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Modelling And Simulation of Shunt Active Power Filter Using Sliding Mode Pi Controller

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Abstract: *In this paper a three-phase three wire shunt active power filter is used to solve the drawback associated with ac mains in AC-DC power supply feeding to a nonlinear load. This paper delts with the issues related to the power quality in an electrical system and hence reducing the voltage and current harmonics. The article summarizes the proposed I-Cos ψ control algorithm to draw the harmonic currents for shunt active power filter (SAPF) to improve the power condition of the system. To handle the DC-link voltage a sliding mode PI controller is endorsed. Simulations using MATLAB/Simulink platform for a system with a SAPF designed for stable non-linear loads and unstable non-linear loads have been carried out under steady state conditions. The triggering pulses are generated by hysteresis current control technique to control the turn on and off of the voltage source inverter (VSI) switches. The proposed solution has achieved a low Total Harmonic Distortion (THD), demonstrating the effectiveness of the presented method*

Keywords: *Shunt active power filter (SAPF), I-Cos ψ control algorithm, Sliding-mode proportional-Integral controller (SMPIC), Mitigating the harmonics, Hysteresis current control technique, Point of common coupling (PCC), Total harmonic distortion (THD).*

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I. Introduction

The private and industrialised appliance of all the service companies across the globe [1-2] uses balanced or unbalanced non-linear electric gadgets which dependence on power electronic switches for its operation. The contamination of electrical energy distribution network is worst at employment stage due to non-linear loads like, variable speed and variable frequency drives, voltage controllers, electronic gadgets such as computers, printers, televisions, servers and telecom systems all of the which uses SMPS power conversion technologies. This results in the energy quality issues, e.g., harmonic overrefinement, voltage instability, unbalanced current, hissing noise [3]. The power loss in low-voltage distribution systems is due to harmonic distortion, poor power factor, electric heat dissipation, insulation hazards, tampering problems in communication systems and electric power system failure [4,5]. Hence, mitigation of energy quality problems has turned into a matter of discussion for the producers as well the consumers [6].

With the intention to pertain the direct inoculation of harmonic currents in to the energy grid, the Institute of Electrical and Electronics Engineering-Standards Association(“IEEE-SA”) superscribe that the total harmonic distortion (THD) of an electric power system, the IEEE criterion should be less than 5% [7,9]. The literature review reveals the most adequate technology to mitigate harmonic distortions that is, power filters. Consistently, to enhance the power condition at the power stations, series and shunt passive power filters are used. Since, non-linear loads in industrial firms are connected to a rigid energy system, it is demanding to model a passive filter to mitigate current harmonic disfigure. Above all, the passive filter has its innate flaw like its extensive size, reverberance with load impedance or supply impedance, unpredictability and inflexible [10] to prevail the typical filter’s drawbacks, active power filters (APFs) which includes voltage source inverters (VSIs) are put forward as an alternative. APFs owns several features, including a rapid dynamic response, flexibility and predominant filtering accuracy, qualifying it as a fitting solution for power quality problems [11]. The current harmonics and quadrature power sensing methods, along with the compensation control algorithm defines the harmonic reduction competence capability of the shunt active power filter [12]. Among the compensation current control methods, I-Cos ψ algorithm is rarely implemented. For the extraction of fundamental and harmonic components many researchers have presented several techniques on drawing out fundamental and harmonic components, such as determining the reference compensation current and regulating the voltage across the DC-link capacitor. In order to restore the distorted currents at the non-linear loads linked at the point of common coupling (PCC), a reference current is estimated using current control algorithm. Gary W. et al. [15]

recommended a methodology to cut back the harmonic current in the unstable voltage conditions. A system had been contemplated to lessen the inherent harmonics impact on the rectifier transformer by eliminating the current distortion along the supply side.[16].

