Mitigation of Harmonics

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Abstract*— Power Quality issues are becoming a major concern of today's power system engineers. Harmonics play significant role in deteriorating power quality, called harmonic distortion. Harmonic distortion in electric distribution system is increasingly growing due to the widespread use of nonlinear loads. Large considerations of these loads have the potential to raise harmonic voltage and currents in an electrical distribution system to unacceptable high levels that can adversely affect the system. IEEE standards have defined limits for harmonic voltages and harmonic currents. Active power filters have been considered a potential candidate to bring these harmonic distortions within the IEEE limits A voltage source inverter with pulse width modulation (PWM) is employed to form the APF.* A diode rectifier feeding capacitive resister load is considered as nonlinear load on ac mains for the elimination of harmonics by the proposed APF.. MATLAB model of the scheme is simulated and obtained results are studied.

Keywords

Harmonics, Power quality, Active Shunt Filter.

Introduction

The quality of electrical power is one of the major growing concerns for utility as well as consumers. The increasing use of non linear and poor power factor loads such as Power electronic converters, Arc furnace, Adjustable speed, uninterruptable power supplies etc. are the responsible factor for the power quality issues. The most important factors of poor power quality are harmonics and high neutral current. Poor power quality factors such as switching phenomena results in oscillatory transients in the electrical supply. Over heating of system components, mechanical oscillations in generators and motors, capacitor and insulation failure due to harmonic resonance, unpredictable behavior of installed protection systems, over heating of transformers and telephone interference.

Various types of tuned passive filters are used to limit a particular order of harmonic. The application of passive tuned filters creates new system resonances, which are dependent on specific system conditions. In addition, passive filters often need to be overrated to account for possible harmonic absorption from the power system Hence increased severity of harmonic pollution problem attracted the attention of power electronics experts in last one decade and large number of publications have appeared on the development of an equipment named as Active Power Filter (APF) to provide a dynamic adjustable solution to eliminate harmonics in ac mains. Major attempts are made on 3-phase active filters considering the bulk power conversion. But there are large numbers of single phase loads in industrial and domestic sectors employing solid state control thus requiring the attention to the problem of harmonic pollution.

This paper is aimed to propose single phase active filter with simple control scheme to mitigate harmonics to a considerable limit.

I .POWER QUALITY AND HARMONICS

A. Power Quality

Can be defined as: "Any power problem manifested in voltage, current, or frequency deviations that result in failure or improper operation of customer equipment. The ideal power distribution system delivers, 100% continuous, real power at a Constant voltage described by the following equation:

P (t) =V(t)*I(t)

Where v (t) =V sin (w t) ; i(t) =I sin(wt)

In the real world this will never happen. Why? Factors which influence Power quality:

-Outages -
Voltage drop
-Power factor
-Transients (lightning and switching surges) -Non-
linear steady-state load conditions (harmonics).

Power system engineers have been dealing with outages, voltage drop, power factor, and Transient conditions since the invention of the first AC distribution system back in the early 1900's. Adverse power system harmonics caused by the installation of non-linear devices loads on the distribution system has become an increasing concern to utilities in the 197 0's and 1980's.

B.Problem identification

Power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment. Power quality problems are common in most of commercial, industrial and utility

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networks. Natural phenomena, such as lightning are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, for example when capacitors are switched, also contribute substantially to power quality disturbances. Also, the connection of high power non-linear loads contributes to the generation of current and voltage harmonic components. Between the different voltage disturbances that can be produced, the most significant and critical power quality problems are voltage sags due to the high economical losses that can be generated. Short-term voltage drops (sags) can trip electrical drives or more sensitive equipment, leading to costly interruptions of production.

For all these reasons, from the consumer point of view, power quality issues will become an increasingly important factor to consider in order satisfying good productivity. On the other hand, for the electrical supply industry, the quality of power delivered will be one of the distinguishing factors for ensuring customer loyalty in this very competitive and deregulated market. Harmonic content and high neutral current in power supply is one of the most important factor effecting power quality.

C. Harmonics

A harmonic is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency of 60 Hz. Harmonics are the multiple of the fundamental frequency, as shown in Figure 1. Total harmonic distortion is the contribution of all the harmonic frequency currents to the fundamental.

