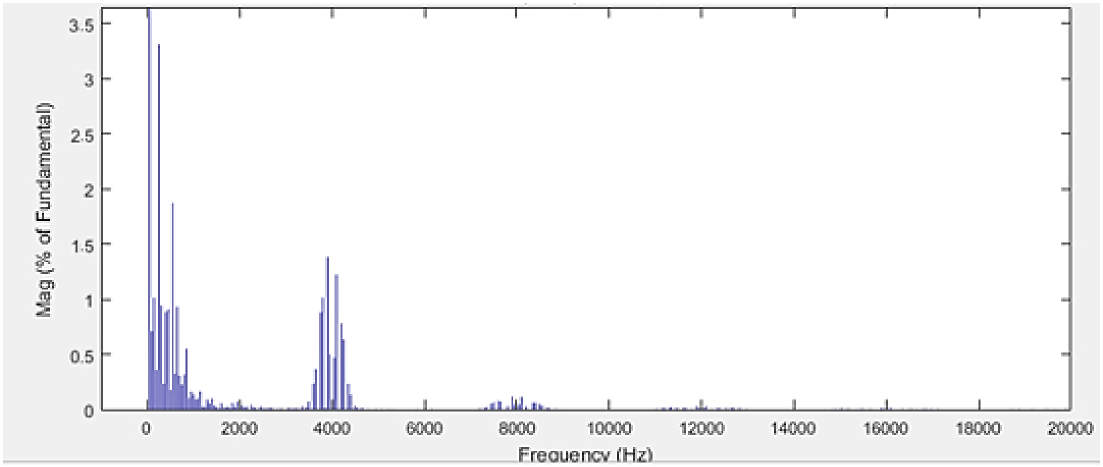



Figure 5.5: Frequency spectrum of three-phase inverter connecting to the distribution system

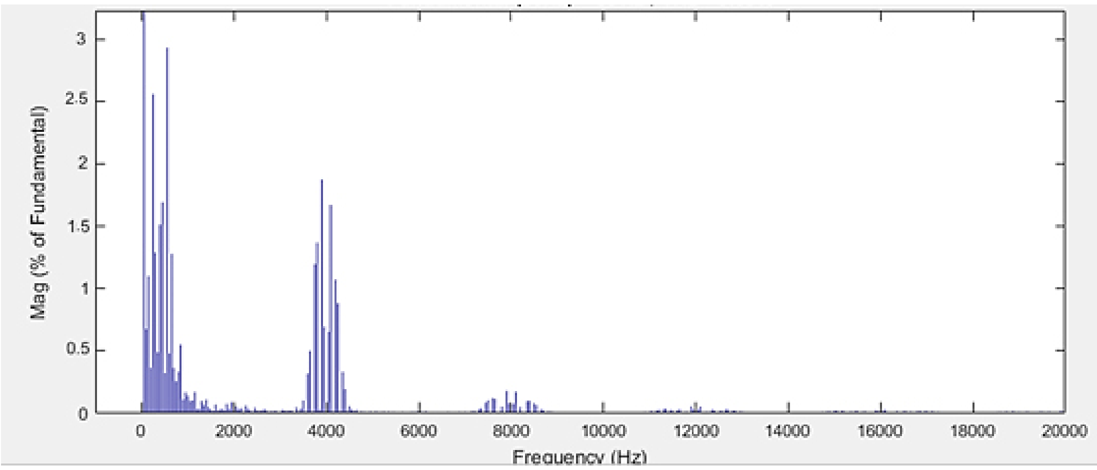



Figure 5.6: Frequency spectrum of same type of two three-phase inverter connecting to the distribution system

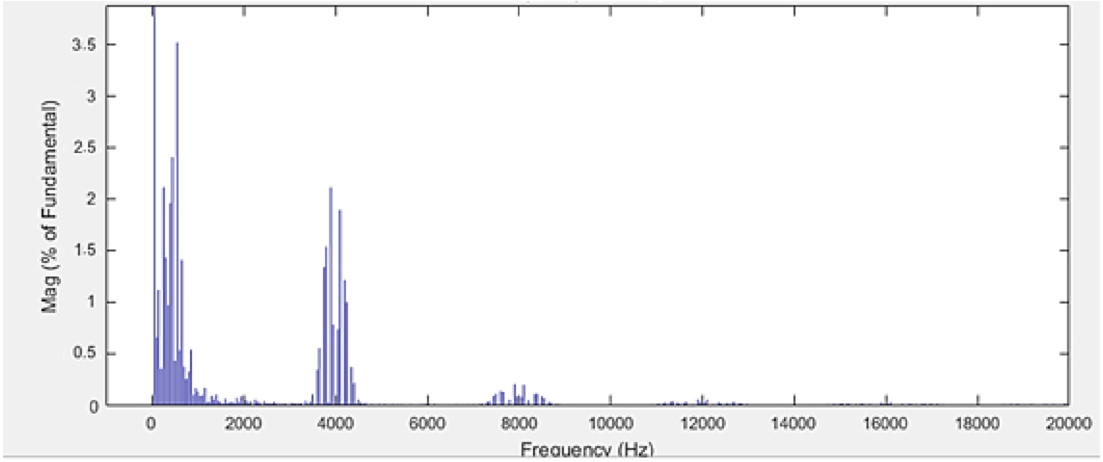



Figure 5.7: Frequency spectrum of same type of two three-phase inverter connecting to the distribution system

Frequency spectrum of the three-phase inverter, Frequency spectrum of the same type of two three-phase inverters and Frequency spectrum of the same type of three three-phase inverters connecting to the distribution system is shown in Figure 5.5, Figure 5.6 and Figure 5.7 respectively.

