HARMONIC REDUCTION IN POWER SYSTEM

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HARMONIC REDUCTION IN POWER SYSTEM

A Project

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Abstract

of

HARMONIC REDUCTION IN POWER SYSTEM

by

Ankit Vashi

The main aim of this project is to explain the effects of Harmonics in the Power System and steps to reduce the effects of Harmonics. This project will also explain how Harmonic distortion is one of the most important problems associated with power quality and creates several disturbances to the Power System. It includes the Harmonic reduction techniques to improve the power quality and it also includes the simulation for the same.

In an inverter DC voltage is converted into an AC output. During this transformation from DC to AC, harmonics affect the the power quality a lot. How harmonic reduction will improve the power quality is explained in detail.

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Chapter 1
INTRODUCTION

The term harmonics referred to Power quality in ideal world would mean how pure the voltage is, how pure the current waveform is in its sinusoidal form. Power quality is very important to commercial and industrial power system designs. Ideally, the electrical supply should be a perfect sinusoidal waveform without any kind of distortion. If the current or voltage waveforms are distorted from its ideal form it will be termed as harmonic distortion. This harmonic distortion could result because of many reasons. In today’s world, prime importance is given by the engineers to derive a method to reduce the harmonic distortion. Harmonic distortion was very less in the past when the designs of power systems were very simple and conservative. But, nowadays with the use of complex designs in the industry harmonic distortion has increased as well.

This project explains the effects of Harmonics in the Power System and steps to reduce the effects of Harmonics. This project will also explain how Harmonic distortion is one of the most important problems associated with power quality and creates several disturbances to the Power System. It includes the Harmonic reduction techniques to improve the power quality and it will also include the simulation for the same.

This project also explains different types of inverters that are used in the Power System. During the transformation from DC to AC, harmonics affect the the power quality a lot. How harmonic reduction will improve the power quality will be explained in detail.
Chapter 2

CAUSE OF POWER QUALITY DETERIORATION

2.1 Introduction

As always, the main objective of the power system would be generation of electrical energy to the end user. Also, associated with power system generation is the term power quality. So much emphasis has been given to power quality that it is considered as a separate area of power engineering. There are many reasons for the importance given to the power quality. One of the main reason is, the consumers are well informed about the power quality issues like interruptions, sagging and switching transients. Also, many power systems are internally connected into a network. Due to this integration if a failure exists in any one of the internal network it would result into unfavourable consequences to the whole power system. In addition to all this, with the microprocessor based controls, protective devices become more sensitive towards power quality variation than were the past generation protective devices.

Following are some of the disturbances which are common in affecting the power system.

1.) Transients

2.) Sagging

3.) Variations in voltage

4.) Harmonics
2.2 Transients:

In terms of power system, the transients can be defined as an action or a situation in power system with variations in power system and which is not desirable in nature. A general understanding of transient is considered to be an oscillatory transient which is damped due to the RLC network. A person who is new to the power system also uses the term “surge” to define transient. A surge may be analyzed as a transient which is resulting from the stroke of lightening where protection is done by using a surge arrester. A person who is more groomed in the field of power engineering would avoid to use the term “surge” unless it is specified as to what exactly the term “surge” refers to. Transient can be divided into two categories i.e. the oscillatory transient and the impulsive transient. [1][3]

2.2.1 Oscillatory Transient:

A voltage or a current whose values change polarity rapidly are part of oscillatory transient. In case of a steady state of voltage and current when there is a sudden non-power frequency change or when there is a non-power frequency change in positive and negative polarity values, such a change is termed as an oscillatory transient. [2][3]

2.2.2 Impulsive Transient:

Impulsive transients are mostly caused due to lightning. Unlike the oscillatory transient, the impulsive transient is such a condition when there is sudden change of non-power frequency in a steady state condition of voltages and currents that is unidirectional in polarity. Impulsive transients also have the ability to produce oscillatory transients by exciting the natural frequency of a power system. [2][3]
2.3 Variations in Voltage:

There are two types of variations in the voltages.

