DESIGN AND SIMULATION STUDY OF HYBRID NON-LINEAR CONTROLLED SHUNT ACTIVE POWER FILTER (APF) FOR POWER QUALITY ENHANCEMENT IN THREE PHASE FOUR WIRE SYSTEM

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Abstract: *This article describes the design and simulation study of Hybrid Non-Linear Controlled (HNLC) Shunt APF (SAPF) for increasing the power quality in three phase four wire system through the reduction of harmonics and reactive power compensation. In many existing SAPF models were tested at non-linear diode rectifier load but in this article traction load model is consider to test the designed HNLC SAPF for harmonic reduction in 3Φ four wire system. A SAPF is a Voltage Source Inverter (VSI). It requires two control loop namely inner hysteresis current loop act as current shaping loop and outer voltage control loop act as regulation of VSI D.C link capacitor voltage. In this article outer loop is selected as HNLC such Sliding Mode Control (SMC) plus PI Controller (PIC) and Fuzzy Logic Controller (FLC) plus Proportional Integral Controller (PIC). The reference current of inner current loop is arrived indirectly from the HNLC and synchronous reference frame theory. The PWM gate pulse from Hysteresis current controller (HCC) for VSI gate switches. The performance of the designed circuit with designed HNLC is analyzed at different load operating conditions by creating Matrix Laboratory (MATLAB)/Simulation Link (Simulink) models. The results are addressed to show proficient of the developed system.*

Key words: *Active Filter, Three-phase Four wire Systems, Hybrid Controller, Power Quality, MATLAB/Simulink.*

1 Introduction

The THD is playing a major power quality difficulty in electric network system. The harmonics are generated in the power system with operating non-linear loads (like: capacitive and inductive loads). Once the THD is mixed in the power supply in power system that can lead to heating, more power loss and damage of various components and equipments. In this regard, it is required to eliminate THD smaller than five percentages as per the IEEE: 519-1992 code for harmonic standard. In order to rectify these problems, many methods were surveyed [1-2]. From this survey, passive filter method has problems with complex filter size, instability, and resonance via. load conditions. Also, another methodology from this survey is Active Power Filter (APF). It consists of shunt APF and series APF. A main role of series APF in power system is utilized to restitute the harmonic voltage and generating the voltage fed to the non-linear traction load but this method could not be compensated for current harmonics in the load. Second approach like shunt APF is applied to compensate fundamental components like current harmonics and reactive power. Therefore, shunt APF is selected for gaining knowledge in 3 phase four wire power system. One of the major problems of shunt APF is the design of control methodology. So many current controllers, voltage controllers and reference current generation theory have been reported [3-8]. However, from this article, hybrid controllers with 3phase, 4-wire systems have not been developed. The repetitive control methodology for shunt APF is well presented [9]. But, in this article, control methodology and implementation is complex. Experimental analysis of shunt compensator with synchronous rotating reference frame based control method [10]. However, this article presents the hysteresis current controller and PI controller is used for current shaping and D.C. link voltage regulation. Improvement analysis of current injection techniques for shunt APF is well presented [11-12]. In addition HCC method is employed for current compensation. FLC being shunt APF presented [13-14]. Moreover, the demerits are 1) more complex to estimate the reference current generation 2) many overshoots in DC link voltage of VSI. The demerits are resolved by a new approach of Hybrid Non-Linear Controlled (HNLC). Therefore, proposes a HNLC shunt APF for power quality enhancement now for 3Ø, 4-wire power system. In this study, Sliding Mode Controller (SMC) plus PIC and FLC plus PIC is used as HNLC for designed system. The designed model is verified by making MATLAB/Simulink at various operating conditions as well as load.

2 Design of Hybrid Non-Linear Controlled Shunt APF

The shunt APF essential compensation principle of is controlling the source compensating current from electric power network. In order that eliminates a current harmonic in grid side and builds the source current in phase with source voltage. The filter inductance which is connects the source and shunt APF. This operates as feedback controlled current source depicting in fig 1. The VSI output voltage D.C link capacitors voltage is regulated with help HNLC.

