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Research Article

An Efficient Space Vector Pulse Width Modulation with BFO Based Self Tuning PI Controller for Shunt Active Power Filter

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Abstract: This research study mainly focuses on using an efficient control strategy for extracting reference currents of shunt active filters under non linear load conditions. In recent decades, the utilization of highly automatic electric equipments has resulted in enormous economic loss. Thus, the power suppliers as well as the power consumers are very much concerned about the power quality issues and compensation approaches. In order to deal with this issue, Active Power Filter (APF) has been considered as an attractive solution due to its significant harmonic compensation. But, the performance of APF is not consistent and is varies based on the output of the controller techniques. An efficient $(i_d - i_q)$ control strategy is used in this approach for attaining utmost profit from grid-interfacing inverters installed in transmission systems. The voltages are controlled through the PI controller which is further tuned by an optimization approach. Bacterial Forge Optimization (BFO) is used in this approach for tuning the PI controller for the optimal value. The inverter used in this approach can be considered as a Shunt Active Power Filter (SAPF) to compensate non linear load current harmonics. In order to improve the overall performance of the system, Space Vector Pulse Width Modulation (SVPWM) is used in this proposed approach which regulates power frequency and produces good circularity through DC-AC part. SVPWM also eliminates the 3rd order harmonics and minimizes the 5th order harmonics effectively. The integration of $(i_d - i_q)$ control strategy and SVPWM has been proposed in this research study. Simulation results are carried out in MATLAB/Simulink and the performance of the proposed approach is compared with other control strategies. This research studies shows unique approach for attaining maximum benefits from RES with suppression of current harmonics.

Keywords: Bacterial forge optimization, shunt active power filter, space vector pulse width modulation

INTRODUCTION

The increasing demand of energy due to the modern industrial society and population growth is the fundamental motivating factor for the active research in alternative energy solutions, in order to improve energy efficiency and power quality issues (Belaidia *et al*., 2011).

Utilities in India suffer from rigorous power shortage and associated power quality issues. The utilization of photovoltaic energy is regarded as the most fundamental resource, as direct solar density may reach up to 1000 W/m2 in countries located in tropical and temperate regions (Rajasekar and Gupta, 2011).

Thus, Photovoltaic system will be chief form of energy fulfilling global energy requirements. Photovoltaic system has been extensively applied in medium sized grid with household utilities. PV panels are connected in series and parallel to create exploitable form of voltage and current (Yang *et al*., 2012; Betka and Moussi, 2004). Voltage level can be raised up through series connection and current density can be raised through parallel connection of the PV panels. The integration of converter configuration could also be efficient and cost effective (Akbaba and Akbaba, 2001).

An interfacing inverter based on the renewable energy system is studied in Pinto *et al*. (2007). In this method the load and inverter current sensing is needed to balance the load current harmonics. The non-linear load current harmonics may effect in voltage harmonics and can create a serious problem in the electric network. Active Power Filters (APF) present in the network gives extra hardware cost used to balance the load current harmonics and nonlinear load (Ozdemir *et al*., 2003).

In this study, the grid interfacing inverter is proposed to perform functions (Hanumantha and Kiran, 2012) like transmission of active power yield from the renewable resources like wind, solar, etc., current harmonics balance and current unbalance in case of 3-phase 4-wire system. Furthermore, with sufficient control of grid-interfacing inverter, all the objectives can be proficient either independently or concurrently.

It is observed that the controls strategy greatly influences the overall performance of the system. Hence, this research study utilizes a novel control

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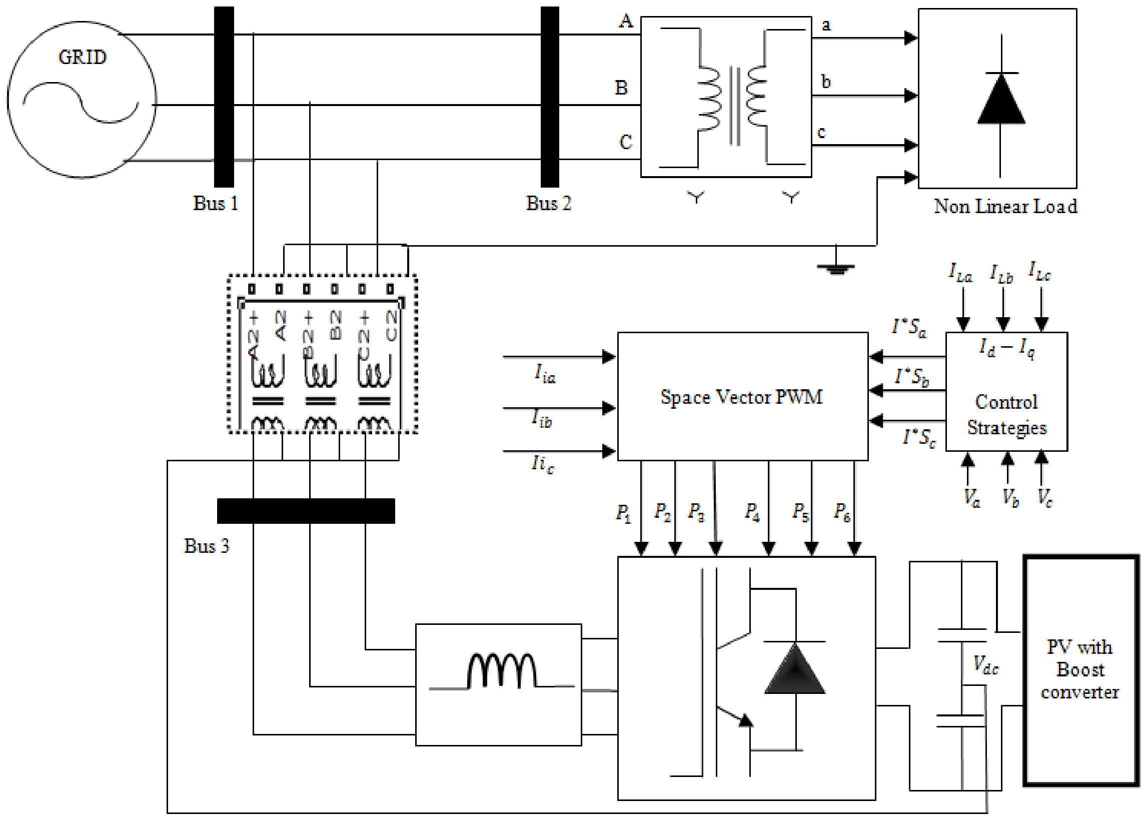


Fig. 1: Proposed architecture of shunt active power filter

strategy using active and reactive current method $(i_d - i_q)$ control strategy and SVPWM for betterment of the current quality and to minimize the THD (Dan *et al*., 2005).

Moreover, BFO algorithm is used in this proposed approach to tune the PI controller. BFO has been widely used in several combinatorial optimization problems. It is observed to provide optimal results (Patnaik and Panda, 2012). Hence, this approach uses BFO for tuning the PI controller effectively.

The proposed system utilizes SVPWM approach which is integrated with $(i_d - i_q)$ control strategy to eliminate the 3rd order harmonics and minimize the 5th order harmonics. The proposed architecture of SAPF with SVPWM and $(i_d - i_q)$ control strategy is shown in Fig. 1.

LITERATURE REVIEW

An improved wind energy conversion system by means of permanent magnet generators and power electronic converters are introduced by Shyam *et al.* (2012). In this system, the inverter is used to control and it can operate as a conventional inverter also as an active power filter. The inverter can be used as a power converter injecting power generated from Renewable Energy Source (RES) to the grid and as a shunt active power filter to recompense for power quality turbulence and load reactive power demand (Shyam *et al*., 2012).

