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An Approach to Mitigate the Current Harmonics of Non-linear Load using Shunt Active Power Filter

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ABSTRACT

In the current era, the application of power electronics converters has been increasing rapidly. The power electronics converters have non-linear characteristics and are considered as non-linear loads. These converters increase the A.C current harmonics and generate non-sinusoidal voltage at the point of common coupling (PCC), where additional loads are linked to the distribution systems. The existence of current harmonics results in more power loss, interference with communication systems, and failures of protecting devices as well as equipment in the distribution systems. Hence, to overcome these issues, a simplistic shunt active power filter control strategy (SAPFCS) is designed to mitigate the harmonic current injected by non-linear load, in which D-STATCOM is acting as shunt active power filter (SAPF). Again, a hysteresis band scheme has been used to generate gate pulses for SAPF owing to its faster response. The recital of the SAPFCS is investigated using the MATLAB / Simulink platform.

Keywords: *Non linear load, SAPFCS, D-STATCOM, Hysteresis controller, THD*

1. INTRODUCTION

The advancement in the advent of power electronics converters has increased the popularity of power semiconductor switches in the power system on a large scale. These switches have non-linear characteristics, and the involvement of these switches in non-linear loads leads to current harmonics in the power distribution network. Also, these switches generate non-sinusoidal voltage at the point of common coupling (PCC). The non sinusoidal PCC voltage in the power distribution network generates numerous issues such as increased power loss, interference with communication lines, failures of equipment, and protecting devices. These drawbacks significantly affect the development of industrial and commercial activities because of the reduction in the output and deterioration of the product quality [1, 2]. The exhaustive use of nonlinear loads has increased the demand for harmonics mitigation and compensation of reactive power. Again, it was proved by several researchers that the non-linear loads are the cause for power factor reduction and high THD [3]. The way to mitigate harmonics is the employ of power switching based devices, such as Distribution Static Compensators (D-STATCOMs). The DSTATCOMs have numerous control algorithms. Among the various algorithms, the instantaneous power (P-Q) theory-based algorithms have been most widely used due to their simplicity [4]. The active power filters are being applied as a proficient method for harmonic mitigation [5]. These types of filters are being taken as a suitable technique to smooth voltage and current distortion [6, 7]. The active power filter injects compensated current with shunt topology or compensated voltage with series topology into the supply to mitigate load harmonics. A number of harmonic current detection and mitigation techniques have been used such as SRF control theory, (P-Q) theory, modified (P-Q) theory, flux-based algorithm, notch filter, and NN [8–11]. The (P-Q) theory has excellent transient and steady-state response [7], but it is inappropriate for estimating reference current under the condition of a non-ideal voltage source [7, 12]. Hence, in this paper, a D-STATCOM has been designed with a non-linear load which is acting as SAPF. The reference current for the SAPF has been obtained by sensing source voltage, source current and non-linear load current by using a novel P-Q theory. Also hysteresis-based scheme has been used to produce gate pulses of SAPF.

2. PRINCIPLE OF D-STATCOM AS A SHUNT ACTIVE FILTER FOR NON LINEAR LOAD

The STATCOM (Static synchronous compensator) is a 3-phase shunt connected power electronics device that works as a moderator to regulate the demand and supply of reactive power [13]. When it is used in a low voltage distribution system, the STATCOM is categorized as D-STATCOM. It is a bi-directional device and is connected at the load end of the distribution system. The components of D-STATCOM include a DC capacitor, a 3-phase inverter, an AC filter, and a control strategy. The operating principle of SAPF is that it injects the harmonic current to the supply in a direction opposite to the flow of non-linear load harmonic current to nullify the impact of harmonics and produce a resultant current that is free from harmonics. It is implemented by connecting a capacitor to the converter of D-STATCOM. The capacitor acts as a source and it is switched at a higher frequency to generate harmonic current. The structure of D-STATCOM as SAPF is depicted in Fig.1.