The literature review presents a firm groundwork by allowing separate study on the shunt active power filter's modelling and regulation. Many researchers have ventured on enhancing the power quality in the balanced system. Yet, this paper describes the modelling and supervising shunt active power filter's (SAPF) using proportional–integral (PI) controller in detail. For reference current extraction by adopting both P-Q theory and I-Cos ψ control algorithm is designed using Simulink. By considering balanced and unbalanced non-linear loads in a 3-ϕ 3-wire network, harmonic current compensation technique is implemented.

II. Methodology

2.1 Performance and Configuration of Shunt Active Power Filter: An Overview

The composition of two circuitry: the control circuitry and the power circuitry which involves shunt active power filter, Figure 1[20,21]. The power circuitry is responsible for generating the appropriate current compensation. It has a voltage source inverter (VSI) built on pulse width modulation (PWM) technique and a DC-link capacitor that stores energy, which also regulates and controls the DC voltage. furthermore, to determine the instantaneous reference currents, the variation in the harmonic current is continuously tracked by the control circuitry and thereby controlling the power circuitry to incorporate the necessary distorted current. The dependency on the harmonic abstraction and technique to control current for the productivity of the harmonic current compensation will be considered in the later section. The flow of current in the network before connecting the active power filters (APF) at the PCC is as referred in equation (1) [23]:

$$i_S = i_L = i_{1L} + i_H \qquad (1)$$

i_S represents supply current, i_L refers to current in load, i_{1L} refers to the primary current element in load and i_H represents the current harmonic element in load.

While the shunt active power filter (SAPF) is equipped near PCC, a pair of supplementary current is present: compensated current produced using SAPF circuit that equals the harmonic current amplitude with a phase shift of 180°; and the current (i_{dc}) that is extracted through SAPF circuit from the supply to keep the potential difference across the capacitor (Vdc) at the set-point. Circulation of current in the electrical network is stated as follows,

$$i_S = i_L = [i_{1L} + i_H] - i_C + i_{dc} \qquad (2)$$

i_C refers to the implanted compensation current also i_{dc} denotes current in the capacitor.

Conceptually, the potential difference across the capacitor of the DC-link decides the harmonious compensation current. For the generated compensation currents, i_C to be uniform with the harmonic currents, i_H extracted through nonlinear load, the potential across the DC-link should be managed at a constant range. Since, both the harmonic currents are equal in magnitude but opposite in phase angle they seem to cancel out each other, therefore restoring back the primary waveform with standard frequency, as in equation (3)[23]:

$$i_S = i_{1L} + i_{dc} \qquad (3)$$

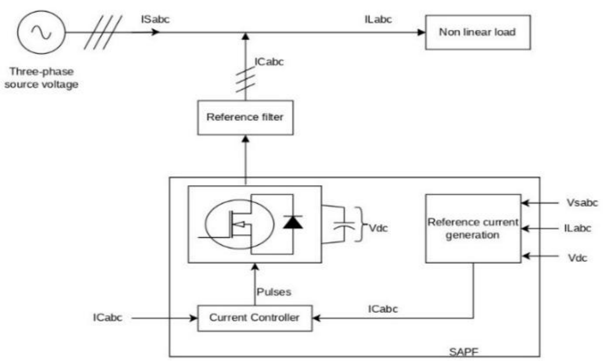

Fig.1 Shunt active power filter arrangement in Three-phase three-wire system

2.2 Abstracting the Harmonic Currents:

The abstraction algorithm in deriving the reference currents, that can be accessed down the two categories: frequency dimension analysis and time dimension analysis. Algebraic transformations and circuit analysis is a simple control process in the time domain study. Also, the frequency dimension analysis should have a large memory for processing and is extra complex. The proposed harmonic current abstraction algorithm is a time dimension approach of I-Cos ψ control algorithm, MATLAB/Simulink can be used to assemble the simulation mode. Figure.2 represents the bond graph presentation of I-Cos ψ compensation current control algorithm.

