"Comparison of Topologies of Shunt Active Power Filter Implemented on Three Phase Four-Wire System"

R. M. Potdar, Chhetal Chowhan

Abstract: Supply of uninterrupted sinusoidal voltage of constant magnitude is the most important aim of the electrical distribution system, but this task is very tough and is becoming more difficult due to the increasing size and number of nonlinear and poor power factor loads. Some of the most important causes of poor power quality is harmonics and high neutral current. Harmonics and neutral current deteriorate power quality as well as affect the system at large and makes significant impact. In this paper a control scheme based on PI controller has been proposed for generation of reference current to mitigate the harmonics and neutral current for two different topologies. The proposed methodology not only reduces the complexity but also offers simplicity to implement and increases reliability of the system. Analysis and simulation of three phase four wire shunt active power filter under balanced and unbalanced load condition have been done using MATLAB/ SIMULINK and detailed simulation level results have been presented to validate the proposed methodology.

Key words: Shunt active power filter, Voltage source inverter, PI controller, THD I

I. 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, connection of high power non-linear loads contributes to the generation of current and voltage harmonic components, voltage sags are generated due to the high economical losses, short-term voltage drops (sags) can trip electrical drives or more sensitive equipment, leading to costly interruptions of production etc.

To ensure the good power quality at utility and consumer end, above mentioned factor must me controlled in prescribed limit. Power quality can be controlled to a greater level by merely controlling two most important factors i.e. harmonics and neutral current [1-9].

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Different topologies and methods have already been proposed to nullify and control these two factors. A control strategy for a three phase four-wire shunt active filter is proposed in [1]. In this work the power circuit is based on a three-leg IGBT inverter, with the dc-link composed by two capacitors connected in split. A disadvantage of this topology is the fact that the size of the dc-link capacitors has to be over-dimensioned. An Experimental investigation of the operation characteristic of 3-phase 3-wire APF in 3-phase 3-wire balanced/unbalanced and 3-phase 4-wire balanced/unbalanced system is proposed in [2]. It is found that three-wire active filter is only suitable for three-phase three-wire system. N. Mendalek in [3] proposes the modeling and control of a 3-phase 4-leg split capacitor shunt active power filter topology.

A simulation model is proposed here, in which shunt active power filter is implemented to compensate harmonic content and neutral current in three phase four wire system. It comprises of voltage source inverter with dc link capacitor, PI controller and hysteresis band for pulse generation. In this paper section I gives the Introduction, II presents problem identification, III describes proposed methodology, IV consists of Control strategy, V consists of Simulation results and at last section VI gives the conclusion.

II. PROBLEM IDENTIFICATION

The definition of power quality given in the IEEE dictionary originates in IEEE Std 1100: 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 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.

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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.

A. Total harmonics distortion (THD)

According to IEEE-519, total harmonics distortion is defined as the summation of the effective value of the harmonics components in the distorted waveform relative to the fundamental component. It can be calculated for either voltage or current.

$$THD_v = \frac{\sqrt{\sum_{h=2}^{hmax} (V_h)^2}}{V_1}$$

$$THD_i = \frac{\sqrt{\sum_{h=2}^{hmax} (I_h)^2}}{I_1}$$

Where V_h is the RMS value of voltage harmonics component h, while I_h is the RMS value of current harmonics component h.

Principles for controlling harmonics: Harmonic distortion is present to some degree on all power systems. Fundamentally, one needs to control harmonics only when they become a problem. There are three common causes of harmonic problems:

1. The source of harmonic currents is too great.
2. The path in which the currents flow is too long (electrically), resulting in either high voltage distortion or telephone interference.
3. The response of the system magnifies one or more harmonics to a greater degree than can be tolerated.

When a problem occurs, the basic options for controlling harmonics are:

1. Reduce the harmonic currents produced by the load.
2. Add filters to remove the harmonic currents off the system, block the currents from entering the system, or supply the harmonic currents locally.
3. Modify the frequency response of the system by filters, inductors, or capacitors.

B. Problem of High Neutral Current in power system can cause following problem

1. Overloading of feeder
2. Overloading of transformers
3. Voltage distortion
4. Common mode noise

III. PROPOSED METHODOLOGY

The APF is aimed to compensate harmonic content in phase currents, neutral current, reactive power and unbalanced nonlinear load currents in three phase 4-wire distribution systems. In addition, the dc-link capacitor voltages are regulated and equalized to eliminate the imbalance problem which is due to the presence of dc component in the neutral wire current.