As per the figure, D-STATCOM is connected to the supply and non-linear load at PCC. Here, the D-STATCOM is a Pulse width modulated voltage source MOSFET inverter supplied by a D.C capacitor voltage Vc. Let, I_{sabc} = phase current of the 3-phase source, I_{Labc} = phase current of the 3-phase non-linear load, and I_{fabc} = 3-phase shunt active filter current then the source current can be expressed as

$$I_{sabc} = IL_{abc} - I_{fabc} \quad (1)$$

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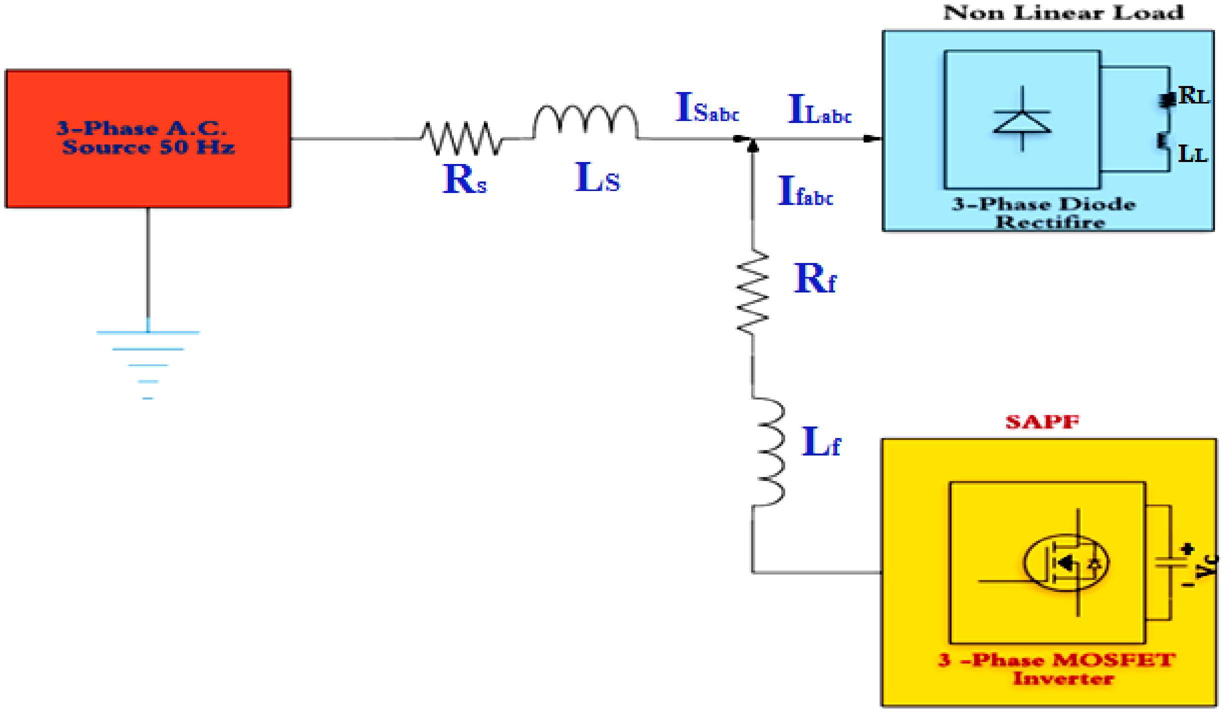

Figure 1 Structure of D-STATCOM as Shunt active power filter (SAPF)