According to the above waveform, amplitudes of the generated harmonics are increased with increasing number of connected inverters to the same location. Based on the Figure 5.5, the magnitude of generated harmonics around 4 kHz is 1.3 % of the fundamental frequency when connecting one three-phase inverter to the distribution system. It is increased to 1.8% with another three-phase inverter as per the Figure 5.6. According to the Figure 5.7, it can be observed that the magnitude of generated harmonics around 4 kHz is 2.2% of the fundamental frequency after connecting three inverters of the same type to the same location. Comparison of concentrated harmonics after connecting different number of three-phase inverters to the same location in distribution system is shown in Table 5.5.

Table 5.5: Comparison of concentrated harmonics after connecting different number of three-phase inverters to the same location in distribution system

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency (No of inverters-one) | Harmonic percentage from fundamental frequency (No of inverters-two) | Harmonic percentage from fundamental frequency (No of inverters-three) |
|---|---|---|---|---|
| 4 kHz | 4 kHz | 1.3% | 1.8% | 2.2% |
| | 8 kHz | 0.1% | 0.3% | 0.4% |

According to the above discussed two parts, the magnitude of the emission of high frequency harmonics is increased with the increasing number of inverters connected to the grid.

## 5.2 Impact of inverter configuration

In this section, three-phase inverters with different switching frequency are used to identify the variation with different inverter configuration. Here, inverters are connected to the same location with different configuration.

A three-phase inverter of 20 kW capacity with an output frequency of 50 Hz is used to analyze the propagation with different inverter configuration in low voltage distribution systems. Different switching frequencies of 4 kHz, 6 kHz and 8 kHz are taken for three-phase inverters with the same parameters for other variables.

Frequency spectrum of two three-phase inverters with the same switching frequency of 4 kHz after being connected to the power distribution system is shown in Figure 5.8. Next, the frequency spectrum of two three-phase inverters with different switching frequency as 4 kHz, 6 kHz and 6 kHz, 8 kHz separately connecting to the power distribution system is shown in Figure 5.9 and Figure 5.10, respectively.

In Figure 5.8, the emission of harmonics can be identified around 4 kHz and 8 kHz. However, it can be found at 4 kHz, 6 kHz, 8 kHz and 12 kHz in Figure 5.9. In Figure 5.10, generated harmonics can be identified around 6 kHz, 8 kHz, 12 kHz and 16 kHz. After analyzing these waveforms, high frequency harmonics are generated around the switching frequency of inverter and around their multiple integer values. When comparing Figures 5.8 and 5.9, the emission of harmonics around 4 kHz is 1.5% and it is reduced to 1%. But, newly generated harmonic are available around 6 kHz. Three-phase inverter with switching frequency of 6 kHz is replaced to one three-phase inverter with switching frequency of 4 kHz. Because of that, magnitude of generated harmonics around 4 kHz is reduced and newly harmonics generated around 6 kHz.

Based on Figure 5.8, emission of harmonics can be identified around 4 kHz, 8 kHz and 12 kHz. Here, 8 kHz and 12 kHz are multiple integer of 4 kHz. And, generated harmonics are available around 4 kHz, 6 kHz, 8 kHz, 12 kHz and 16 kHz according to Figure 5.9. Here, 8 kHz, 12 kHz are multiple integer of 4 kHz and 16 kHz is multiple integer of 8 kHz.

As same as discussed example, three-phase inverter with switching frequency of 8 kHz is replaced to other three-phase inverter with switching frequency of 4 kHz. According to Figure 5.10, emission of harmonics can be identified around 6 kHz, 8 kHz, 12 kHz and 16 kHz. Comparison of concentrated harmonics around switching frequency and it’s integer multiples after connecting three-phase inverters with different switching frequencies are shown in Table 5.6.