A. Four-Wire Active Filter Topologies

For three-phase, four-wire system, four leg approaches are proposed in place of three single-phase converters. The four-wire converters can take either of the two forms as shown in Fig. 1(a) and (b)

a) Capacitor midpoint topology, and
b) Four Switching-leg topology

The 1st approach utilizes a standard three-phase converter where DC link capacitor is spitted and the midpoint of the capacitor is connected to the fourth wire, to provide the return path for the neutral current. The second approach uses four switching legs in which three of the switching legs are connected to the three phase conductors through a series inductance, while the fourth leg is connected to neutral conductor, to provide the return path.

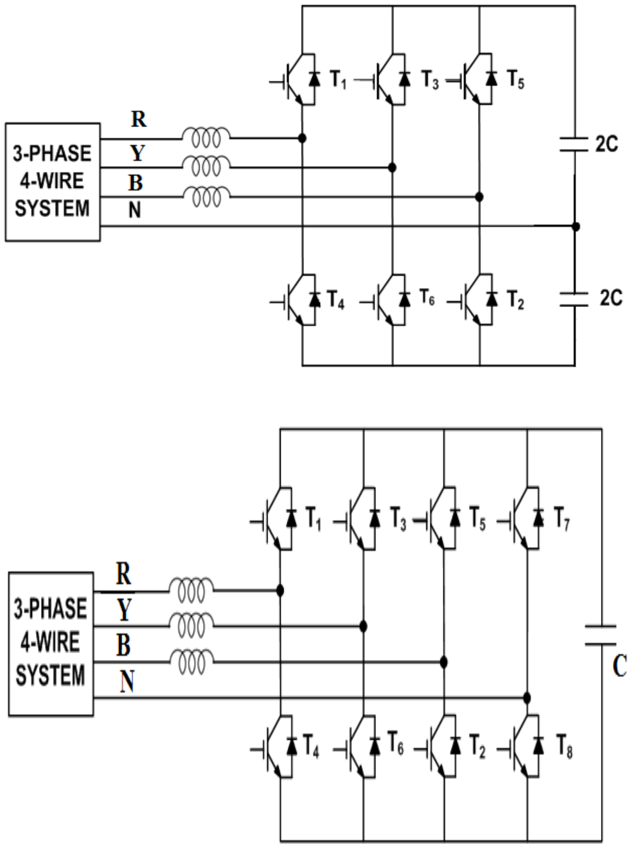

Fig.1 (a) Capacitor midpoint topology, (b) Four switching-leg topology

B. Significance of D.C. Capacitor

Under steady state operating conditions the dc voltage control loop keeps the dc voltage constant. However, transient changes in the instantaneous power absorbed by the load generate voltage fluctuations across the dc capacitor. The amplitude of these voltage fluctuations can be controlled effectively with an appropriate dc capacitor value.

When designing the capacitor the following assumptions are made:

i) In steady state, the fluctuating voltage of the capacitor is very small compared to the average voltage.
ii) The converter is lossless.

The voltage fluctuation in the dc capacitor under steady state is due to the variation of the harmonic power 80w and the energy stored in the inductor. The current in the inductor has two components, the distorted current and the ripple current superimposed on the reference due to the switching action of the converter. The first current is a periodic ac waveform, hence the energy variation is null. The second part consists of the energy that the inductor discharges in the capacitor within one switching period. During the on state, energy is accumulated across the inductor and this energy is absorbed by the capacitor during the off state. Because the switching frequency is high, the effect of this energy variation on the dc bus is neglected.

The capacitors are designed to limit the dc voltage ripple to a specified value, typically 1 to 2 %. In our case the capacitor should be designed for the worst case. Since the active filter will operate in several modes (single phase or unbalanced load). It follows that the capacitor value is load dependent and simulation is one way of evaluating the worst possible case.

In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation of the active filter, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load. If the DC capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again.