- Short duration voltage variations

- Long duration voltage variations.

2.3.1 Short Duration Voltage Variations:

Short duration voltage variations are usually caused by faults in the power system. Short duration voltage variations consist of sags which are caused depending on the system conditions and faults that are caused in the power system. It really depends on what kind of fault is caused in the power system under what condition which may lead to voltage drops, voltage rise and even interruptions in certain conditions. When such faults takes place, protective devices are used in order to clear the fault. But, the impact of voltage during such faulty conditions is of short-duration variation. [3]

Interruptions:

When there are reductions in the voltage or current supply interruptions take place. Interruptions may occur due to various reasons, some of them being faults in the power system, failures in the equipment, etc. [3]

Sagging:

A short duration voltage variation is often referred to as sagging. When there is a decrease between 0.1 to 0.9pu in rms voltage sagging takes place. There are many ways to obtain the magnitude of sagging from the rms voltages. Most of the times lowest value
obtained during the event is considered. Sagging normally has constant rms value during the deep part of the sag. Thus, lowest value is an acceptable approximate value. [1][3]

2.3.2 Long Duration Voltage Variations:

Long duration voltage variations are comprised of over voltages as well as under voltages conditions. These under voltage and over voltage conditions are caused by variations in the power system and not necessarily due to the faults in the system. The long duration voltage variations refers to the steady state condition of the rms voltage of the power system. The long duration voltage variations are further divided into three different categories i.e. interruptions, over voltage and under voltage. [1][3]

Under Voltage:

There are many reasons for the under voltage conditions in the power system. When there is a decrease in the rms ac voltage to less than 90% of a power system for some amount of time then under voltage condition exists. Load switching on or switching off of a capacitor bank can also cause under voltage condition. Also, when a power system is overloaded it may result into under voltage condition. [1][3]

Over Voltage:

Compared to the under voltage condition, over voltage is an increase in the rms ac voltage to greater than 110% of the power system for some amount of time. Unlike under voltage condition, load switching off or capacitor bank getting energized are main reasons for the over voltage conditions. [1][3]
2.4 Harmonics:

Harmonics are one of the major concerns in a power system. Harmonics cause distortion in current and voltage waveforms resulting into deterioration of the power system. The first step for harmonic analysis is the harmonics from non-linear loads. The results of such analysis are complex. Over many years, much importance is given to the methods of analysis and control of harmonics. Harmonics present in power system also has non-integer multiples of the fundamental frequency and have aperiodic waveform. The harmonics are generated in a power system from two distinct types of loads.

First category of loads are described as linear loads. The linear time-invariant loads are characterized such that application of sinusoidal voltage results in sinusoidal flow of current. A constant steady-impedance is displayed from these loads during the applied sinusoidal voltage. As the voltage and current are directly proportional to each other, if voltage is increased it will also result into increase in the current. An example of such a load is incandescent lighting. Even if the flux wave in air gap of rotating machine is not sinusoidal, under normal loading conditions transformers and rotation machines pretty much meet this definition. Also, in a transformer the current contains odd and even harmonics including a dc component. More and more use of magnetic circuits over a period of time may get saturated and result into generation of harmonics. In power systems, synchronous generators produce sinusoidal voltages and the loads draw sinusoidal currents. In this case, the harmonic distortion is produced because of the linear load types for sinusoidal voltage is small.
Non-linear loads are considered as the second category of loads. The application of sinusoidal voltage does not result in a sinusoidal flow applied sinusoidal voltage for a non-linear devices. The non-linear loads draw a current that may be discontinuous. Harmonic current is isolated by using harmonic filters in order to protect the electrical equipment from getting damaged due to harmonic voltage distortion. They can also be used to improve the power factor. The harmful and damaging effects of harmonic distortion can be evident in many different ways such as electronics mis-timings, increased heating effect in electrical equipments, capacitor overloads, etc. There can be two types of filters that are used in order to reduce the harmonic distortion i.e. the active filters and the passive filters. Active harmonic filters are electronic devices that eliminate the undesirable harmonics on the network by inserting negative harmonics into the network. The active filters are normally available for low voltage networks. The active filters consist of active components such as IGBT-transistors and eliminate many different harmonic frequencies. The signal types can be single phase AC, three phase AC. On the other hand, passive harmonic filters consist of passive components such as resistors, inductors and capacitors. Unlike the active filters which are used only for low voltages, the passive filters are commonly used and are available for different voltage levels.[4][3]
2.4.1 Active Harmonic Filter:

As explained earlier, the active harmonic filters are used for low voltages where reactive power requirement is low. The way this filter works is, the output load with the voltage waveform is obtained by boosting the voltage throughout each half cycle by the filter. The voltage which is thus produced tends to rectifiers in the power supply to gain current. The duty cycle and power factor are thus improved. Depending on the active harmonic filter used, the output distortion is reduced. Also, current that is produced due to load is monitored by the harmonic filter and generates a waveform which coincides with the exact shape of the nonlinear portion of the load current. [3][5]

2.4.2 Passive Harmonic Filter:

As shown before, the passive harmonic filters are such that they are used for different voltage levels. In case of passive harmonic filters, the harmonics are reduced by using series or parallel resonant filters. The way these passive harmonic filters works is, a filter connected in parallel with the load and in series with inductance and capacitance is a current acceptor. A current acceptor is a parallel filter which is in parallel with the load and is in series with the inductance and capacitance. The filter which is near the resonant frequency of the parallel array provides maximum attenuation. The filter passes as much current as the harmonic voltage nears the filter resonant point. The passive filters thus eliminate the harmonics. If the individual load requirement is more than that of the input load, the harmonic current should be eliminated. A capacitor in series with
an inductance is a passive filter. The reduced harmonic frequency must be equal to the resonant frequency of the circuit. The impedance of the network and the low impedance of the filter thus eliminate the harmonic current. [3][5]

More detailed explanation of Active and Passive Harmonic filters used in Power System will be explained in detail in next chapter.
Chapter 3
FILTERS USED IN POWER SYSTEM

3.1 Introduction:

Presence of harmonics has been a lot since the 1990’s and has led to deterioration in the quality of power. Moreover, there has also been an increase in use of devices and equipments in power system also including the nonlinear loads and electronic loads used in residential areas there by loading the transmission and the distribution systems. This is because they operate at very low power factors which increases the losses in line and also causes poor regulation in voltage further leading the power plants to supply more power. Also, some nonlinear loads and electronics equipments are such that instead of drawing current sinusoidally they tend to draw current in short pulses thus creating harmonics. Some of the examples of nonlinear loads would be rectifiers, inverters, etc. Some of the examples of electronics equipments would be computers, scanners, printers, etc.

Some of the major issues concerned with harmonics in nonlinear loads are overheating, temperature increase in generators, etc. These effects may result into permanent damage of the devices. [3]

One of the way out to resolve the issue of harmonics would be using filters in the power system. Installing a filter for nonlinear loads connected in power system would help in reducing the harmonic effect. The filters are widely used for reduction of harmonics. With the increase of nonlinear loads in the power system, more and more filters are required.
3.2 Roles of Filters in Power System:

There are two types of filters

- The Passive Filters
- The Active Filters

Capacitors are frequently used in the Active and Passive filters for harmonics reduction.

The Passive filters are used in order to protect the power system by restricting the harmonic current to enter the power system by providing a low impedance path. Passive filters consist of resistors, inductors and capacitors.

The Active filters are mostly used in distribution networks for sagging in voltage, flickering, where there are harmonics in current and voltages, etc. Using the filter would result into a better quality of power.

