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Hybrid Active Filters: Panacea to Harmonic Distortion Losses in Power Distribution Networks

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Abstract:
The Nigerian electric power industry is facing a lot of challenges. From generation to distribution, the system's reliability is far below expectation. Modeling hybrid active filters with Matlab/Simulink environment to mitigate harmonics stress by a non-linear load is the focus. The load was connected directly to the supply, with the modeled hybrid active filter connected in parallel to the distribution network. The hybrid consists of a passive filter and an active power filter connected to the distribution system. The passive power filter was used to filter the low order harmonic current with a large power rating, while the active power filter with a low power rating was used to filter the other high order harmonics. The Simulink showed the effect of modeled non-linear load on the distribution network by distorting the ideal waveform of current and voltage from the supply. After the simulation, the total harmonics presented in the current waveform were reduced from 23.52% to 0.01%, and for the voltage, it reduced from 9.18% to 0.27%.

Keywords: *Non-linear, hybrid, harmonics, power system, energy*

1. Introduction

The electrical power industry in Nigeria is facing a lot of challenges in terms of quality, from generation to distribution (Ogunyemi, 2012). Its reliability has gone far below expectation. In recent years, power quality has been a cogent concern for all utilities, facilities, and Consulting Engineers. The provision of sustainable, adequate, reliable, and efficient electricity supply to residential, commercial, and industrial consumers is major to national development. The end user equipment is sensitive to any disturbances starting from supplying power systems and within the customer facilities. The major challenge that the power system is facing is the generation of harmonics from semiconductor-based devices like:

- Diodes,
- Thyristors or Silicon-Controlled Rectifiers (SCR),
- Gate Turn-off Thyristors (GTO),
- Triacs,
- Bipolar Junction Transistors (BJT),
- Power MOSFET, and
- Integrated Gate-Commutated Thyristors (IGCT)

The increase in the use of electronic equipment produces a large number of harmonics in the distribution system because of the non-sinusoidal currents consumed by non-linear loads. For high-quality power, the voltage and current waveforms should be sinusoidal. However, it is disturbed in actual practice, and this is called 'Harmonic Distortion'.

Many social and economic activities rely solely on electrical energy quality and its efficiency. Therefore, mitigation of the current harmonics or voltage harmonics generated by the load is paramount. Various standards have been established to regulate the severity of harmonics distortion (Dehini et al., 2010).

2. Theoretical Framework

Harmonics distortion is defined as a steady state deviation from an ideal sine wave of fundamental frequency due to the presence of sinusoidal components having frequencies as integer multiples of the fundamental frequency. The term usually used to quantify harmonics distortion is THD, i.e., Total Harmonics Distortion. It is defined as the ratio of the RMS

(Root Means Square) of the harmonics content to the RMS value of the fundamental quantity, expressed as a percentage of the fundamental.

According to Chen (2004), in an ideal power system, electric energy should be delivered from the source to load with sinusoidal voltage and current at a constant frequency. However, in practice, the existence of non-linear elements, especially power electronic devices such as speed drives, arc furnaces, uncontrolled and controlled rectifiers, and other non-linear loads, in the distribution system has been the source of pollution in the network with harmonics. They continuously produce harmonic distortion in the system. For instance, an industrial application may need to convert DC voltage to AC voltage. It means that the usage of an inverter is inevitable. However, inverters or any other equipment, such as converters, rectifiers, etc., which consist of power electronics, inject harmonics into the system. The distortion in current resulting from the switching operation of thyristors and its harmonic amplitude is greatly affected by the impedance on the ac side. This type of harmonic source behaves like the current source harmonic. The introduction of strict legislation, which is IEEE519, limits the maximum amount of harmonics that a supply system can tolerate for a particular type of load. Harmonics in the network not only increases the losses but also produces unwanted disturbances to the distribution network. More voltage and/or current stress is caused.

Harmonics is divided into two types, namely even and odd harmonics with fundamental frequency represented as *f*. Even harmonics type comprises harmonics with an even number of harmonics multiple. They include: 2*f*, 4*f*, 6*f*, 8*f*, 10*f*, etc. They get cancelled because of their symmetrical nature (Salmer'on et al., 1996). On the other hand, odd harmonics has a very great impact on electrical appliances. It is sub-divided into three groups, namely: negative sequence, zero sequence, and positive sequence, which have to be eliminated.