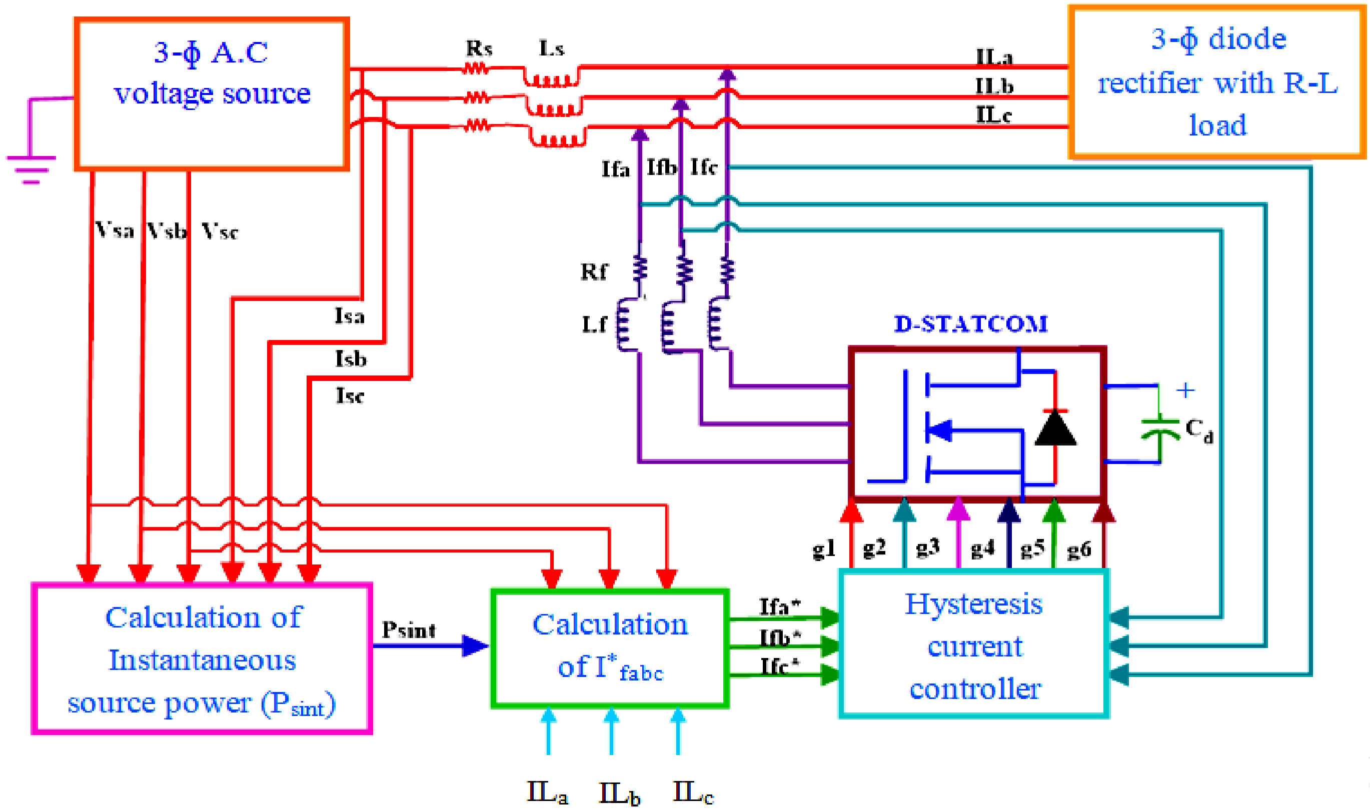

Figure 2 Block diagram for control strategy

The recital of SAPF depends primarily on the process used to recognize and extort the reference current and also on the approach of inverter control [10, 14]. The current harmonics from SAPF has been obtained by operating the voltage source inverter in the current controlled mode with interfacing inductor filter [15].

3. SHUNT ACTIVE POWER FILTER CONTROL STRATEGY (SAPFCS)

The block diagram for the SAPFCS is depicted in Fig.2. The block diagram has the following component blocks:

1. 3-phase A.C voltage source

2. Calculation of instantaneous power (P_{sint})

3. Calculation of I^*_{fabc}.

4. Hysteresis current controller

5. D-STATCOM as shunt active power filter.

6. Non-linear load

A.C VOLTAGE SOURCE:

The first block of SAPFCS is 3-phase A.C voltage source. It is not ideal, it has internal impedance. If source resistance is R_s and source inductance is Ls then the internal impedance

Zs= Rs + jωLs (2)

Where ω = angular frequency of supply in radian/second
The instantaneous voltages of 3-phase A.C source is expressed by the following relationships

$$V_{sa} = V_m \sin \omega t \quad (3)$$

$$V_{sb} = V_m \sin(\omega t - 120^0) \quad (4)$$

$$V_{sc} = V_m \sin(\omega t - 240^0) \quad (5)$$

CALCULATION OF INSTANTANEOUS POWER:

The instantaneous power supplied by the source (P_{sint}) can be expressed as

$$P_{sint} = V_{sa}I_{sa} + V_{sb}I_{sb} + V_{sc}I_{sc} \quad (6)$$

Where I_{sa}, I_{sb}, I_{sc} represents the instantaneous source currents respectively.