IV. CONTROL STRATEGY

The peak value of the reference compensating currents (I_{max}) is estimated by regulating the DC link voltage. The reference current templates (I_{sr}*, I_{sy}* and I_{sb}*) are obtained by multiplying this peak value (I_{max}) by the three-unit sine vectors (U_{sr}, U_{sy} and U_{sb}) in phase with the three source voltages. These unit sine vectors are obtained from the three sensed line to neural voltages. The reference neutral current (I_{sn}*) is obtained by negative sum of the three-phase reference currents. Also, three current sensors are used to sense the three line currents (I_{sr}, I_{sy} and I_{sb}) as compared to two used in three-phase, three-wire system, and neutral current is obtained by negative sum of the three line currents. The complete schematic diagram of the three-phase, four-wire shunt active filter is shown in Fig.2. The conventional three-phase PWM converter is replaced by a four switching-leg converter.

The actual capacitor voltage is compared with a set reference value. The error signal is then fed to a PI controller. The output of PI controller is considered as peak value of the supply current. This peak value of the current is multiplied by the unit sin vectors (U_{sr}, U_{sy} and U_{sb}) in phase with source voltages to obtain the reference currents (I_{sr}*, I_{sy}* and I_{sb}*). Difference of these estimated reference source currents and sensed actual currents, are given to a hysteresis based, carrier less PWM current controller to generate the switching signals of PWM converter. The difference of reference current template and the actual current decides the operation of the switches. To increase the current of particular phase the lower switch of the PWM converter of that particular phase is switched on while to decrease the current the upper switch of the respective phase is switched on. These switching signals after proper isolation and amplification are given to the switching devices. Due to these switching actions current flows through the filter inductor L_{AF}, to compensate the harmonic current and reactive power of the load, so that only active power is drawn from the source.