Positive sequence harmonics gives a rotational sequence in the direction of the fundamental frequency. Examples include: 1^{st}, 7^{th}, 11^{th}, 19^{th}, etc.

Negative sequence harmonics gives a rotational sequence in the opposite direction or anti-clockwise to the fundamental frequency. Examples include: 5^{th}, 13^{th}, 17^{th}, etc.

Zero sequence harmonics gives rotation that is not in phase with either itself or fundamental energy rotation. They are in order word, which is called triplen harmonics. Examples include: 3rd, 9th, 15th, etc. This contains multiple harmonics with odd numbers, including f, 3f, 5f, 7f, 9f, 11f, 13f, and 15f. From the odd component of the harmonics, triplen harmonics is also extracted, which include: 3f, 9f, 15f, 21f, etc. These zero-sequence harmonics currents do not cancel each other but add up arithmetically on the neutral bus, creating a primary source of excessive neutral current (Watanabe et al., 1993).

In general, even harmonics type cancels each other because of the nature of the symmetrical component, unlike odd harmonics type, which has to be eliminated by using filters. In reality, harmonics occur when the current flowing across the load is non-sinusoidal or related linearly to the applied voltage. In a situation where the load is a full wave rectifier using 3-phase, six pulse converter produces harmonic distortion in order of 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, etc., and contains no harmonics lower than 5^{th}. In contrast, in a 12-pulse converter, the lowest is the 11^{th} harmonics. Current flows only when the supply voltage exceeds the stored voltage in the reservoir capacitor. The waveform in this reaction will deviate from the sine wave. The harmonics is caused when non-linear loads draw current in abrupt short pulses rather than in a smooth sinusoidal way (Inzunza et al., 2005).

3. Types and Applications of Filters in Mitigating Harmonics

A filter is a device that helps to pass electric signals at certain frequencies or frequency ranges while preventing the passage of others. A filter is divided into two types:

- Active and
- Passive filter
- It can be classified according to their:
- Circuit configuration,
- Power circuit, and
- Control scheme

The generalized classification and configuration are shown in figure 1.

3.1. Active Power Filter

This is the most reliable method of mitigating total harmonics distortion within the IEE norms during load change. The efficiency of this method is based on the reference signal and its speed of computation. Active power filters mitigate the defect in the wave-produced load current and effectively filter harmonics (Zhou et al., 2014). The current produced by the active power filter flows into the power grid through an injection circuit. So the output filter sieves out the switching harmonics caused by non-linear load devices. Active power filters can also be connected in series, shunt, or hybrid.

There are two types of inverter used in active power filter for connection, namely:

- Voltage source inverter, and
- Current source inverter

While voltage source converters contain a capacitor that resists transient voltage changes, current source converters contain an inductor that resists transient current changes. The choice between the two sources depends on the distortion or harmonics source at the bus, equipment cost, and the amount of correction desired. Active power filter basically is to cancel harmonics and compensates for harmonics current.

3.2. Series Active Power Filters

This is shown in figure 1 as part of the configuration of the active power filter. Series active power filter senses load current and extracts harmonics components of the load current to produce a reference current.

This is done by eliminating the undesired harmonics to compensate for the reactive power and recharge capacitor value requested by voltage direct current to enable suitable power transmission to supply inverter. SAPF has voltage output which performs the function of an isolator for voltage harmonics (Bhattacharya et al., 1995). A distortion voltage appears at the right side of the filter. Voltage source distortion is controlled by series active power filter causing the non-linear loads. This is done using a high impedance path to the flow of the current harmonics that pushes high-frequency current to pass through an LC passive filter connected in parallel to the load by Singh et al. (1998). The high impedance generated by SAPF is created by generating a voltage of equal frequency for the current harmonics component that will be eliminated (Kim et al., 2004, P. 276-282). For better performance of generating reference source current, park's and dq transformation is used. Series active power filter uses a low power rating for filters with a higher order of harmonics, i.e., 13th to 29th harmonics.