Table 5.6: Comparison of concentrated harmonics around switching frequency and it's integer multiples after connecting three-phase inverters with different switching frequencies

| Inverter | Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency |
|---|---|---|---|
| 1st inverter | 4 kHz | 4 kHz | 1.5% |
| 2nd inverter | 4 kHz | 8 kHz | 0.2% |
| 1st inverter | 4 kHz | 4 kHz | 0.9% |
| 2nd inverter | 6 kHz | 6 kHz | 0.4% |
| | | 8 kHz | 0.2% |
| | | 12 kHz | 0.1% |
| 1st inverter | 4 kHz | 6 kHz | 0.3% |
| 2nd inverter | 6 kHz | 8 kHz | 0.2% |
| | | 12 kHz | 0.1% |

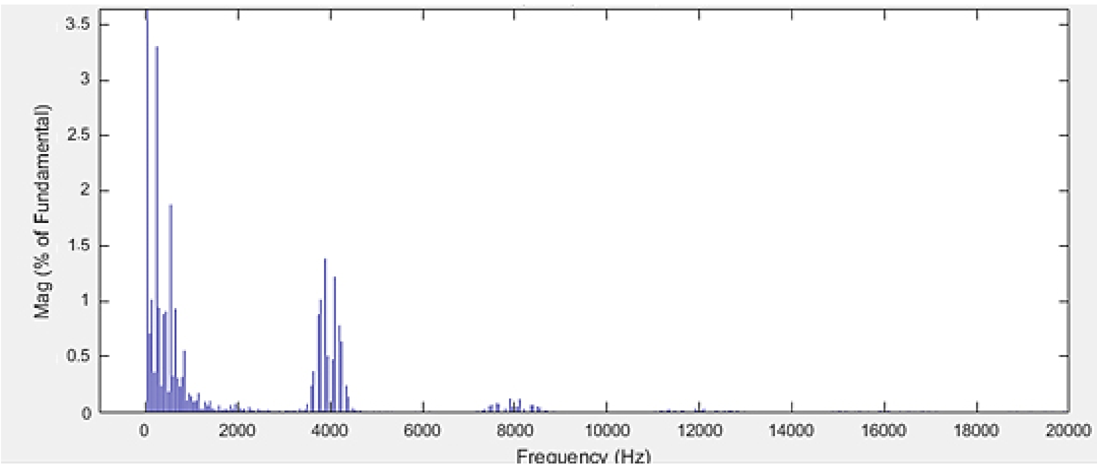



Figure 5.8: Frequency spectrum of two three-phase inverters with same 4 kHz switching frequency after connecting to the distribution system

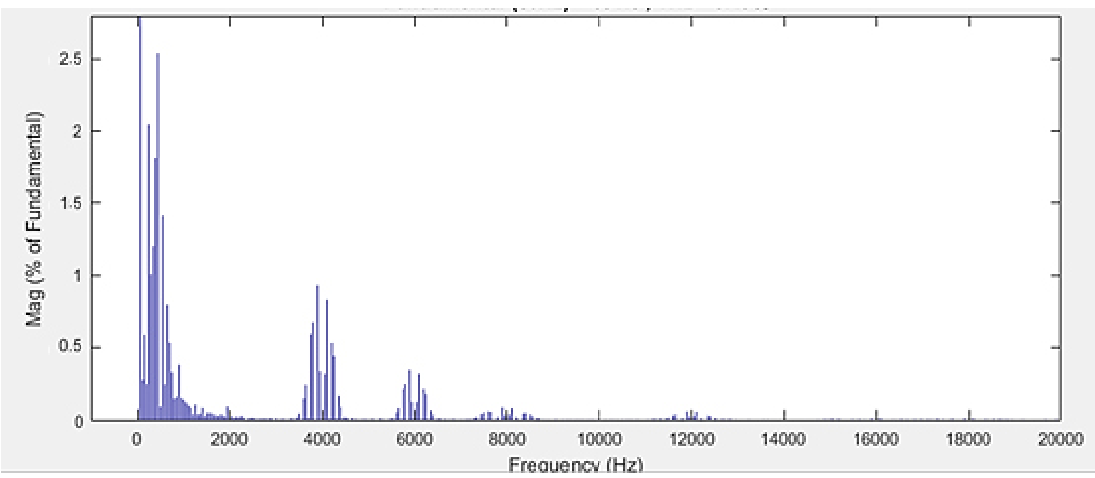



Figure 5.9: Frequency spectrum of two three-phase inverters with 4 kHz and 6 kHz switching frequency after connecting to the distribution system

