Performance Enhancement in 3-phase Variable Speed AC Drive by Harmonic Reduction using PI Controller based Active Power Filter

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Abstract* – Enhancement of quality of power always becomes a challenge for engineers. Harmonics play significant role in deteriorating quality of power. Harmonic distortion in electric distribution system is increasingly growing due to the widespread use of nonlinear loads in industries such as variable Speed Drives. Large considerations of such loads raise harmonic voltage and currents in an electrical system to unacceptable high levels that can adversely affect the system. IEEE standards have defined limits for harmonic voltages and harmonic currents. Various power filters have been considered a potential candidate to bring these harmonic distortions within the IEEE limits. This paper deals with active power filter (APF) based on simple control along with comparison with hybrid power filters. The hybrid power filter combines the compensation characteristics of resonant passive and active power filters . A voltage source inverter with pulse width modulation (PWM) is employed to form the Active Power Filter. A vector controlled variable Speed Drive is considered as nonlinear load on ac mains for the elimination of harmonics by the proposed schemes. MATLAB model of the various schemes are simulated and obtained results are studied and compared.

Keywords: APF-Active Power Filter, variable Speed Drive, PWM Controller, hybrid filter, THD-Total Harmonic Distortion.

I. INTRODUCTION

The variable speed drives are extensively used in almost all areas of industry and utility services such as material handling plants, transportation systems, tracking systems, manufacturing processes, cement mills, rolling mills, robots, CNC machines, pumps, fans, compressors etc., The de-facto industrial standard necessitates the drive to have swift torque & speed response, four quadrant operation capability, high torque-to-weight ratio in addition to the overall economy.

With the advances in power electronics, especially the development of voltage source inverters, which can provide variable voltages at variable frequencies, induction motors are also being used as variable speed drives. The 3-phase induction motors are most preferable for drive applications because of their ruggedness, smaller size and low cost.

This work presents a method capable of designing power filters to reduce harmonic distortion. The proposed method minimizes the designed filters' total investment cost such that the harmonic distortion is within an acceptable range. Among the type used are active filters which block low harmonics such as 3rd, 5th, 7th order and etc harmonics and also harmonics of higher order with large frequency range. There are two types of filters that are usually used, passive and active filters. This project focuses on analysis using PI Voltage Controller based active power to eliminate harmonics.

Calculations are a major part of design process in all aspects of engineering applications. This laborious and time consuming process can be made really easy by the aid of a high level engineering software, i.e MATLAB.

A. Harmonics and harmonic order :

Harmonics are the integer multiples of the fundamental frequency of any periodical waveform are called e.g.

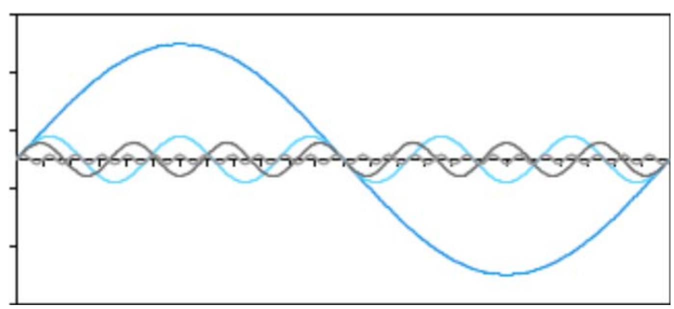


Fig. 1.1 Harmonics and harmonic orders

Acoustic waves

Electrical 'waves'

For power networks, 50 Hz (60 Hz) is the fundamental frequency and 150 Hz (180 Hz), 250 Hz (300 Hz) etc. are higher order harmonics viz. 3rd & 5th

=> Odd Harmonics (5th, 7th…..)

=> Even Harmonics (2nd , 4th ….)

=> Triplen Harmonics (3rd, 9th , 15th ..)

Non-integer multiples of the fundamental frequency of any periodical waveform are called Inter-harmonics e.g. 2.5th => 125 Hz at 50 Hz base

B. Harmonic Distortions

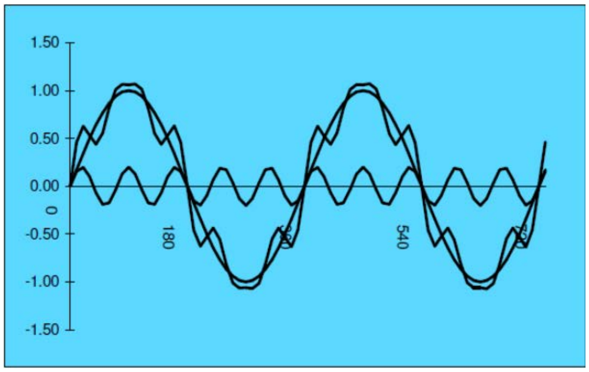


Fig. 1.2 Harmonics Distortions

C. Harmonics representations

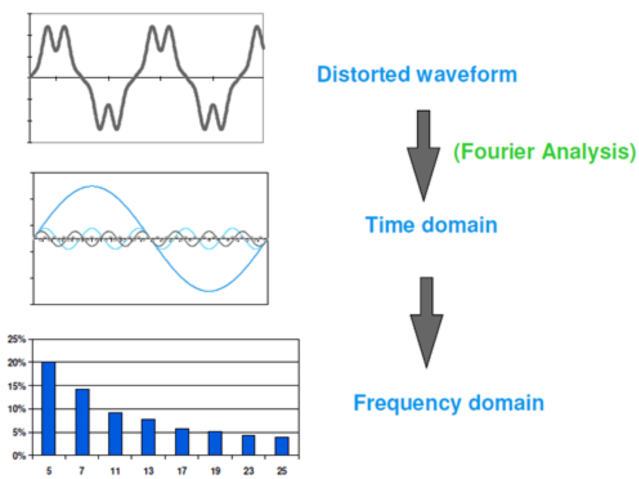


Fig. 1.3 Harmonics Representation

D. Where do the harmonics come from

Non-linear loads such as:

Variable speed drives, Uninterruptible power supplies (UPS), Industrial rectifiers, Welding machines, Fluorescent lighting systems (electronic ballast), Computers, Printers, Servers, Electronic appliances

E. Reducing Harmonics

Structural modification

Improved internal filtering (chokes)

12 or more pulse drive

Controlled active rectifier

Strengthen supply etc

External Passive Filter

Capacitor + series reactor

External Active Filter

Active harmonic filter Technology

F. Introduction to Electrical Drives

Whenever the term electric motor or generator is used, we tend to think that the speed of rotation of these machines are totally controlled only by the applied voltage and frequency of the source current. But the speed of rotation of an electrical machine can be controlled precisely also by implementing the concept of drive. The main advantage of this concept is, the motion control is easily optimized with the help of drive. In very simple words, the systems which controls the motion of the electrical machines, are known as electrical drives. A typical drive system is assembled with a electric motor (may be several) and a sophisticated control system that controls the rotation of the motor shaft. Now a days, this control can be done easily with the help of software. So, the controlling becomes more and more accurate and this concept of drive also provides the ease of use. This drive system is widely used in large number of industrial and domestic applications like factories, transportation systems, textile mills, fans, pumps, motors, robots etc. Drives are employed as prime movers for diesel or petrol engines, gas or steam turbines, hydraulic motors and electric motors.

Advantages

a. Flexible control characteristic – This is particularly true when power electronic converters are employed where the dynamic and steady state characteristics of the motor can be controlled by controlling the applied voltage or current.

b. Available in wide range of speed, torque and power.

c. High efficiency, lower noise, low maintenance requirements and cleaner operation.

d. Electric energy is easy to be transported.

A typical conventional electric drive system for variable speed application employing multi Machine system. The system is obviously bulky, expensive, inflexible and require regular maintenance. In the past, induction and synchronous machines were used for constant speed applications – this was mainly because of the unavailability of variable frequency supply.

With the advancement of power electronics, microprocessors and digital electronics, typical electric drive systems nowadays are becoming more compact, efficient, cheaper and versatile this is shown in Figure 1.1. The voltage and current applied to the motor can be changed at will by employing power electronic converters. AC motor is no longer limited to application where only AC source is available, however, it can also be used when the power source available is DC or vice versa.

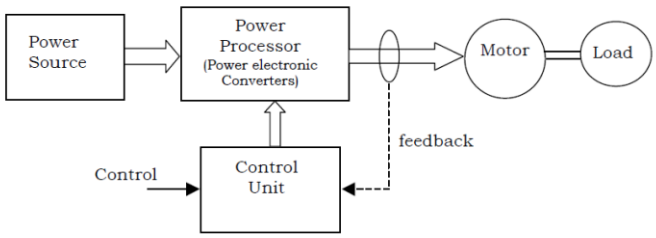


Fig. 1.4 Advanced Electric drive system

G. *Proportional Integral (PI) Control*

A variation of Proportional Integral Derivative (PID) control is to use only the proportional and integral terms as PI control. The PI controller is the most popular variation, even more than full PID controllers. The value of the controller output u(t) is fed into the system as the manipulated variable input.

$$e(t)=SP-PV$$

$$u(t)=ubias+Kce(t)+Kc\tau I\int t0e(t)dt$$

The ubias term is a constant that is typically set to the value of u(t) when the controller is first switched from manual to automatic mode. This gives "bumpless" transfer if the error is zero when the controller is turned on. The two tuning values for a PI controller are the controller gain, Kc and the integral time constant τI. The value of Kc is a multiplier on the proportional error and integral term and a higher value makes the controller more aggressive at responding to errors away from the set point. The set point (SP) is the target value and process variable (PV) is the measured value that may deviate from the desired value. The error from the set point is the difference between the SP and PV and is defined as $e(t)=SP-PV$.

Discrete PI Controller

Digital controllers are implemented with discrete sampling periods and a discrete form of the PI equation is needed to approximate the integral of the error. This modification replaces the continuous form of the integral with a summation of the error and uses Δt as the time between sampling instances and nt

as the number of sampling instances.

$$u(t)=ubias+Kce(t)+Kc\tau Int\sum i=1ei(t)\Delta t$$

Overview of PI Control

PI control is needed for non-integrating processes, meaning any process that eventually returns to the same output given the same set of inputs and disturbances. A P-only controller is best suited to integrating processes. Integral action is used to remove offset and can be thought of as an adjustable ubias

II. SYSTEM MODEL

A. *Active Filters*

This method uses sophisticated electronics and power section IGBT's to inject equal and opposite harmonics onto the power system to cancel those generated by other equipment. These filters monitor the non-linear currents demanded from non-linear loads(such as AFDs) and electronically generate that match and cancel the destructive harmonic currents. Active filters are inherently non-resonating and are easily connected in parallel with system loads.