There is also a third type of filter which is used i.e. The Hybrid Filter. Hybrid filters are composed of the passive and active filters both. [3]

3.3 Passive Filters:

As explained earlier, passive filters consists of resistors, inductors and capacitors. They are not expensive and are often used to restrict the harmonic currents from entering the power system there by minimizing the effect of harmonics due to nonlinear loads. Also, the passive filters are kept close to the source of harmonic generation i.e. the nonlinear loads. Doing so, the passive filters produce better results in reducing the
harmonic effect. Figure 1 shows a single phase representation of distribution system with the nonlinear load and passive shunt filter.

Figure 1 : Single Phase Representation of Non Linear load and Passive Shunt filter [3]

One of the most important aspect in installing the passive filters in the power system is that they should be installed based on the order of the harmonics that are supposed to be filtered. For example, in order to install a filter for the 3rd order of harmonics, it is required that the filter of 1st order of harmonics is already installed.

In order to reduce the harmonic effect, the passive filters create a resonance frequency. This resonance frequency is kept away from the nonlinear load’s harmonic distortion. Also, the passive filters are calibrated at a point which is a bit lower than the point at which the harmonics is supposed to be reduced so that, if there is any change in the parameters there is still margin for improvement. If this is not done, then there might be a condition in power system due to capacitance and inductance of filter that the resonance is shifted causing unfavourable conditions in the power system. [3]
3.3.1 Types of Passive Filters:

There are two types of passive filters:

- Shunt Passive Filters and
- Series Passive Filters

These filters are used for single phase and three phase power system. One important thing to note is that, more than one shunt and series passive filters can be used with and without each other in a system.

Some of the basic differences between the shunt passive and series passive filters are as follows.

- The shunt passive filters carry only part of the total load current while the series passive filter carries full load current.
- The shunt passive filters are cheaper compared to the series passive filters so they are used more often than the series passive filters.

Figure 2 and 3 shows the single phase passive filter with shunt and series configuration respectively.
Figure 2: Single Phase Passive filter with Shunt Configuration [3]

Figure 3: Single Phase Passive Filter with Series Configuration [3]

Figure 4 and Figure 5 shows three phase three wire passive filter for shunt and series configuration respectively.
Figure 4: Three Phase, Three Wire Passive Filter for Shunt Configuration. [3]

Figure 5: Three Phase, Three Wire Passive Filter for Series configuration. [3]
Normally more than 3 filters are connected in a system to reduce the harmonics.
The first two filters are connected in order to reduce the effect of harmonics which are less effective and then a high pass filter is used.

Figure 6 and 7 shows shunt and series connected passive filters respectively.

Figure 6: Shunt Passive Filter Block. [3]

Figure 7: Series Passive Filter Block. [3]
3.4 Active Filters :

Active filters are a perfect alternative to the passive filters. The active filters are used in a condition where the harmonic orders change in terms of magnitudes and the phase angles. In such conditions it is feasible to use the active elements instead of passive ones in order to provide dynamic compensation.

The active filters are used in nonlinear load conditions where the harmonics are dependent on the time. Just like the passive filters, active filters can be connected in either series or parallel depending on the type of sources which create harmonics in the power system. The active filters minimize the effect of harmonic current by using the active power conditions to produce equal amplitudes of opposite phase there by cancelling the harmonics that are caused in the nonlinear components and replace the current wave from the nonlinear load.

Advantages of Active Filter over Passive Filter:

- One of the main advantage of using an active filter over the passive filter is that it can be used to reduce the effects of harmonics of more than one order.
- Active filters are also useful in flickering problems that are caused in the power system.

One disadvantage of an active filter over a passive filter is that

Disadvantages of Active Filter over Passive Filter:

- Active filters cost more than the passive filters
- Active filters cannot be used for small loads in a power system
• Due to the presence of harmonics in both current and voltage, active filter may not be able to resolve the issue in certain typical applications.

For the conditions where both voltage and current are leading to a deterioration in power system, more complex filters are used which are made up of combination of active and passive filters. Such filters are called as Hybrid Filters. [3]

Figure 8 and 9 shows single phase active filters in shunt and series configuration respectively.

