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Adaptive Hysteresis Based SHAF Using PI and FLC Controller for Current Harmonics Mitigation

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Abstract**—**Due to the increased use of the power electronic equipment, harmonics in the power system has increased to a greater extent. These harmonics results a poor power quality causing a major effect on the customers. Shunt active filters (SHAF) are used for the mitigations of the current harmonics and to maintain constant DC link voltage. PI and Fuzzy logic controllers (FLC) were used to control the performance of the shunt active filter under both balance and unbalance source voltage condition. The results found were not satisfying the IEEE-519 standards of THD to be less than 5%. Hysteresis band current control was used to obtain the gating signals for SHAF, though it has some drawbacks and thus to obtain a better performance of the SHAF to mitigate the harmonics, adaptive hysteresis band current control scheme is implemented. Adaptive hysteresis based SHAF is used to obtain better compensation of current harmonics and to regulate the DC link voltage in a better way.

Keywords**—**DC Link Voltage, Fuzzy Logic Controller, Adaptive Hysteresis, Harmonics, Shunt Active Filter.

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I. INTRODUCTION

THE power quality has been an important and growing problem because of the proliferation of nonlinear loads such as power electronic converters in typical power distribution systems in recent years. Particularly, voltage harmonics and power distribution equipment problems result from current harmonics produced by nonlinear loads [1]-[5]. Problems caused by power quality have great adverse economic impact on the utilities and customers. Power quality has become more and more serious with each passing day.

In the earlier research on power quality, hysteresis band current controller based SHAF for PI and FLC controller [5], [8] under balanced voltage source and unbalanced voltage source was considered which worked effectively enough to mitigate the harmonics that causes enormous economic loss every year [6]-[13]. Though this controller was working properly to mitigate harmonics to a larger extend but the results were not matching the standards of IEEE-519, according to which the THD content of any power system should be below 5% [1], [2]. Hence the results show the failure of hysteresis band current controller [7], [13] in obtaining the perfect or so called perfect harmonics mitigation. The controller has some drawbacks such as modulation frequency, varies in a band and, as a result, generates non-optimal current ripple in the load. Thus we need to have a controller which does not have variable modulation frequency and thus we go for adaptive hysteresis band current controller [7].

The controller selected for the mitigation of the harmonics should also be able to maintain the DC link voltage to a constant value. It should be also noted that the controller along with the SHAF should be able to maintain the real power requirement of the system and hence, adaptive hysteresis band current controller [6] is selected and the results obtained under various loading conditions for various supply is studied. The THD results obtained by the Hysteresis band current controller based SHAF for PI and FLC under balanced voltage source and unbalanced voltage source makes us understand that the THD mitigation for SHAF for FLC controller for balanced voltage source is quite better than the THD mitigation obtained for SHAF for FLC controller for unbalanced voltage source condition [1], [4].

In adaptive hysteresis band current controller the band is modulated with system parameters to maintain the modulation frequency to nearly constant. It changes the hysteresis band current controller's bandwidth as a function of reference compensator current variation to optimize switching frequency and THD of supply current. The switching variation depends on the rate of change of current from the upper limit to the lower limit or even from lower the limit to the upper limit. The MATLAB/SIMULINK results obtained after replacing Hysteresis band current controller with Adaptive Hysteresis band current controller are far better and satisfy the IEEE-519 standard of THD, according to which the amount of THD in any power system should be less than 5%, so that the system remains stable and overall economic losses can be reduced to a much larger extend than earlier. Further, after the clear information regarding the behavior of the waveforms of outputs, it was concluded that Adoptive Hysteresis band current controller is the best controller for the mitigation of harmonics.

Here we are dealing with current harmonics [3] so we will use SHAF instead of series filters which are used for mitigation of voltage harmonics. The SHAF used here along

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with adaptive hysteresis band current controller for PI and FLC is Voltage-fed-type APF. It has a self-supporting DC bus with a large DC capacitor. It is lighter cheaper than Current-fed-type APF and unlike Current-fed-type APF, Voltage-fed-type APF [11], [12] can be expandable to multilevel or multistep versions to enhance the performance with lower frequency and hence it is more commonly used.