CALCULATION OF I^*_{fabc}:

The instantaneous reference currents or harmonic current of SAPF i.e. I^*_{fabc} is obtained by using the following steps:
1. Calculation of reference source currents I_{sabc*} using equation (6) i.e.

$$\begin{bmatrix} I^*_{sa} \\ I^*_{sb} \\ I^*_{sc} \end{bmatrix} = \frac{P_{sint}}{V_{sa}^2+V_{sb}^2+V_{sc}^2} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (7)$$

2. Measurement of instantaneous load currents IL_{abc}.
3. Calculation of instantaneous reference currents or harmonic currents of SAPF using the relationship

$$I^*_{fabc} = I^*_{sabc} - IL_{abc} \quad (8)$$

HYSTERESIS CURRENT CONTROLLER:

The hysteresis controller depicted in Fig.3 has been used for the control of SAPF.
It has two bands: 1. Upper band (UB), 2. Lower band (LB) having a bandwidth of 2HB (-HB to +HB through 0) and it provides switching signals to the switches of MOSFET so as to keep the actual injected harmonic current (Ifabc) within the hysteresis bandwidth. Also, it generates the reference harmonic currents within the fixed band gap. In this controller, the reference harmonic current (If*) of a given phase is being compared with the measured current (If) and the error (er) is being fed to the comparator. When the error (er) passes the lower band (LB), the upper group switches of MOSFET inverter are being turned on. But when the error (er) passes the upper band (UB), the bottom group switches of MOSFET inverter are being turned on. The controlling action is represented mathematically as given below:

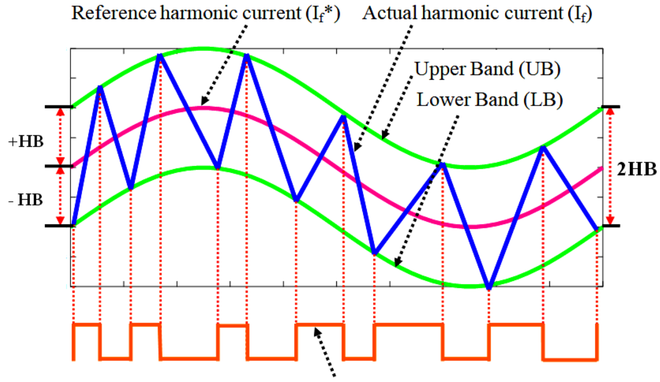

Figure 3 Diagram of Hysteresis current controller

If $e_r \geq +HB$ or $(I_f^* - I_f) \geq +HB$ then SW_1 or SW_3 or SW_5 off and SW_4 or SW_6 or SW_2 on
(8)
If $e_r \leq -HB$ or $(I_f^* - I_f) \leq -HB$ then SW_1 or SW_3 or SW_5 on and SW_4 or SW_6 or SW_2 off

Where (SW_1 SW_3 SW_5) represents the upper group switches and (SW_4 SW_6 SW_2) represents the lower group switches of the 3-phase MOSFET inverter as depicted in fig.4.