Figure 8 : Single Phase Active Filter, Shunt Configuration. [3]
Figure 9: Single Phase Active Filter, Series Configuration. [3]
Chapter 4

HARMONIC REDUCTION IN INVERTERS

4.1 DC-AC Inverter:

DC to AC inverters are those devices which are used to produce inversion by converting a direct current into an alternating current. If the output of a circuit is AC then depending on the input i.e. either AC or DC, the devices are called as AC-AC cycloconverters or DC-AC inverters. DC to AC inverters are such devices whose AC output has magnitude and frequency which is either fixed or variable. In case of DC to AC inverters the output AC voltage can be either single phase or three phase. Also, the magnitude of the AC voltage is from the range of 110-380 VAC while the frequencies are either 50Hz, 60Hz or 400Hz.

Some of the basic applications of inverters would be an UPS (uninterruptible power supply). When the main power is not available UPS uses batteries and inverter to supply AC power. A rectifier is used to recharge the batteries used when the main power is back. Other applications of an inverter included Variable frequency drives. The variable frequency drives controls the frequency and voltage of power supplied to the motor, thus controlling the speed of AC motor. An inverter is used in the variable frequency drives to provide controller power. An inverter is also used in an induction motor to regulate the speed by changing the frequency of AC output. [6][7]

4.1.1 Block Diagram of DC-AC Inverter:

As explained in earlier chapters, the harmonics can be present in any system. Similarly, the harmonics are present in a system where inverters are used as well. Ideally, the main aim of using an inverter is to produce an ac output from the dc source.
Theoretically the output voltage waveform is expected to be sinusoidal, but in practical terms there is definitely going to be distortions due to harmonics present in the system which results into distorted output waveforms. As a result of this, inverters are used in a system in order to produce output waveforms which are purely sinusoidal and distortion free.

Figure 10 shows a circuit showing DC-AC inverter along with filters which are used to reduce the effect of harmonics to provide distortion free output ac signal. The front part of the circuit consists of AC to DC converters. These AC to DC converters has one ac frequency i.e. the line frequency and it relies on line communication for switching. The system also consists of DC to AC inverters which are used to turn on or off the power switches. Unlike AC to DC converters in DC to AC inverters, the ac frequency is not the line frequency. The figure also shows a voltage control where variable frequency drives are used to control the speed of motors and provide variable output voltage. Due to this complex structure, the inverter circuits require proper control signals to produce the expected ac output voltage. The figure also shows a filter circuit which is used to reduce the harmonics in the system to produce clean sinusoidal output ac voltage. A comparator circuit is also employed which compares the output ac voltage with the reference ac voltage. If he output ac voltage is more distorted as compared to the reference ac voltage then filter circuits are used again to produce the desired clean sinusoidal AC voltage.[6][7]
4.2 Types of Inverters:

There are three types of inverters

- Single Phase Inverters
- Three Phase Inverters
- Multilevel Inverters

4.2.1 Single Phase Inverters:

There can be many different topologies that can be used for inverter circuits. Inverter circuits are designed differently depending on the way the inverter is intended to be. The figure 11 shows a single phase inverter. The way the switches and the load are connected, it is also called a H bridge inverter. H bridge can be called a circuit which is used to apply voltage to the load in both the directions. This single phase inverter
consists of four IGBT devices (also called power control devices) where two each IGBTs are connected in series with each other. Each power control devices have diodes connected in parallel with each other but in opposite direction. There are also loads connected between the two IGBT devices and the diodes. The way these diodes are connected is, if the two IGBT devices are turned off, then the diodes provide a path for the current of load to flow. For eg. If the IGBT2 is turned on, it will carry current towards the negative bus and through the diode which is connected in parallel. Now when this IGBT2 is turned off, the current will travel through the diode which is connected in parallel in opposite direction and reach to the IGBT1. Also, controllers can be used in order to control the turning on and off of the IGBT circuits. The controllers will command the switches such that when IGBT1 is on, IGBT2 will be off and when the IGBT2 is on, IGBT1 will be off. [7]