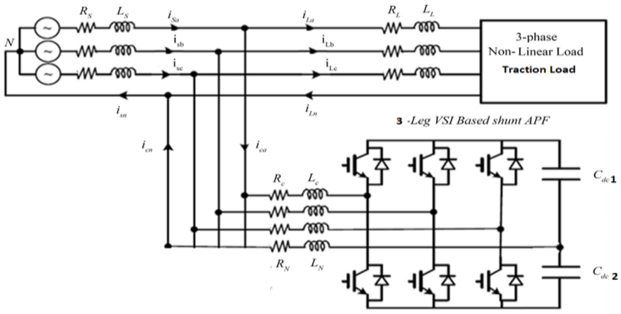


Fig.1. 3phase, four wire, Shunt APF with Traction Non-linear load

In this article, synchronous reference frame theory is used to find reference current generation of shunt APF. It is also called as d-q theory. At this point, the reference frame (d-axis, q-axis) is determined by the angle θ used in the d-q theory. One of the merits of this technique is that the angle θ is computed straightly from the supply voltages and making this method frequency independent. As a result the synchronizing problem between imbalanced and distorted voltages is also eliminated. Thus with i_d, i_q a huge frequency operating range can be attained. After, the i_d–i_q currents are evaluated from the park transformation. The i_d–i_q currents flow through a filter circuit to mitigate the DC parts in the non-linear load. The i_d–i_q current shown in Fig.2.

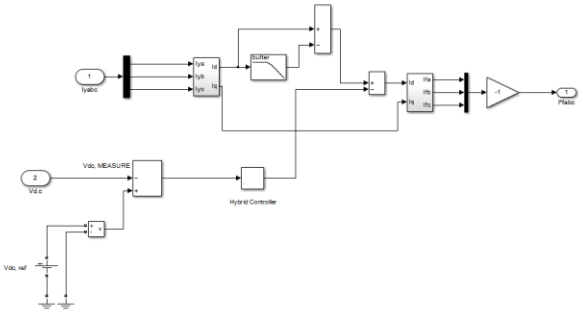


Fig.2. Synchronous reference frame (SRF) theory for generation of reference current

3. Design of HNLC shunt APF

This portion presents the HNLC with shunt APF which improves the power quality parameters. In this article, HNLC is selected as a combination of PI controller plus FLC and PI plus SMC and it is regulate the D.C link voltage of shunt APF. Inner hystereses current control (HCC) loop is used to produce PWM pulses for power electronic switches of shunt APF to shape the source current and reduce the harmonics in source current. The reference current for HCC is obtained from d-q theory method.

3.1. PI controller

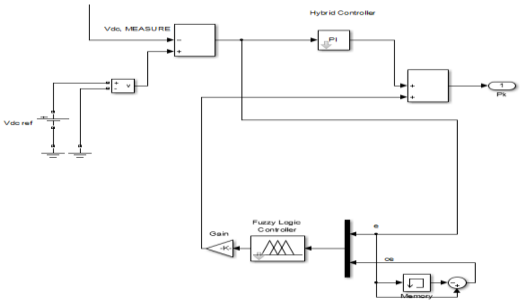
A PI controller is selected for providing the excellent voltage from the DC link capacitor of shunt APF for voltage regulation and suppressed error (steady state error). In this article, the PI controller constants of this converter (K_p and T_i)

are found from the Zeigler – Nichols technique (K_p= 0.6 and K_i=500).

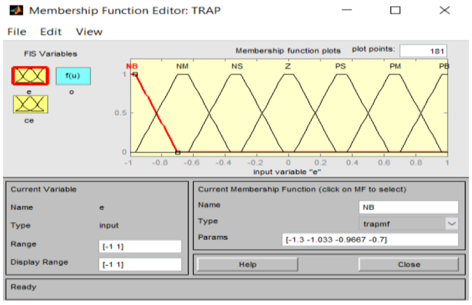
3.2. Design of FLC

The benefits of FLC over linear control methods are that it does not need any complex mathematical models, which are always essential for highly complex non-linear models. The FLC use the heuristic reasoning ability based on the human experience of the model [13]. The structure of the FLC for shunt APF is depicted in Fig. 3. In this article, the sugeno-method FLC is an outer voltage loop to modulate the switches of the VSI. The Fig. 3(a) to(c) shows the applied inputs of the FLC and outputs for the shunt APF. The both error signal (voltage error (e)) and reference error (change-in error (ce)) of this converter is given to FLC as a input and the output is o (note the control signal for the power converter switches). For convenience, the arithmetic input values as well as the output of the FLC may be standardized and showed in Figs.3b to 3d (output (o) = [-0.5 -0.4 -0.3033 0 0.4 0.3033 0.5]). The equivalent fuzzy logic sets [NB, NM, NS, Z, PS, PM, PB] here, NB (-ve big), NS (-ve small), Z (zero), PS (+ve small), PM (+ve medium), PB (+ve big) in sequentially. The trapezoidal membership functions are illustrated in Fig 3.

The collection of fuzzy rules is totally turned to dynamic behavior of the proposed shunt APF. Here, 49 rules are framed (Table - 1). Then, the average method used for defuzzification and applied to close the FLC design.