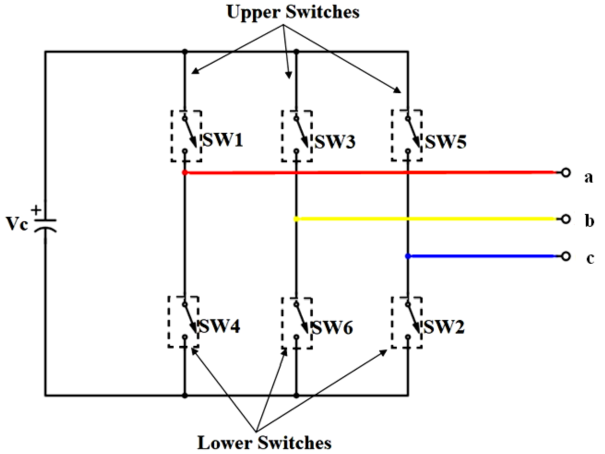

Figure 4 Configuration of 3-phase MOSFET inverter

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Generation of switching signals (g_1, g_2, g_3, g_4, g_5& g_6) for all the six switches to get 3-phase AC outputs is shown in fig.5.

For phase a, actual harmonic current (I_{fa}) is compared with the reference harmonic current (I_{fa^*}) and error signal (e_{ra}) is passed through the hysteresis controller. When e_{ra} <= -HB then SW_1 is turned on and SW_4 is turned off but when e_{ra} >= +HB then SW_4 is turned on and SW_1 is turned off i.e. the controller generates complementary signals for SW_1 & SW_4 represented by SSGa (g_1) and $\overline{SSGa}$ (g_4) respectively. Procedure is same for other two phase's b and c as shown in fig.5.

D-STATCOM AS SHUNT ACTIVE POWER FILTER:

D-STATCOM has a combination of voltage source converter (VSC), coupling inductors, and D.C link capacitor. This combination acts as a source or sink of reactive power. The VSC produces a set of three controllable output voltages of frequency magnitude the same as A.C power system frequency. This controllable output voltage controls the reactive power exchanged between the converter and the A.C power system. There are three different conditions arrived depending upon the magnitude of source voltage and controllable output voltage.

1. If the magnitude of output voltage exceeds above A.C system voltage, then-current, is supplied by the converter to the A.C power system through coupling inductor. So the converter works as an inverter and generates reactive power.
2. If the magnitude of output voltage falls below the A.C system voltage, then-current is supplied by the A.C system voltage to converter through the coupling inductor. So the converter works as a rectifier and absorbs reactive power.
3. If the magnitude of the output voltage is the same as AC system voltage, then there is no reactive power exchanged between converter and A.C power system.

The function of the SAPF is to inject current harmonics to the P.C.C to mitigate the harmonic distortion of the load current. The D-STATCOM can be used as an SAPF, if the converter supplies power to the P.C.C or if the converter acts as an inverter. It is possible only if the D.C link capacitor acts as a source of supply. As depicted in fig.2, the D.C link capacitor (C_d) supplying power through MOSFET inverter, coupling inductor (L_f), and coupling resistor (R_f) to the P.C.C.

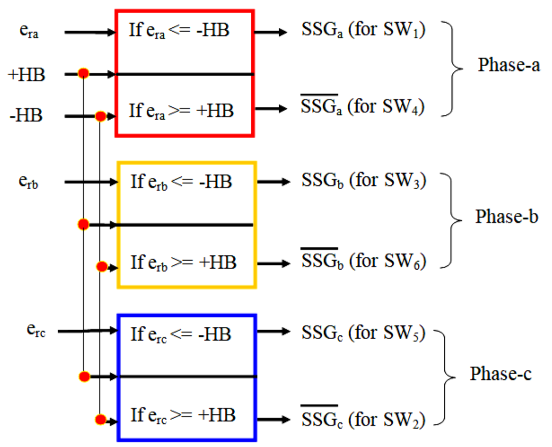

Figure 5 Generation of switching signals for MOSFET

NON-LINEAR LOAD:

A non-linear load provides non-sinusoidal current due to the variation of impedance. This non-sinusoidal current causes harmonic distortion that affects both distribution system equipment and its connected load. In this paper, a 3-phase diode bridge rectifier with inductive load has been taken as a non-linear load with parameters R_L and L_L.