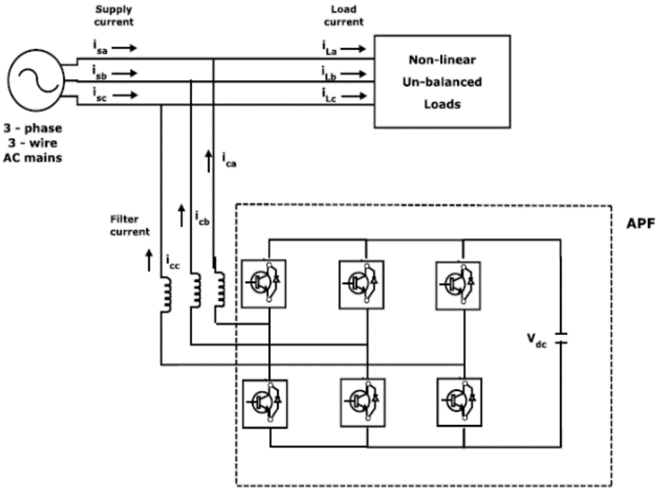


Fig. 1 SHAF for Three-phase, Three-wire system

Fig. 1 shows the schematic diagram SHAF [5], feeding a Three-phase Three-wire system along with the three phase non-linear load. Due to the non-linearity in the load the source voltage and source current is affected, unity power factor is disturbed. The SHAF injects the compensating current so that source current becomes purely sinusoidal and the power factor is maintained at unity. The SHAF has three-leg IGBT based voltage source inverter (VSI), interface inductor and a DC bus capacitor [12]. The SHAF is controlled to obtain the best performance and thus PI controller as well as FLC [5], [9] are used. The performance of SHAF is studied under balanced and unbalanced source voltage condition for normal load and increase load. The results show that the controlling of the SHAF offered by the FLC is much better than the controlling offered by the PI controller. When the source voltage is balanced, both the controller offers the same amount of compensation, a minimal change is observed, but when the source voltages are unbalanced, the FLC offers an outstanding compensation as compared to the PI controller.

In this work, controlling of the SHAF using the PI controller and FLC with triangular membership function is analyzed and studied. In Section I, the types of the power filters and the compensation principle of the voltage fed SHAF are explained. Section II focuses on the of the DC link voltage regulation in the shunt active filter and Adaptive Hysteresis band current controller. Section III includes the simulation part and followed by Section IV which deals with the results and its analysis. Section V gives the final conclusion of this paper followed by references.

II. POWER FILTERS

A. Shunt Active Power Filters

The presence of harmonics in the system gives enables us to take measures against their existence and hence power filters are designed so that the harmonics reduction is done and the DC link voltage regulation is also possible. When there is a change in load demand, the DC link voltage [12] is disturbed and hence the power filters work and maintain the DC link voltage to the constant and also nearer to the reference voltage [2], [7]. Power filters were initially bulky consisting of large LC filters or a bank of capacitance which were known as passive filters. They were cheap, easy to design and have high efficiency but they have several disadvantages too, such as they are bulky, the tuning frequency is not accurate, unable to mitigate multiple order harmonics content and they require a lot of calculations. Hence after the introduction of power electronics, active power filters were developed and the advantages were far more than those obtained by passive power filters. The active power filters are small in size and the tuning frequency is accurate. It even mitigates the harmonics of multiple order and DC link voltage regulation possible. The disadvantage of active power filters is that they sometimes generate internal harmonics due to the presence of power electronics devices in them. Power filters are further divided into three categories, they are: series power filters, shunt power filters and hybrid power filters. The series active filters are used to mitigate the problems of the voltage harmonics and are placed in series with the power system [8],[9]. The shunt active filter is used to mitigate the current harmonics present in the system and they are placed in the system at a point of common coupling (PCC). The hybrid filters are used to mitigate the current as well as the voltage harmonics present in the power system.

B. Voltage-Fed-type SHAF Compensation Principle

The APF [11] is controlled by using both controllers, to draw/supply the compensating current from/to the load to cancel out the current harmonics on AC side, to maintain the DC link voltage constant by maintaining the real power flow in the system and reactive power flow from/to the source, thereby making the source current in phase with source voltage.

Fig. 2 shows the basic compensation principle of the voltage fed shunt active power filter and due to the capacitor present, it becomes an energy storage element to supply the real power difference between load and source during the transient period. The shunt active filters are also used for reactive power compensation, unbalance current compensation (for 3 phase systems) and neutral current compensation (for 3 phase 4 wire systems) [7]-[9]. When the load changes the real power in the system too changes, thus the real power disturbance is cleared by the DC link capacitor and in doing so the voltage across the DC link capacitor changes away from the reference voltage.

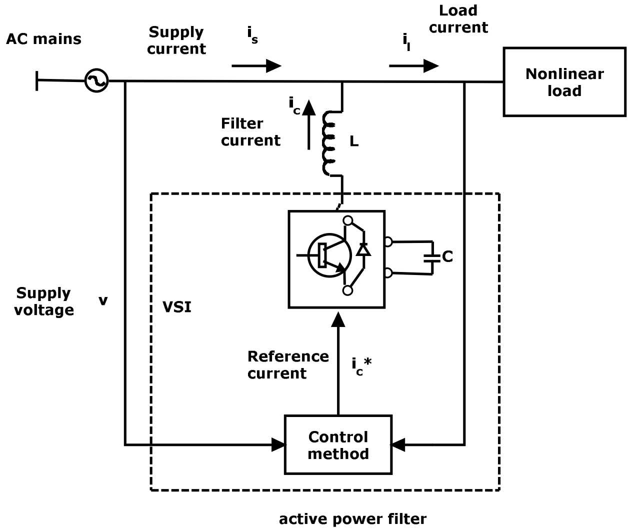


Fig. 2 Compensation Principle of a Voltage-Fed-Type SHAF

The peak value of the reference source current can be obtained by regulating the average voltage of the DC capacitor and if it attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again.