(a) Simulink model of HNLC for shunt APF



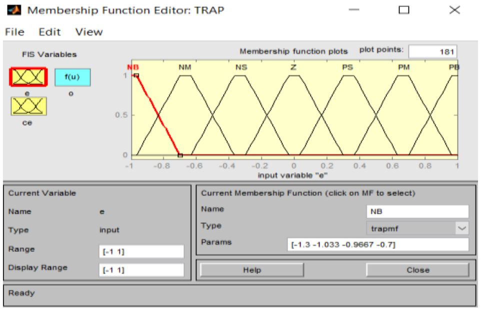
plot points: 181

Current Variable
Name: e
Type: input
Range: [-1 1]
Display Range: [-1 1]

Current Membership Function (click on MF to select)
Name: NB
Type: trapmf
Params: [-1.3 -1.033 -0.9667 -0.7]

Ready

(b) error membership function



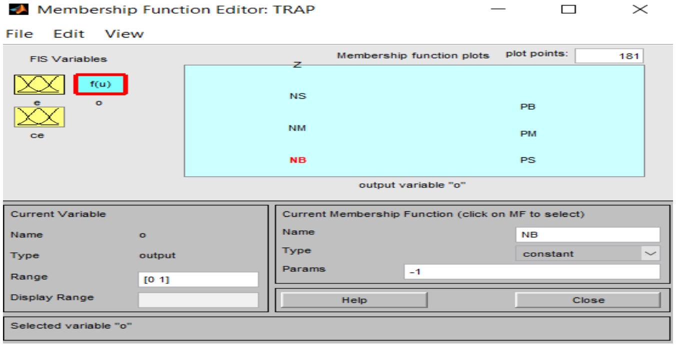
plot points: 181

Current Variable
Name: e
Type: input
Range: [-1 1]
Display Range: [-1 1]

Current Membership Function (click on MF to select)
Name: NB
Type: trapmf
Params: [-1.3 -1.033 -0.9667 -0.7]

Ready

(c) change in error membership function



plot points: 181

Current Variable
Name: o
Type: output
Range: [0 1]
Display Range:

Current Membership Function (click on MF to select)
Name: NB
Type: constant
Params: -1

Selected variable "o"

(d) output memberships function.

Fig.3 HNLC for shunt APF

Table. 1 Fuzzy logic SET for shunt APF

e \ ce	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	PM	PM	NB	NS	NM	NB
NS	NB	NB	NB	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	NB
PS	NM	NS	NM	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	NB	PB
PB	Z	PS	PM	PB	NM	PB	PB

3.3. Sliding Mode Controller

Sliding mode control (SMC) simulation introduces a signum function for the current with two values: $I_{d,\ max}$ and $I_{d,\ min.}$ SMC algorithm is given in equation (1). The simulation result for the DC link voltage of shunt APF is given in the Fig. 4.

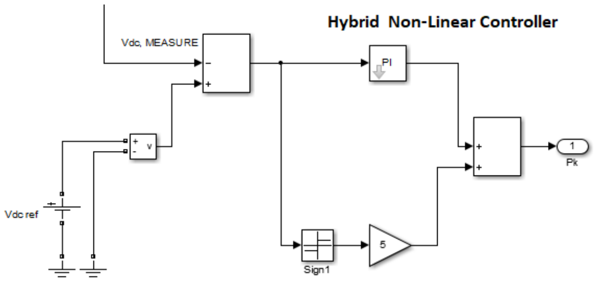


Fig. 4. Matlab model Sliding Mode Controller plus PI controller for shunt APF.

$$i_d = \begin{cases} i_{d,\min} & \Delta V_{dc} \succ 0 \\ i_{d,\max} & \Delta V_{dc} \prec 0 \end{cases} \qquad (1)$$

Where,

$$\Delta V_{dc} = V_{dc} - V_{dc,ref}$$

4. Results and Discussions

In this part the simulation result and analysis of HNLC shunt APF at different operating conditions and its specifications are listed in Table 2. Fig. 5 and 6 show the simulation model of HNLC with shunt APF.

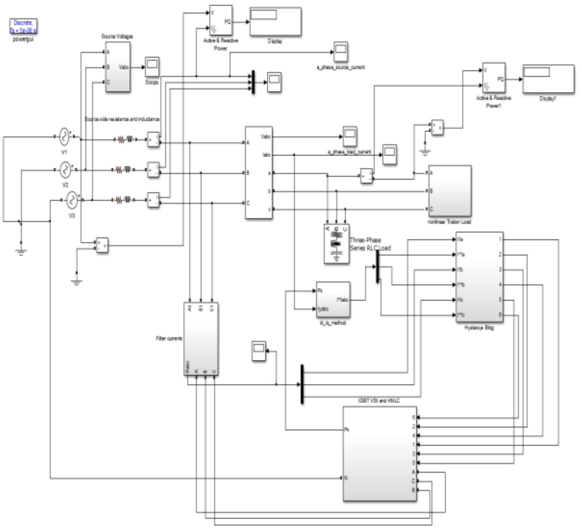


Fig.5. Simulink model HNLC for shunt APF.