Deriving the 3-phase supply voltages from the line voltage and

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = 1/3 \begin{bmatrix} 2 & 1 & 0 \\ -1 & 1 & 0 \\ -1 & -2 & 0 \end{bmatrix} . \begin{bmatrix} v_{sab} \\ v_{sbc} \\ 0 \end{bmatrix} \qquad (13)$$

the phase amplitude voltage can be calculated using the 3-phase supply voltages

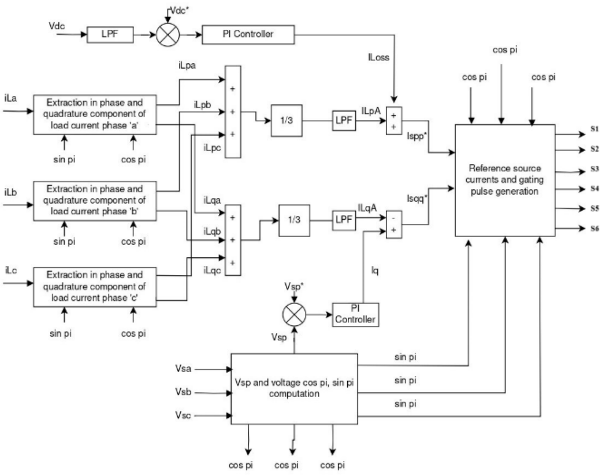

Fig.2 Bond graph of I-Cos ψ algorithm

$$V_{sp} = \sqrt{\frac{2}{3}\left(v_{sa}^2 + v_{sb}^2 + v_{sc}^2\right)} \qquad (14)$$

Where, v_{sa}, v_{sb}, v_{sc} are the phase voltages, v_{sab}, v_{sbc} are the line voltages, V_{sp} is the phase amplitude voltage.

On dividing equation 13 and 14 we get to derive the in-phase unit template and quadrature unit templates are obtained by phase leading the each in-phase unit template by 90 degrees, as explained below.

$u_{sa}=v_{sa}/V_{sp}$, $u_{sb}=v_{sb}/V_{sp}$, $u_{sc}=v_{sc}/V_{sp}$

$u_{sa}=\cos\Phi_{pa}$, $u_{sb}=\cos\Phi_{pb}$, $u_{sc}=\cos\Phi_{pc}$ (15)

$u_{saq}=(-u_{sb}+u_{sc})/\sqrt{3}$, $u_{sbq}=(3u_{sa}+u_{sb}-u_{sc})/2\sqrt{3}$,

$u_{scq}=(-3u_{sa}+2u_{sb}-u_{sc})/2\sqrt{3}$

$u_{saq}=\sin\Phi_{qa}$, $u_{sbq}=\sin\Phi_{qb}$, $u_{scq}=\sin\Phi_{qc}$ (16)

where, u_{sa} , u_{sb} , u_{sc} are the in-phase unit template and u_{saq} , u_{sbq} , u_{scq} are the quadrature unit template

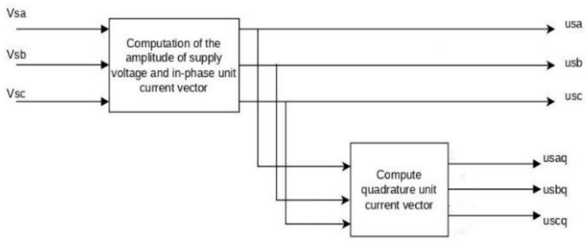

Fig.3 Unit Template based algorithm

The amplitude of active power component (I_{Lpa}) and reactive power component (I_{Lqa}) of phase a is extracted from the load current (I_{La}) at the zero crossing of the in-phase unit template($\cos\Phi$) and quadrature-phase unit template($\sin\Phi$) of three phase PCC voltage. A zero-crossing detector and sample and hold logic are used to extract the phase and the quadrature load currents. Similarly, amplitude of active and reactive components of the other two phase's currents are estimated.

To provide load balancing, the amplitude of active power (I_{LpA}) and reactive power (I_{LqA}) components of load currents is obtained by taking the average of the amplitude of active and reactive components of each three phase currents.