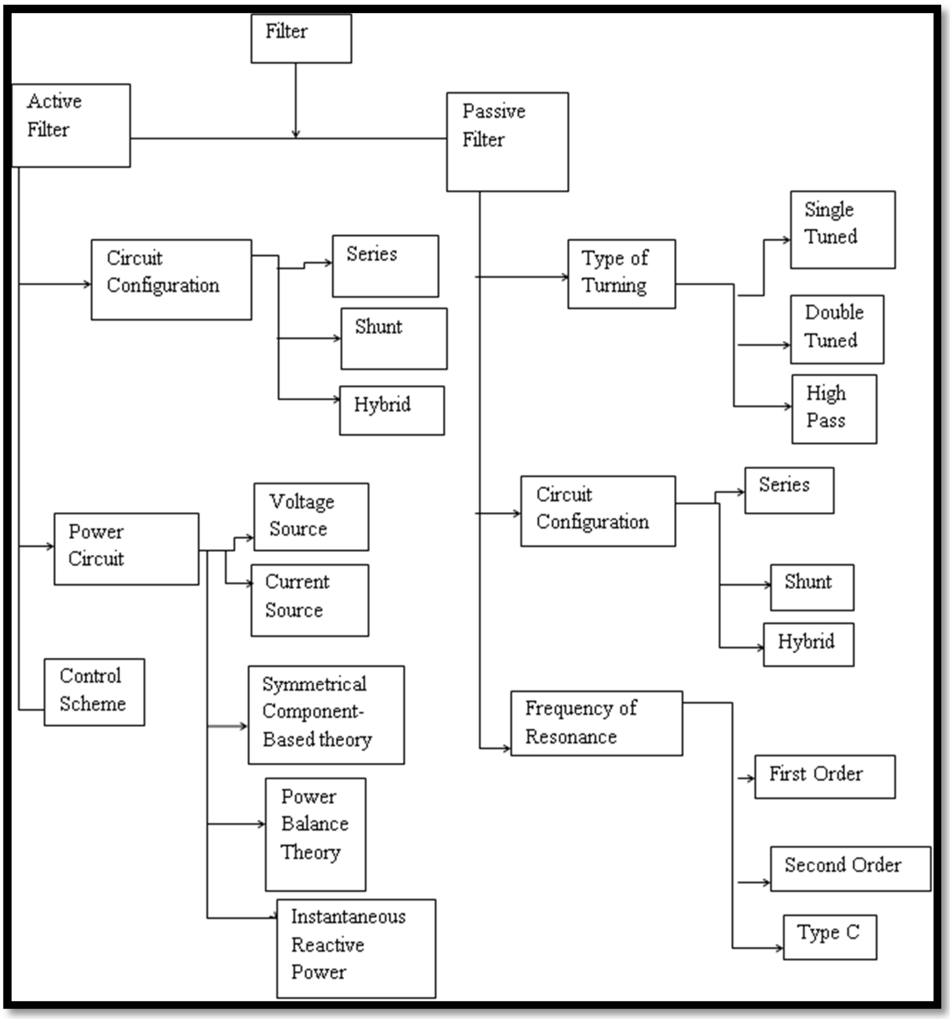

Figure 1: Classification of Filters

3.3. Passive Filters

Passive filters contain passive elements, i.e., Resistor, Inductor, and Capacitor. It can be classified according to connection to the main circuit, sharpness of tuning, and frequency of resonance. This is shown in figure 1.

3.4. Series Passive Filters

Series passive filters are always placed in series to supply electricity and manage the load. They are good for singl e-phase application and are specially suited to mitigate third harmonics (Akagi et al., 2005, P. 2128-2147). They do not pro duce resonance and offer high impedance to the frequencies to which they are tuned. These filters have parallel inductors and capacitors. The following are its characteristics which include:

- Low impedance at fundamental frequency,
- High impedance to harmonics current on load side,
- Preventing harmonics current entry by using shunt passive filter with low impedance to the frequency

3.5. Shunt Passive Filter

This is divided into two major parts, which are:

- Single tuned filter, and
- High-pass filter

The Single Tuned Filter is a series LC (inductor, capacitor) circuit and is tuned to one of the lower harmonics frequ encies [3rd, 5th, 7th, 11th, and 13th harmonics]. It provides a very low impedance path to allow harmonics current to circu late in the load. The reactance should be low, with a frequency higher than the fundamental frequency. The resistor value o f the tuned filter determines the quality factor of the filter. It is equal to the ratio of the inductive or capacitive reactance at resonance to the resistor. It is shown in figure 2 as part of the circuit configuration for a passive filter.