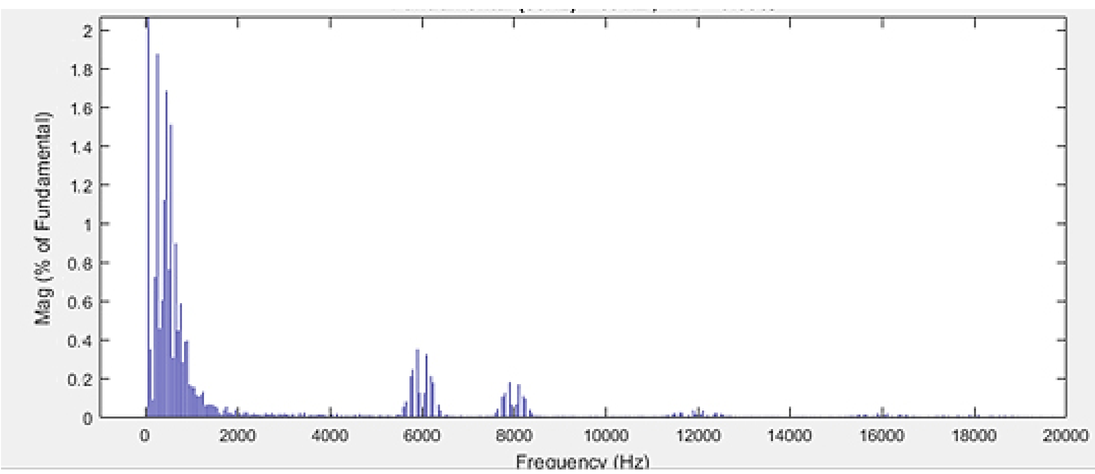



Figure 5.10: Frequency spectrum of two three-phase inverters with 6 kHz and 8 kHz switching frequency after connecting to the distribution system

After analyzing above three waveforms, the emission of high frequency harmonics can be identified around the switching frequency and the integer multiples of the switching frequency

### 5.3 Analysis of harmonic propagation

In this section, single-phase and three-phase inverters are used to identify the propagation in power distribution system with connecting inverters in different location of power distribution system. Furthermore, inverter configuration does not changed when analyzing this part.

As first part, A 2 kW, single-phase inverter with an output frequency of 50 Hz and a switching frequency of 16 kHz is used to analyze the propagation in a low-voltage power distribution system. In Figure 5.11, the block diagram of the simplified low voltage power distribution system is used to indicate the selected locations, when connecting the inverters to different locations.

The single-phase inverter is connected to location B1 and the frequency spectrums are taken from different locations in the power distribution system. Here, the simulated frequency spectrum at location B1, B2 and B3 are shown in Figure 5.11, Figure 5.12 and Figure 5.13 respectively. When comparing figures, the magnitude of the emission of harmonics is reducing with increasing distance between connected inverter and the harmonic measuring location. The high frequency harmonic concentrate around 16 kHz is 5%. It is reduced to 4.7% and 4.3% with increasing the distance to the inverter. Furthermore, generated harmonic around 32 kHz is 3%. It is reduced to 2.7 % and 2.5% with increasing distance to the connected inverter. Comparison of concentrated harmonics in different locations in distribution system without changing single-phase inverter location are shown in Table 5.7.

Table 5.7: Comparison of concentrated harmonics in different locations in distribution system without changing single-phase inverter location

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency (Measuring location – B1) | Harmonic percentage from fundamental frequency (Measuring location – B2) | Harmonic percentage from fundamental frequency (Measuring location – B3) |
|---|---|---|---|---|
| 16 kHz | 16 kHz | 5.1% | 4.7% | 4.3% |
| | 32 kHz | 3% | 2.7% | 2.5% |
| | 48 kHz | 2.1% | 1.9% | 1.7% |

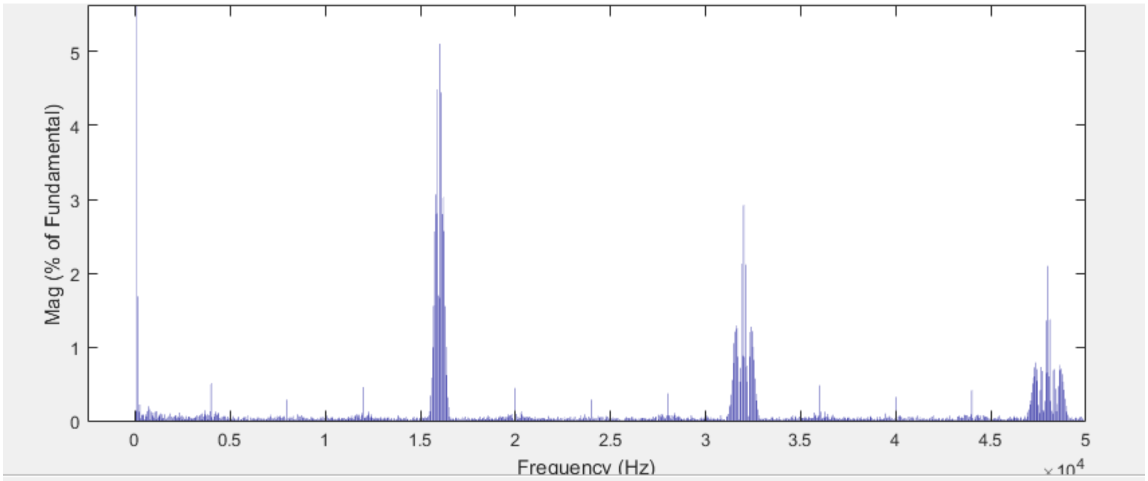



Figure 5.11: Frequency spectrum location B1 (Single-phase inverter is connected to location B1)