The system called Power Electronics for Renewable Energy at NTNU is proposed by Galami *et al.* (2012), where to investigate how distributed resources can be used for Power Quality (PQ) improvement in existence of nonlinear loads, preventing them from spreading approximately in the grid. The simulation results were carried out in Matlab simulation and Sim power to simulate the power system and shunt active filter equipment, to evaluate and improve the design and relative parameter.

Tang *et al.* (2012) discussed about the design, control and implementation of an LCL-filter-based SAPF, which compensates for harmonic currents due to nonlinear loads in power system. SAPF provides significant and better harmonic compensation due to the LCL filter at its output with much reduced passive filtering components. Therefore, the output currents have high slew rate for following the targeted reference closely. Smaller inductance of the LCL filter results in smaller harmonic voltage drop across the passive output filter, which also reduces the possibility of over modulation, especially for scenarios where high modulation index is needed. These benefits along with overall system stability can be assured only via proper consideration of critical design and control issues, like choosing LCL parameters, communications between resonance damping and harmonic compensation, bandwidth design of the closed-loop system and active damping implementation with fewer current sensors.

Shayanfar and Navabi (2010) proposed an active filter to eradicate harmonics of line current and correct its waveform. The controller of this active filter is using fuzzy logic as its base. Initially, this filter is defined as the injection compensation current by Fourier analysis and then the controller switches the filter to generate and inject this current to the system. In order to improve the overall performance, this controller is optimized by Ant Colony System (ANS). For enhancing the filter performance for light loads, the controller is improved by integrating another tuning controller which tunes the output parameter of the main controller. Simulation indicates that installation of this controller in the system removes harmonics and corrects the waveform of the line current.

PROPOSED METHODOLOGY

Solar array characteristics: The solar array characteristics profoundly influence the converter and control system and therefore these will be briefly reviewed in this section (Bose *et al*., 1985). More generally, the array cell static characteristics, as a function of light intensity and temperature, are given by the following equations:

$$I = I_{LG} - I_0 \left\{ exp\left[\frac{q}{AKT}(V + I_A R_S\right] - 1\right\} \quad (1)$$

where,

$$I_0 = I_{0r}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{qE_{G0}}{BK}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}\right] \quad (2)$$

$$I_{LG} = [I_{SCR} + K_1(T_C - 28]\lambda/100) \quad (3)$$

All the symbols in Eq. (1), (3) can be defined as in the following Table 1.

For boosting up the voltage level from solar array, DC Voltage is boosted up to 325 V (V_{rms}) to attain the peak voltage (V_{peak}) based on the following formulation:

$$V_{rms} * \sqrt{2} = V_{peak}$$

Boost convertor is more preferable due to less number of devices and simple control. Hence, in this approach, boost converter is used (Akbaba and Akbaba, 2001).

The converter which is connected at the array terminal can be denoted by an equivalent resistive load at static condition. The intersection of the load line with conductance slope G and the array VA-IA curve defines the operating point and the corresponding dc power absorbed by the converter.

Table 1: PV panel modelling

Symbols	Explanation
I	Cell output current
V	Cell output voltage
I_0	Cell saturation current
T	Cell temperature in K
K/q	Boltzmann's constant divided by electronic 8.62×10-5 eV/K
TC	Cell temperature in °C
K	Short circuit current temperature coefficient 0.0017 A/°C
X	Cell illumination (mW/cm2)
I_{SCR}	Cell sort circuit current at 28°C and 100 m 2.52 A
I_{LG}	Light-generated current
E_{GO}	Band gap for silicon = 1.11 eV
B = A	Ideality factors = 1.92
T_r	Reference temperature = 301.18 K
I_{or}	Saturation current at T_r = 19.9693×10-6
R_s	Series resistance = 0.001

Shunt active power filter: The active and the passive components are combined together to form active filters and these filters needs an external power source (Ravindra *et al*., 2011). Operational amplifiers are regularly used in active filter designs. These filters have high Q and are able to attain resonance without the use of inductors. Though, their higher frequency limit is restricted by the bandwidth of the amplifiers used. Multiple element filters are typically built as a ladder network. These are capable of an extension of the L, T and π designs of filters. Additional elements are required when it is desired to develop some parameter of the filter such as stop-band rejection from pass-band to stop-band.

A three-phase system provide for an inverter load has been chosen to learn the operation of the APF system. From the experiential study, due to the characteristics of non linear load of the power electronics loads, the Total Harmonic Distortion (THD) of the source current and the terminal voltage fall below the IEEE-519 standard. The principle of APF system is to infuse a current equal in magnitude other than in phase opposition to harmonic current to get a purely sinusoidal current wave in phase with the supply voltage (Afonso *et al*., 2001).

($\mathbf{i_d - i_q}$) Control strategy: Transformation of the phase voltages like V_a, V_b and V_c the load currentsi_{La},i_{Lb} and i_{Lc} into the α - β orthogonal coordinates are given in Equation (4 and 5). The objective of active power filters is studied in Montero *et al*. (2007) is the harmonics there in the input currents. The proposed structural design represents three phase three wire and it is recognized with constant power control approach (Akagi *et al*., 2007):

$$\begin{bmatrix} V_0 \\ V_\propto \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} I_0 \\ I_\propto \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (5)$$