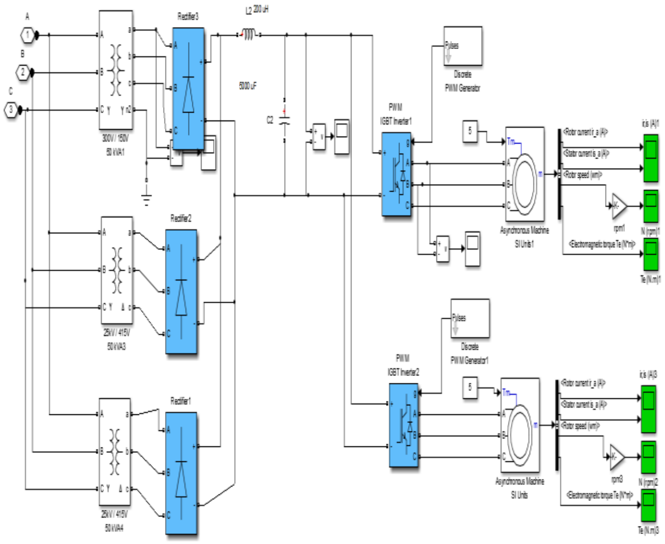


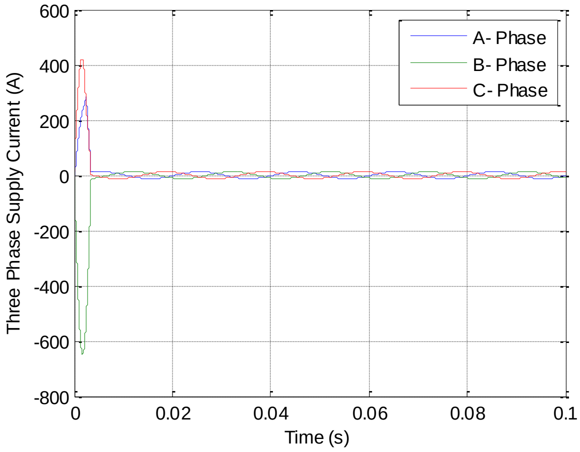
Fig.6. Simulink model of Traction load.

Table.2. Circuit parameters of designed shunt APF

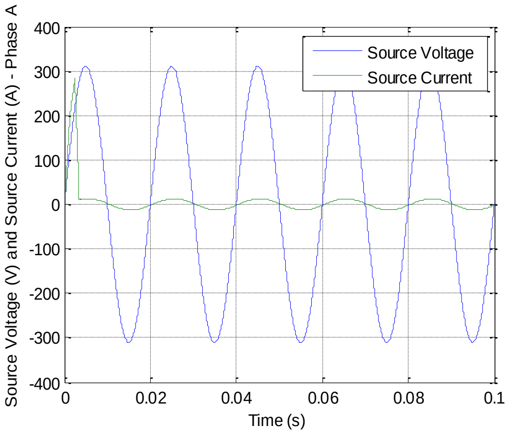
Name of the Parameters	Numerical value
(V_{SA}) per phase - Source voltage	220V, 50 Hz
DC Capacitor C_1=C_2 & DC link voltage	3000µF, 800V
Source Impedance (R_S) &(L_S)	0.01 ohms,0.1e-3H
Diode Rectifier - Load parameters	50 ohms,60 mH
Filter parameters (L_F) & (C_F)	0.1 ohm, 1mH
Switching frequency	1KHZ

4.1. Shunt APF without filter

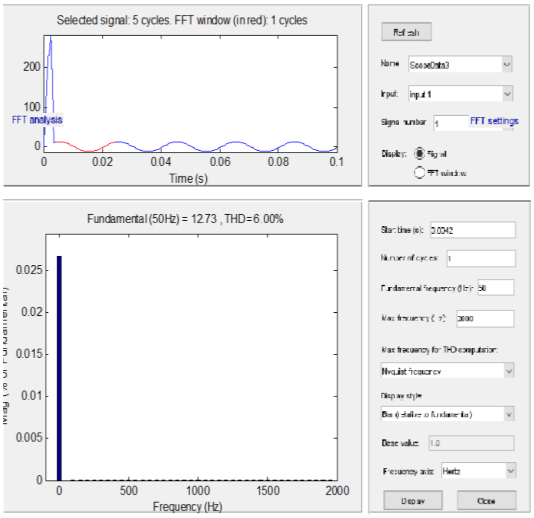
The Fig. 7 depicting the simulation output of AC side current, voltage, THD analysis and load side current of 3phase, 4 wire systems without shunt APF for traction load. From these results, it is evident that THD of the power system without filter has been indentified 6% for traction load.