3.6. High Pass Passive Filters

High pass passive filters offer low impedance over a large band of frequencies, e.g., 17^{th} – 29^{th} harmonics. The type includes: First order, Second order, and third order type with type C.

First Order type has a large capacitor and excessive power loss with frequency scarcely being used.

Second and third Order type is simple to apply and gives good filtering performance.

Third Order type has Lower losses at fundamental frequency.

Less effective in filtering action to reduce power loss, type C is used. Type C uses a Bypass resistor at fundamental frequency, susceptible to frequency variation because of fundamental frequency tuning. It has high filtering action to reduce power loss.

4. Limitations of Passive Filters

There are some disadvantages posed by passive filters, which make them not recommendable in mitigating harmonics in power systems. These include source impedance which strongly affects the filtering of harmonics. Passive filters are unable to adjust to changes in the frequency of the network and filter component variation. The series and parallel resonance between passive filter components and network impedance can cause amplification of harmonics current on the side at a specified frequency. The passive filter acts as a current sink to harmonics voltage included in the supply source. Passive filters can be overloaded when the source harmonics voltage is significant. It is bulky and expensive when low total harmonics is required.

5. Hybrid Active Power Filter (HAPF) Topology

HAPF is classified in terms of its circuit configuration, power circuit, and control mechanism. The distribution system starts from the source of supply to the consumption point, where the non-linear load is connected. The non-linear load includes:

- Fans,
- Blender,
- Farcing devices, and
- Variable speed drive devices

The non-linear load is generally known as a source of harmonics to the distribution system. Hybrid active power filter (HAPF) is composed of active and passive components in series and parallel to improve the system's compensation characteristics. HAPF topology is composed of many passive components, such as capacitors, reactors, and resistors. Mostly for active filters, power circuit can be either a Voltage-Source Pulse Width-Modulation (VSC-PWM) converter equipped with a dc capacitor or a Current-Source PWM converter equipped with a dc inductor. Currently, the VSC is more convenient and easy to use than Current-Source Converter (CSC) in terms of cost, physical size, and efficiency.

Hybrid filters are more attractive and efficient in harmonics filtering than pure active filters from both viability and economic points of view, especially for high-power applications. However, three-phase active filters attract more attention than single-phase active filters because single-phase filters are limited to low-power applications except for electric traction.

The two passive filters are designed to absorb 5th, 7th, and 11th harmonic currents with the principle of series resonance, and SHAPF compensates for the remaining harmonics.

6. Statement of Problem

In an ideal power system, electric energy should be delivered from the source to load with sinusoidal voltage and current at a constant frequency. However, in practice, the existence of non-linear elements, especially power electronic devices such as speed drives, arc furnaces, uncontrolled and controlled rectifiers, and other non-linear loads, in the distribution system has been the source of pollution in the network with harmonics. They continuously produce harmonic distortion into the system hence the need to design and simulate a hybrid active filter for harmonics mitigation in distribution networks stressed by non-linear loads.

7. Methodology

7.1. Modeling of Three Phase Distribution Supply Source

The power distribution source developed in the simulation model of HAPF is a balanced 3-single phase system consisting of 415V, 50 Hz sinusoidal ac voltage source. It is developed using three single phase ac source blocks from

'SimPower Systems/Electrical Source' library and is connected in the star configuration as shown in figure 2. Resistor and inductor are connected in series with each phase to limit inrush current. This is modeled using 'Series RL Branch' block set.