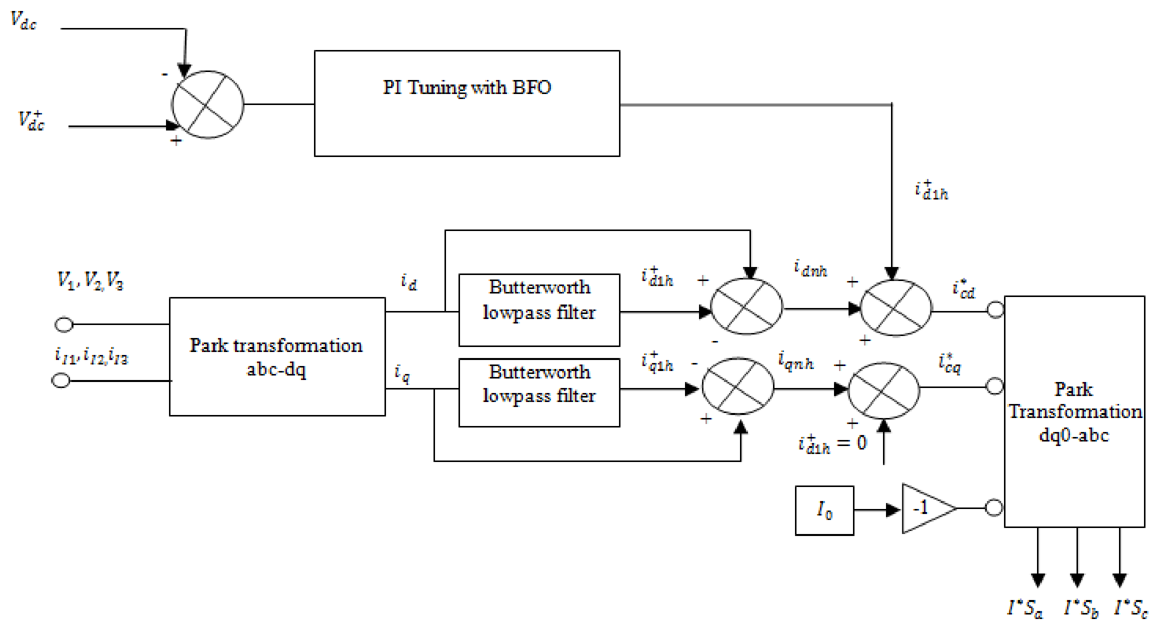


Fig. 2: Park transformation and harmonic current injection circuit

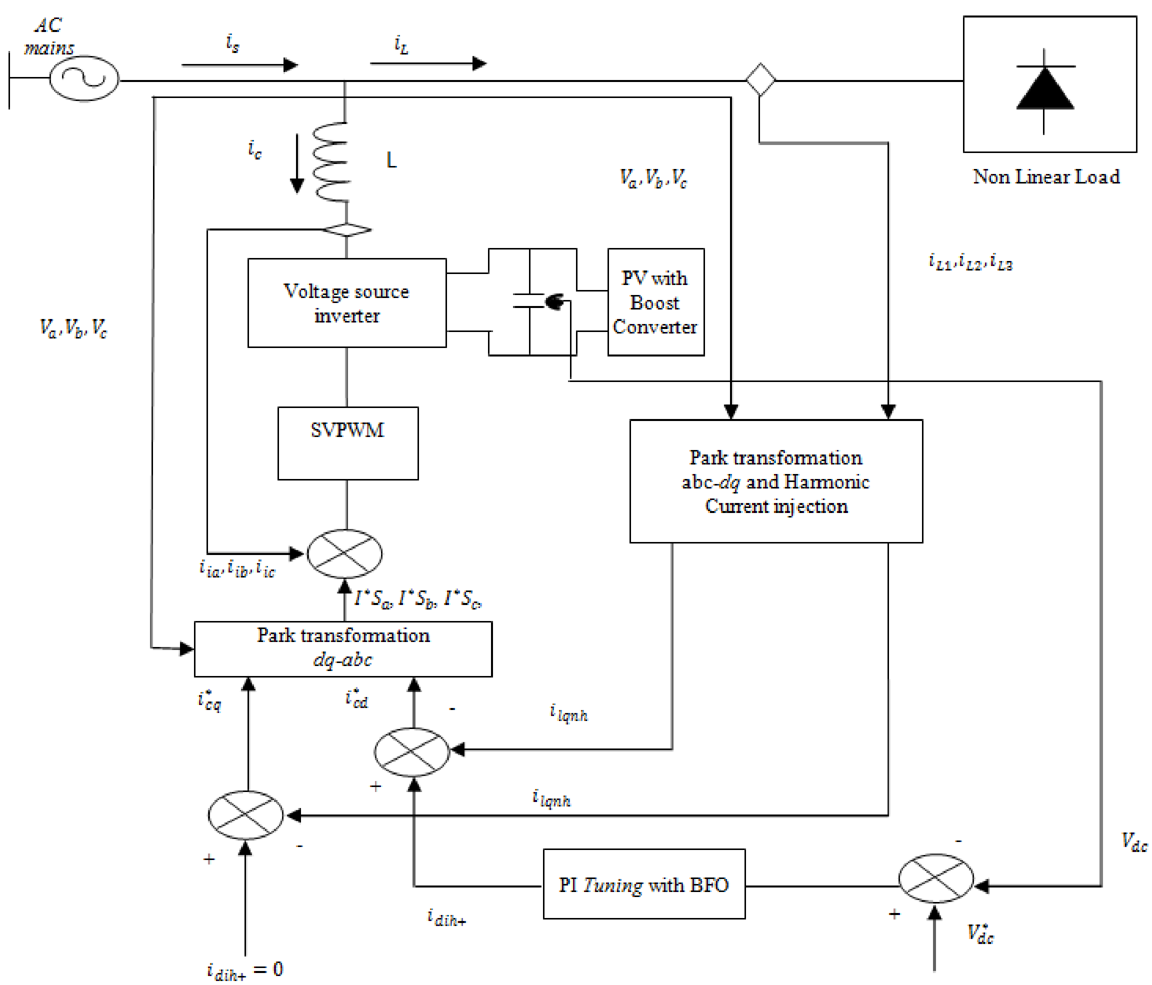


Fig. 3: Shunt active filter control circuit

In $(i_d - i_q)$ Control Strategy method, reference currents are attained through instant active and reactive currents i_d and i_q of the non linear load. A result follows alike to the instant power theory, though $d_q$load currents can be getting from Eq. (6). Two stage transformations provide relation between the motionless and rotating reference frame with active and reactive current method. Mathematical relations is given below in Eq. (6):

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{V_\propto^2 + V_\beta^2}} \begin{bmatrix} V_\propto & V_\beta \\ -V_\beta & V_\propto \end{bmatrix} \begin{bmatrix} I_\propto \\ I_\beta \end{bmatrix} \quad (6)$$

where, $I_\propto$, I_β are the instantaneous α-β axis current references.

This method is used to measure the angle θ from main voltages and therefore this method makes the frequency autonomous by not including PLL in the control circuit is one of the advantages of this control strategy. So, synchronizing problems with disturbed and hazy conditions of main voltages also avoided. Thus $i_d - i_q$ obtain large frequency operating limit fundamentally by the cut-off frequency of Voltage Source Inverter (VSI) (Soares *et al*., 1997).

Figure 2 and 3 show the park transformation and harmonic injection circuit and control diagram for shunt active filter. The load currents i_d and i_q are get from park transformation then they are permitted to flow via the high pass filter to eradicate dc mechanism in the nonlinear load currents. Butterworth filter is used here to reduce the control of high pass filter a Substitute High Pass Filter (AHPF) can be used in the circuit. It can be attained through the Low Pass Filter (LPF) of same order and cut-off frequency merely difference between the input signal and the filtered one, is shown in Fig. 4. Butterworth filters used in harmonic injecting circuit have cut-off frequency equal to one half of the main frequency ($f_c = f/2$), with this a small phase shift in harmonics and adequately high transient response can be obtained. I_0 Obtained from Eq. (5) is used as the zeroth frame.

DC voltage regulator ($\mathbf{i_d - i_q}$): The process of voltage regulator on dc side is carry out by Proportional Integral (PI) controller, inputs to the PI controller are, change in dc link voltage (V_{dc}) and reference voltage (V_{dc}^*), on regulation of first harmonic active current of positive sequence id1 h+ it is feasible to control the