$I_{LpA}=(I_{Lpa}+I_{Lpb}+I_{Lpc})/3$, $I_{LqA}=(I_{Lqa}+I_{Lqb}+I_{Lqc})/3$

The amplitude of the fundamental active power (I_{spp}^*) and reactive power (I_{sqq}^*) components of reference supply current

$I_{spp}^*=I_{Loss}+I_{LpA}$, $I_{sqq}^*=I_q-I_{LqA}$

Estimation of active power(i_{sp}^*) and reactive power(i_{sq}^*) components of reference supply current

$i_{sap}^*=I_{spp}^*\cos\Phi_{pa}$, $i_{sbp}^*=I_{spp}^*\cos\Phi_{pb}$, $i_{scp}^*=I_{spp}^*\cos\Phi_{pc}$

$i_{saq}{}^{*}=I_{spq}{}^{*}\ sin\Phi_{qa}$, $i_{sbq}{}^{*}=I_{spq}{}^{*}\ sin\Phi_{qb}$, $i_{scq}{}^{*}=I_{spq}{}^{*}\ sin\Phi_{qc}$
Estimation of reference harmonic currents
$i_a{}^{*}=i_{sap}{}^{*}+i_{saq}{}^{*}$, $i_b{}^{*}=i_{sbp}{}^{*}+i_{sbq}{}^{*}$, $i_c{}^{*}=i_{scp}{}^{*}+i_{scq}{}^{*}$

2.3 Techniques to Control the Current:

For the effective performance of the filter switching states by defining the control pulses that can be derived by various control methods. Amid these methods, the gating signals to the voltage source inverter switches are generated by employing the hysteresis band current control method. Though there are many approaches to control the compensation current, but hysteresis current control technique is extensively pre-owned because of its absolute stable performance, easy circuit configuration, exactness, and quick counter.

Through the hysteresis control technique, about the reference current the substantial current is held at the presumed range called the hysteresis band (HB), as in Figure 4. The reference current (i_a*, i_b*, i_c*) in comparison with substantial current (i_{Sa}, i_{Sb}, i_{Sc}) so as to conserve the substantial current within the hysteresis limit, based on the error produced, VSI switches are plugged in and out. The gate pulses generated to drive VSI are turned off or vice versa, when the substantial current surpasses the maximum limit of the hysteresis range. Generally, when the current at the output side wants to augment, the potential across the DC-link goes to the highest value, and when the current wants to decrease then voltage goes to the lowest value [25].

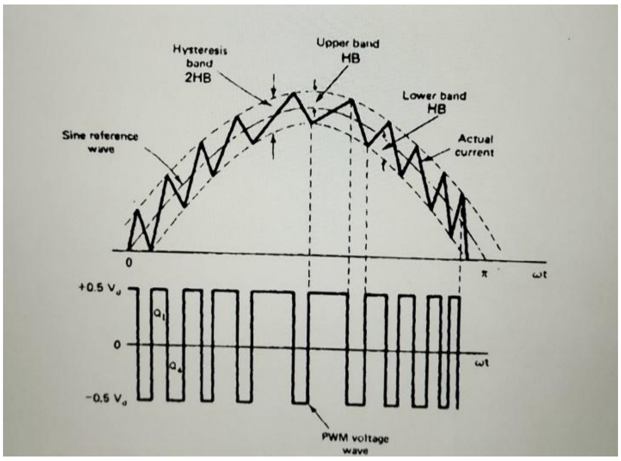

Fig.4 Hysteresis-based control algorithm

2.4 Sliding mode PI controller

Sliding mode PI controller Sliding mode PI control is a controlling strategy used on a nonlinear system, and its working rules are as stated. A sliding surface or a switching function is defined on the phase plane. Then, the state values of a system in the phase plane can approach the switching function in confined duration, and the state values are constrained on a sliding plane. In this constrained action of the control law, $u(x)$ any non-linear higher order system behaves as a 1st order linear system. The course of SMPIC involves a reaching phase and a sliding phase, the reaching phase is when the different state eigen values of the system in the phase plane approaches the switching function, and the sliding phase is when the state values present on the switching function slides to the origin. The bond graph of the Sliding mode PI controller is shown in Figure 7, where the inputs of the controller is the error between the reference voltage, v^*_{dc} and the voltage across the DC link capacitor v_{dc}, Δi_d is the output.