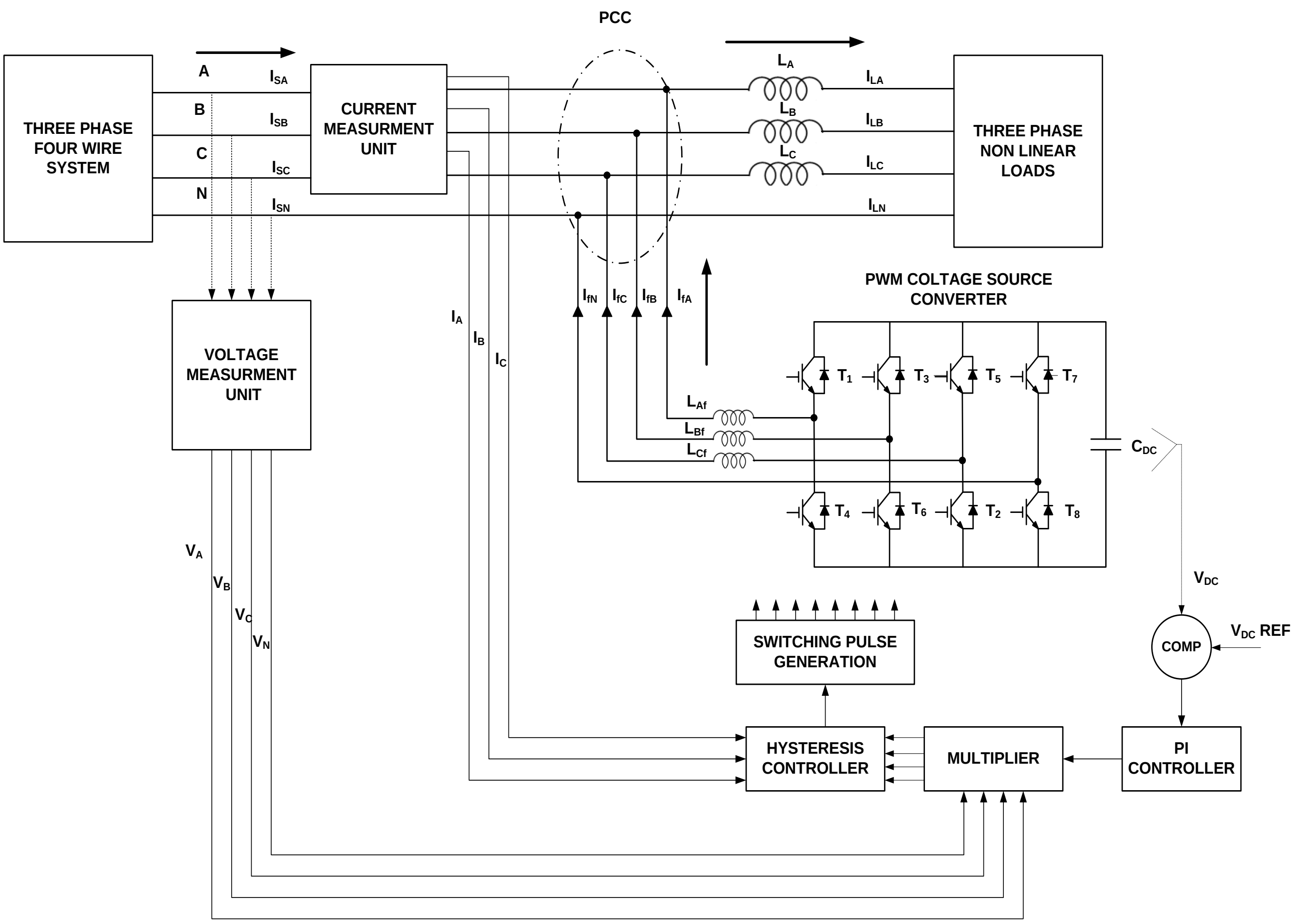

Fig.2 Schematic diagram of three phase four wire system

V. RESULT

Simulation model is built using MATLAB/SIMULINK/r2010a version and its tool of simpower system. Model is simulated for both the balanced and unbalanced load conditions and for both the topologies. Simulation model is as shown in fig.3. Table 1 described earlier different parameters selected for the simulation for 5 kVA compensation capacity for both the topology.

Table I. Simulation parameter

Supply voltage	$V_{s(peak)}$=230V
DC link Capacitor Voltage	$V_{dc\ ref}$=480 V
Controller line inductance	L_{AF}=0.4 mH
Controller line resistance	R_{AF}=0.3 Ω
DC link capacitor	C=1800µF
Switching frequency	10kHz
PI Controller Gain	K_i =10 ,K_p =0.5
Supply frequency	50 Hz

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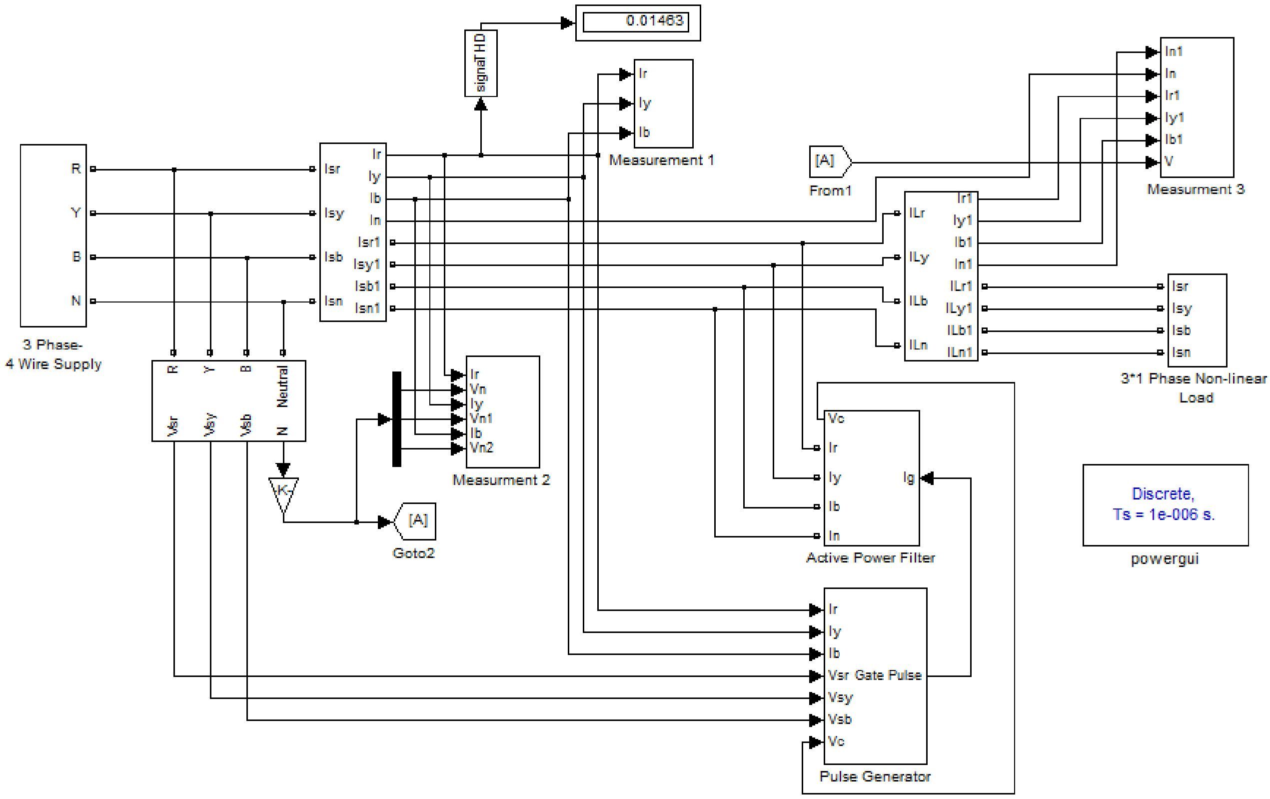