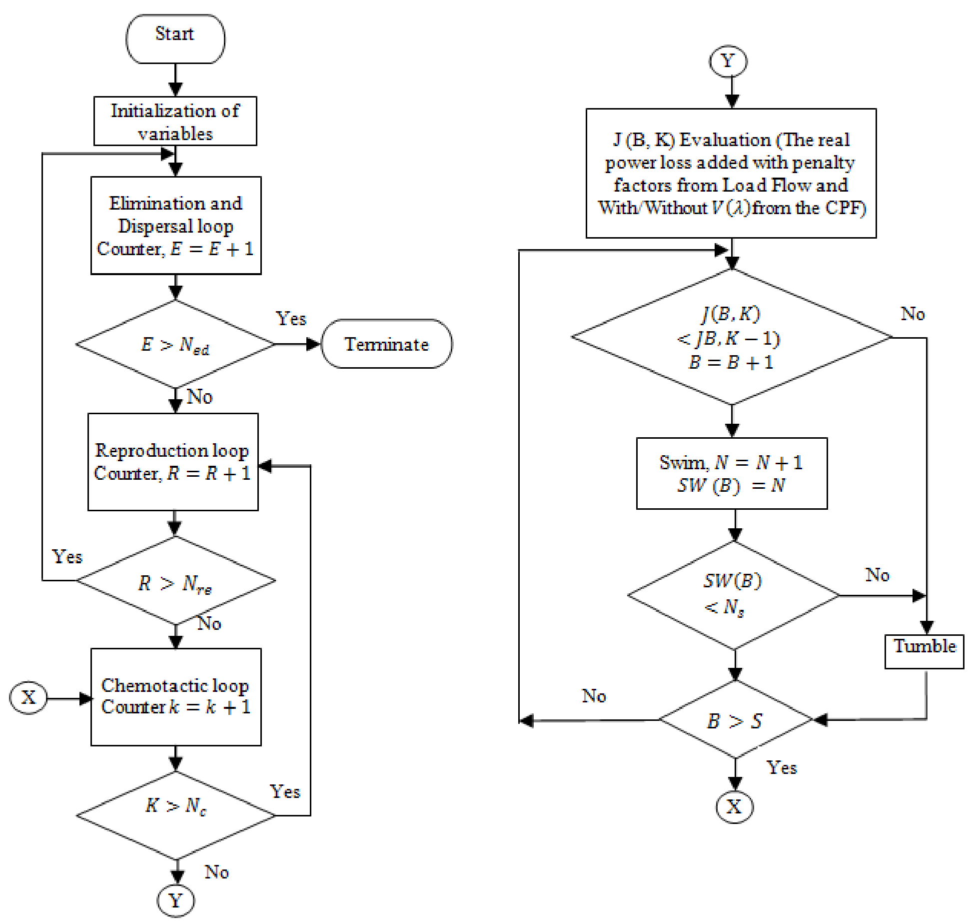


Fig. 4: Flowchart of the proposed BFO for PI tuning

active power flow in the VSI and accordingly the capacitor voltage V_{dc}.

Similarly, reactive power flow is controlled by first harmonic reactive current of positive sequence iq1h+. On the converse the primary end of the active power filters is the elimination of the harmonics caused by nonlinear loads so the current iq1h+ is always set to zero (Berbaoui *et al*., 2011).

PI controller tuning with the assumption of linear SVPWM model leads to unsatisfactory results under varying operating conditions. Optimal tuning of PI gains is required to get the best response of PI controllers. The optimization of PI regulator's parameters is crucial. In this study, the problem of design current PI controller is formulated as an optimization problem. The problem formulation taken for consideration in this approach are proportional gain (k_p), integral gain (k_i) and saturation limit as the objective function to determine the PI control parameters for getting a well performance under a given system. An optimization method for SAPF is proposed to improve the compensation performances and reduce harmonic distortion through electrical lines distribution under all voltages conditions. These objectives are obtained by minimizing the fitness function.

Bacterial forging optimization: Bacterial Foraging Optimization Algorithm (BFOA) is an effective global optimization algorithm for solving distributed optimization problems. BFOA is based on the social foraging behavior of Escherichia coli. BFOA is observed to be very efficient in handling real-world optimization problems in various engineering domains. The fundamental biological concept in the foraging strategy of E. coli is followed and used for the optimization algorithm (Das *et al*., 2009).

The main notion of BFOA is based on the fact that natural selection removes animal with ineffective foraging strategies and favour those having efficient foraging approaches. After particular number of iterations, poor foraging approaches are either eliminated. The foraging strategy of BFOA is governed by four processes, namely, chemotaxis, swarming, reproduction and elimination and dispersal (Datta *et al*., 2008; Passino, 2002):

- **Chemotaxis:** This process of Chemotaxis is based on swimming and tumbling. Based on the rotation of the flagella in each bacterium, it decides whether it should move in a predefined direction (swimming) or in a different direction (tumbling), in the entire lifetime of the bacterium. A unit length random direction, namely $\phi(j)$, denotes the tumble and defines the direction of movement after a tumble (Tripathy and Mishra, 2007). In particular:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\varphi(j) \tag{7}$$

where, $\theta^i(j,k,l)$ represents the ith bacterium at jth chemotactic, kth reproductive and lth elimination and dispersal step. $C(i)$ denotes the size of the step taken in the random direction specified by the tumble. "C" represents the "run length unit."

- **Swarming:** It is a necessary point that the bacterium that has looked for the optimum path of food should attract other bacteria in such a way that the bacteria arrive at the desired place more quickly. Swarming makes the bacteria assemble into sets and therefore move as concentric models of groups with high bacterial density. Swarming can be denoted by:

$$J_{cc}\big(\theta, P(j,k,l)\big) = \sum_{i=1}^{S} J_{cc}^{i}(\theta, \theta^i(j,k,l)) = \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-w_{attract}\sum_{m=1}^{p}\left(\theta_m - \theta_m^i\right)^2\right)\right] = \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-w_{repelent}\sum_{m=1}^{p}\left(\theta_m - \theta_m^i\right)^2\right)\right] \tag{8}$$

where, $J_{cc}(\theta, P(j,k,l))$ denotes the cost function value to be added to the actual cost function to be reduced to present a time varying cost function. "S" denotes the total number of bacteria and "p" represents the number of parameters to be optimized in each bacterium. $d_{attract}, \omega_{attract}, h_{replent}, \omega_{replent}$ and are different coefficients that are to be selected sensibly.

- **Reproduction:** The least healthy bacteria would vanish and each and every healthiest bacteria split into two bacteria, which are placed in the same location. This makes the population of bacteria constant.
- **Elimination and dispersal:** It is a probable solution that in the local environment, the life of a population of bacteria alters either slowly by consumption of nutrients or suddenly due to some other influence. Events can kill or disperse all the bacteria in a region. They have the possibility of demolishing the chemotactic progress, but on the contrary they also support it, as dispersal may place bacteria near good food sources. Elimination and dispersal facilitates in minimizing the behavior of stagnation (i.e., being trapped in a premature solution point or local optima) (Mishra, 2005).

Problem formulation: The objective function of this approach would be to minimize the Total Hormonic Distortion (THD) of the model:

$$\text{Minimize } f(x) = \text{THD} \tag{9}$$

The constraints used in the approach are:

- Equality constraint
- Inequality constraints

The parameters which have to be optimized in this approach are $f(k_p, k_i, sat)$. The subject of limits considered in this research study is:

$$kp_{min} < k_p < kp_{max} \quad (10)$$

$$kI_{min} < k_p < kI_{max} \quad (11)$$

$$sat_{min} < sat < I_{upper} \quad (12)$$

The BF algorithm (Mishra, 2005) is modified so as to speed up the convergence. The modifications are discussed below:

- In (Mishra, 2005), the average value of all the chemotactic cost functions is taken to decide the health of specific bacteria in that generation, before sorting is performed for reproduction. In this study, instead of the average value, the minimum value of all the chemotactic cost functions is maintained for deciding the significance of the bacteria's health. This speeds up the convergence, as in the average scheme (Mishra, 2005), it may not retain the fittest bacterium for the subsequent generation. On the other side, the global minimum bacterium among all chemotactic stages passes onto the following stage.
- For swarming, the distances of all the bacteria in a new chemotactic phase is computed from the global optimum bacterium until that point and not the distances of each bacterium from the rest of the others, as given in Mishra (2005).

The algorithm is discussed here in brief.
The following variables are initialized:

- Number of bacteria (S) to be used in the search.
- Number of parameters (p) to be optimized
- Swimming length.
- The number of iterations in a chemotactic loop.
- The number of reproduction.
- The number of elimination and dispersal events.
- The probability of elimination and dispersal.

This section models the bacterial population chemotaxis, swarming, reproduction and elimination and dispersal. (Initially, $j = k = l = 0$). For the algorithm updating, θ^i automatically results in updating of "p":

$$Elimination - dispersal\ loop: l = l + 1$$
$$Reproduction\ loop: k = k + 1$$
$$CHemotaxis\ loop: j = j + 1$$

For $i = 1, 2, \ldots S$, compute cost function value for each bacterium i as follows

Compute value of cost function *J*(*I*, *j*, *k*, l). Let $J_{sw}(i, j, k, l) = J(i, j, k, l) + J_{cc}(\theta^i\ (j, k, l),\ P(j,\ k,\ l))$. $P(j, k, l)$ is the location of bacterium corresponding to the global minimum cost function out of all the generations and chemotactic loops until that point:

- Let $J_{last} = J_{sw}(i, j, k, l)$ to save this value as a better cost may be found via a run.
- End of For Loop

For $i = 1, 2, \ldots, S$, take the tumbling/swimming decision.