III. DC LINK VOLTAGE

A. DC Link Voltage Regulation

The frequent varying of load disturbs the real power flowing in the system which needs to be stabilized again. The capacitor and hence the DC link voltage also changes. If the active power flowing into the filter can be controlled in such a way that it is equal to the losses inside the filter, the DC link voltage can be maintained at the desired value. Thus the main purpose of the active power filter is to eliminate the current harmonics in the system and also to maintain the DC link voltage value to be constant by proper DC link voltage regulation. This paper represents the control offered by two different controllers namely PI controller which is a linear controller and Fuzzy Logic Controller [8], [9] which is a non-linear controller to control the adaptive hysteresis based shunt active filter (SHAF).

B. Adaptive Hysteresis Band Current Controller

In an adaptive hysteresis band current controller the band is modulated with the system parameters to maintain the modulation frequency to be nearly constant [7]. It changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and THD of the supply. The adaptive hysteresis band current controller changes the hysteresis bandwidth according to the modulation frequency, supply voltage or DC capacitor voltage. The switching frequency of the hysteresis band current control method depends on how fast the current changes from the upper limit of the hysteresis band [13] to the lower limit of the hysteresis band or vice versa. The rate of change of actual active power filter line current vary the switching frequency, thus the switching frequency remains constant throughout the switching operation. Adaptive Hysteresis control strategies are much better in controlling the active power filters by providing proper gating signals which are generated perfectly as the modulation frequency do not vary much and the signals are generated as per the rate of change of source current.

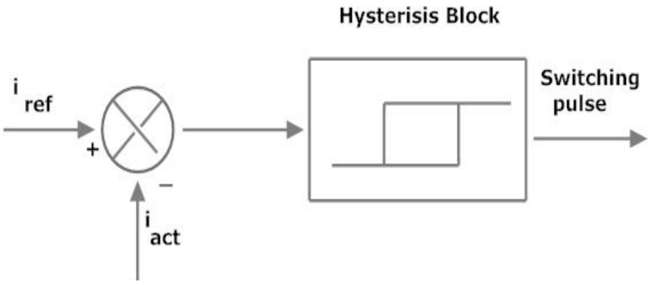


Fig. 3 Adaptive Hysteresis block

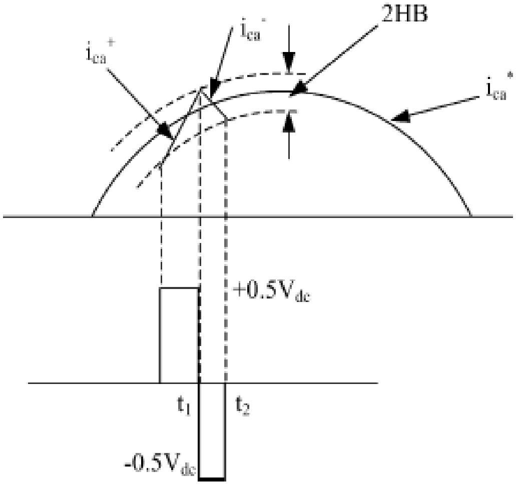


Fig. 4 Adaptive hysteresis band current controller

From Fig. 4 we have the equation

$$\frac{di_{ca}^{+}}{dt} = \frac{1}{L}(0.5V_{dc} - V_s) \tag{1}$$

$$\frac{di_{ca}^{-}}{dt} = -\frac{1}{L}(0.5V_{dc} + V_s) \tag{2}$$

From the Fig. 4 it is clear that

$$\frac{di_{ca}^{+}}{dt}t_1 - \frac{di_{ca}^{*}}{dt}t_1 = 2HB \tag{3}$$

$$\frac{di_{ca}^{-}}{dt}t_2 - \frac{di_{ca}^{*}}{dt}t_2 = -2HB \tag{4}$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \tag{5}$$

t1 & t2 are the respective switching intervals and fc is the switching frequency.

Adding (3) and (4) and substituting in (5), we get

$$t_1\frac{di_{a}^{+}}{dt} + t_2\frac{di_{a}^{-}}{dt} - \frac{1}{f_c}\frac{di_{ca}^{*}}{dt} = 0 \tag{6}$$

Substituting (4) from (3), we get

$$4HB = t_1 \frac{di_{ca}^{+}}{dt} - t_2 \frac{di_{ca}^{-}}{dt} - (t_1 - t_2) \frac{di_{ca}^{*}}{dt} \tag{7}$$

Substituting (2) in (7), we get

$$4HB = (t_1 + t_2) \frac{di_{ca}^{+}}{dt} - (t_1 - t_2) \frac{di_{ca}^{*}}{dt} \tag{8}$$

Substituting (2) in (6), we get

$$t_1 - t_2 = \frac{\frac{di_{ca}^{*}}{dt}}{f_c(\frac{di_{ca}^{-}}{dt})} \tag{9}$$

Substituting (9) in (8), we get

$$HB = \{\frac{0.125V_{dc}}{f_c L}\left[1 - \frac{4L^2}{V_{dc}^2}\left(\frac{v_s}{L} + m\right)^2\right]\} \tag{10}$$

Thus from the above equations we can develop the hysteresis band. Fig. 3 shows the block diagram of the adaptive hysteresis controller in which the difference between the actual current and reference current is measured. This difference current measured is given in the form of pulses to control the working of the active power filters.