(a) Source current



(b) Source current and voltage



Selected signal: 5 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 12.73 , THD= 6.00%

Name: ScopeData3

Input: input 1

Signal number: 1

Display: ● Signal ○ FFT window

Start time (s): 0.0042

Number of cycles: 1

Fundamental frequency (Hz): 50

Max frequency (Hz): 2000

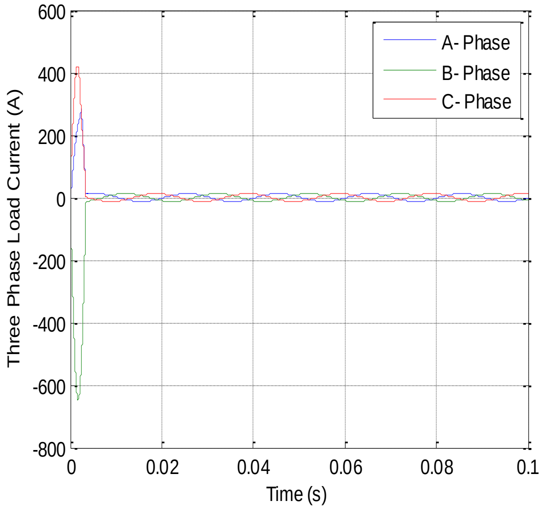
Max frequency for THD computation: Nyquist frequency

Display style: Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

(c) THD analysis

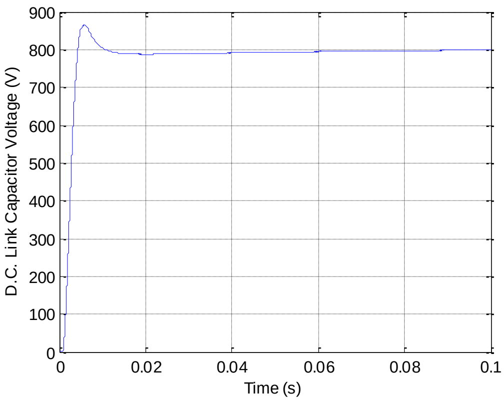


(d) Load current.

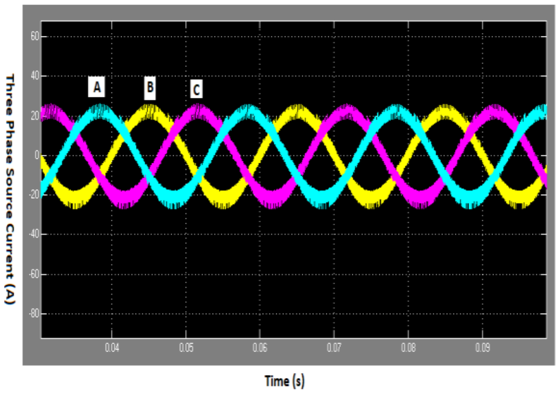
Fig. 7. Simulation output of 3Ø, 4 wire system without shunt APF for traction load.

4.2. Shunt APF with PI plus HCC

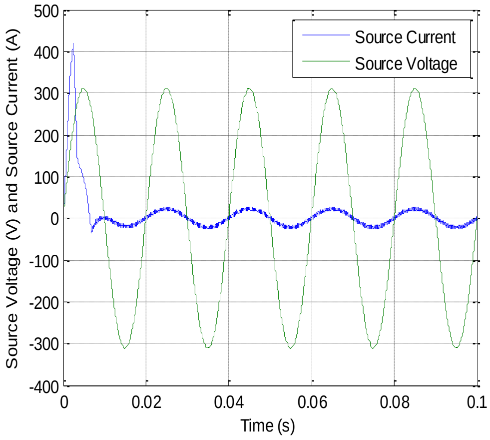
The Fig. 8 represents the simulated results of source current, source voltage, THD analysis, compensated filter current, D.C link voltage and load current of 3-phase, 4 wire system using shunt APF for traction load with PI controller plus HCC. From this result, it is found that THD of the power system with filter has been 4.87% for traction load. Also, the settling time of D.C link voltage is quick with small transient overshoots with this controller at load condition.