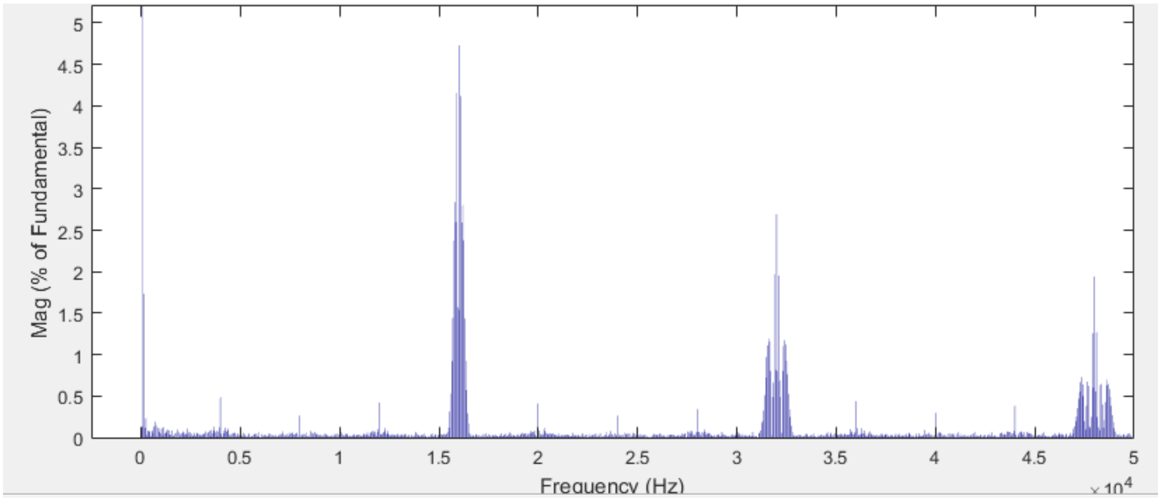



Figure 5.12: Frequency spectrum in location B3 (Single-phase inverter is connected to location B1)

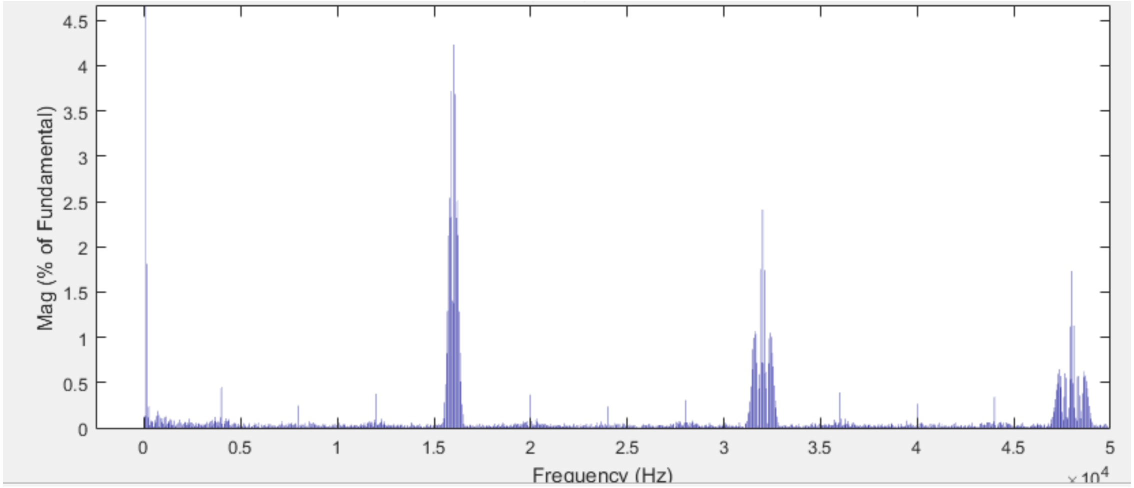



Figure 5.13: Frequency spectrum in location B2 (Single-phase inverter is connected to location B1)

As second part, A 20 kW, a three-phase inverter with an output frequency of 50 Hz and a switching frequency of 4 kHz is used to analyze the propagation in a low-voltage distribution system.

The three-phase inverter is connected to location B1 and frequency spectrums are taken from different locations in the power distribution system. Here, the resultant frequency spectrum at location B1, B2 and B3 are shown in Figure 5.14, Figure 5.15 and Figure 5.16 respectively.

According to the below figures, the magnitude of the emission of harmonics is reduced with increasing distance between connected inverter and the measuring location as same as first part. The high frequency harmonic concentrate around 4 kHz is 2.3%. It is reduced to 1.4% and 0.9% with increasing the distance to the inverter and measuring location. Comparison of concentrated harmonics in different locations in distribution system without changing three-phase inverter location are shown in Table 5.8.