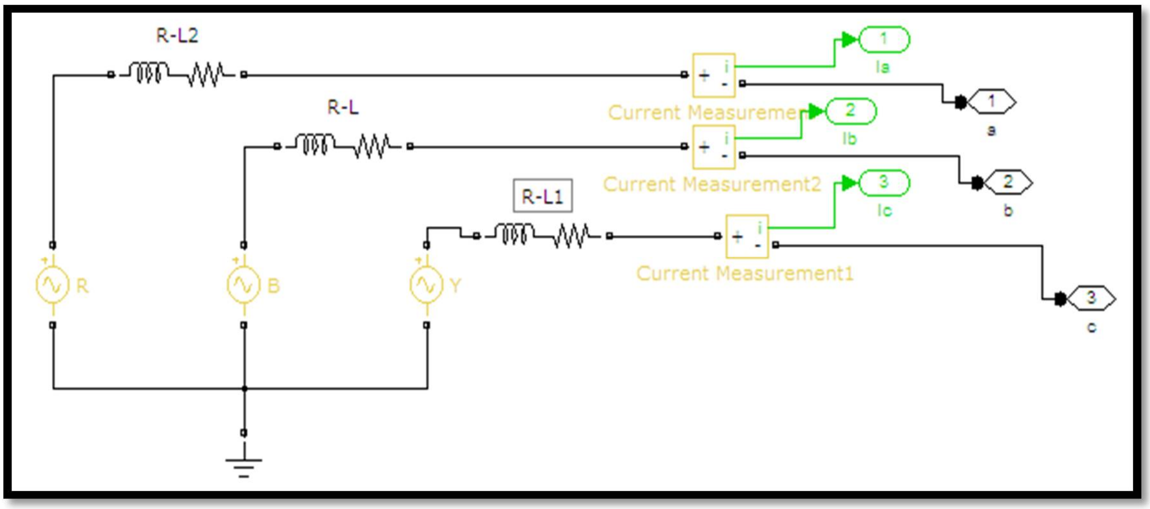

Figure 2: Simulink Model of Three Phase Distribution Source

The current signal is sensed using 'Current Measurement' block sets from 'SimPower Systems/ Measurements' library. A three-phase ac source is connected to a three-phase diode bridge rectifier load through a distribution line. The distribution line is modeled using a three-phase RL circuit connected in series with a power supply source.

7.2. Modeling of Three-Phase Non-Linear Load

The three-phase non-linear load consists of a three-phase full-bridge diode rectifier constructed by using 'Diode' blocks from Simulink library. A resistor-inductor (R-L) load (R=20 ohms and L=50 µH) is connected on dc side of the rectifier using 'series RL element' from Simulink/elements library. This non-linear load can produce harmonic current as most of the power electronics equipment. Hence, it is considered a non-linear load in this thesis. Figure 3 shows modeled non-linear load.

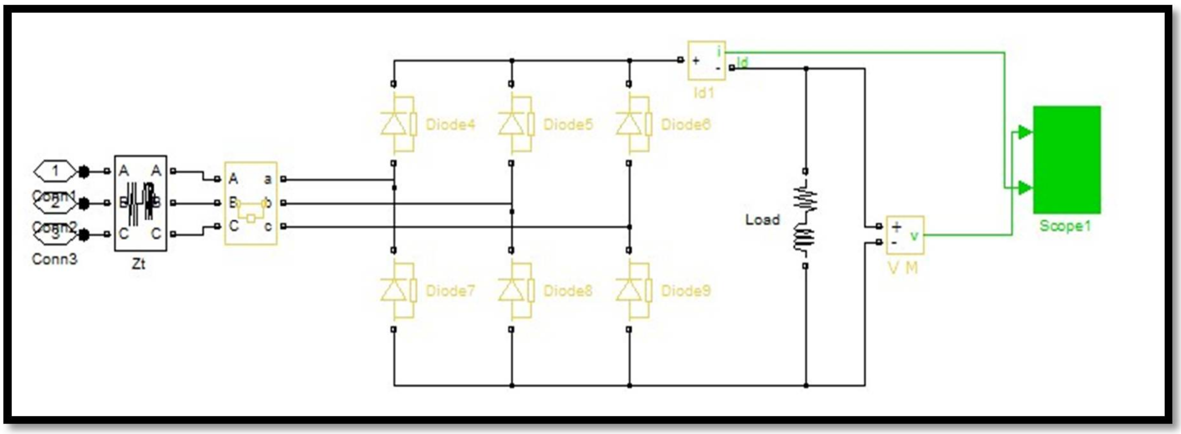

Figure 3: Simulink Model of a Distribution Network with Three Phase Non-Linear Load Block

7.3. Modeling of Passive Filter (PF)

The passive filter model comprises two series of connected single and double-tuned passive filter branches connected in parallel to the non-load through the transmission line, as shown in figure 3. Although we have different configurations of shunt passive filter (SHPF), the simplicity of single and double-tuned passive filters fosters its consideration in this work. The basic principle of the shunt passive filter principle is to:

- Trap harmonic load currents in LC circuits,
- Tune up the harmonic filtering frequency, and
- Eliminate it from the power system

In a single-tuned passive filter, the reactance of the inductor is equal to that of the capacitor at a resonant frequency. In the proposed hybrid active power filter, single-tuned passive filters are tuned to absorb 5th, the double-tuned passive filter is tuned to absorb 7th and 11th harmonic currents, and the other higher order harmonics are suppressed by SHAPF.