IMPLEMENTATION OF SAPFCS:

The implementation of SAPFCS has the following steps:
Step-1: Calculation of instantaneous power of source (P_{sint}) by using expression (5).
Step-2: Calculation of SAPF reference 3-phase currents (I^*_{fabc}) using equation (7) i.e.

$$\left.\begin{aligned} I^*_{fa} &= I^*_{sa} - IL_a \\ I^*_{fb} &= I^*_{sb} - IL_b \\ I^*_{fc} &= I^*_{sc} - IL_c \end{aligned}\right\}$$

Step-3: Generation of switching signals for MOSFET (g_1 - g_6) using the condition given in equation (8)

4. SIMULATION RESULTS AND DISCUSSIONS

The following simulation results were obtained using the simulation parameters as given in Table-II.

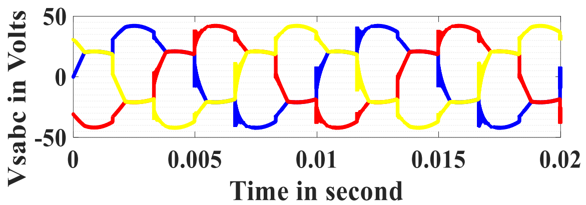

Figure 6 Variation of phase voltages (Vsabc) of 3-phase source with Rs, Ls and non linear load w.r.t time

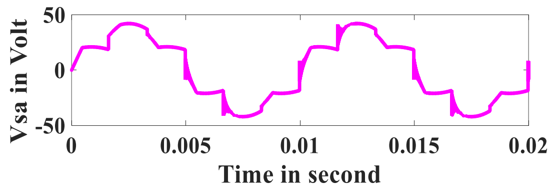

Figure 7 Variation of phase-a voltage of 3-phase source with Rs, Ls and non linear load w.r.t time

The source voltage waveform as shown in fig.6 is non-sinusoidal and its magnitude is less than actual value, this is owing to the existence of non-linear load and source impedance.

Phase-a voltage is shown in fig.7.

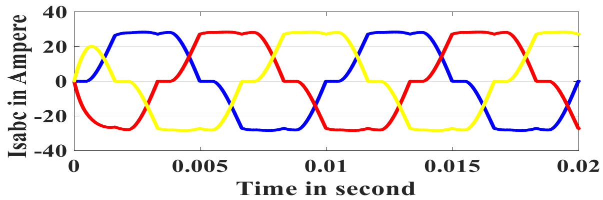

Figure 8 Variation of source currents (Isabc) of 3-phase source with Rs, Ls and non linear load w.r.t time

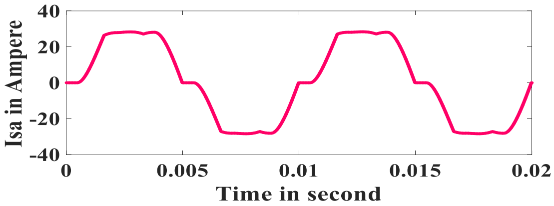

Figure 9 Variation of phase-a current of 3-phase source with Rs, Ls and non linear load w.r.t time

Fig. 8 , Fig. 9 shows the 3-phase source current , phase-a source current waveforms respectively. The current waveforms are distorted owing to the presence of non-linearity in the load.

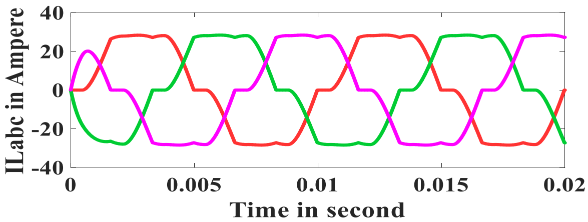

Figure 10 Variation of load currents (ILabc) of non-linear load w.r.t time without using SAPF (taking into account source Rs & Ls)

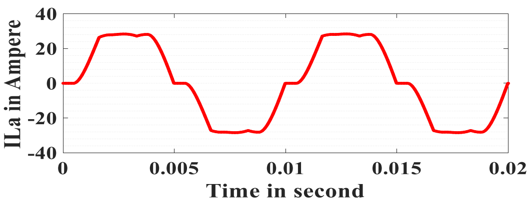

Figure 11 Variation of phase–a load current (ILa) of non-linear load w.r.t time without using SAPF (taking into account source Rs & Ls)