Table 5.8: Comparison of concentrated harmonics in different locations in distribution system without changing three-phase inverter location

| Switching Frequency | Concentrated Harmonics around switching frequency and it's integer multiples | Harmonic percentage from fundamental frequency (Measuring location – B1) | Harmonic percentage from fundamental frequency (Measuring location – B2) | Harmonic percentage from fundamental frequency (Measuring location – B3) |
|---|---|---|---|---|
| 4 kHz | 4 kHz | 2.3% | 1.4% | 0.9% |
| | 8 kHz | 0.3% | 0.1% | 0.1% |

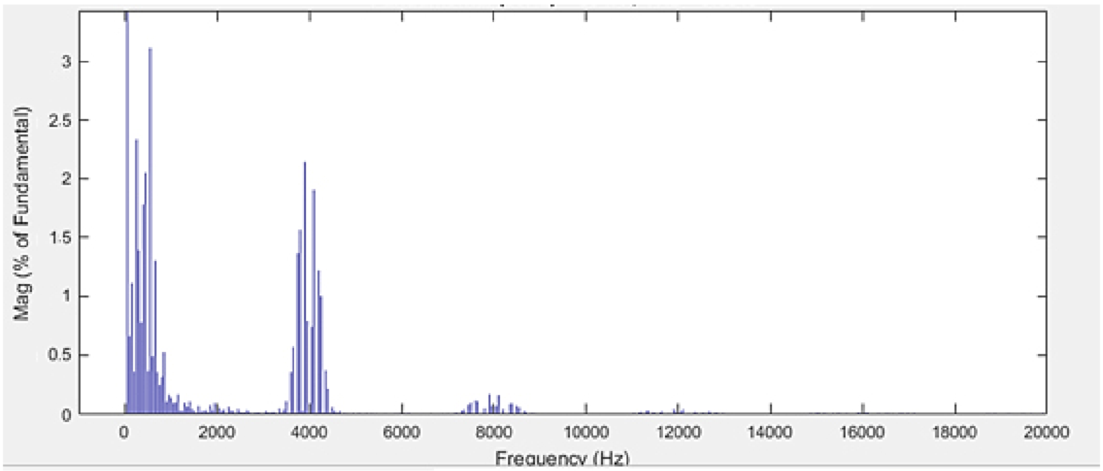



Figure 5.14: Frequency spectrum in location B1 (Three-phase inverter is connected to location B1)

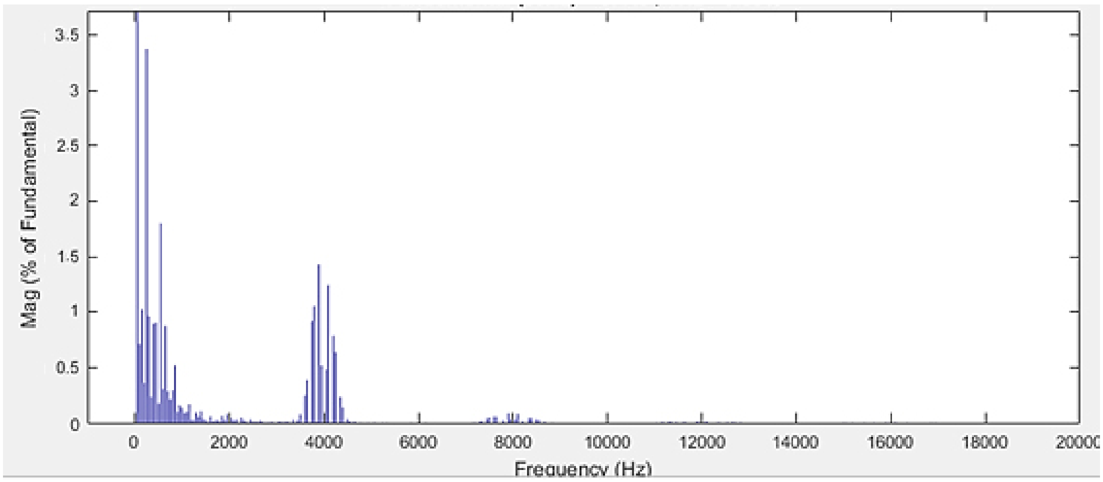



Figure 5.15: Frequency spectrum in location B2 (Three-phase inverter is connected to location B1)