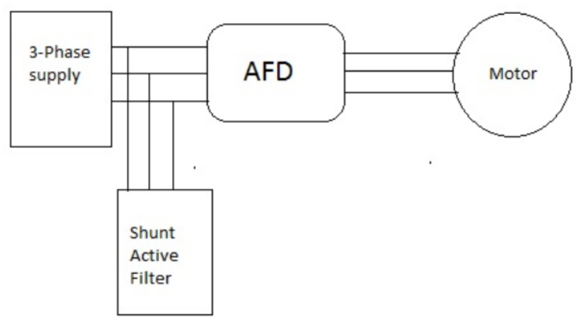


Fig. 2.1 Active filter block diagram

B. *Control Scheme*

Fig. 2.2 shows the block diagram of an overall control scheme for the APF system. DC bus voltage and supply voltage and current are sensed to control the APF. AC source supplies fundamental active power component of load current and a fundamental component of a current to maintain average dc bus voltage to a constant value. The later component of source current is to supply losses in VSI such as switching loss, capacitor leakage current etc. in steady state and to recover stored energy on the dc bus capacitor during dynamic conditions such as addition or removal of the loads.

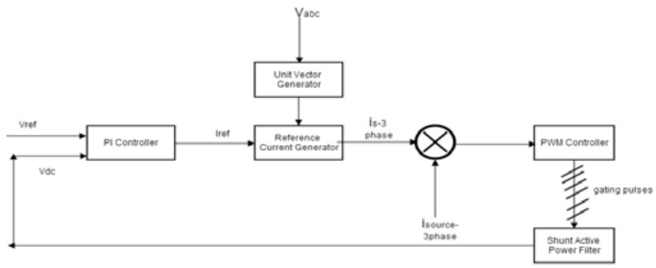


Fig. 2.2 Control Scheme of APF

The sensed dc bus voltage of the APF along with its reference value are processed in the P-I voltage controller. The truncated output of the P-I controller is taken as peak of source current. A unit vector in phase with the source voltage is derived using its sensed value. The peak source current is multiplied with the unit vector to generate a reference sinusoidal unity power factor source current. The reference source current and sensed source current are processed in hysteresis carrier less PWM current controller to derive gating signals for the MOSFETs of the APF. In response to these gating pulses, the APF impresses a PWM voltage to flow a current through filter inductor to meet the harmonic and reactive components of the load current. Since all the quantities such as dc bus voltage etc. are symmetric and periodic corresponding to the half cycle of the ac source. A corrective action is taken in each half cycle of the ac source resulting in fast dynamic response of the APF.

Analysis And Model Equations

The proposed APF system is comprised of a voltage controller, a current controller, a voltage source inverter bridge with dc bus, a non-linear load with input impedance and a filter inductance at the input of the APF. All parts are modelled separately and then joined together in order to simulate the APF system.

A) Voltage Controller

A P-I (proportional-integral) controller is used to regulate the dc bus capacitor voltage of the APF. The dc bus capacitor voltage Vdc is sensed using a voltage sensor and compared with set reference voltage (VF). The resulting voltage error (Ve(n)) at nth sample instant is expressed as :

$$Ve(n) = Vr(n) - Vdc(n) \quad (1)$$

The output of the P-I voltage controller Vo(n) at the nth sampling interval is expressed as :

$$Vo(n)= Vo(n-1) + Kp\{ Ve(n) - Ve(n-1) \} + Ki\, Ve(n) \quad (2)$$

Where Kp and Ki are proportional and integral gun constants of the voltage regulator.

Vo(n-1)a nd Ve(n-1), are the output of controller and voltage error at (n-I) th sampling

instant. This output Vo(n) of the voltage controller is limited to safe permissible v% and resulting limited output I' taken as peak value of supply current Ism*

(B) Reference Current Generation

From sensed supply voltage (VsmSinwt), a unit vector template is estimated by computing its peak value (Vsm), The unit vector is as :

$$u(t) = Vs/Vsm = \sin wt \quad (3)$$

This unit vector is multiplied to peak estimated value of source current Ism*. The resulting signal is taken as reference source current as :

$$Is^*(t) = Ism^*\, U(t)= Ism^* \,\mathrm{Sin}\, wt \quad (4)$$

C) Current Controller

The carrier less PWM hysteresis current controller contributes the switching pattern of the APF devices. The input reflected PWM voltage of the APF, V(t) is expressed in terms of switching functions.

$$Va = Vdc\, (SA - SB) \quad (5)$$

Where SA and SB are switching functions of the APF devices. SA is taken 1 if S1 is ON and SA is considered zero if S2 is ON. Similarly SB is taken one or zero when S3 or S4 are ON. Switch ‘S’ is comprised with a MOSFET with an anti parallel diode. Therefore, either diode or MOSFET may be conducting when switch is considered in ON state.

D) Active Power Filter

The active power filter is modelled in terms of its two basic volt-current equations on ac as well as dc side. The ac side volt-ampere equation is as follows.

$$Rc\, ic + Lc\, p.ic + Va = Vs \quad (6)$$

Where ic is current flowing into the APF, Vs and Va are the supply and APF voltages, respectively. Rc and Lc are the resistance and inductance of the APF inductor. p is the differential operator (d/dt).

Equation (6) may be expressed in state space derivative form as :

$$pic = \{ Vs-Va-Rcic\}/ Lc \quad (7)$$

Similarly, dc side basic electrical equation may be written as:

$$pVdc = idc/Cc \quad (8)$$

III. PREVIOUS WORK

The idea came from study of research paper of Singh, B.; Al-Haddad, K.; Chandra, A.; “A review of active filters for power quality improvement”. In that particular paper they explained how active filtering of electric power has now become a mature technology for harmonic and reactive power compensation in two-wire (single phase), three-wire (three phase without neutral), and four-wire (three phase with neutral) ac power networks with nonlinear loads.