The resonance frequencies of the 5th, 7th, and 11th harmonic order are 250Hz, 350Hz, and 550Hz, respectively. Figure 4 shows a model of a tuned passive filter based on the design.

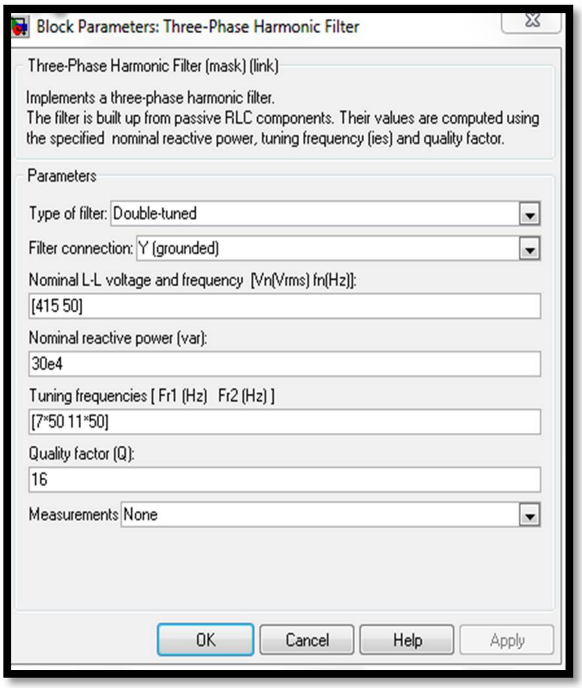

Figure 4: Simulink Dialogue Box of Tuned Passive Filter

7.4. Modeling of Three-Phase Shunt Active Power Filter (SHAPF)

The shunt active power filter takes input (load voltage and current generated by non-linear load) from the distribution line and generates compensation current equal to harmonics load current that is in opposite phase to it and injects it into the point of common coupling (PCC) through an interfacing inductor. The source current(s) is desired sinusoidal and in phase with the source voltage (Vs) to give the maximum power factor. The shunt active power filter is divided into the following sections:

- Voltage source converter, and
- Control section (Clarke transformation, sub-control system, outer dc-link voltage control, and hysteresis current control with proportional integral and compensating current block)

The SHAPF uses a Voltage Source Converter (VSC) and capacitor connected on the dc side to act as a storage element, as shown in figure 4**.** The basic SHAPF is a three-phase ac/dc boost converter. The main energy storage element is provided by the capacitor, and the inductors are used to control the filter currents by means of the converter voltages. Conversely, the main function of the voltage source converter is to generate equal but opposite higher order harmonics and reactive components of current into a line that has to be compensated. However, the shape of the wave is also important.

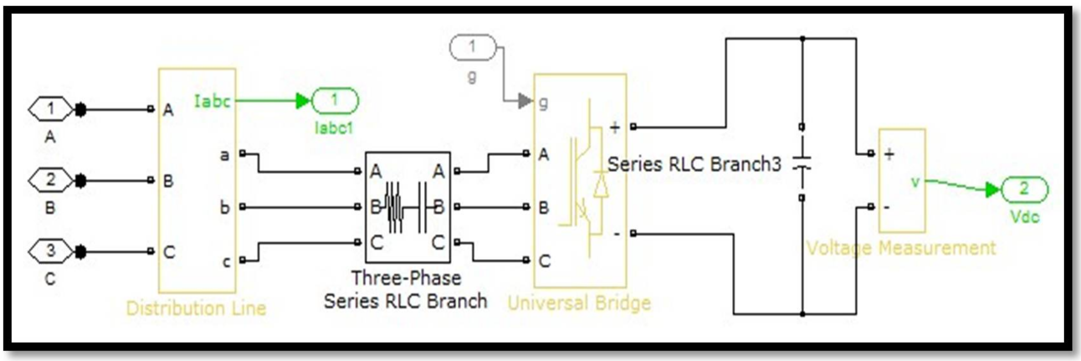

Figure 5: Simulink Model of VSC Block Set

8. Results Discussion

The modeling carried out using Matlab/Simulink 4 was simulated for a period of 0.1 seconds. The distortion produced by a non-linear load in figure 3 and the rectification done by the hybrid active filter is shown as a waveform. The maximum frequency of oscillation has been fixed to 1000Hz. The results show peak-to-peak magnitude against time in seconds.