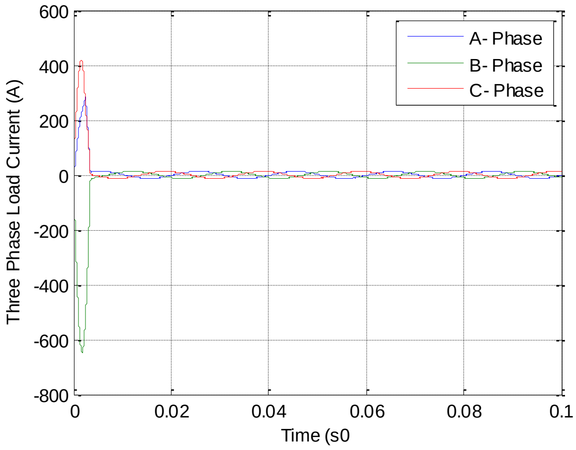
(a)). D.C link capacitor voltage with shunt APF



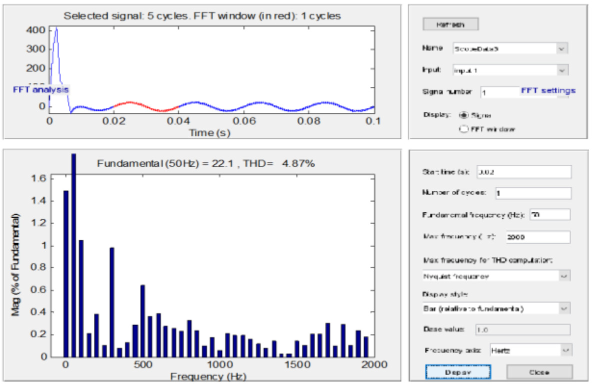
(b)). Source current



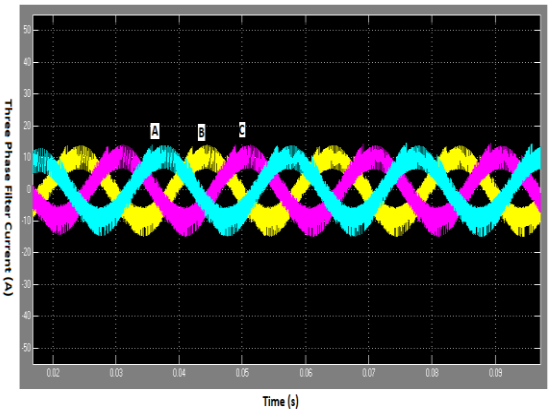
(c) Source current and voltage



(d) Load current


Name: ScopeData5
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.02
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 2000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

(e) THD analysis

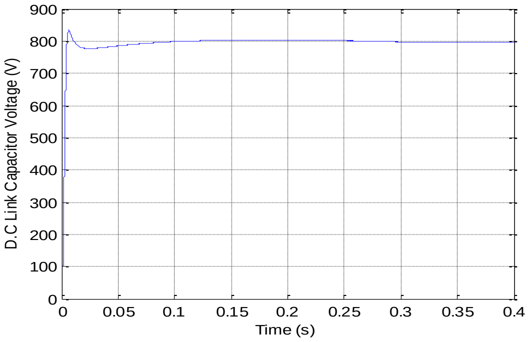


(f) Compensated filter current

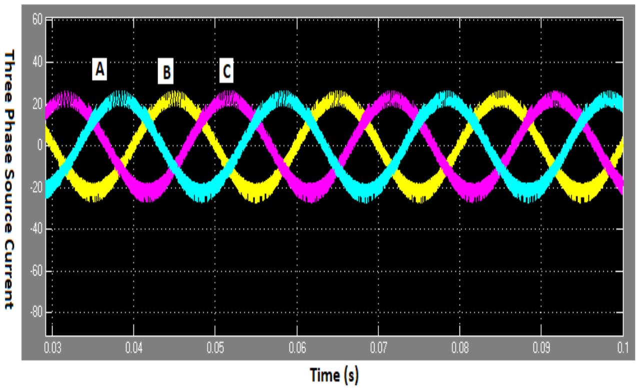
Fig.8. Simulation output of 3Ø, 4 wire power system for traction load using PI plus HCC,

4.3. Shunt APF with FLC, PI and HCC

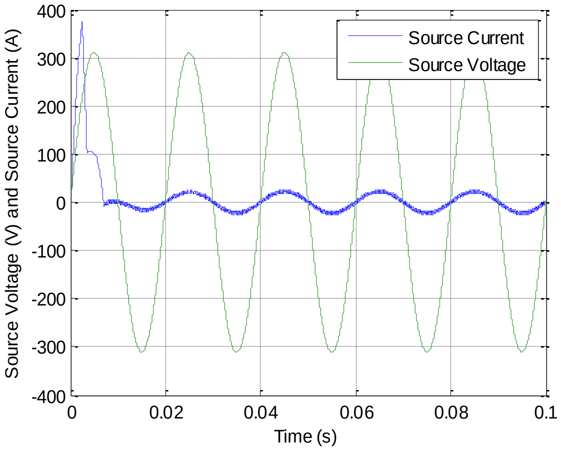
The simulated output diagram of source current, source voltage, THD analysis, compensated filter current, D.C link voltage and load current of 3Ø, 4 wire power system using shunt APF for traction load with FLC plus PI controller (HNLC) and HCC are shown in fig 9. From these results, it is found that THD of the power system with filter has been found 4.47% for traction load. Also, the settling time of D.C link capacitor voltage is rapid with low transient overshoots with this controller at both load conditions.