The characteristic harmonics are based on the

Number of rectifiers (pulse number) used in a circuit and can be determined by the following equation:

h = (n x p) _1

Where: n = an integer (1, 2, 3, 4, 5 …) p = number of pulses or rectifiers

Harmonics Sequence

Harmonic sequence is the phase rotation relationship with respect to the fundamental component.

Positive sequence harmonics (4th, 7th, 10th… (6n+1) th) have the same phase rotation as the fundamental component. These harmonics circulate between the phases.

Negative sequence harmonics (2nd, 5th, 8th ……… (6n-1) th) have the opposite phase rotation with respect to the fundamental component. These harmonics circulate between the phases.

Zero sequence harmonics (3rd, 6th, 9th… (6n-3) th) do not produce a rotating field. These harmonics circulate between the phase and neutral or ground.

This third order or zero sequence harmonics, unlike positive and negative sequence harmonic currents, do not cancel but add up arithmetically at the neutral bus.

D.Harmonic Waves

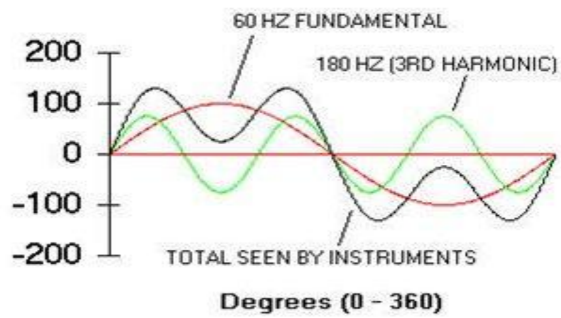

Fig.I.D.1

Each term in the series is referred to as a harmonic of the fundamental. The third harmonic would have a frequency of three times 60 Hz or 180 Hz. Symmetrical waves contain only odd harmonics and un-symmetrical waves contain even and odd harmonics.

A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An un-symmetrical wave contains a DC component (or offset) or the load is such that the positive portion of the wave is different than the negative portion. An example of un-symmetrical wave would be a half wave rectifier. Most power system elements are symmetrical. They produce only odd harmonics and have no DC offset. There are exceptions, of course, and normally-symmetrical devices may produce even harmonics due to component mismatches or failures. Arc furnaces are another common source of even harmonics but they are notorious for producing both even and odd harmonics at different stages of the process.

E. How harmonics are produced and sources of harmonics

Harmonics are the by-products of modern electronics. They occur frequently when there are large numbers of personal computers (single phase loads), uninterruptible power supplies (UPSs), variable frequency drives (AC and DC) or any electronic device using solid state power switching supplies to convert incoming AC to DC. Non-linear loads create harmonics by drawing current in abrupt short pulses, rather than in a smooth sinusoidal manner see figure.

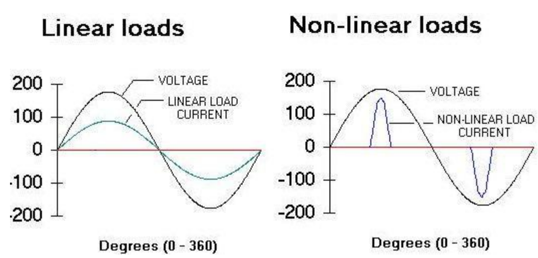

Fig.1.E.2

The terms "linear" and "non-linear" define the relationship of

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current to the voltage waveform. A linear relationship exists between the voltage and current, which is typical of an across-the-line load. A non-linear load has a discontinuous current relationship that does not correspond to the applied voltage waveform. For this reasons total harmonic reduction is required.