For the single phase inverters, the modulation of the left IGBT circuits will be inverse of the right IGBT circuits and right IGBT circuits will have large duty cycle for the lower IGBT while left IGBT circuits will have it for upper IGBT. The output of an inverter with a sinusoidal frequency is given by the following formula: [7]

\[ V_{ac1} (t) = m_a \cdot V_{dc} \cdot \sin(\omega_t t) \]

\( m_a \) = modulation factor, where \( 0 \leq m_a \leq 1 \)

\( V_{dc} \) = input voltage

\( V_{ac1} \) = output voltage
4.2.2 Three Phase Inverters:

Similar to the Single Phase Inverters, the Three Phase Inverters also have different topologies which can be used. Figure 12 shows a three phase inverter circuit. It is an extension of H bridge circuit as it consists of three single phase inverters each connected to one of the three load terminals. In case of single phase inverter, there is a phase shift of 180 degrees between different legs, while in case of three phase inverter there is a phase shift of 120 degrees. This phase shift of 120 degrees in three phase inverter helps in eliminating the odd harmonics from the three legs of the inverter. Also, if the output is pure AC waveform then the even harmonics can be eliminated as well. In order to modulate the output of a three phase inverter, the amplitude of output voltage is reduced by a factor with respect to the input voltage. This factor is given by the following equation: [7]

$$\frac{3}{2PE} \cdot \sqrt{3} = 82.7\%$$
4.2.3 Multi Level Inverters:

Multi level Inverters are a type of inverters whose construction is similar to the single and three phase inverters as explained earlier. The figure 13 shows a multi level inverter which is an extension of single and three phase inverters. Here, four IGBT circuits are connected in three different legs and the diodes are connected in parallel to each legs in opposite direction. Also, the loads are connected between two IGBT circuits for each leg as shown in figure.

Advantages of using multi level inverters instead of single and three phase inverters are as follows: [7]

- Multi level inverters can be used for higher voltage levels
- Also, multi level inverters have higher capability of reducing the harmonics because of multiple dc levels.
4.3 Methods for Harmonic Reduction in Inverters:

As explained earlier, one of the most important aspect of a system is the reduction of harmonics that are present in the system. In case of an inverter, it is very important to remove the harmonics from the ac output.

The harmonics present in a dc to ac inverter are very much obvious compared to the harmonics that can be present in an ac to dc converter. This is because of the output of dc to ac inverter being ac. Thus, the filters that are used in dc to ac inverter have different designs compared to the filters used in ac to dc converters. In case of ac to dc
converters, the main objective is to improve the output voltage ripple. Thus, passive filters can be easily used in order to improve the output of an ac to dc converter. While, in case of dc to ac inverter, the harmonic reduction is harder and it also includes the use of active filters.

As the output of dc to ac inverters is alternating, it is very important to produce sinusoidal output waveforms. In order to produce such sinusoidal waveforms, filters are implemented which reduce the harmonic effect by removing the third and higher harmonics from the system. The filters used to remove the harmonics from the inverters are more complex and consists of large number of inductors and capacitors to remove the harmonics of higher order. This also results into more costly filters to remove harmonics from the inverter.

Thus, in order to avoid the cost of such expensive and complex filters controlling the width or reducing the number of pulses may result into reduction of harmonics. One such technique is explained below.[6][7]

4.3.1 Pulse Width Modulation Technique:  

Figure 14 shows a single phase inverter block diagram with a high frequency filter that is used in order to remove the harmonics from the output waveform. Here, vo is the ac output while vin is the input dc voltage.
Figure 14: Single Phase Inverter with Filter [6]

Figure 15 shows output waveforms that get produced based on the Pulse width modulation technique when it is employed.