Fig. 4 shows adaptive hysteresis band current controller and it is the modulation frequency which is maintained constant. There is no phase or amplitude error over a wide range of range of output frequency for Adaptive Hysteresis control strategy and the dynamic response of the system is boosted with much greater stability to the system. Adaptive hysteresis with fixed band which derives the switching signals of three phase IGBT based VSI is used because the switching of IGBT device should be such that the error signal should approach to zero, thus to provide quick response in order to get the accurate control. The switching signals are produced directly when the error exceeds an assigned tolerance band. The controller generates the sinusoidal reference current of desired magnitude and frequency that is compared with the actual motor line current. If the current exceeds the upper limit of the hysteresis band [7], [13], the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the actual current is forced to track the reference current within the hysteresis band.

IV. SIMULATIONS

The three-phase three-wire system with a non-linear load is equipped with shunt active filter for mitigating the current harmonics using adaptive hysteresis band current controller. PI controller and FLC are used to control the shunt active filter under balanced and unbalanced source voltage condition for normal load as well as increase load. Table I shows the system parameters of the balance source voltage condition circuit that has been analyzed and Table II shows the system parameters of the Unbalance source voltage condition circuit that has been analyzed. Simulations results of PI and FLC controller are generated for the better understanding of the system so that the stability of the system is maintained good by providing the compensating current and the losses can be reduced.

A. Performance of FLC Based SHAF Under Balanced Sinusoidal Condition Using Adaptive Hysteresis Band Current Control Scheme:

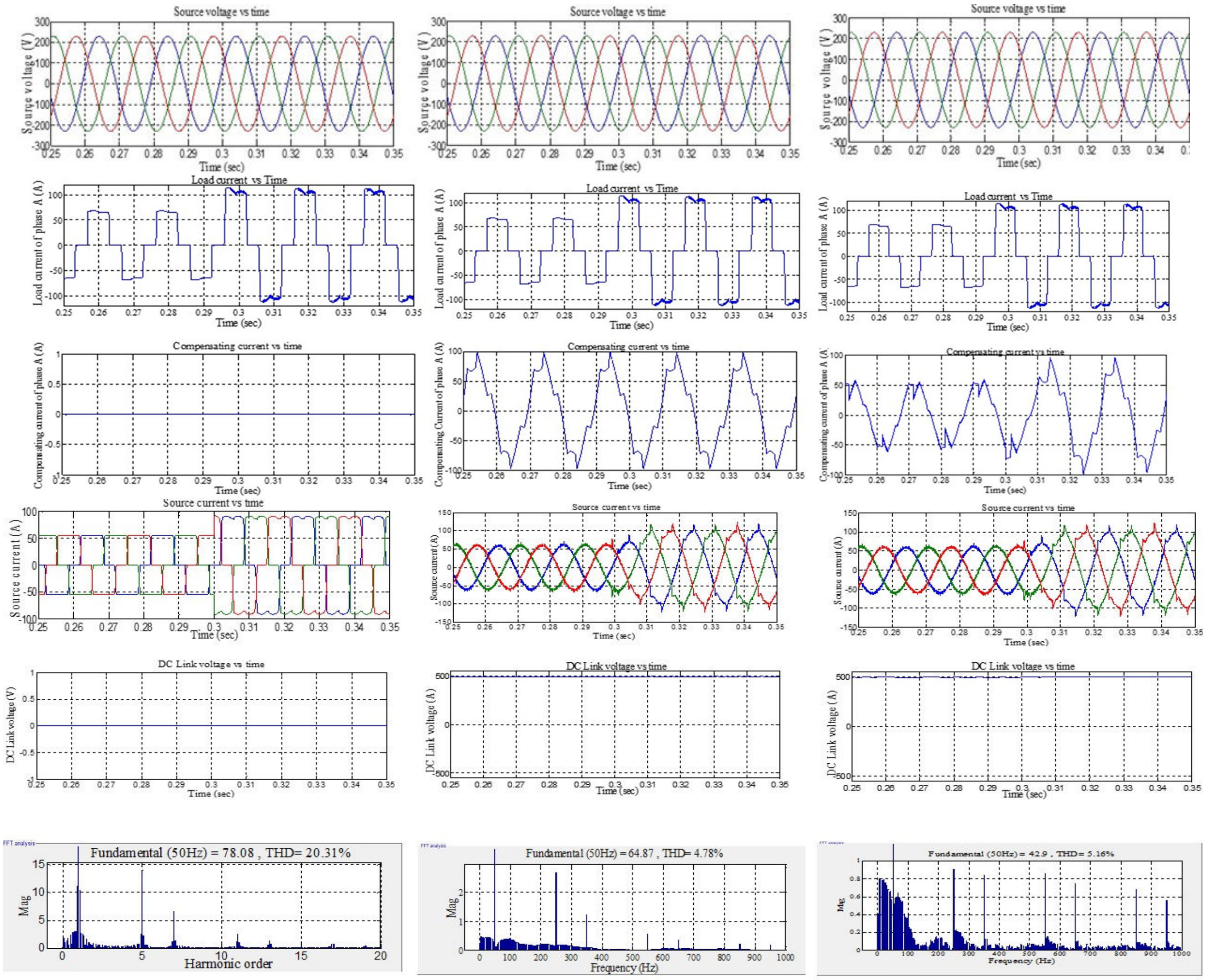
Fig. 5 highlights the performance of FLC based SHAF underbalanced Sinusoidal conditions, using MATLAB/ SIMULINK. As load is highly inductive, current draw by load is integrated with rich harmonics. Fig. 6 gives the details of source voltage, load current, compensation current, source current with filter, DC link voltage, THD (total harmonic distortion) of FLC using MATLAB under un-balanced sinusoidal supply voltage conditions.