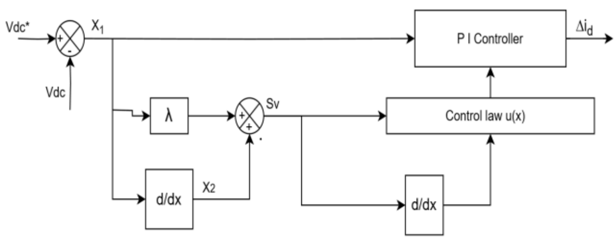

Fig.5 Bond graph of sliding mode PI controller

From Fig. 7, the voltage error x_1 and its derivative x_2 is defined as

$$\begin{cases} x_1 = v_{dC}^* - v_{dC} \\ x_2 = \dot{x}_1 \end{cases} \quad (15)$$

The switching function s_v and its derivative $\dot{s}_v$ are

$$s_v = Cx_1 + x_2 \quad (16)$$

and

$$\dot{s}_v = C\dot{x}_1 + \dot{x}_2 \quad (17)$$

consequently, where C is a positive constant.

On sliding phase, the state values concurrence speed be modified by changing the value of C.

From equation 15 and from the state equation of the system $\dot{x} = f(x, u)$, the equation could be altered as

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -k \end{bmatrix} v(x) \quad (18)$$

where k is a positive constant.

$$\begin{cases} s_v < 0, \text{then } \dot{s}_v > 0 \\ s_v > 0, \text{then } \dot{s}_v < 0 \end{cases}$$

Based on this condition the state values will be moving towards s = 0, satisfying the reachability condition, $s_v \cdot \dot{s}_v < 0$ sign of s_v should be opposite to that of $\dot{s}_v$.

From equation 17 and 18, control law, $u(x)$ can be determined.

The common format of the reaching law function is

$$\dot{s}_v = -\varepsilon\, sgn(s_v) - f(s_v) \quad (19)$$

Where ε is a positive constant, $f(s_v)$ is a variable function, and $sgn(s_v)$ is a sign function defined as

$$sgn(s_v) = \begin{cases} 1\ , & s_v < 0 \\ -1, & s_v \geq 0 \end{cases} \quad (20)$$

From (19) and (20), if $f(s_v)$ = 0, then $\dot{s}_v$ is an even speed reaching law function, and when $f(s_v) = -ks_v$, then $\dot{s}_v$ an exponential reaching law function,

The speed and time of the state variables reaching the sliding surface can be controlled by variable function $f(s_v)$. The extreme speed of the state variables will result in serious chattering, hence an apt value of $f(s_v)$ must be chosen. The transfer function of PI control in SMPIC is

$$T(s) = \frac{(k_p s + k_i)}{s}$$

where k_P is the proportional controller gain and k_i is the integral controller gain. These parameters are resolved by

$$\begin{cases} k_P = \{[1 + sgn(s_v)]k_p^+ - [1 - sgn(s_v)]k_p^-\} + K_P \\ k_i = \{[1 + sgn(s_v)]k_i^+ - [1 - sgn(s_v)]k_i^-\} + K_i \end{cases}$$

k_p^+, k_p^-, K_P, k_i^+, k_i^-, and K_i are the positive constants. The sliding mode PI controller considerably reduces overshoot and it has high robustness to external disturbances.