Figure 15: Output waveforms Produced Based on PWM Technique [6]

In a single phase inverter, the varying width of the output pulse is used to control the output voltage. Thus, this process of controlling the output voltage of inverter in
order to reduce the harmonics is known as Pulse Width Modulation. The Pulse Width Modulation is classified into two techniques. [6]

- Non sinusoidal Pulse Width Modulation
- Sinusoidal Pulse Width Modulation

4.3.2 Non Sinusoidal Pulse Width Modulation:

In case of Non sinusoidal pulse width modulation, all the pulses that have same pulse width are modulated together. The pulse widths of pulses are adjusted together in same proportion on order to remove the harmonics from the system. A typical representation of Non sinusoidal pulse width modulation is shown in figure 16 shown below.[6]

![Figure 16](image)

Figure 16 : Representation of Non Sinusoidal Pulse Width Modulation [6]
4.3.3 Sinusoidal Pulse Width Modulation

Sinusoidal Pulse Width Modulation is a bit different compared to the Sinusoidal Pulse Width Modulation. In case of sinusoidal pulse width modulation, all the pulses are modulated individually. Each and every pulse is compared to a reference sinusoidal pulse and then they are modulated accordingly to produce a waveform which is equal to the reference sinusoidal waveform. Thus, sinusoidal pulse width modulation modulates the pulse width sinusoidally.[6]

Figure 17 shows a representation of Sinusoidal Pulse Width Modulation.

Figure 17 : Representation of Sinusoidal Pulse Width Modulation [6]
Note:

For figures 16 and 17,

- $t_s = \text{Time of the triangular waveform}$
- $f_s = \text{frequency of the triangular waveform}$
- $V_{\text{ref}} = \text{Reference voltage of the square or sinusoidal waveform}$
- $V_{p,\text{ref}} = \text{Peak value of the reference voltage}$
- $t_o = \text{Time of the output waveform of the Inverter which is desired}$
- $f_o = \text{Frequency of the output waveform of the Inverter which is desired}$
- $m_a = \text{Amplitude modulation index of Inverter}$
- $m_f = \text{Frequency modulation index of Inverter}$
- $k = \text{Number of pulses per half cycle}$
Chapter 5

SIMULATION AND CALCULATIONS

5.1 Introduction

This chapter shows how harmonic elimination is done in Inverter by Pulse Width Modulation technique by solving the non linear equations. Equations are used to determine switching angles of an Inverter. Switching angles play an important role to produce the desired output by eliminating selected harmonics.

In order to form the equation set, fundamental component is given desired output value and all other harmonics are equated to zero. In my simulation I find the switching angles for the 5$^{th}$, 7$^{th}$ and 11$^{th}$ harmonics. [9]

The equation which is derived for Total Harmonic Distortion of the output voltage of an inverter is used in order to reduce the harmonics that are produced in the inverter. The percentage of the Total Harmonic Distortion is given by the following formula.[9]

\[
\text{%THD} = \left[ \frac{1}{a_1^2} \sum_{n=5}^{\infty} (a_n^2) \right]^{\frac{1}{2}} \times 100
\]

where \(n = 6i \pm 1(i = 1, 2, 3, \ldots)\)

The switching angles which are required for the THD are calculated as shown in the figures and the simulation codes. The codes for THD is also shown in detail.

Simulation Results:
Figure 18: Plot of Switching angle (\(\Theta_1\)) Vs Modulation index
Figure 19: Plot of Switching angle ($\Theta_2$) Vs Modulation index
Figure 20: Plot of Switching angle (Θ3) Vs Modulation index
Figure 21: Plot of Switching angle (Θ4) Vs Modulation index
Figure 22: Plot of Switching angle ($\Theta_1, \Theta_2, \Theta_3, \Theta_4$) Vs Modulation Index
5.2 Matlab Code for Switching angle calculation and Harmonic reduction

clc

V=5; % dc sources

dMI=0.5; % Step size of modulation index

MIstart=1.2; % The initial modulation index

MI=MIstart*V;