- Three phase full wave rectifier converter in 6 or 12 pulse modes
-Imperfect AC sources
-Variable frequency motor drives
(VFD) -Adjustable speed drive
-Arc furnace

F. Total Harmonic Distortion

Harmonics in the electric power system combine with the fundamental frequency to create distortion. The level of distortion is directly related to the frequencies and amplitudes of the harmonic current. The contribution of all harmonic frequency currents to the fundamental current is known as "Total Harmonic Distortion" or THD. This THD value is expressed as a percentage of the fundamental current. THD values of over 10% are reason for concern.

$$\% \quad THD(voltage) = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \cdots + V_n^2}{V_1^2}}$$

$$\%THD(current) = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \cdots + I_n^2}{I_1^2}} \times 100$$

III. Effect of harmonics

Effects can range from spurious operation of equipment to a shutdown of important plant equipment, such as machines or assembly lines Harmonics can lead to power system inefficiency. Some of the negative ways that harmonics may affect plant equipment are listed below:

Motor-

There is an increasing use of variable frequency drives (VFDs) that power electric motors. The voltages and currents emanating from a VFD that go to a motor are rich in harmonic frequency components. Voltage supplied to a motor sets up magnetic fields in the core, which create iron losses in the magnetic frame of the motor. Hysteresis and eddy current losses are part of iron losses that are produced in the core due to the alternating magnetic field. Hysteresis losses are proportional to frequency, and eddy current losses vary as the square of the frequency. Therefore, higher frequency voltage components produce additional losses in the core of AC motors, which in turn, increase the operating temperature of the core and the windings surrounding in the core. Application of non-sinusoidal voltages to motors results in harmonic current circulation in the windings of motors. Due to skin effect, actual losses would be slightly higher than calculated values. Stray motor losses, which include winding eddy current losses, high frequency rotor and stator surface losses, and tooth pulsation losses, also increase due to harmonic voltages and currents.

The phenomenon of torsional oscillation of the motor shaft due to harmonics is not clearly understood, and this condition is often disregarded by plant personnel. Torque in AC motors is produced by the interaction between the air gap magnetic field and the rotor-induced currents. When a motor is supplied non-sinusoidal voltages and currents, the air gap magnetic fields and the rotor currents contain harmonic frequency components.

The harmonics are grouped into positive (+), negative (-) and zero (0) sequence components. Positive sequence harmonics (harmonic numbers 1,4,7,10,13, etc.) produce magnetic fields and currents rotating in the same direction as the fundamental frequency harmonic. Negative sequence harmonics (harmonic numbers 2,5,8,11,14, etc.) develop magnetic fields and currents that rotate in a direction opposite to the positive frequency set. Zero sequence harmonics (harmonic numbers 3, 9, 15, 21, etc.) do not develop usable torque, but produce additional losses in the machine. The interaction between the positive and negative sequence magnetic fields and currents produces torsional oscillations of the motor shaft. These oscillations result in shaft vibrations. If the frequency of oscillations coincides with the natural mechanical frequency of the shaft, the vibrations are amplified and severe damage to the motor shaft may occur. It is important that for large VFD motor installations, harmonic analyses be performed to determine the levels of harmonic distortions and assess their impact on the motor.

Capacitor banks

Many industrial and commercial electrical systems have capacitors installed to offset the effect of low power factor. Most capacitors are designed to operate at a maximum of 110% of rated voltage and at 135% of their kvar ratings. In a power system characterized by large voltage or current harmonics, these limitations are frequently exceeded, resulting in capacitor bank failures. Since capacitive reactance is inversely proportional to frequency, unfiltered harmonic currents in the power system find their way into capacitor banks, these banks act like a sink, attracting harmonic currents, thereby becoming overloaded.

A more serious condition, with potential for substantial damage, occurs as a result of harmonic resonance. Resonant conditions are created when the inductive and capacitive reactance become equal in an electrical system. Resonance in a power system may be classified as series or parallel resonance, depending on the configuration of the resonance circuit. Series resonance produces voltage amplification and parallel resonance causes current multiplication within an electrical system. In a harmonic rich environment, both types of resonance are present. During resonant conditions, if the amplitude of the offending frequency is large, considerable damage to capacitor banks would result. And, there is a high probability that other electrical equipment on the system would also be damaged.

Telephone Interference

The juxtaposition of telephone and power lines on utility poles creates opportunities for power frequency interference with telephone communication. Since human hearing sensitivity and telephone response peak near 1 kHz, power system harmonic frequencies can present greater problems than fundamental frequency. The interference can be expressed by several different measures that are discussed in and. One of the measures is the telephone influence factor (TIF) that incorporates frequency, magnitude, and a weighting factor for the frequency. A common measure is the IT product which is the product of the rms current and the TIF. An IT product of less than 10,000 should not cause problems while a product of over 25,000 probably will cause interference problems.