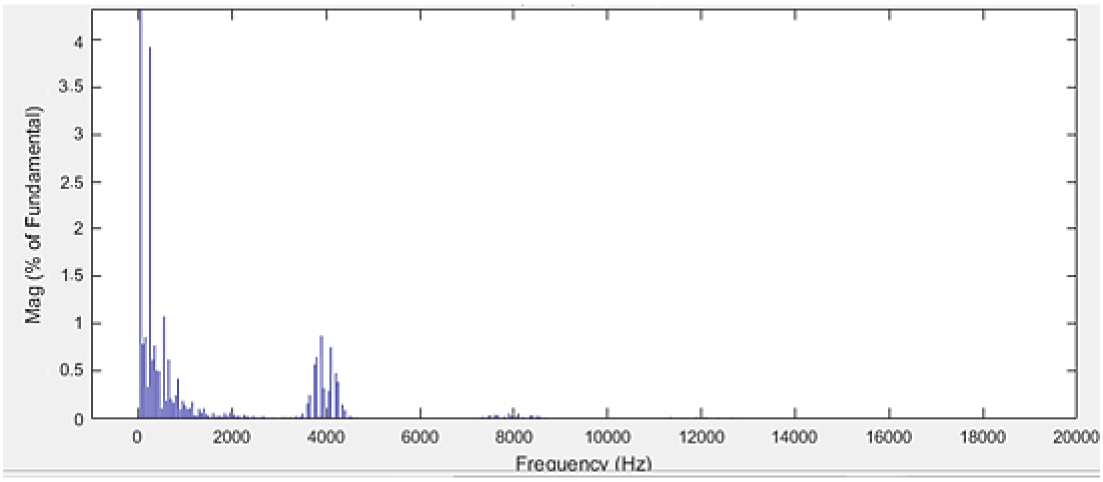



Figure 5.16: Frequency spectrum in location B3 (Three-phase inverter is connected +to location B1)

According to the result of single phase and three-phase inverter simulation, Generated HF harmonics impact is reduced with the increasing distance with the connected inverter.

## Conclusion and Recommendations for Further Studies

With the proliferation of renewable energy system, photovoltaic inverters have become more popular in recent years due to diverse technical merits of the generation of solar energy. Because of that, the single-phase photovoltaic inverters and the three-phase photovoltaic inverters have been analyzed in terms of high frequency harmonics. Here, high frequency harmonics or supra-harmonics is taken as the frequency range of 2 to 150 kHz.

Specially, main features can be identified after analyzing the resultant waveforms from inverter connected to the distribution system. As a first point, the high frequency harmonics are concentrated around the switching frequency of the photovoltaic inverter and the integer multiples of that switching frequency, so that the installed capacity is not affected.

As second point, the amplitude of high frequency harmonics emission is increased with the increasing number of inverters connected to the grid. As third point, generated high frequency harmonics impact is reduced with the increasing distance with the connected inverter, those are unlikely to propagate far into the distribution network.

As a final point, the input impedance of the photovoltaic inverter varies in a high frequency range with multiple resonance points according to the impedance waveforms of the inverter.

Furthermore, the high frequency models of single-phase and three-phase PV inverters can be used as first stage of modelling approaches of PV inverters for supra harmonics emission studies. The models were developed assuming a standard 230V/50Hz supply and basic parameters of inverter taken in chapter 4. However, further improvement of inverter configuration is required to control the inverter with future studies. When developing model for PV inverter, there is usually a compromise between the accuracy of the model and the complexity of the modelling approach. Therefore, a rough estimate of the supra harmonic behavior of a PV inverter is given by the simulations.

High frequency behavior of PV inverters can only be studied by developing comprehensive modelling where no much efforts related to HF harmonics are reported in the literature. In some research, a simple frequency domain model with a current source behind a capacitor is proposed based on experimental findings. Although such a model can successfully deal with both primary and secondary emission, further comprehensive HF models are required in order to carry out thorough studies on emissions from different equipment.