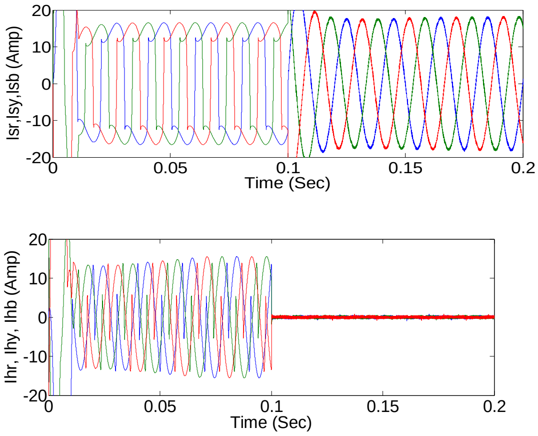
Fig. 3 Simulation model of three-phase, four-wire shunt active filter

A. **Four Switching-Leg Topology**

Simulation results of four wire converter using four switching leg topology under balanced and unbalanced load are given below:

i) **Balanced load condition**

Simulation results are given here for balanced non-linear load. Three single phase diode rectifiers with R-L element on its DC side are connected between each phase and neutral as nonlinear loads. Harmonic distortion of the line current drawn by the single phase-phase diode rectifier is observed more, as compared to the three diode rectifier. Fig. 4 shows the simulation results of three phase four wire shunt active power filter under balanced load condition. THD of the input current is reduced from 36.01% to 1.45% for phase R, 36.01% to 1.43% for phase Y and 36.01% to 1.12% for phase B which is well below the recommended 5% limit.



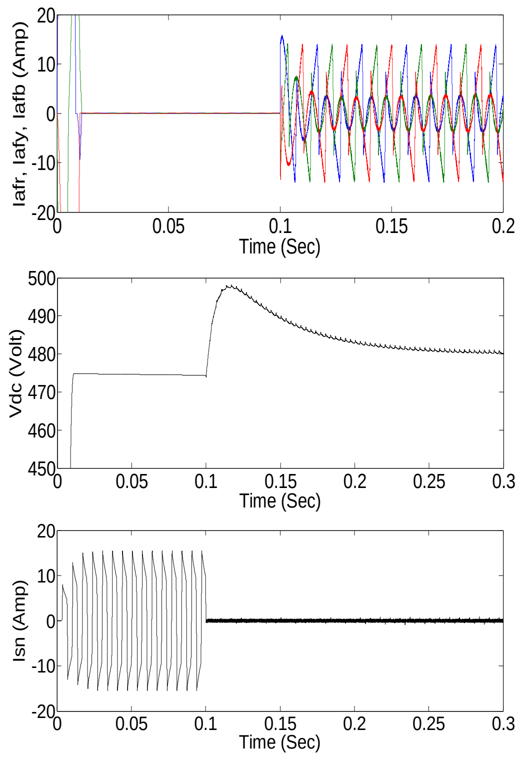


Fig. 4 Simulation results of three phase four wire shunt active power filter supplying 3×1-Ø diode rectifiers with unbalanced load

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ii) Unbalanced load condition

Fig. 5 shows the simulation results under unbalanced load condition. THD of the input current is reduced from 31.66% to 2.55% for phase R, 33.21% to 2.77% for phase Y and 36.42% to 2.53% for phase B which is well below the recommended 5% limit.