- Tumble: Generate a random vector
- Move: let

$$\theta^i(j + 1, k + l) = \theta^i(j, k, l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (13)$$

Fixed step size in the direction of tumble for bacterium i is considered:

- Consider *J*(*i*, *j*+1, *k*, l) and then let $J_{SW}(i, j + 1,$ k,l=Ji, j+1, k, l+j∞θij +1, k,l, Pj+1, k,l

- Swim
  - Let $m = 0$; (counter for swim length)
  - While $m < N_s$ ((have not climbed down too long)
- Let $m = m + 1$
- If $J_{SW}(i, j + 1, k, l) < J_{last}$ (if doing better), let $J_{last} = J_{SW}(i, j + 1, k, l)$ and:

$$\theta^i(j + 1, k + l) = \theta^i(j, k, l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (14)$$

Use this $\theta^i(j + 1, k + l)$ to compare the new $J(i, j + 1, k, l)$.

- Else let $m = N_s$. This is the end of the "While" statement
- Go to next bacterium $(i + 1)$ if $i \neq S$ (i.e., go to "b") to process the next bacterium.
- If $j < N_c$, go to step 3. In this case, continue chemotaxis since the life of the bacteria is not over.
- Reproduction
  - For the given k and l and for each $i = 1, 2, \ldots S$, let $J^i_{health} = \min_{j \in \{1 \ldots N_c} \{J_{SW}(i, j, k, l)\}$ be the health of the J_{health} (Higher cost means lower health).
  - The $S_r = S/2$ bacteria with highest J_{health} values die and other S_r bacteria with the best value split (and the copies that are made are placed at the same location as their parent)

- If $k < N_{re}$, go to; in this case we have not reached the number of specified reproduction steps, so we start the next generation in the chemotactic loop.
- Elimination-dispersal: For $i = 1, 2, \ldots S$, with probability P_{ed}, removes and disperses each bacterium (this keeps the number of bacteria in the population constant). For this process, if one eliminates a bacterium, it is simply dispersed to a random location on the optimization domain.

The flowchart of the improved algorithm is shown in Fig. 4.

Space vector PWM: The Space vector PWM is used for a two-level voltage source inverter in linear region of operation is explained in Kerkman *et al*. (1991). In space vector PWM six switching devices are present only three of them are independent as the operation of two power switches of the same leg are flattering. The grouping of these three switching states gives eight feasible space voltage vectors.

With 6 distinct sectors the space vectors forms a hexagon, at any time, the inverter can generate only one space vector. In space vector PWM a two active and a zero vectors can be chosen to produce the preferred voltage in each switching period.

Out of eight structures six (states 1-6) generates a non-zero output voltage and they are known as active voltage vectors and the remaining two structures (states 0 and 7) generates zero output voltage and are known as zero voltage vectors, different feasible switching states are shown in Fig. 2. Space vector is defined as (Kerkman *et al*., 1991):

$$v_s^* = \frac{2}{3}\left(v_a + \underline{a}v_b + \underline{a}^2 v_c\right) \tag{15}$$

where, $\underline{a} = \exp\left(\frac{j2\pi}{3}\right)$

The space vector is a concurrent representation of all the three-phase quantities (Teichmann and Bernet, 2005). It is a complex variable and is function of time in contrast to the phasors. Phase-to-neutral voltages of a star-connected load are most easily found by defining a voltage difference between the star point *n* of the load and the negative rail of the dc bus *N*:

$$V_{ab} = V_{aN} - V_{bN}$$
$$V_{bc} = V_{BN} - V_{CN} \tag{16}$$
$$V_{ca} = V_{cN} - V_{aN}$$

Since the phase voltages in a start connected load sum to zero, summation of Eq. (17) yields:

$$V_{nN} = \left(\frac{1}{3}\right)(V_{ab} + V_{bc} + V_{ca}) \tag{17}$$

Substitution of (16) into (17) yields phase-to-neutral voltages of the load in the following form:

$$V_{an} = 2/3V_{aN} - 1/3V_{bN} - 1/3V_{cN}$$

$$V_{bn} = -1/3V_{aN} + 2/3V_{bN} - 1/3V_{cN}$$

$$V_{cn} = -1/3V_{aN} - 1/3V_{bN} + 2/3V_{cN}$$

The purpose of PWM is to control the inverter output voltage and to reduce the Total Harmonics Distortion (THD). Moreover, filters such as LC, LCL, etc do not eliminate the lower order harmonics and hence, PWM has been used for elimination of such lower order harmonics. But, there are some drawbacks in PWM such as:

- 3rd and 5th order harmonics cannot be eliminated effectively.
- Increase of switching losses due to high PWM frequency
- Reduction of available voltage
- EMI problems due to high-order harmonics

So, various PWM techniques have been developed to overcome the above said drawbacks. In this research study, Space Vector PWM (SVPWM) has been used.

Principle of space vector PWM: The Space Vector PWM is used to reduce the current ripples by which the Total Harmonics Distortion (THD) gets reduced. The Space Vector PWM which treat the sinusoidal voltage as a steady state amplitude vector revolving at constant frequency. The PWM took similar reference voltage V_{ref} by a grouping of the eight switching patterns (V_0 to V_7). A three-phase voltage vector is changed into a vector in the motionless d-q coordinate frame which correspond to the spatial vector sum of the three-phase voltage is called as coordinate transformation. The vectors (V_1 to V_6) divide the plane into six sectors, each sector represents 60 degrees (Gupta and Khambadkone, 2007):