IV. PROPOSED METHODOLOGY

Non linear Speed Drive load is simulated along with various filter schemes. First a simple system is shown in which three phase ac supply is connected to variable Speed Drive as shown in fig.4.1

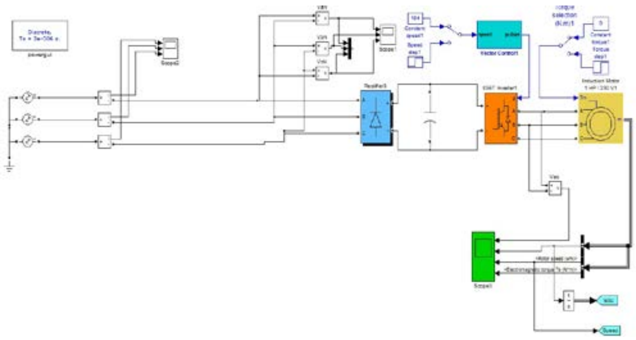


Fig.4.1 Simulation model when connected without any filter

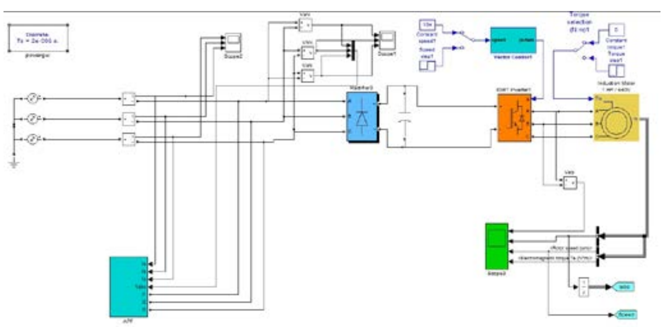


Fig. 4.2 Simulation model with Shunt APF

Thus a harmonic analysis has been done on it. In next step the simulation model is connected with shunt active power filter as shown in fig.4.2 the internal filter model is shown in fig. 4.3 where the control mechanism or PWM is employed to generate gate signals using PI controller. Fig. 4.4 shows a simulink model of a drive system connected to a hybrid filter in shunt. A hybrid filter comprises of a passive filter branch connected to active filter.

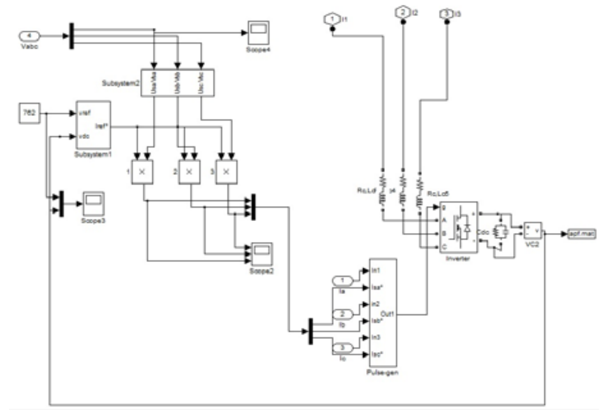


Fig. 4.3 Shunt APF model with PI Controller

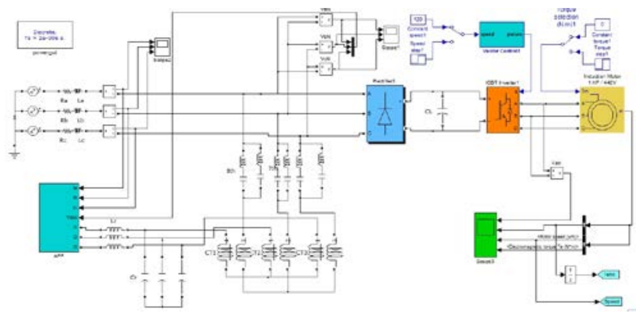
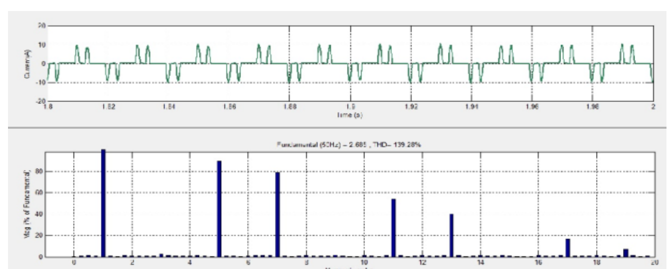


Fig. 4.4 Simulink model of Hybrid filter

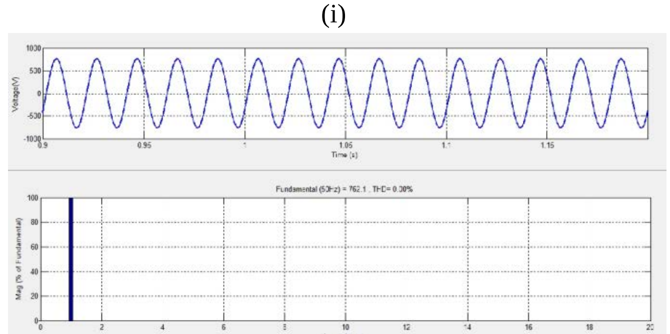
V. SIMULATION/EXPERIMENTAL RESULTS

Harmonic analysis were performed at different speeds without filter as shown:

1. 500 rpm or 52 rad/sec(approx)



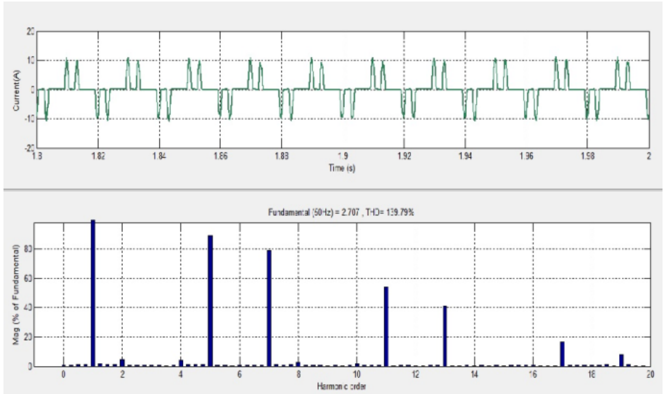
(i)



(ii)

Fig. 5.1 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD for 500rpm motor speed

2. 750 rpm or 78 rad/sec(approx)



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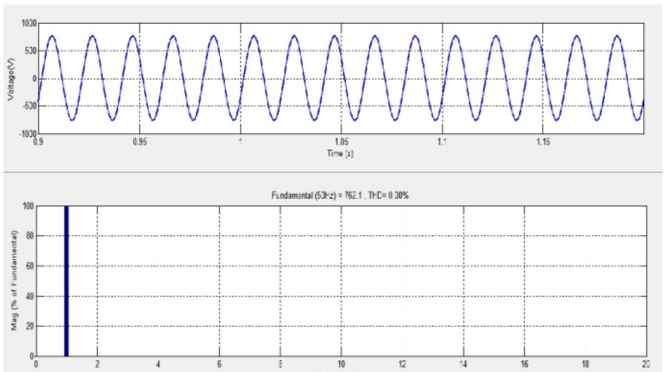
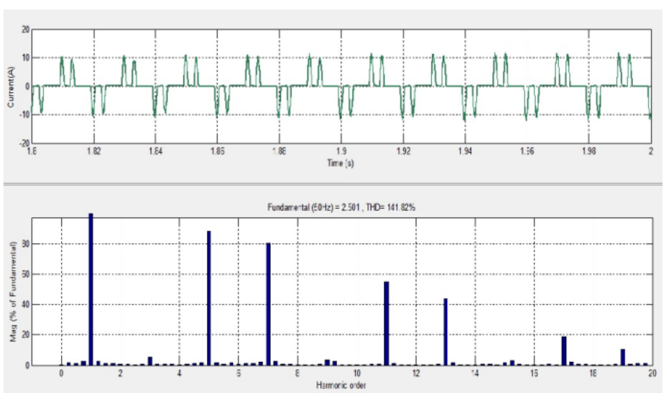


(ii)

Fig. 5.2 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD for 750rpm motor speed

3. 1000rpm or 104rad/sec(approx)



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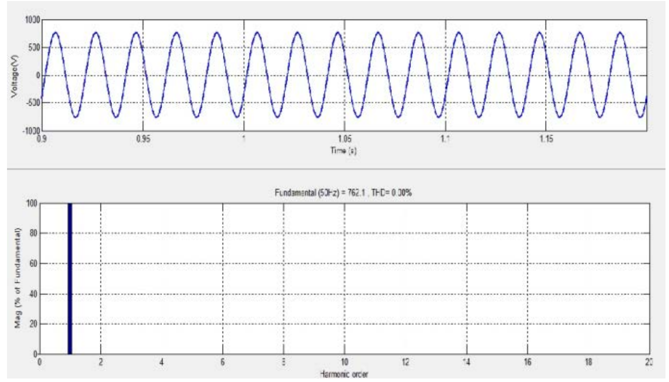
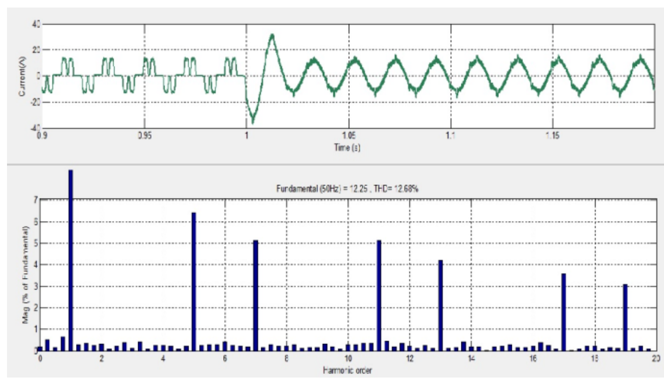


(ii)

Fig. 5.3 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD for 1000rpm motor speed

Harmonic analysis in presence of active filter at different speeds is as follows:

1. 500 rpm or 52 rad/sec



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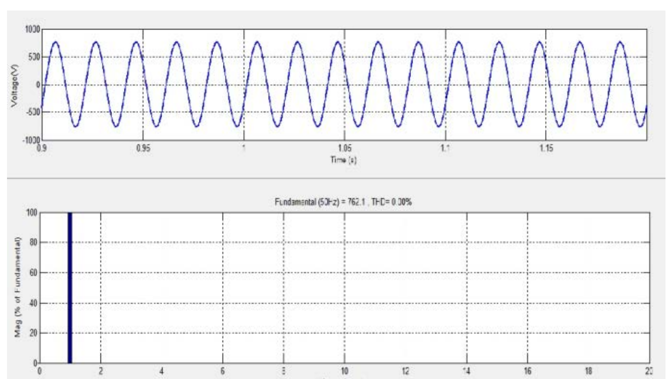