III. Results and Discussions

The propounded current control technique with regard to SAPF is executed by employing MATLAB/Simulink power tool to mitigate harmonic currents due to the nonlinear loads. The Simulation exemplary includes (i) a 3-ϕ AC voltage supply, (ii) a non-linear load with a stable and un-stable system, also (iii) a SAPF can be seen in figure 7 Table1 lists the system parameters for the simulation. By considering stable and un-stable non-linear system, the SAPF's efficiency on the current harmonic mitigation is tested.

Table 1. Network parameters

Parameters	Values
AC voltage supply	415 V_{PH-PH}
Supply frequency	50 Hz
Supply impedance	Rs = 0.001Ω, Ls = 0.1mH
Filter impedance	RS = 0.0Ω, Ls = 0.1mH
DC-link capacitor	1000μF
K_p	0.4
K_I	0.02
λ	0.06
k	0.01
k_1	0.5

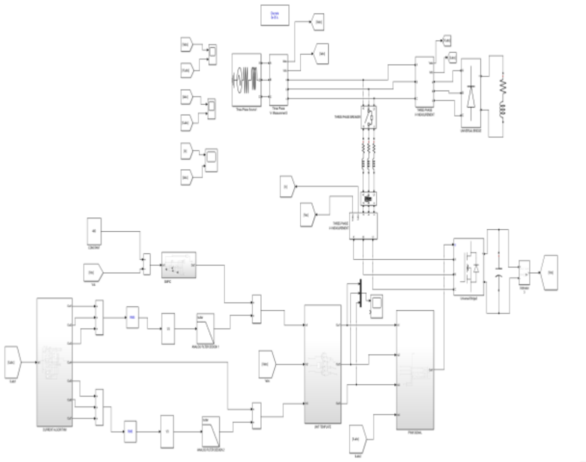

Fig.6 The propounded shunt active power filter (SAPF) Simulink model

3.1 Non-linear Load with Balanced System

The disfigured 3-ϕ supply current(i_S) and non-linear load current (i_L) wave shapes of a non-linear stable load is shown in the figure 8. Because of the non-linear nature of the load, the supply current is being disfigured. Figure 9 shows the supply currents' total harmonic distortion (THD) as 24.59%, that transcends the harmonic standard limit set by IEEE as shown in the fast Fourier Transform (FFT) analysis [8].

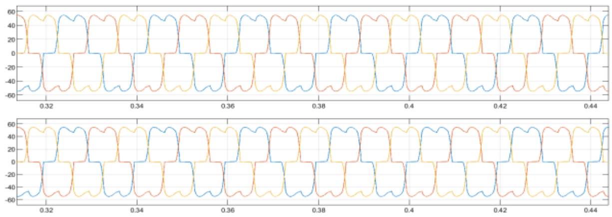

Fig.7 (a) supply current; (b) load current prior to the compensation

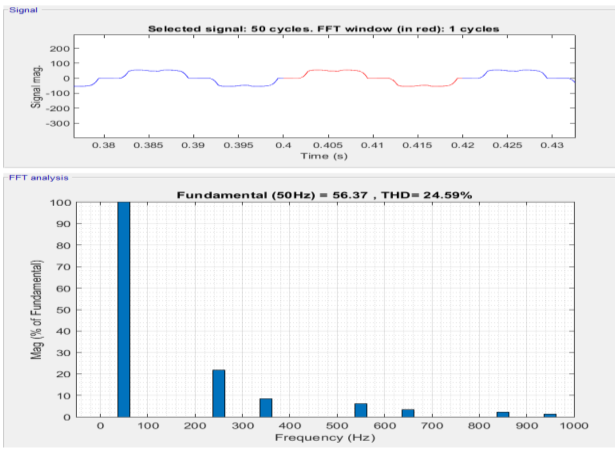

Fig.8 FFT analysis of the supply current prior to the compensation

When the SAPF is connected at PCC along the lateral side of non-linear load, the compensated supply current and the load current waveshapes can be observed in the figure 16. The Total Harmonic Distortion (THD) has decreased to 0.06% from 24.59%. The FFT interpretation shows the acceptable value when matched along 5% IEEE criterion as in figure 17.