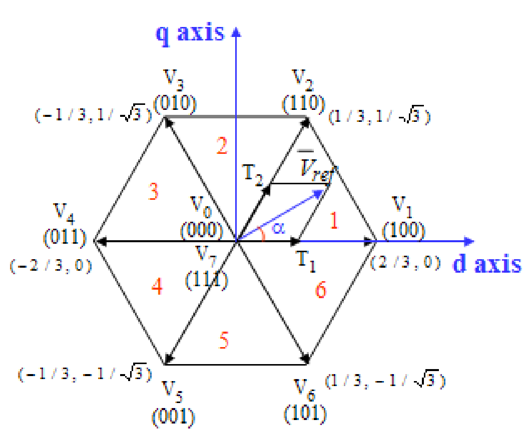


Fig. 5: Basic switching vectors and sectors

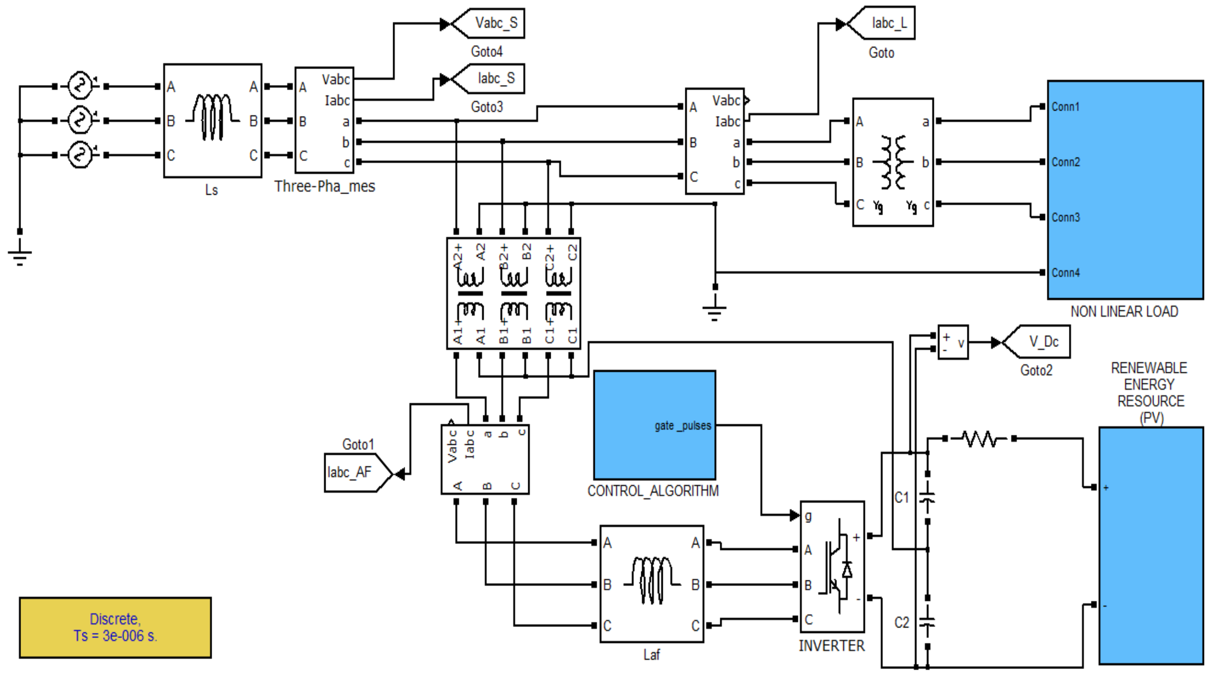


Fig. 6: Overall simulation set up of the proposed approach

- **Basic switching vectors and sectors:** 6 active vectors (V_1, V_2, V_3, V_4, V_5, V_6)
  - Axes of a hexagonal
  - DC link voltage is supplied to the load
  - Each sector (1 to 6): 60 degrees
  - 2 zero vectors (V_0, V_7)
  - At origin
  - No voltage is supplied to the load

The eight vectors as well as the zero voltage vectors can be conveyed geometrically as shown in Fig. 5. All of the space vectors, in the diagram represent the six voltage steps produced by the inverter with the zero voltages V_0 (0 0 0) and V_7 (1 1 1) situated at the source. Space Vector PWM needs to average of the adjacent vectors in each sector. Two adjacent vectors and zero vectors are used to blend the input reference resolved for sector I. Using the suitable PWM signals a vector is produced.

Advantages of SVPWM: It produces less harmonic distortion in the output voltage or currents in evaluation with sine PWM It gives more efficient use of supply voltage in comparison with sine PWM. Thus, the proposed approach uses SVPWM and ($i_d - i_q$) control strategy in reducing the ripple current in non-linear load conditions.

SIMULATION RESULTS AND DISCUSSION

The proposed BFO based SAPF approach has been simulated in MATLAB 2010. The overall simulation setup of the proposed approach for three phase three wire system is shown in Fig. 6. The simulation parameters used in this proposed approach is shown in Table 2.

Table 2: Simulation parameters

System parameters	Symbol used	Value
Supply frequency	f	50 Hz
Input inductance	L_s	0.01 m H
Filter inductance	L_{af}	1 mH
Dc-link capacitance	C_{dc}	3000 μF
Reference Dc-Link voltage	V_{dc}^*	325 V
Load side isolation transformer	-	1:1, 50 Hz, 230 V_{rms}
Injection transformer	-	1:1, 50 Hz, 230 V_{rms}
Load parameters	R_L, L_L	20 Ω, 25 mH

The waveforms based on the transformation of the phase voltages and load currents are given in figure. The phase voltages namely $V_\propto$ and V_β is clearly shown in the figure. Moreover, load currents $I_\propto$ and I_β are shown in the figure.

ABC to ∝, β conversion: Figure 7 shows ∝, β coordinates graph. This graph conversion is equivalent to the dqo transformation. Transformation of the phase voltages v_a, v_b and v_c and the load currents i_{La}, i_{Lb} and i_{Lc} into the α - β orthogonal coordinates waveforms are shown in the figure.

i_d and i_q current: Figure 8 shows the i_d and i_q current. This figure clearly shows that the positive reference current i_d and the negative reference current i_q is separated using Eq. (15)