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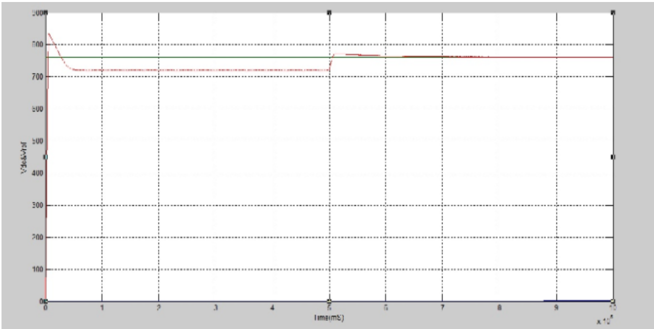

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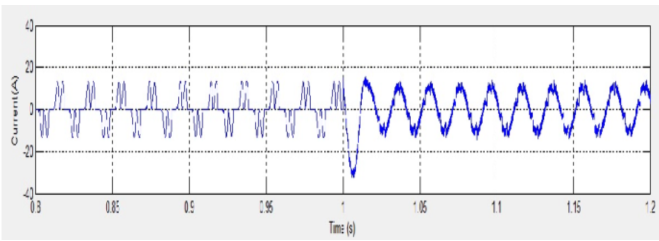
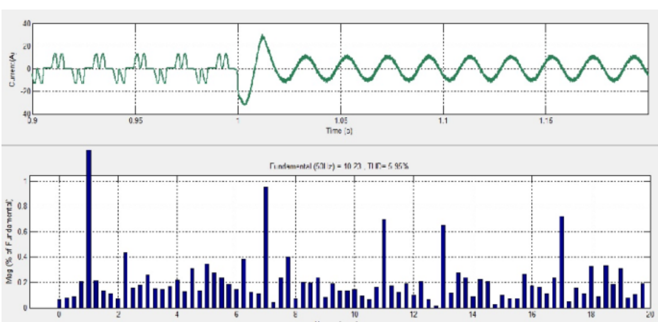


(iv)

Fig. 5.4 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD (iii)Vdc and Vref and (iv) Inverter phase current for 500 rpm motor speed.

2. 750 rpm or 78 rad/sec



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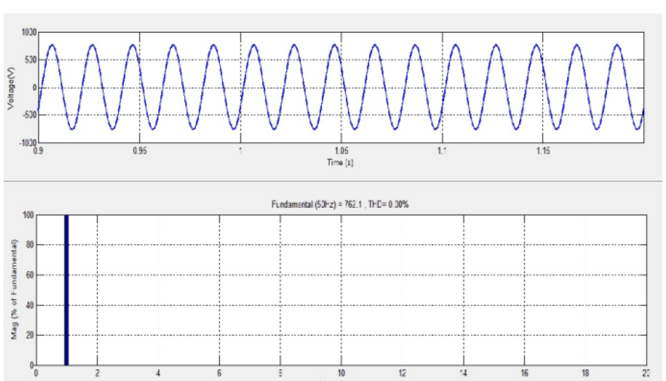

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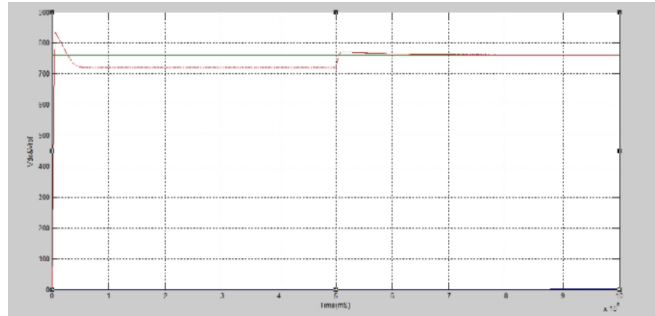

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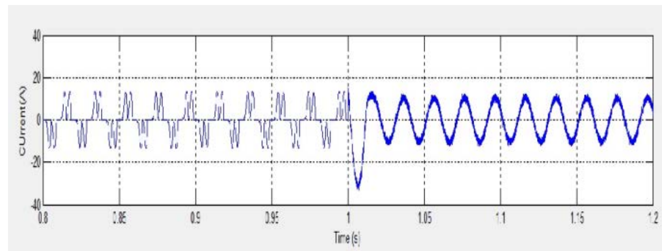
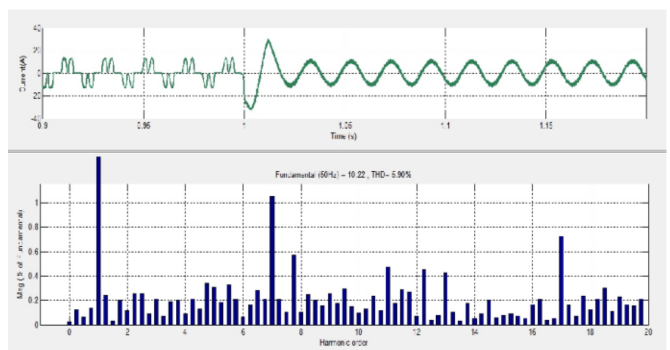


(iv)

Fig. 5.5 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD (iii)Vdc andVref and (iv) Inverter phase current for 750 rpm motor speed .