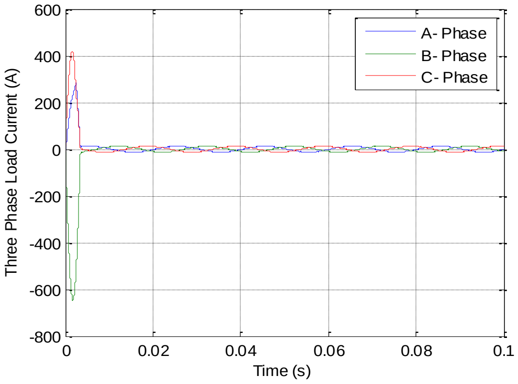
(a) D.C link capacitor voltage



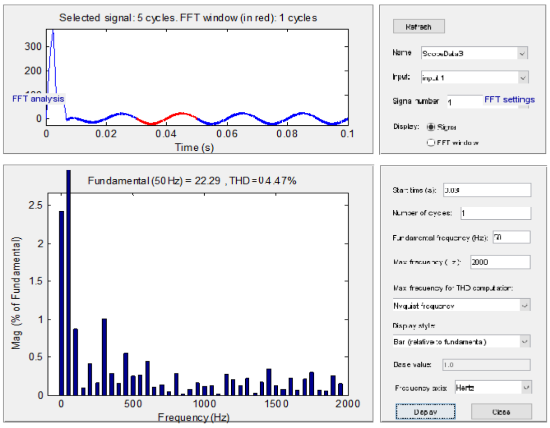
(b) Source current



(c) Source current and voltage



(d) Load current



Name: ScopeData3

Input: input 1

Signal number: 1

Display: ● Signal ○ FFT window

Start time (s): 0.03

Number of cycles: 1

Fundamental frequency (Hz): 50

Max frequency (Hz): 2000

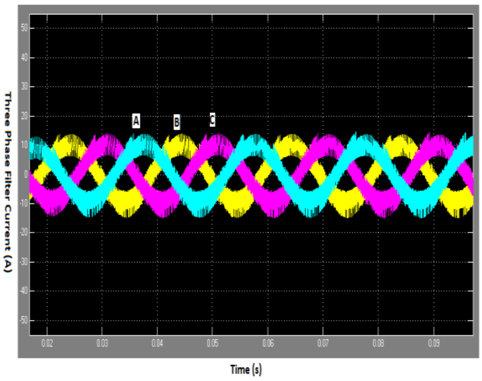
Max frequency for THD computation: Nyquist frequency

Display style: Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

(e) THD analysis

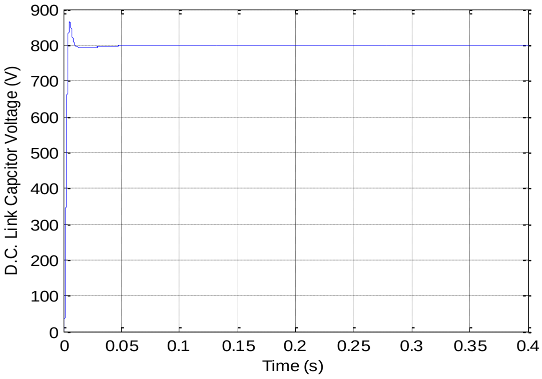


(f) Compensated filter current

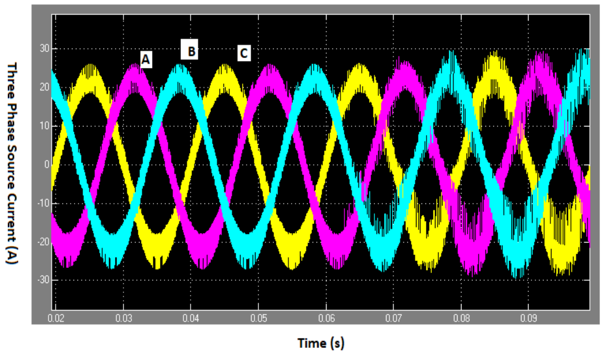
Fig.9. Simulated results of 3 phase, 4 wire power system with shunt APF for traction load using FLC plus PI and HCC