Table I gives the system parameters for balance condition with FLC. The SHAF is controlled using the FLC so that it offers better current harmonics compensation and better DC link voltage regulation. It is seen from Fig. 5 that the load current is highly distorted and this load current also affects the source current and thus compensating current has to be given so that it cancels out the harmonic and sinusoidal current is obtained. It is shown in Fig. 6 that the THD value under balanced source voltage condition with increased load condition is less than 5%, as mentioned in IEEE standard-519 but to reduce it further a new approach is needed and thus instead of hysteresis band current control scheme, Adaptive hysteresis band current control scheme is implemented. The current harmonics mitigation obtained using the Adaptive hysteresis is much better than the current harmonics mitigation obtain using Hysteresis band current control scheme.

TABLE I
SYSTEM PARAMETERS FOR BALANCED CONDITION

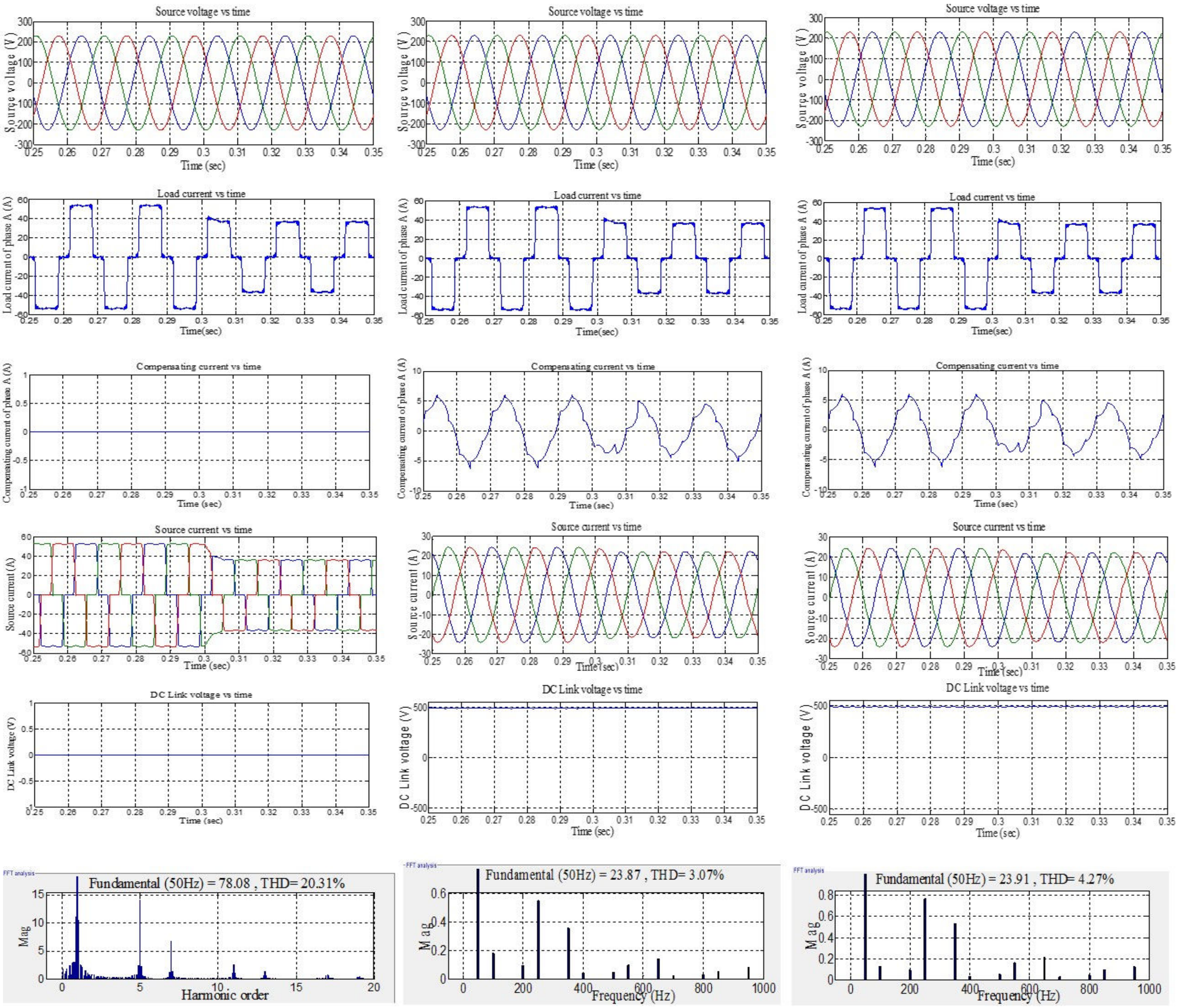
Specifications	Units
Source voltage of phase A	230 V
Source voltage of phase B	230 V
Source voltage of phase C	230 V
Smoothing resistance	0.1 Ω
Smoothing reactance	0.15 mH
DC link capacitor	2 mF
Sample interval	0.00001 S
Normal load resistance	6.7 Ω
Normal load reactance	20 mH
Increased load resistance	6.7 Ω
Increased load reactance	100 mH
Step input	0.3 S
FIS type for FLC	Mamdani
Membership function for FLC	5X5 Triangular
Implication for FLC	Min
Deffuzification	Centroid

V = voltage, Ω = ohm, H = henry, F = faraday, S = second.