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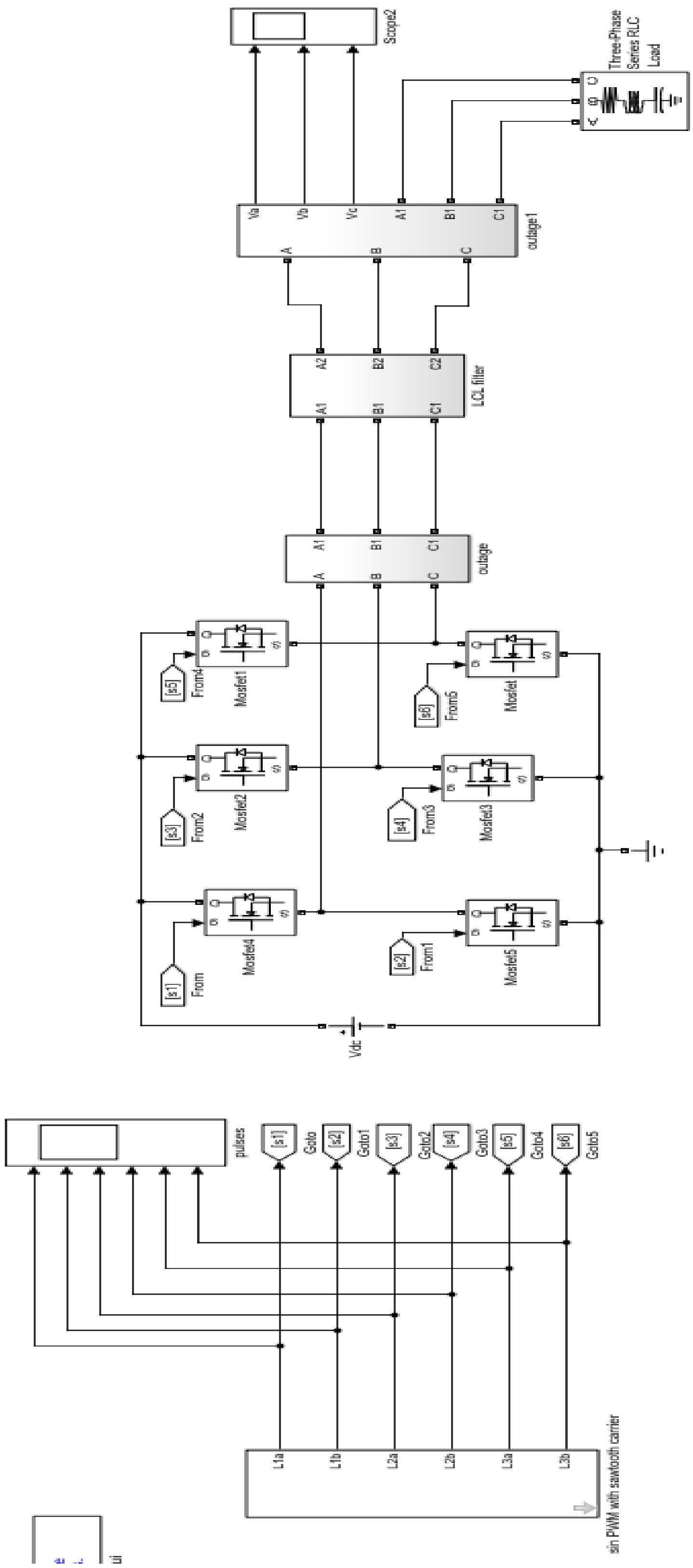
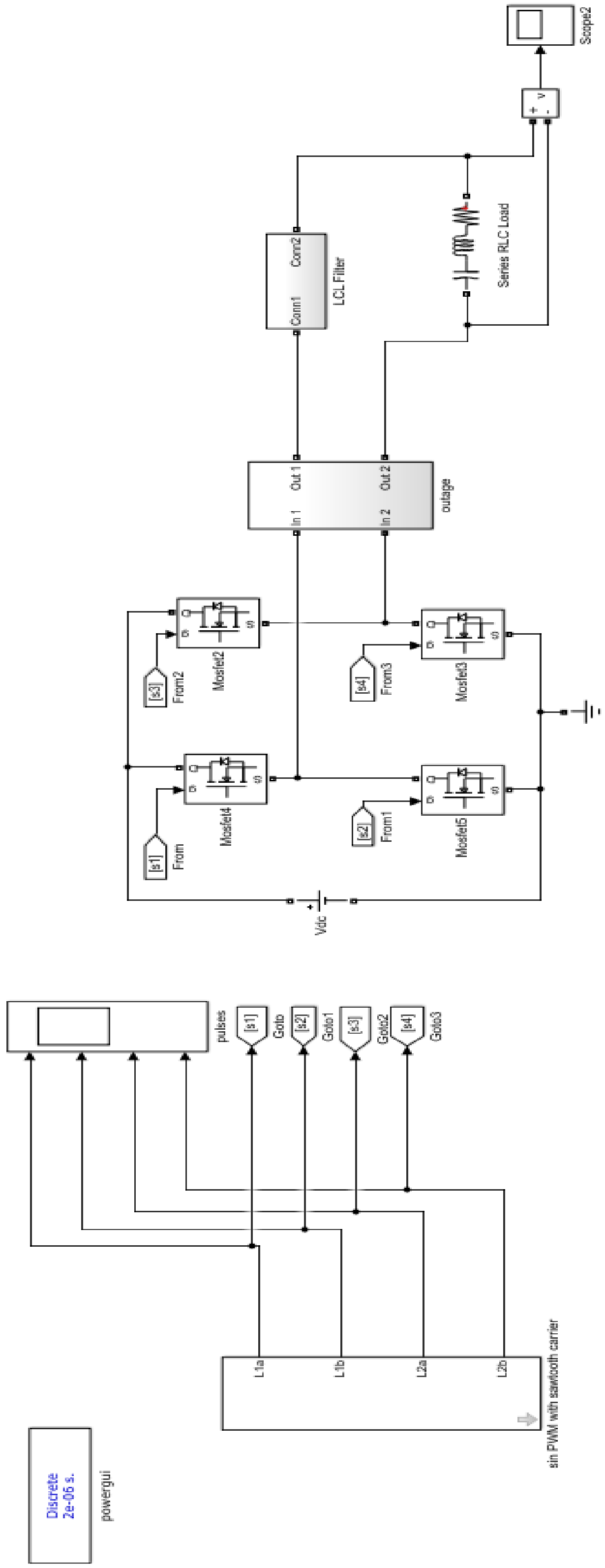
## Appendix 1: Three phase inverter matlab/ Simulink model



**Appendix 2 : Single phase inverter matlab/ Simulink model**



# Appendix 3: Matlab/ Simulink Model for power distribution system