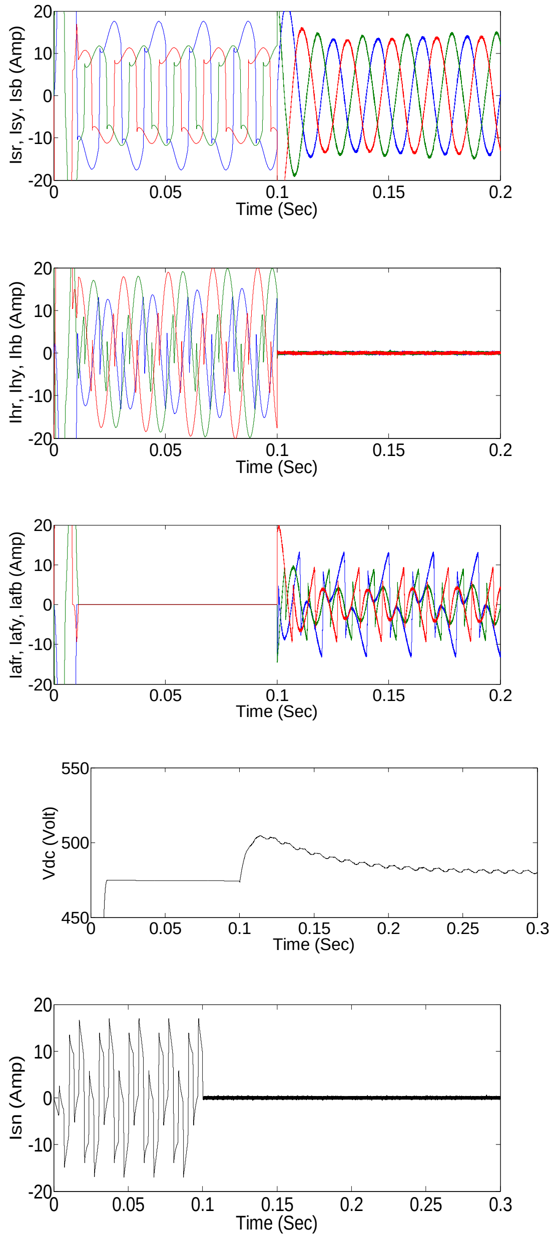


Fig. 5 Simulation results of three phase four wire shunt active power filter supplying 3×1-Ø diode rectifiers with unbalanced load

B. Mid Point Capacitor Split Topology

i) Balanced Load Condition

Fig.6 shows the simulation result when capacitor split mid-point point topology is applied, After compensation,THD of the input current is reduced from 26.18% to 2.03% for phase R, 26.35% to 2.09% for phase Y and 26.35% to 2.09% for phase B which is well below the recommended 5% limit.

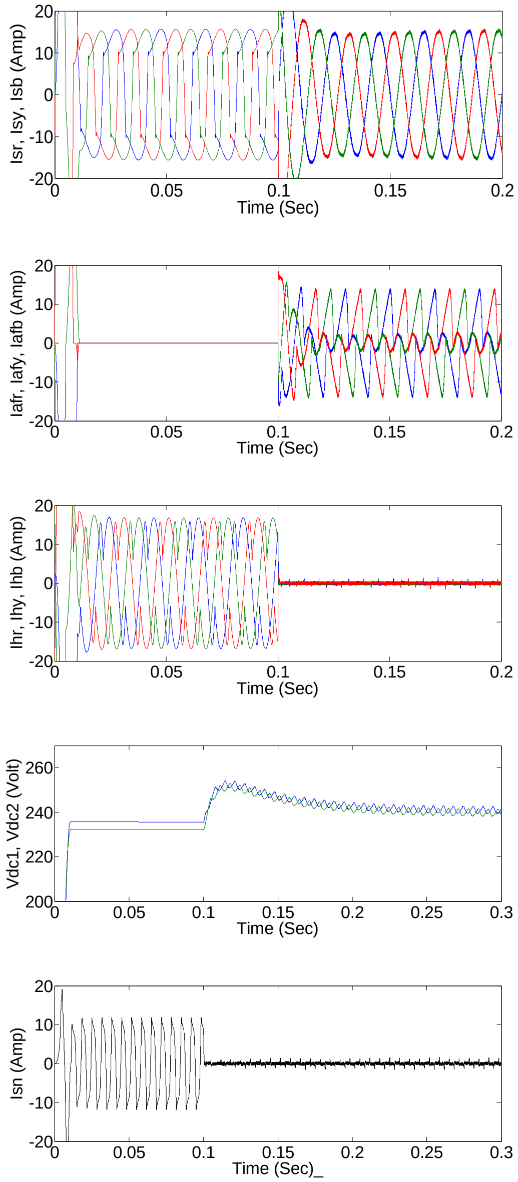
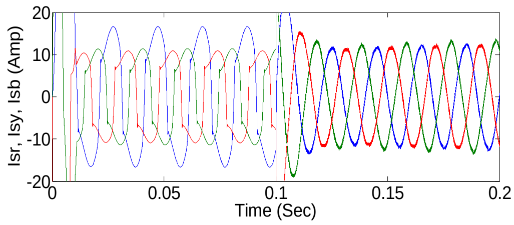