(a) (b) (c)

Fig. 5 PI controller based SHAF response under: (a) Balanced source voltage condition without controller, (b) Balanced source voltage condition using Adaptive hysteresis for normal load, (c) Balanced source voltage condition using Adaptive hysteresis for increased load

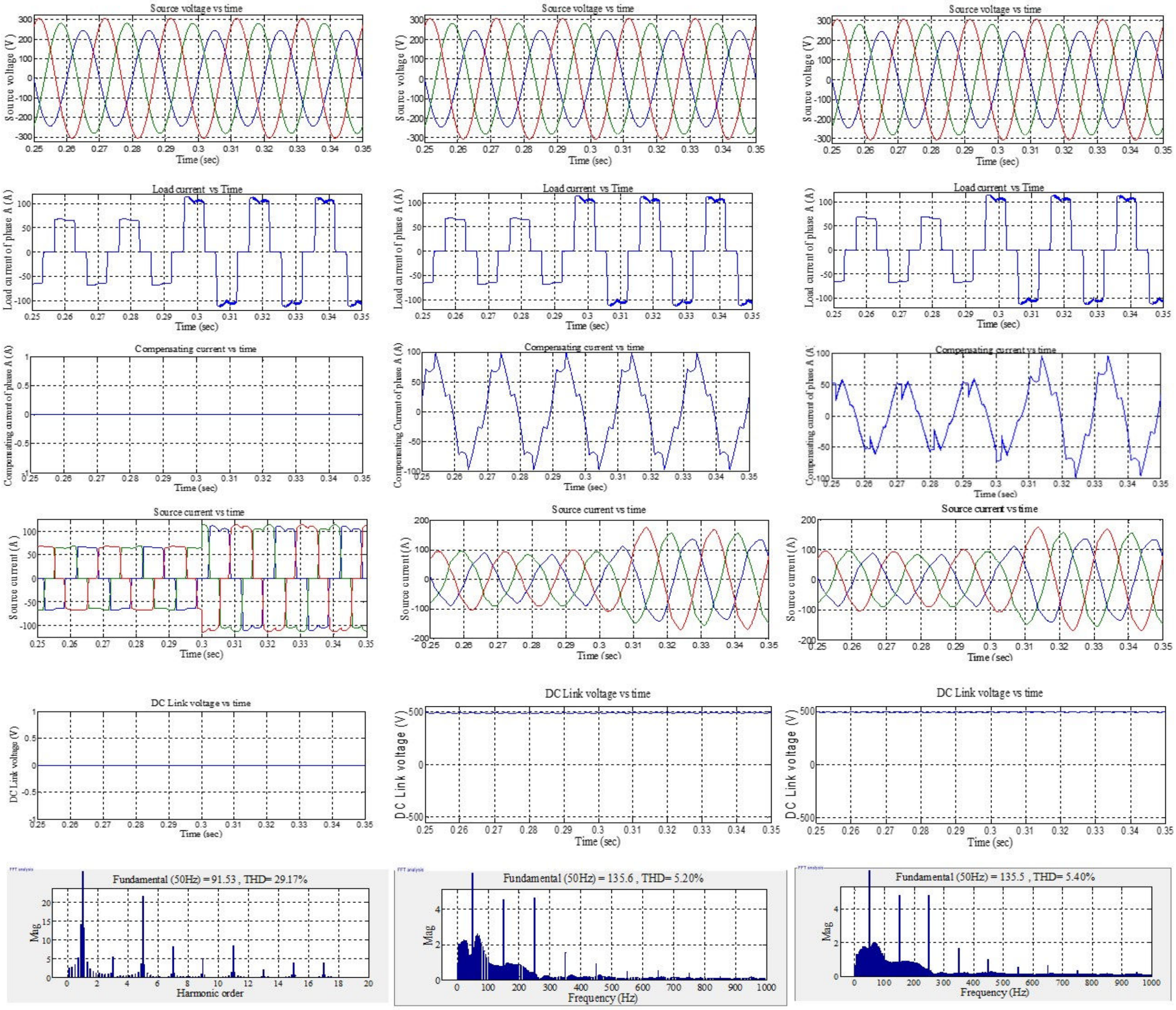


(a) (b) (c)

Fig.6 FLC based SHAF response under: (a) Balanced source voltage condition without controller, (b) Balanced source voltage condition using Adaptive hysteresis for normal load, (c) Balanced source voltage condition using Adaptive hysteresis for increased load