Fuses and Circuit Breakers

Harmonics can cause false or spurious operations and trips, damaging or blowing components for no apparent reason.

Transformers

Have increased iron and copper losses or eddy currents due to stray flux losses. This causes excessive overheating in the transformer windings. Typically, the use of appropriate "K factor" rated units is recommended for non-linear loads.

Generators

Have similar problems to transformers. Sizing and coordination is critical to the operation of the voltage regulator and controls. Excessive harmonic voltage distortion will cause multiple zero crossings of the current waveform. Multiple zero crossings affect the timing of the voltage regulator, causing interference and operation instability. Computers/Telephones: may experience interference or failures.

IV. How harmonics can be reduced

Harmonics can be reduced by some of the steps given below, Isolate harmonic loads on separate circuits (with or without harmonic filters).

1. In-line reactors (chokes)
2. Zigzag transformers
3. Passive filters
4. Active filters

A. Harmonic filter

Harmonics can be reduced by use of filters. There are two approaches to mitigate harmonic problems order to improve the power quality problems. The passive and active power filters are connected to line system either in series shunt confugurations.Passive filters has been most commonly used to limit flow of harmonic currents in distribution systems. They usually custom designed for the application. However, performance is limited to a few harmonics and they introduce resonance in the power system Also, a separate filter is necessary for each harmonic frequency. Among different new filters to improve harmonic problem is active power filter. The idea of using active power filter is compensate for current and voltage disturbances in power distribution system but their practical development was made possible with the good control strategy in reducing harmonic distortion as well as with cost reduction. . It also introduces resonance that can move a harmonic problem from one frequency to another.

Through power electronics, active filter produces current or voltage components, which cancel the harmonic components of the nonlinear loads supply lines, respectively. These active filters relatively new and a number of different topologies are being proposed. This paper describes the simulation results an extensive investigation to evaluate the performances between passive and active power filters.

B.Comparison between active and passive filter

Influences of parameters	LC	Active Filter
Influences of increase in current	Risk of over load damage	No risk of over load damage
Added equipment	Requires modification to the filter	No problems if harmonic urrent is greater than load current
Harmonic control by filter order	Very difficult	Possible via parameters
Harmonic current control	Requires filter for each frequency	Simultaneously monitors many frequencies
Influence of frequency variation	Reduced effectiveness	No effect
Influence of modification in the impedance	Risk of resonance	No effect
Modification in fundamental frequency	Cannot be modified	Possible via reconfiguration
Dimensions	Large	Small
Weight	High	Low

V. Basic Principle of active filter

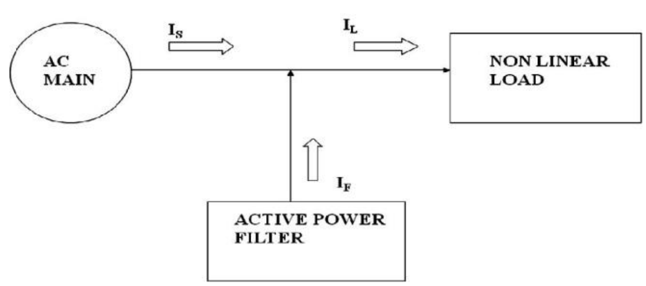

Fig.V.4

The basic concept of APF is explained in figV.4

$I_L = I_S + I_F$ (1)

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The load current having fundamental and harmonic content, and IF is the harmonic compensating current.