8.1. Case I: Load Voltage before Hybrid Active Filter Was Connected

The figure above shows distortions in voltage waveform produced by the non-linear load on the distribution network in figure 3. The total distortions in the waveform indicate the presence of harmonics produced by the non-linear load connected to the network. This was obtained before the proposed hybrid active filter in figures 4, and 5 was connected to the distribution network. The phase magnitude of the waveform was reduced due to the harmonics.

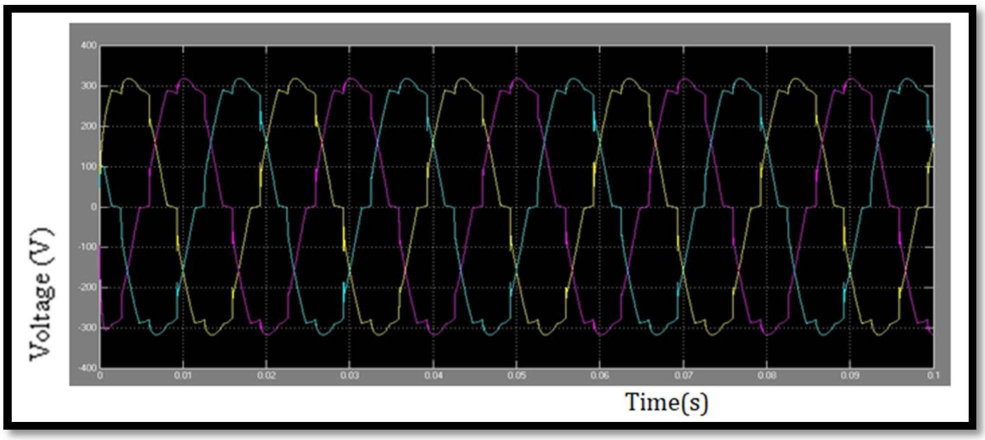

Figure 6: Load Voltage before Hybrid Active Filter Was Connected

8.2. Case II: Source Voltage after Hybrid Active Filter Was Connected

Figure 7 shows a perfect sinusoidal waveform in the voltage signal obtained from the distribution network after the proposed hybrid active filter, as shown in figure 4 and figure 5, has been connected. The waveform in this figure indicates the absence of harmonics in the network due to the filter that was connected. The waveform indicates a high level of reduction in the harmonics present in the voltage waveform as the waveform first follows the ideal sine waveform, and the magnitude is restored to the magnitude of the supply voltage.

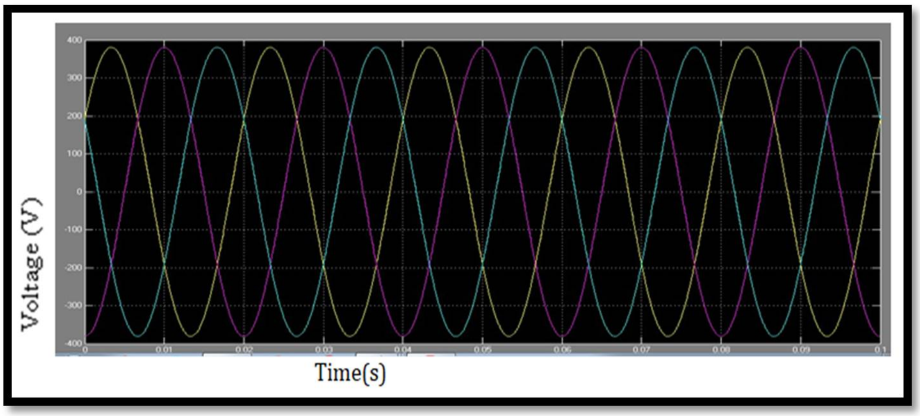

Figure 7: Source Voltage after Hybrid Active Filter Was Connected

8.3. Percentage THD of Load Voltage before Hybrid Active Filter Was Connected

In figure 7, the use of Fast Fourier Transform shows a total percentage of 9.18 harmonics present in the load voltage signal in the frequency domain on the network due to the impact of non-linear loads in the distribution network before the proposed HAPF was connected. The non-linear load contributes a very large percentage of total harmonics in current to the distribution network. The non-linear loads generate an excessive current which disrupts the wave shape of the supply.