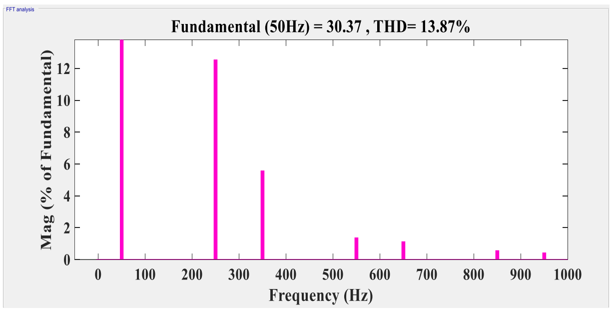

Figure 12 Harmonic analysis of ILa without using SAPF

Without SAPF, the nature of the input current of load is non-sinusoidal because the 3-phase diode rectifier itself injects harmonic in its input as per fig.10 and fig.11, also the percentage of THD injected to the input current I_{La} by the load is 13.87 as shown in Fig.12.

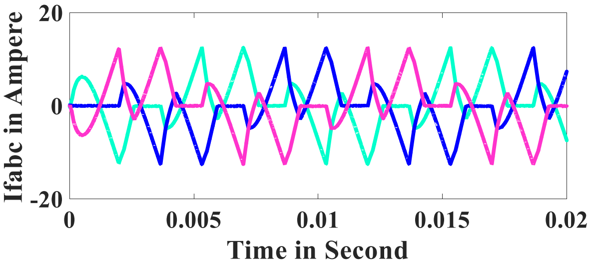

Figure 13 Variation of SAPF 3-phase actual current (Ifabc) w.r.t time

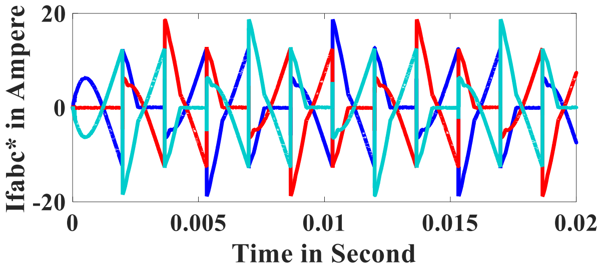

Figure 14 Variation of SAPF 3-phase reference current (I*fabc) w.r.t time

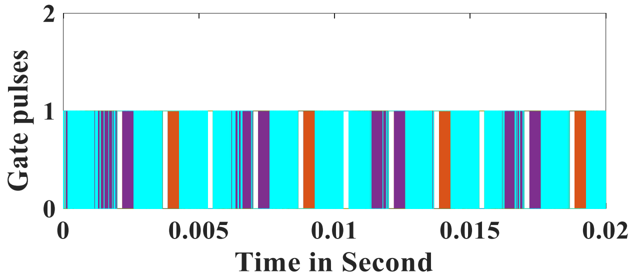

Figure 15 switching signals for the switches of MOSFET for harmonic mitigation

The 3-phase waveforms of generated reference SAPF current (I^*_{fabc}) and actual SAPF current (I_{fabc}) are shown in fig.13 & fig.14 respectively. I^*_{fabc} and I_{fabc} are compared and error signal is passed through hysteresis controller for generation of signals of inverter. The required sequence of gate signal of switches to mitigate the current harmonics is shown in fig.15.

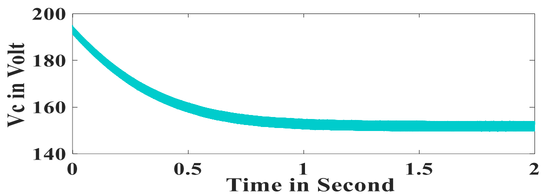

Figure 16 Variation of capacitor voltage Vc of SAPF w.r.t time

To inject the desired current for current harmonic mitigation, a charged capacitor has been coupled with the system with an initial voltage of 195V as depicted in Fig.16. From the figure, it is noticed that the capacitor supplying power (discharging initially) and becoming stable at 150V after 1 second, when the magnitude of injected harmonic current canceling the supply harmonic contents.