$I_L + I_H = I_S + I_H$ (2)

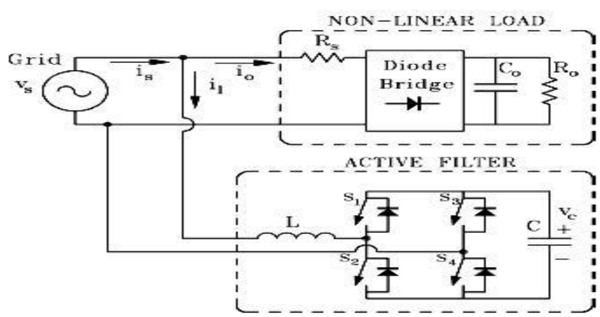
Filter provide harmonic requirement of the load

$I_L + I_H = I_S + I_H$

(3) $I_L = I_S$ (4)

Thus the supply current represents the fundamental waveform input output harmonics. Fig.V.4. shows the configuration of active shunt filter with non-linear load and the full bridge converter. which is almost widely used to eliminate current harmonics, reactive power compensation and balancing the unbalanced currents.

A. Basic Block diagram



FigV.A.5

Fig shows the basic circuit of APF including inverter having an energy storage capacitor on dc side. Pulse width modulation (PWM) is employed to generate gating pulses to the switches of APF. The dc based load fed from diode bridge rectifier with a capacitor is a non-linear load on the ac mains. The proposed APF is to eliminate harmonics and to improve the power factor of supply.

1. Voltage fed inverter

A single phase voltage source IGBT bridge with an energy storage capacitor on dc side, connected in parallel with the load-thus forming a voltage fed inverter. The full bridge inverter is built by four IGBTs that chosen according to their suitable ratings. Anti-parallel diodes are connected across these power switches in term of protection and providing power conversion in reverse direction in order to recharge the dc capacitor whenever its level goes lower than a reference value. Large size capacitor is connected to the inverter such that constant level of voltage could be maintained over each switching cycle.

2. Interface Filter

The filter provides smoothing and isolation for high frequency components. Control of the injected current wave shape is limited by the switching frequency of the inverter and the available driving voltage across the interfacing inductance. The driving voltage across the interfacing inductance determines the maximum di/dt that can be achieved by the filter. This is important because high values of di/dt may be needed to cancel higher order harmonic components. A large value of interfacing inductance is better for isolation but it limits the ability of an active filter to cancel higher order harmonics.

3. PWM Controller

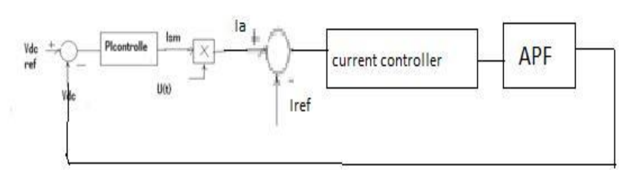
A simplified P-I (Proportional-Integral) control of the dc capacitor average voltage is used to generate reference source current in phase with ac source voltage to result in unity power factor of the source current. The pulse width modulation (PWM) is employed to generate gating signal for IGBTs to control the phase and magnitude of the inverter output. PWM is chosen as a controller in this work due to its ability to reduce the distortion factor and lower order of harmonics as well besides that the phase and the magnitude of the full-bridge inverter can be easily changed.

4 .Non-linear loads

In this paper typical diode rectifier with capacitor-resistive load is taken as non-linear load on the ac main for simulation as shown in Fig.

VI.PROPOSED CONTROL SCHEME

As shown in Fig the sensed dc voltage of the APF is compared with its set reference value in the error detector. The voltage error is processed in the P-I voltage controller. Its output is limited to the maximum permitted value. This output of the voltage controller is taken as peak value of supply current.