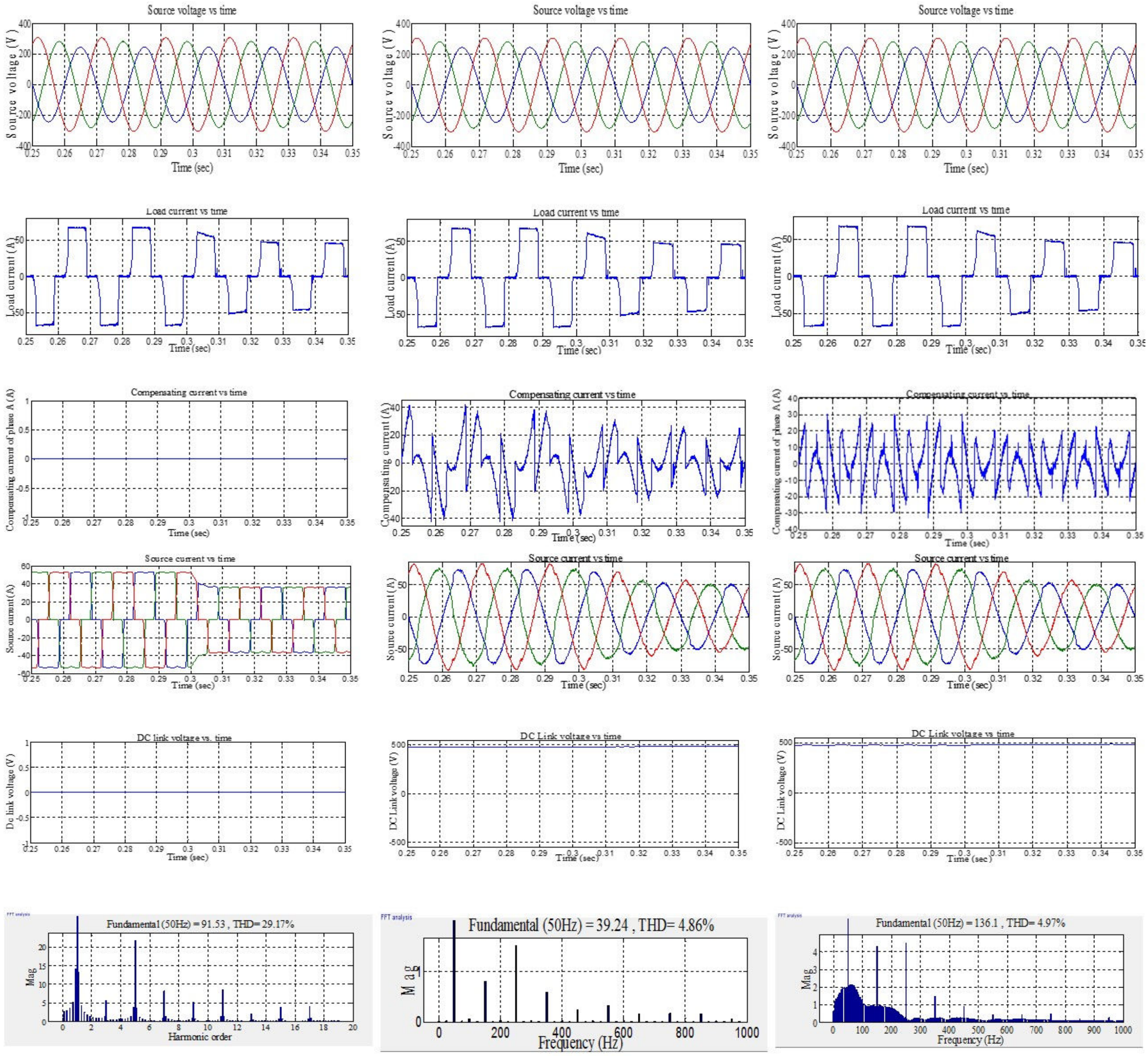
B. Performance of PI Controller Based SHAF under Un-Balanced Sinusoidal Condition Using Adaptive Hysteresis Band Current Control Scheme:

Fig. 7 highlights the performance of PI controller based SHAF under un-balanced sinusoidal conditions, using MATLAB/SIMULINK. As load is highly inductive, current draw by load is integrated with rich harmonics. Fig. 7 gives the details of source voltage, load current, compensation current, source current with filter, DC Link Voltage, THD of PI controller using MATLAB under un-balanced sinusoidal supply voltage conditions.



(a) (b) (c)

Fig. 7 PI controller based SHAF response under: (a) Unbalanced source voltage condition without controller, (b) Unbalanced source voltage condition using Adaptive hysteresis for normal load, (c) Unbalanced source voltage condition using Adaptive hysteresis for increased load



(a) (b) (c)

Fig. 8 FLC controller based SHAF response under: (a) Unbalanced source voltage condition without controller, (b) Unbalanced source voltage condition using Adaptive hysteresis for normal load, (c) Unbalanced source voltage condition using Adaptive hysteresis for increased load

Table II gives the system parameters for balance condition with PI controller. The SHAF is controlled using the PI controller so that it offers better current harmonics compensation and better DC link voltage regulation. It is seen from Fig. 7 that the load current is highly distorted and this load current also affects the source current and thus compensating current has to be given so that it cancels out the harmonic and sinusoidal current is obtained.