3. 1000 rpm or 104/rad/sec



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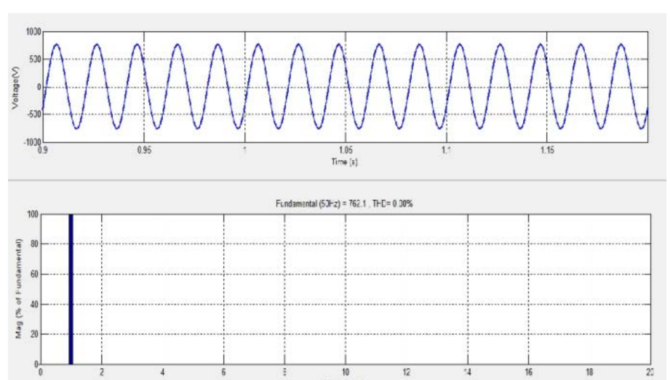

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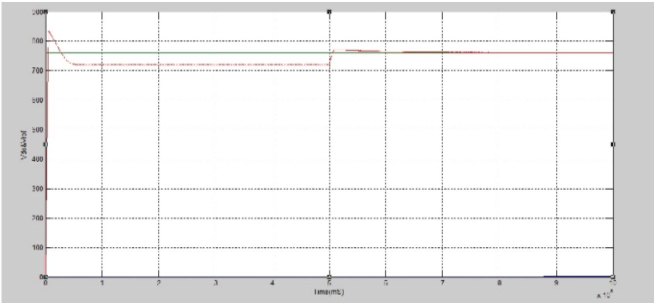

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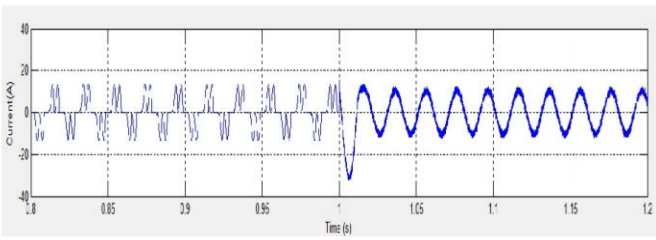


(iv)

Fig. 5.6 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD (iii)Vdc and Vref and (iv) Inverter phase current for 1000 rpm motor speed.

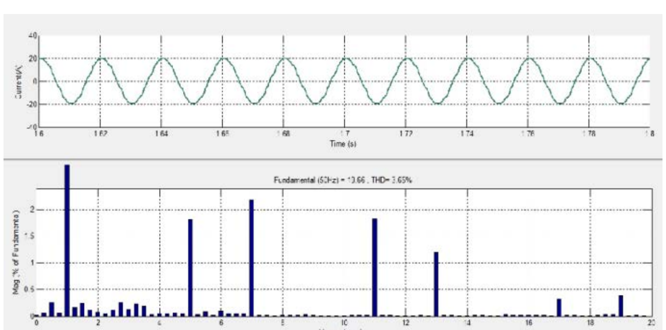
Further hybrid filter method is adopted to reduce harmonic to much lesser level such that it can satisfy IEEE 519 1992 standards.

Hybrid filter method is adopted as shown in fig. 10

The simulink model of hybrid filter is shown in fig.10. Here the method adopted for development of hybrid filter is quite simple. In this case active power filter is connected LC passive filter in series through a coupling transformer. Rest control scheme is same as that used in APF.

The harmonic analysis at different speeds is shown

1. 500 rpm or 52 rad/sec



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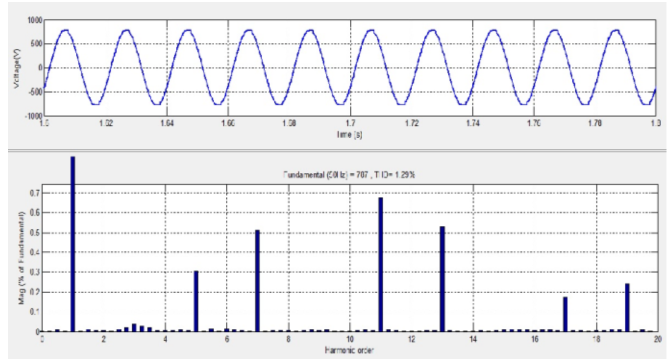
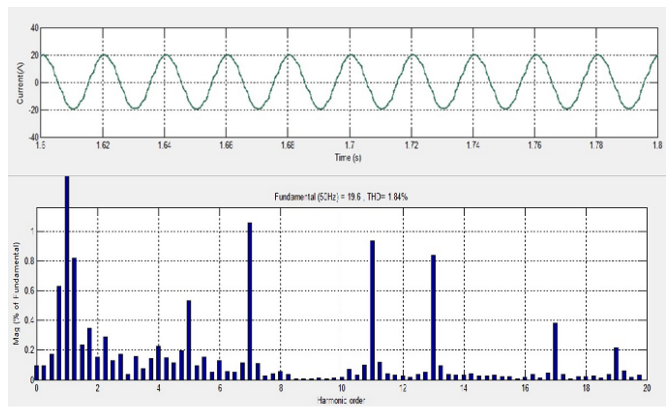


(ii)

Fig. 5.7 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD for 500 rpm motor speed