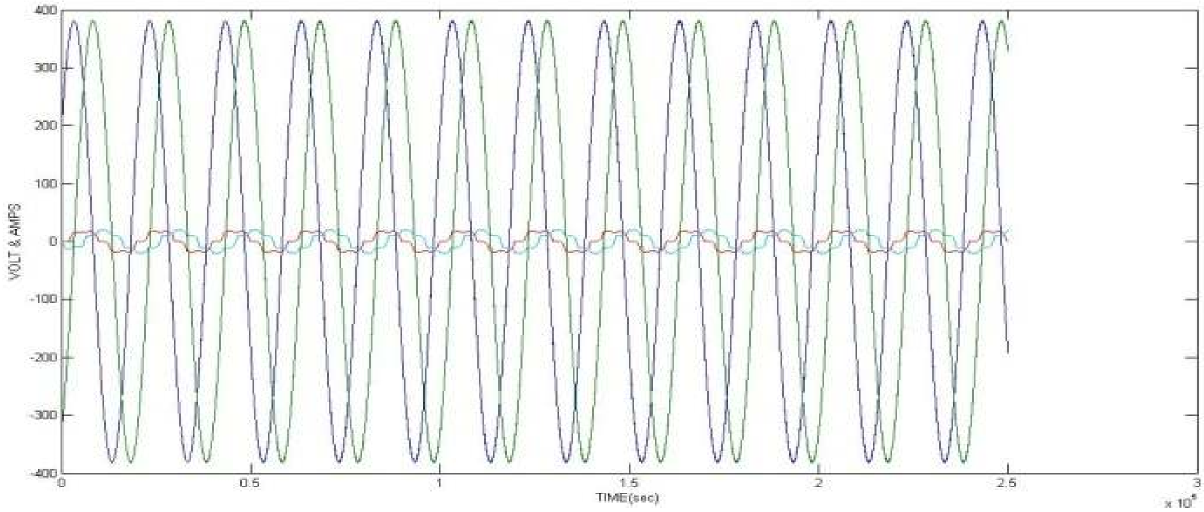


Fig. 7: ABC to ∝, β conversion

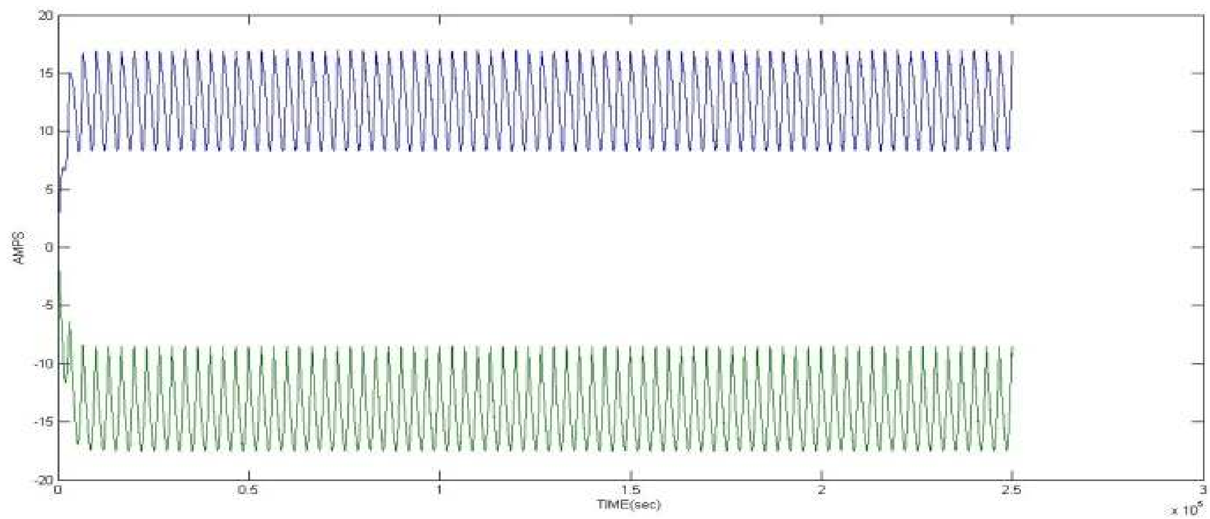


Fig. 8: i_d and i_q current

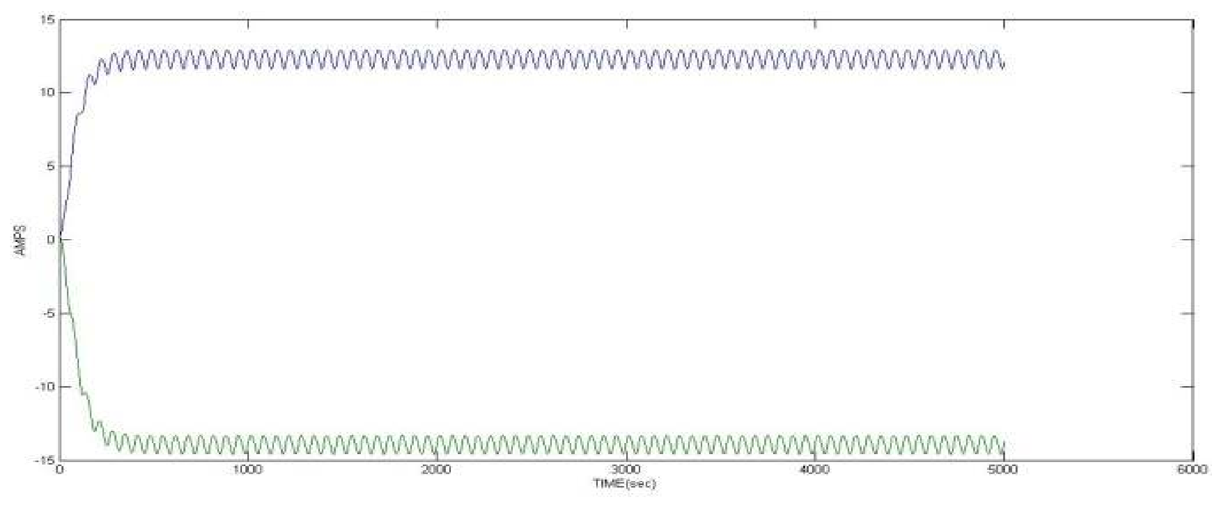
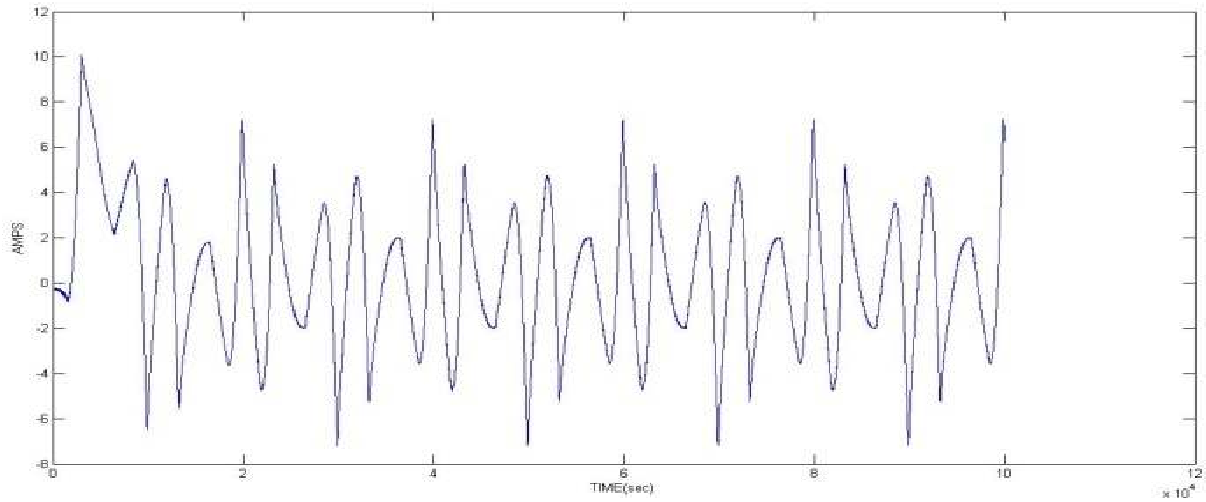
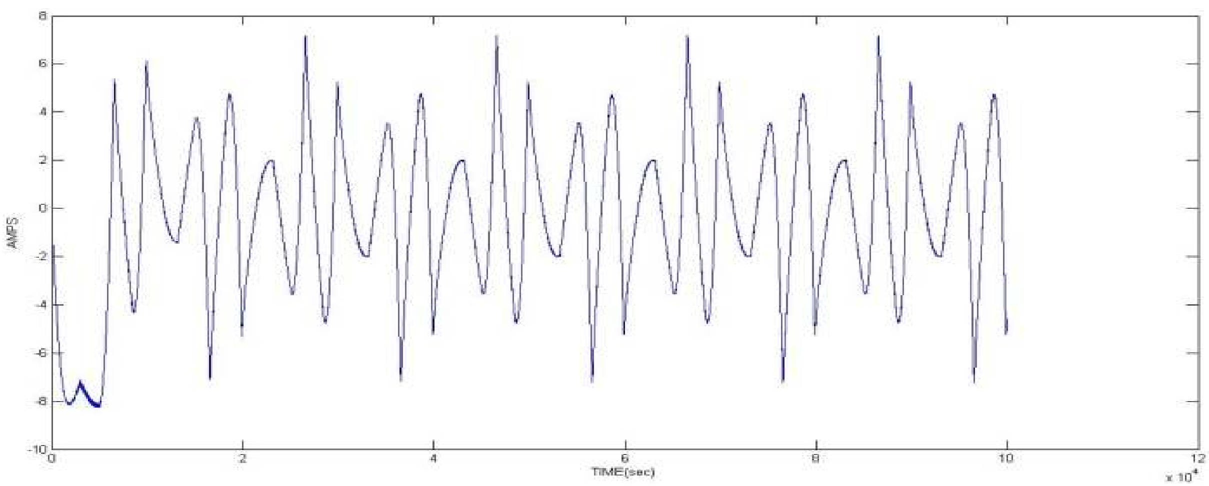