Fig. 6 Simulation results of three phase four wire shunt active power filter supplying 3×1-Ø diode rectifiers with balanced load

ii) Unbalanced Load Condition

Fig.7 gives the simulation result of three phase four wire shunt active power filter under unbalanced load condition. After compensation,THD of the input current is reduced from 21.96% to 3.06% for phase R, 24.56% to 3.24% for phase Y and 27.85% to 3.06% for phase B which is well below the recommended 5% limit.



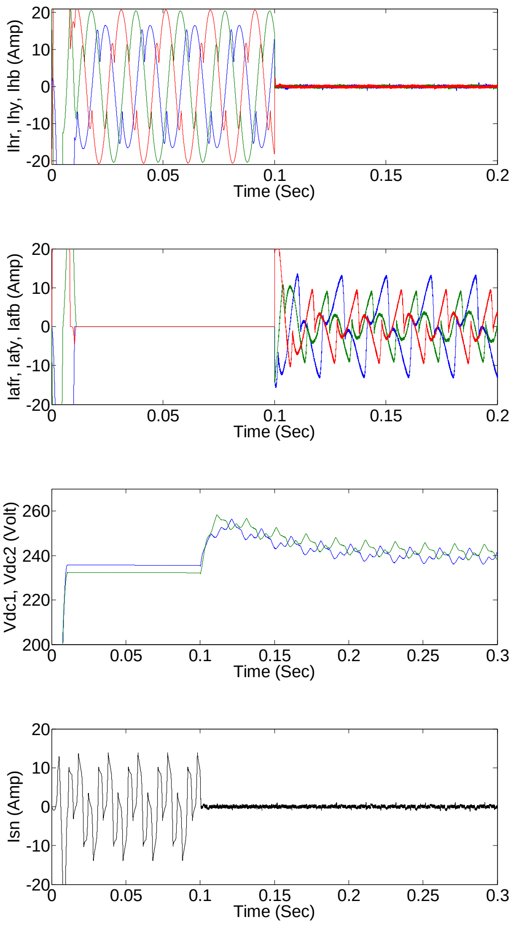


Fig. 7 Simulation results of three phase four wire shunt active power filter supplying 3×1-Ø diode rectifiers with unbalanced load

VI. CONCLUSION

Both the topologies (four switching leg topology and capacitor mid-point topology) of three phase four wire shunt active power filter has been investigated for the compensation of harmonic, reactive power, neutral current, power factor improvement and input current balancing in three-phase, four wire system. Theoretical concepts have been proved by simulation results. Both the topologies worked satisfactorily with the proposed control scheme but the four switching leg topology is preferred over capacitor mid-point topology.

With all the parameters kept constant, THD obtained is less through four switching leg topology in comparison to capacitor mid-point topology, although the number of switches required is more in four switching-leg topology. But in capacitor mid-point topology, two capacitors of double value for same peak to peak ripples in dc voltage are required. Also in the capacitor midpoint topology, third harmonic current components would flow in an uncontrolled manner through DC capacitor, as compared to four switching-leg topology. As the entire neural current flow through the DC link capacitor, it is recommended to use capacitor midpoint topology in smaller rating system, if preferred due to the requirement of less switches.

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