2. 750 rpm or 78 rad/sec



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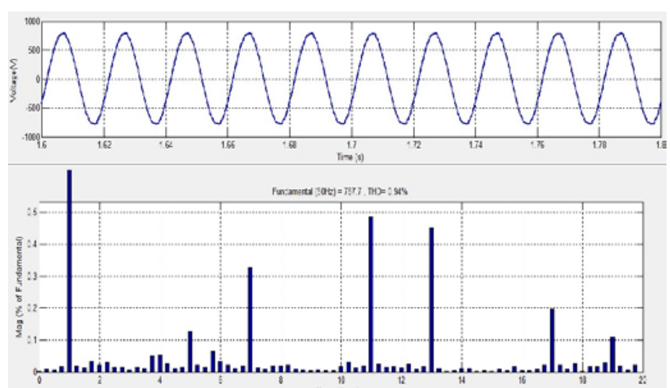
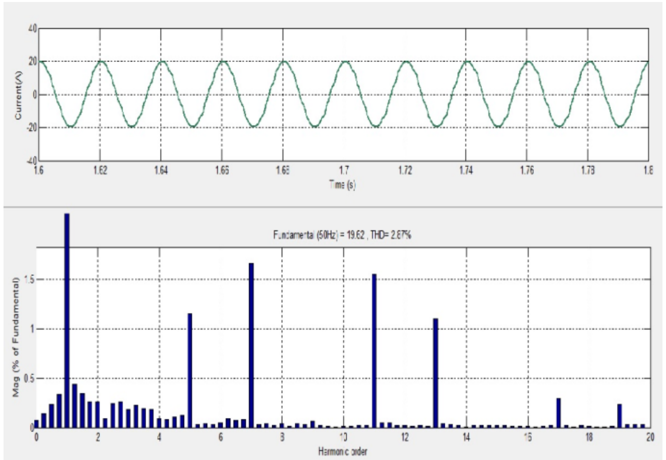


(ii)

Fig. 5.8 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD for 750 rpm motor speed

3. 1000 rpm or 104 rad/sec



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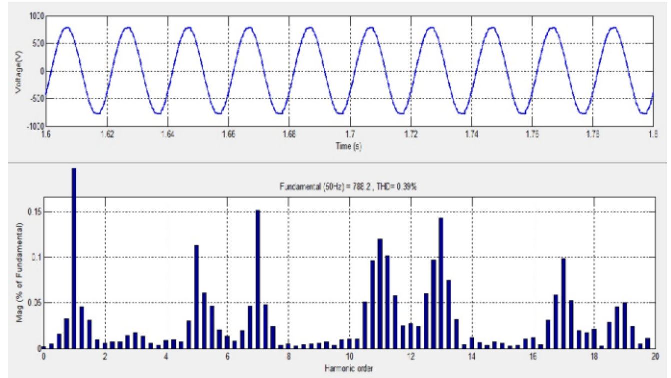

(ii)

Fig. 5.9 waveforms of (i) line current and current THD (ii) phase-phase voltage and voltage THD for 1000 rpm motor speed.

TABLE 5.1 COMPARISON OF METHODS ADOPTED FOR HARMONIC SUPPRESSION FOR DRIVE

S. No.	Speed (rpm)	No Filter (Current THD)	No Filter (Voltage THD)	Active (Current THD)	Active (Voltage THD)	Hybrid (Current THD)	Hybrid (VoltageTHD)
1	500	139.28 %	0.00 %	12.66 %	0.00 %	3.65 %	1.29 %
2	750	139.79 %	0.00 %	5.95 %	0.00 %	1.84 %	0.94 %
3	1000	141.82 %	0.00 %	5.90 %	0.00 %	2.87 %	0.39 %

The harmonic analysis using different filters is done:

At 500 rpm motor speed, current THD is 139.28% with no voltage harmonics. Active filter has reduced it to 12.66% with no voltage harmonics and finally hybrid filter has reduced current THD to 3.65% (improvement of 135.63%) with 1.29% voltage THDs.

At 750 rpm motor speed, current THD is 139.79% with no voltage harmonics. Active filter has reduced it to 5.95% with no voltage harmonics and finally hybrid filter has reduced current THD to 1.84% (improvement of 137.95%) with 0.94% voltage THDs.

At 1000 rpm motor speed, current THD is 141.82% with no voltage harmonics. Active filter has reduced it to 5.90% with no voltage harmonics and finally hybrid filter has reduced current THD to 2.87% (improvement of 138.95%) with 0.39% voltage THDs.

VI. CONCLUSION

In this paper harmonic analysis and its suppression techniques to enhance performance of AC drive were implemented using a simulation model with variable Speed Drive load. Fig. 5.2, 5.5 and 5.8 shows the input end current in presence of no filter, active filter and hybrid filter at 78 rad/sec. motor speed. It has been observed that there is no voltage distortion when no filter scheme is employed and little harmonics in hybrid filter scheme. Fig. 5.3, 5.6 and 5.9 shows the current waveforms and THD respectively of all the three schemes. It has been seen that the percentage THD gets reduced with increase in speed of the motor connected at load end. Table 5.1 gives a brief summary of the experiments performed to eliminate harmonics. So it is concluded that PI controller based active filters can reduce the current percentage THD to around 7% with no voltage harmonics. The implementation of hybrid filters have provided with great results with current and voltage THD below 1% and within IEEE 519 standard limits.

VII. FUTURE SCOPES

1. Further development of simulink model and be done using different control schemes such as fuzzy logic control and sliding mode control and then comparison can be done for all the control schemes
2. Experimental investigations can be done on shunt active power filter and hybrid filter by developing a prototype model in the laboratory to verify the simulation results.
3. The prototype model can also be implemented using different control schemes.

4. The prototype model can be practically implemented on various loads in industrial and\ commercial purposes such as drives.

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