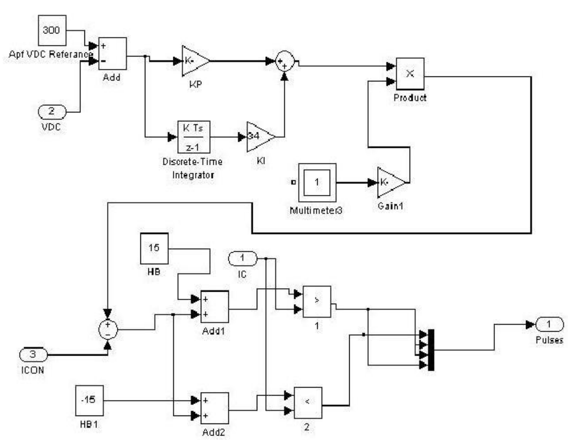
FigVI.6

A. Operation of controller loop

Being connected to the PCC (Point of Common Coupling), during non-switching operation, APF charges dc capacitor via diodes to the maximum value of system voltage. Voltage of the dc capacitor experiences the second harmonic ripple of the ac mains fundamental frequency. Thus dc storage capacitor voltage is symmetric about half the period of the ac cycle under steady state operating condition. This voltage is averaged over the half cycle of ac mains for the use in P-I voltage controller. This P-I voltage controller will try to maintain constant dc capacitor voltage to a reference value. For that, it will draw the necessary power from ac source to meet the losses in the APF such as switching loss, capacitor leakage current, etc. in addition to the real power the load.

Under any disturbance in the load (either increase or decrease), the load will try to draw new increased or decreased value of current. This increased load current will be supplied immediately from the APF resulting in decreased energy storage on dc capacitor. It reduces the average voltage across dc capacitor. This reduction in dc capacitor voltage of the APF will activate the P-I controller and increases the supply current. This increased source current tries to restore the stored energy of the capacitor in addition to increased load active power. Supply current settles to new steady state value within few cycles. Vice-versa operation will be performed for load current decrease.
Since the corrective action of the P-I voltage controller is taken within the half cycle of the ac mains it results in fast response.

B.Modeling of Single Phase APF and PI



FigVI.B.7

Explanation:-

-Instantaneous dc bus voltage (V_{dcc}), supply voltage (V_{in}) and converter current (icon) are sensed to obtain the switching signals to control the switching devices of APF.

-The sensed dc bus voltage (Vdcc) is compared with the dc reference voltage (V_{dcref}). The output of the comparator is error signal e (t).

-This error signal is then processed in a P-I controller and the peak value of reference supply current (I_{sm}*) is obtained.

-The unit vector u(t) of supply voltage is derived from its sensed value. The peak value of reference supply current (I_{sm}*) is multiplied with the unit vector to generate reference sinusoidal unity power factor current (i_s*) The reference supply current (i_s*) is compared with the actual converter current (i_{con}) to give reference APF current (i_c*).

-The actual APF current (i_c) and the reference APF current (i_c*) are processed in a hysteresis current controller to derive gating signals of the devices (MOSFETs) of the APF.

-P-Icontroller: $e(t)=V_{dcref}-V_{dcc}$

$$I_{sm}^*=e(t)*K_p+K_i/T_i*\int e(t)dt$$

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where, K_p and K_i are the proportionality and integral gain constants of the P-I controller. The I_{sm}* is the peak value of reference supply current.

Estimation of reference supply current:

$$I_s^*=u(t).I_{sm}^*$$

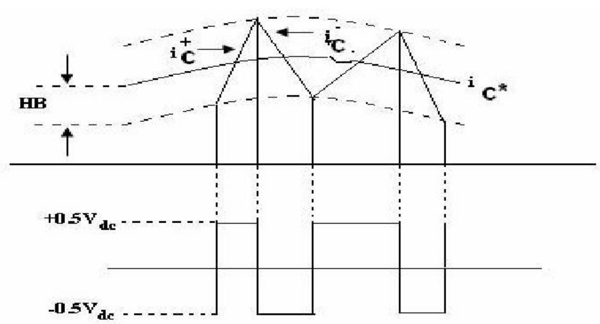
where, u(t) is the unit vector for input voltage Vin. Estimation of reference APF current:

$$I_c''=i_s''+i_{con}$$

where, i_{con} is the input current of the ac-to-dc converter without APF.

Hysteresis current controller:

The hysteresis current control scheme used for the control of shunt active filter is shown in Fig. 15 .The reference for compensation current to be injected by the active filter is referred to as i_c* and the actual current of the active filter is referred to as i_c. The control scheme decides the switching pattern of active filter in such a way to maintain the actual injected current of the filter to remain within a desired hysteresis band (HB) as indicated in Fig.



FigVI.B.8

If (i_c>i_c + hb) S1'and S2' ON, S3 'and S4 ' OFF

If (i_c<i_c -hb) S1'and S2' OFF, S3'and S4' ON

SI', S2', S3', S4' are the switching devices of the APF and hb is the hysteresis bandwidth in ampere.