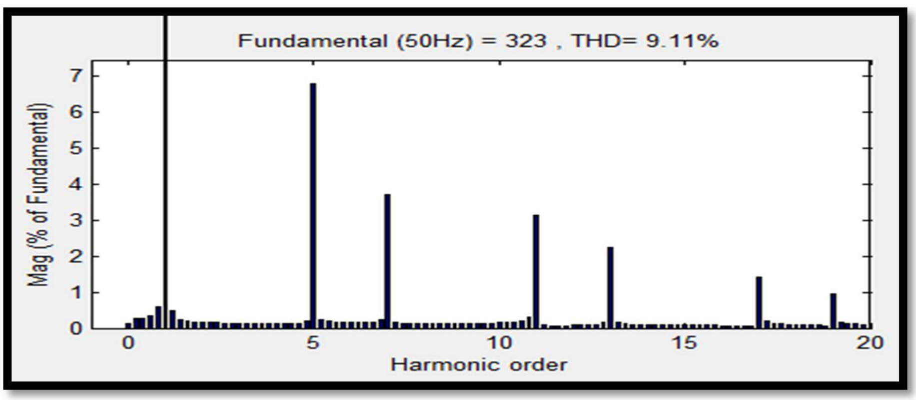

Figure 8: Percentage THD of Load Voltage before Hybrid Active Filter Was Connected

8.4. Percentage THD of Source Voltage after Hybrid Active Filter Was Connected

The harmonics is voltages in 5th, 7th and 11th order are significantly high in magnitude. 5th order gives the high magnitude of 4% of harmonics content. From figure 7, the use of Fast Fourier Transform (FFT) shows a reduced total percentage of 0.27 of harmonics voltage signal in the frequency domain present in the network due to the impact of non-linear loads in the distribution network after the proposed hybrid active filter is connected.

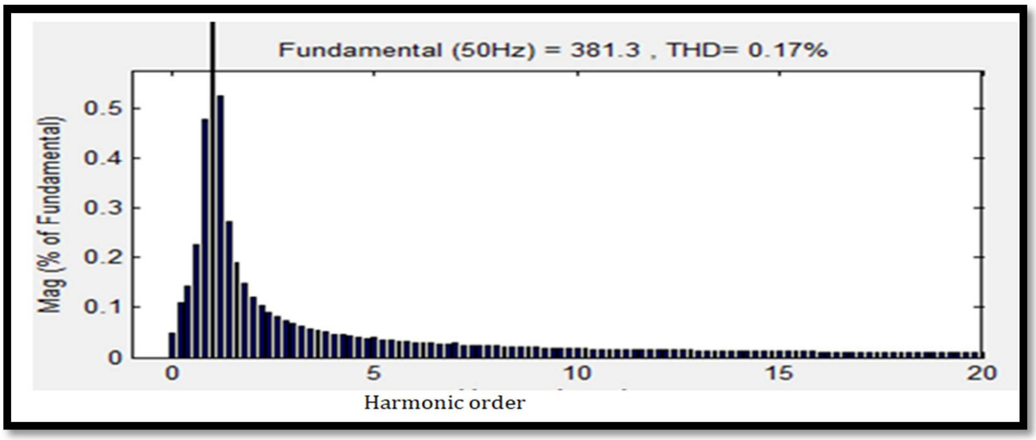

Figure 9: Percentage THD of Source Voltage after Hybrid Active Filter Was Connected

9. Conclusion

Fast Fourier transform analysis was introduced to show the percentage of harmonics present in the distribution s ystem when a non-linear load was connected, and the percentage of the harmonics remaining in the distribution system af ter a hybrid active filter was connected to the system showed that Harmonics was reduced on current waveform from 23.4 0 % to 1.56 % and likewise on voltage waveform from 9.11 % to 0.17 %. Also, fast Fourier transform analysis showed the c urrent harmonics in 5th and 7th order were reduced from 20.80% and 8.94% to 0.01% and 0.01%. Likewise, voltage harm onics in 5th and 7th order was reduced from 6.68% and 3.69% to 0.24% and 0.01%, respectively. Hence, hybrid active filte r introduction will be of high impact value to mitigate losses on distribution networks.

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