4.4. Shunt APF with Sliding Mode Control, PI and HCC

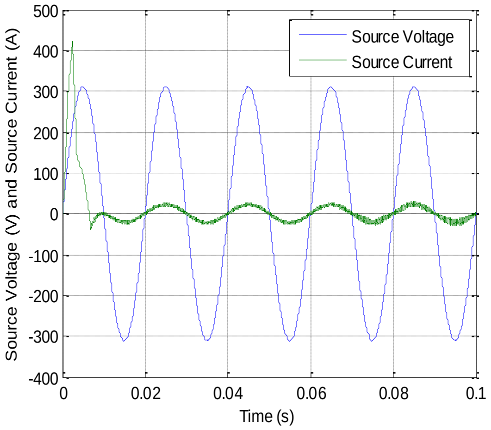
The Fig. 10 displays the simulated wave form of source current, source voltage, THD analysis, compensated filter current, D.C link capacitor voltage and load current of 3-phase, 4 wire power system using shunt APF for traction load with SMC plus PI controller (HNLC) and HCC. From these results, it is found that THD of the power system with filter has been indentified that as 2.92% for traction load. Also, the settling time of D.C link capacitor voltage is very quick with minimal transient overshoots with this controller at the load condition. And also, it is found that the designed shunt APF using designed controller has been produced excellent performance via. THD, power factor and time domain specifications at various load conditions.



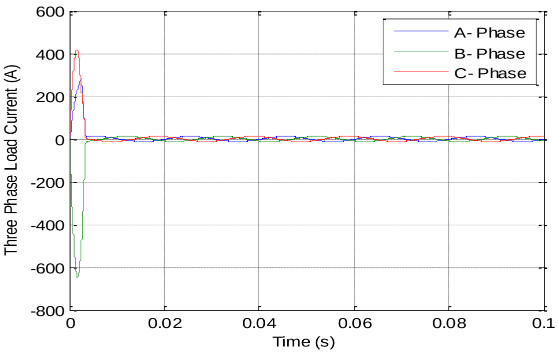
(a) D.C link capacitor voltage



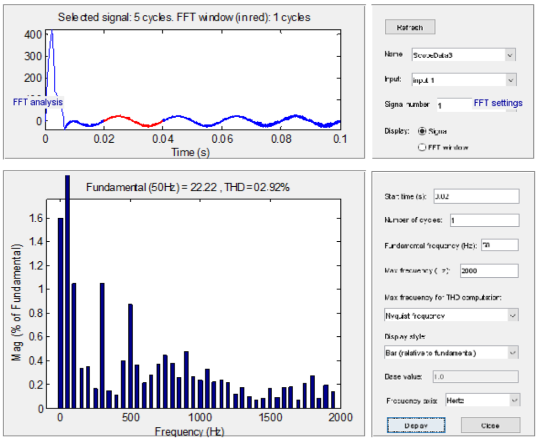
(b) Source current



(c) Source current and voltage



(d) Load current



Name: ScopeData3

Input: input 1

Signal number: 1

Display: ● Signal ○ FFT window

Start time (s): 0.02

Number of cycles: 1

Fundamental frequency (Hz): 50

Max frequency (Hz): 2000

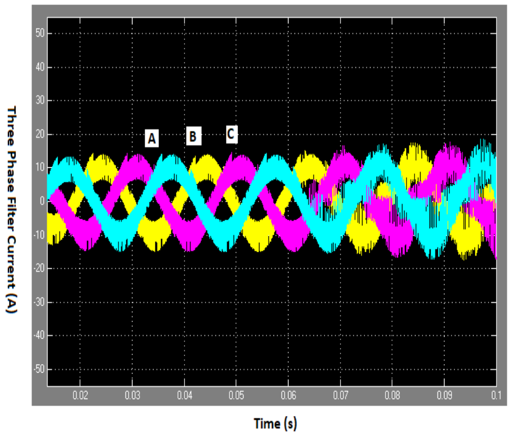
Max frequency for THD computation: Nyquist frequency

Display style: Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

(e) THD analysis



(f) Compensated filter current

Fig.10. Simulated output of 3 phase, 4 wire power system with shunt APF for traction load using SMC plus PI and HCC

5. Conclusions

The design and study of HNLC shunt APF for increasing the power quality in 3-phase four wire systems through the reduction of harmonics and reactive power compensation has been successfully demonstrated in MATLAB/Simulink software platform. Many results were presented to show the proficient of the designed model in both the traction load through the THD, power factor and time domain analysis. The SMC plus PI controller (HNLC) shunt APF has produced good D.C link voltage regulation, quick settling time and minimal steady state error in comparison with FLC plus PI controller and PI controller. The HCC is used to generate the PWM pulse for gate switches of shunt APF to produced quick response. Also, d-q theory is used to determine the reference current of designed system.

References

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