APF Analysis

The V, is the ac PWM voltage reflected on the ac input side of the APF. Vs can be expressed in terms of switching functions as;

$$V = V_{dcc} * (SA - SB)$$

where,

$$V_{dcc}=1/C_c. \int i_{dc}\, dt$$

SA and SB are the switching functions. These functions generate gating signals for the switches of the APF.

SA = 1, if Sl'is ON andSA = 0, if S4'is ON

SB = 1, if S3'is ON andSB = 0, if S2'is ON

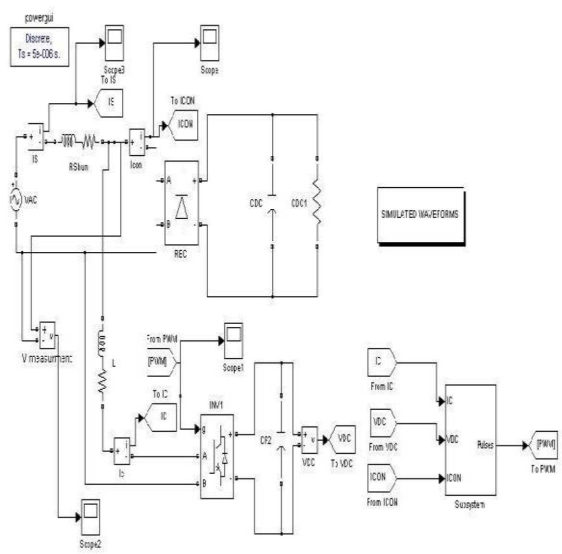
$$R_c i_c + L_c (di_c / dt) + V_s = V_{in}$$

$$idc = (SA - SB) * ic$$

ic is the actual current generated by the APF. Rc and Lc are the resistance and inductance of the APF inductor respectively.

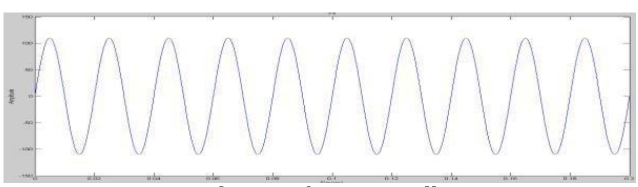
System Parameters- L_c = 0.05 mH, C_c =8000uf, RC = 0.0152, hb = 0.1, V_{dcref} = 600 V, K_p = 0.32, K_i = 0.3.

C.Simulink Model

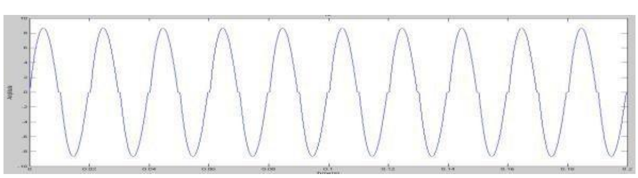


FigVI.C.9

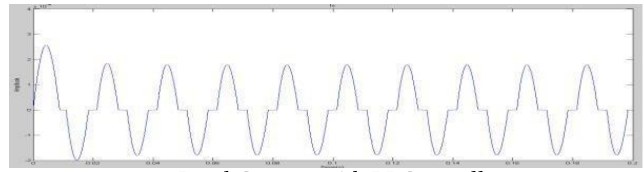
Result



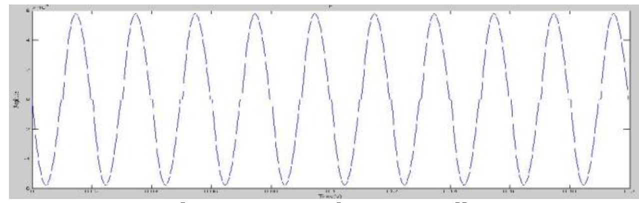
Source voltage with PI Controller



Source Current with PI Controller



Load Current with PI Controller



Filter Current with PI Controller

VII.Conclusion

1.APF improves the power quality and THD and gives us the pure sinusoidal wave.

2.Hysteresis current controller is used to obtain the gate signals for switching devices of APF.

3.Design active power filter of capacity range between 5KVA to 12 KVA suitable for harmonics generating load

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