It is shown in Fig. 8 that the THD value under un-balance source voltage condition with increased load condition is quite more and thus to reduce it and to make it less than 5%, a new approach is needed and thus instead of hysteresis band current control scheme, Adaptive hysteresis band current control scheme is implemented. The current harmonics mitigation obtained using the Adaptive hysteresis is much better than the current harmonics mitigation obtain using Hysteresis band current control scheme.

TABLE II
SYSTEM PARAMETERS FOR UNBALANCE CONDITION

Specifications	Units
Source voltage of phase A	200 V
Source voltage of phase B	230 V
Source voltage of phase C	250V
Smoothing resistance	0.1 Ω
Smoothing reactance	0.15 mH
DC link capacitor	2 mF
Sample interval	0.00001 S
Normal load resistance	6.7 Ω
Normal load reactance	20 mH
Increased load resistance	6.7 Ω
Increased load reactance	100 mH
Step input	0.3 S
FIS type for FLC	Mamdani
Membership function for FLC	5X5 Triangular
Implication for FLC	Min
Deffuzification	Centroid

V = voltage, Ω = ohm, H = henry, F = faraday, S = second.

V. RESULT AND ANALYSIS

The results obtained from the simulation shows that the compensation offered by PI controller as well as by fuzzy logic controller is same (though THD of FLC is bit less) when the source voltage is balanced (ideal). When the source voltage is unbalanced (non-ideal), it is observed that the compensation offered by the FLC is much better than the PI controller.

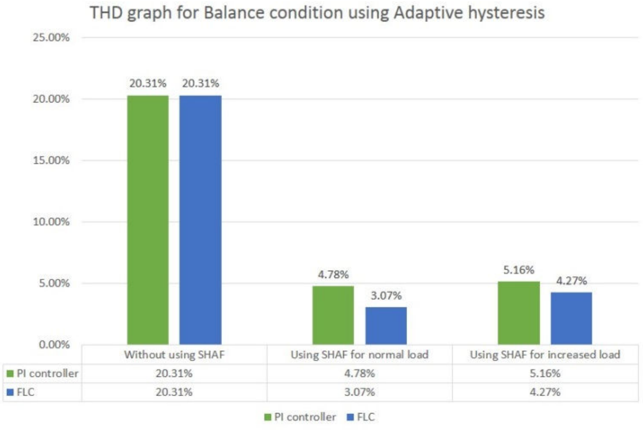


Fig. 9 THD graph for balance condition using PI controller and FLC with Adaptive Hysteresis

The THD for normal load under balance condition using PI controller is 4.78% and using the FLC it is 3.07%. The THD for increased load under balance condition using PI controller is 5.16% and using the FLC it is 4.27%. The THD for normal load under unbalanced condition using PI controller is 5.20% and using FLC it is 4.86%. The THD for increased load under unbalance condition using PI controller is 5.40% and using FLC it is 4.97%. The THD value should be less than 5% as per IEEE-519 standards. It is seen from the simulation results that THD value is less than 5% under balance condition and unbalanced condition using FLC and nearly 5% under unbalance condition, using the PI. Thus it is clear that Adaptive Hysteresis gives outstanding results in THD mitigation and DC link voltage regulation.

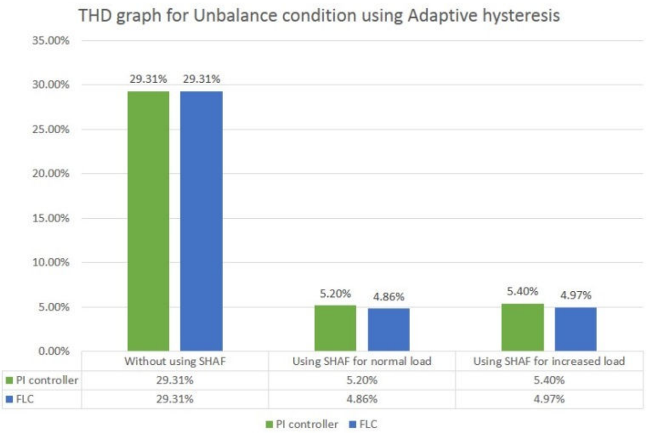


Fig. 10 THD graph for un-balance condition using PI controller and FLC with Adaptive Hysteresis

VI. CONCLUSION

In the present work two controllers, PI controller and fuzzy logic controllers are used to control the adaptive hysteresis based shunt active filter (here voltage fed is used as current harmonics are there), which is used to compensate the current harmonics. The simulation results showed that, even if the supply voltage is unbalanced (non-ideal) the performance of adaptive hysteresis based SHAF using FLC with triangular MF comfortably outperformed the results obtained using adaptive hysteresis based SHAF with PI controller. The THD value offered by the SHAF when controlled by FLC (with triangular MF) is much less as compared to the THD value obtained using PI controller. Thus it can be concluded that FLC offers a better controlling to the shunt active filter than the PI controller.

While considering the SHAF with FLC, the SHAF has been found to meet the IEEE 519-1992 standard recommendations on harmonic levels, making it easily adaptable to more severe constraints such as unbalanced supply voltage. The DC bus voltage of SHAF is almost maintained at the reference value under non-ideal conditions, which confirm the effectiveness of the Fuzzy logic controller.

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