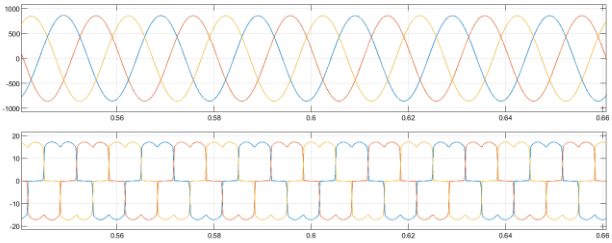

Fig.9 (a) supply current; (b) load current after compensation

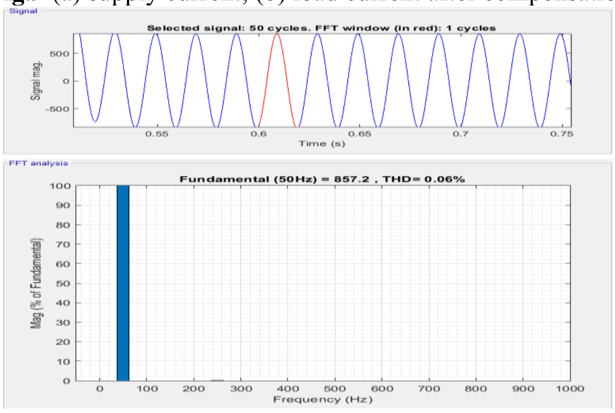

Fig.10 FFT interpretation of supply current after compensation

3.2 Non-linear Load with Unbalanced System

An unstable 3-ϕ L-C-R load that are affiliated with unconfined diode bridge rectifier is contemplated as the unstable system with non-linear load. Figures 18 and 19 shows, current waveshapes of the supply, the load and the FFT study of the 3-ϕ system prior to the compensation, respectively. The FFT interpretation shows the THD of the system as 24.27%, which rule against the IEEE criterion to a notable stretch.

The disfigured supply current waveform as in Figure 18 is revived to the fundamental sine wave through SAPF as in figure 20. The SAPF minimizes the THD of the supply current from 24.27% to 0.13%, that can be seen in the FFT interpretation in Figure 21. Table2 recapitulate the supply current's THD results by considering several dissimilar circumstances in this study.