MIrange=10; % Calculations range

s1=40*pi/180; s2=49*pi/180; s3=68*pi/180; s4=79*pi/180; % Assume values of switching angles

s=[s1 s2 s3 s4]'; % The angle matrix

for j=1:MIrange

t=[MI*pi/4 0 0 0]'; % harmonic matrix

    dA=1;

    for i=1:70
    s1=s(1,:); s2=s(2,:); s3=s(3,:); s4=s(4,:);

    deltaA=[-sin(s1) +sin(s2) -sin(s3) +sin(s4) ;
    -5*sin(5*s1) +5*sin(5*s2) -5*sin(5*s3) +5*sin(5*s4) ;
    -7*sin(7*s1) +7*sin(7*s2) -7*sin(7*s3) +7*sin(7*s4) ;
    -11*sin(11*s1) +11*sin(11*s2) -11*sin(11*s3) +11*sin(11*s4) ] % matrix

    A=[cos(s1) -cos(s2) +cos(s3) -cos(s4) ;
    cos(5*s1) -cos(5*s2) +cos(5*s3) -cos(5*s4) ;
    cos(7*s1) -cos(7*s2) +cos(7*s3) -cos(7*s4) ;
    cos(11*s1) -cos(11*s2) +cos(11*s3) -cos(11*s4) ] % matrix

    Anew=[cos(s1)-cos(s2)+cos(s3)-cos(s4);
    cos(5*s1)-cos(5*s2)+cos(5*s3)-cos(5*s4);
\[
\begin{bmatrix}
\cos(7s_1) - \cos(7s_2) + \cos(7s_3) - \cos(7s_4) \\
\cos(11s_1) - \cos(11s_2) + \cos(11s_3) - \cos(11s_4)
\end{bmatrix} \quad \text{matrix}
\]

dA = \text{inv(deltaA)} * (t - A\text{new}); \quad \% \text{error in calculation}

s = s + dA; \quad \% \text{calculate new value}

\textit{end}

MI = MI - dMI;

mm(j) = MI / V; \quad \% \text{modulation index}

x1(j) = \text{abs(cos(s1))};
x2(j) = \text{abs(cos(s2))};
x3(j) = \text{abs(cos(s3))};
x4(j) = \text{abs(cos(s4))};

\textit{end}

\% \text{plotting}
p1 = \text{abs(cos(x1))}
p2 = \text{abs(cos(x2))}
p3 = \text{abs(cos(x3))}
p4 = \text{abs(cos(x4))} \quad \% \text{positive angles}

\text{plot(mm,p1*180/pi)}
\text{plot(mm,p2*180/pi)}
\text{plot(mm,p3*180/pi)}
\text{plot(mm,p4*180/pi)}

axis([mm(MI\text{range}) mm(1) 0 90]);
5.3 Matlab Code for Total Harmonic Distortion (THD) Calculation:

```matlab
% THD calculation
for j=1:length(p1)
    add=0;
    addl=0;
    for i=1:200
        c=2*i-1;
        amp(c)=(cos(c*p1)+cos(c*p2)+cos(c*p3)+cos(c*p4))/c;
        % Calculation of harmonic amplitude
        end
    for i=2:200
        add=amp(i)^2+add;
        end
    THD(j)=sqrt(add)/amp(1)*100; % THD Phase Voltage calculation
for i=2:100
    c=2*i-1;
    ck=round(sin(c*2*pi/3)); % Rounding
    if ck ~= 0
        addl=addl+amp(c)^2;
        end
    THD1(j)=sqrt(addl)/amp(1)*100; % Calculate line voltage THD
end
plot(MI,THD,'c:',MI,THD1,'r');
xlabel('Modulation Index');
ylabel('THD (%)');
```
REFERENCES


9.) An application of PSO technique for harmonic elimination in a PWM inverter from World Wide Web

http://www.sciencedirect.com/science?ob=ArticleURL&_udi=B6W86-4WGK6J4-4&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1114896328&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=d9e37378c6181659a1d2856fabb00184