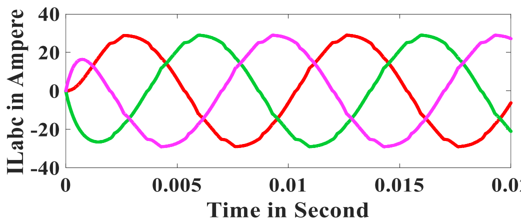

Figure 17 Variation of load currents (ILabc) of non-linear load w.r.t time with SAPF (taking into account source Rs & Ls)

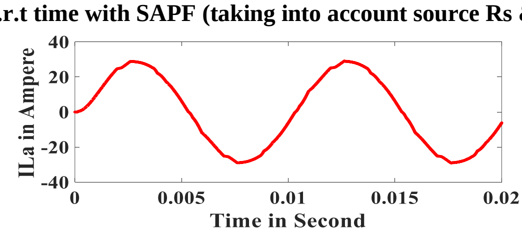

Figure 18 Variation of phase–a load current (ILa) of nonlinear load w.r.t time with SAPF (taking into account source Rs & Ls)

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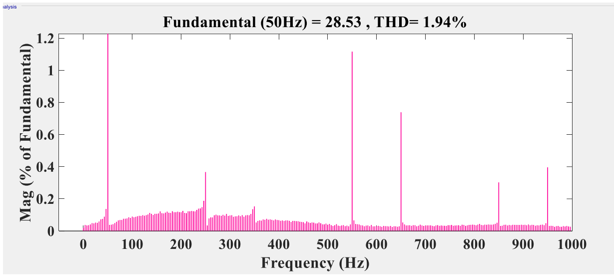

Figure 19 Harmonic analysis of ILa with SAPF

With SAPF, the variation of load currents (IL_{abc}) and phase-a current (I_{La}) is shown in fig.17 and fig.18 respectively. It is observed from the figures that the harmonics have been reducing to a great extent by using SAPF because the waveforms are approaching a sinusoidal waveform. The harmonic analysis of phase-a current with SAPF is depicted in fig.19. From the figure, it is observed that the THD percentage has been reduced to 1.94%. A comparison of phase-a load current waveform with and without SAPF is shown in fig.20. The comparison results are tabulated in Table-I.

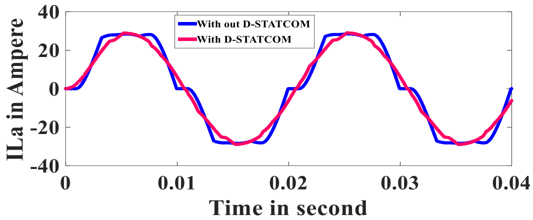

Figure 20 Comparison of waveform of ILa with and without SAPF

TABLE-I

Comparison of %THD of IL_a with and without SAPF

% THD of ILa without SAPF	% THD of ILa with SAPF	% THD reduction using SAPFC
13.87	1.94	11.93

TABLE-II

Parameter table

S. No.	Parameters	Value
1.	Source Voltage	L to L - 86.6V L to N - 50V
2.	Frequency	50Hz
3.	Source resistance (R_s)	1Ω
4.	Source inductance (L_s)	0.98mH
5.	Filter resistance (R_f)	2Ω
6.	Filter inductance (L_f)	6.64mH
7.	D.C link capacitor (C_d)	2030μF
8.	Hysteresis band Limit	U_{upper}=0.01 U_{lower}=-0.01
9.	Load resistance(R_L)	2.2Ω
10.	Load inductance(L_L)	2mH

5. CONCLUSION:

This paper presented an SAPF control strategy to control the harmonic current of non-linear load using the hysteresis band current control technique. The behaviour of the above control strategy was examined using MATLAB/ Simulink environment. From the simulation results, it was estimated that the SAPF control strategy controlled the THD of the non linear load by 11.93% i.e. it reduced the THD from 13.87% to 1.94% which is well below 5% as per IEEE 519 standard. Hence, it is concluded that SAPFCS is a good option to reduce harmonics current of non-linear load in the distribution system.

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