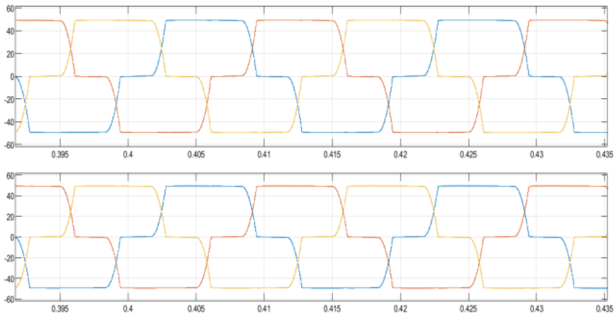

Fig.11 (a) supply currents; (b) load currents prior to the compensation

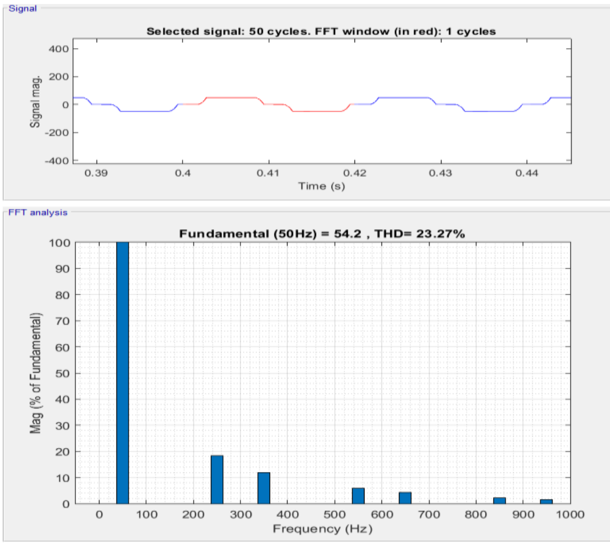

Fig.12 FFT interpretation of the supply current prior to the compensation

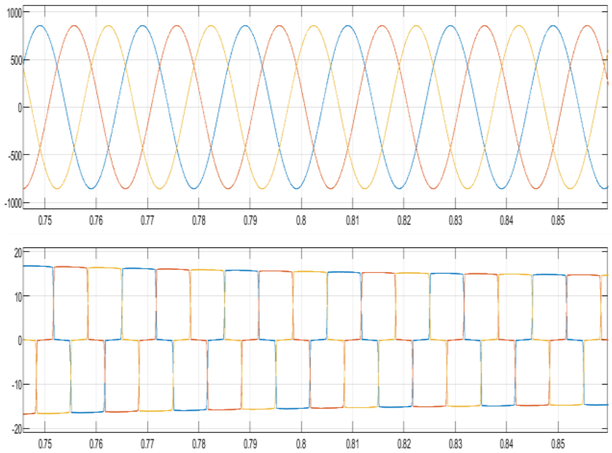

Fig.13 (a)supply currents; (b)load currents after compensation.

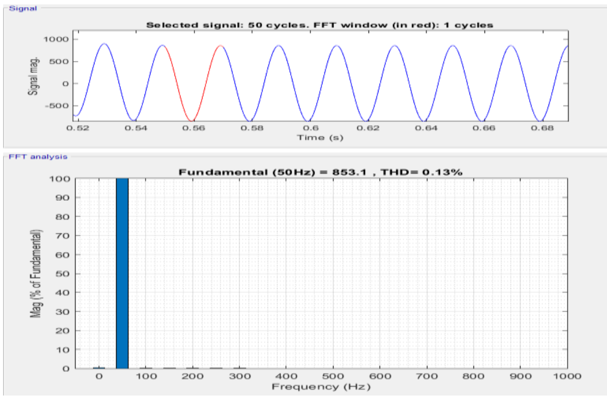

Fig.14 FFT interpretation of the supply current after compensation

Table 2. Total harmonic distortion (THDs) supply current

No	Load Depiction	% THD of Supply Current
1	Non-linear load, stable network in absence of SAPF	24.59
2	Non-linear load, stable network in presence of SAPF	0.06
3	Non-linear load, unstable network in absence of SAPF	24.27

4	Non-linear load, unstable network in presence of SAPF	0.13

IV. Conclusion

The main objective of Power quality studies is to maintain the electric systems' voltage and current as a fundamental sine wave with a 120 degrees phase shift amongst the phases in a 3-ϕ energy system with amplitude and frequency of 1 p.u. Non-linear loads that abstracts distorted currents is responsible for the power quality problems due to harmonic deformity which is a major cause for power quality decline. The plot of this paper, includes the instantaneous quadrature power theory, hysteresis current control and PI control algorithm of a SAPF in a 3-ϕ 3-wire network has been simulated with the aid of MATLAB /Simulink platform. Under stable and unstable nonlinear load condition the influence of the APFs' in reducing the harmonious current has been interpreted.

The consecutive points lead to the negotiation on shunt active power filter through simulation interpretation;

- The propounded shunt active power filter is capable of restoring its fundamental sinusoidal waveform from the disfigured supply current;
- The study concludes that the propounded filter was able to diminish the harmonic currents notably below the IEEE criterion of a non-linear load under stable and unstable conditions;
- By utilizing the propounded SAPF the FFT interpretation reveal that, the THDs was reduced from 24.59% to 0.06% for stable and from 24.27% to 0.13% for unstable networks;
- The harmonics current from both stable and unstable networks can be mitigated efficiently with the help of designed shunt active power filter.

The proposed energy network can be developed in to a paradigm by using appropriate control specifications.

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