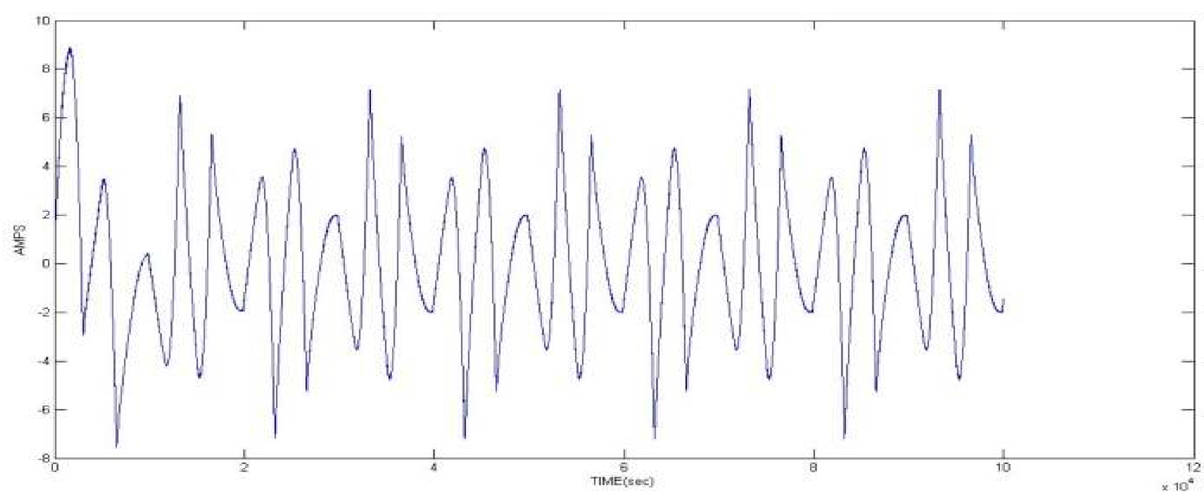
Fig. 9: Ripple rejection of i_d and i_q current



(a) Reference current ‘$I^{*}S_a$

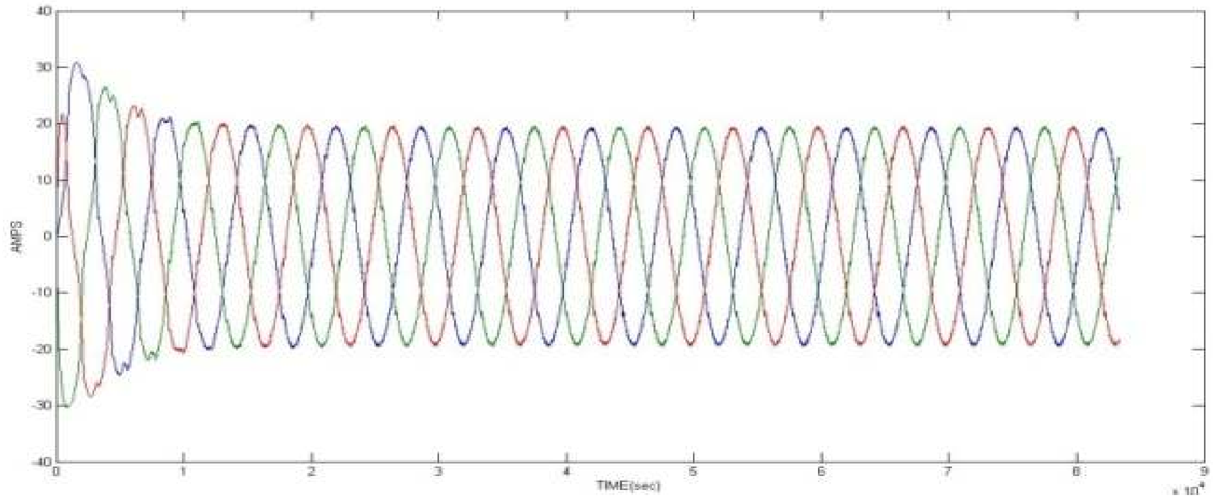


(b) Reference current $I^{*}S_b$

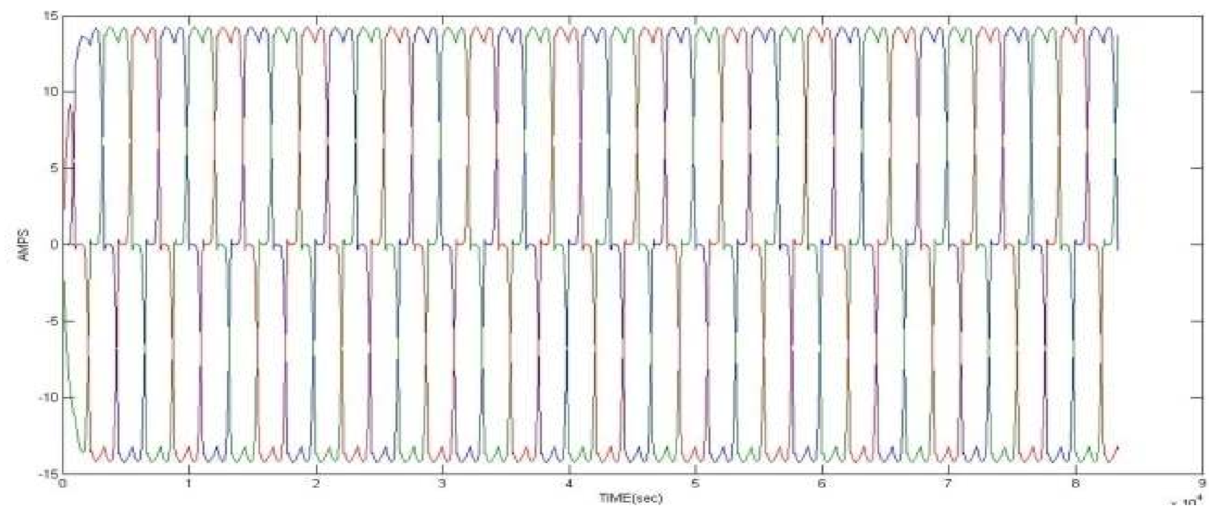


(c) Reference current $I^{*}S_c$

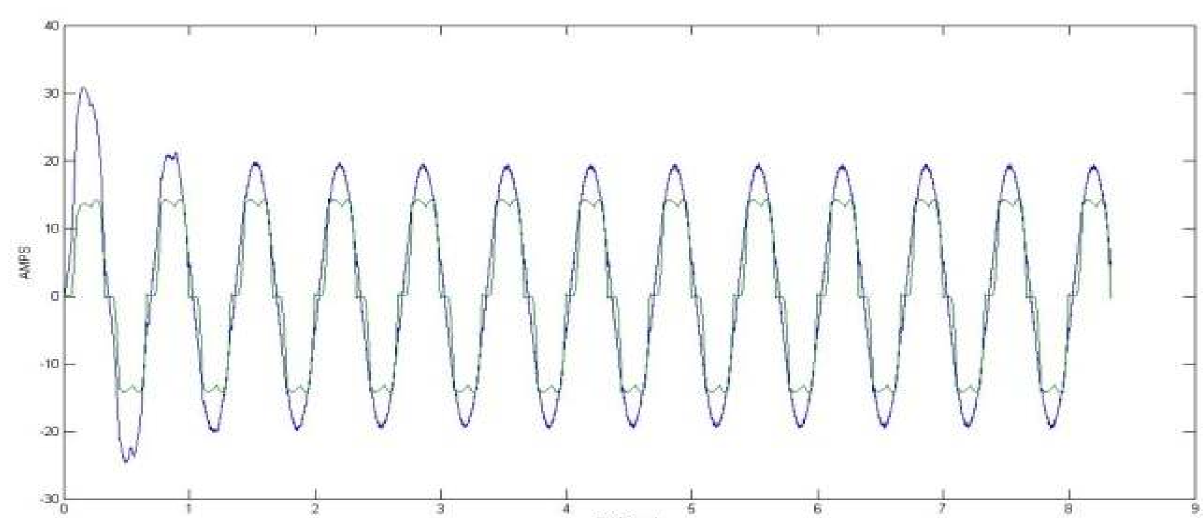
Fig. 10: Reference currents of SAPF



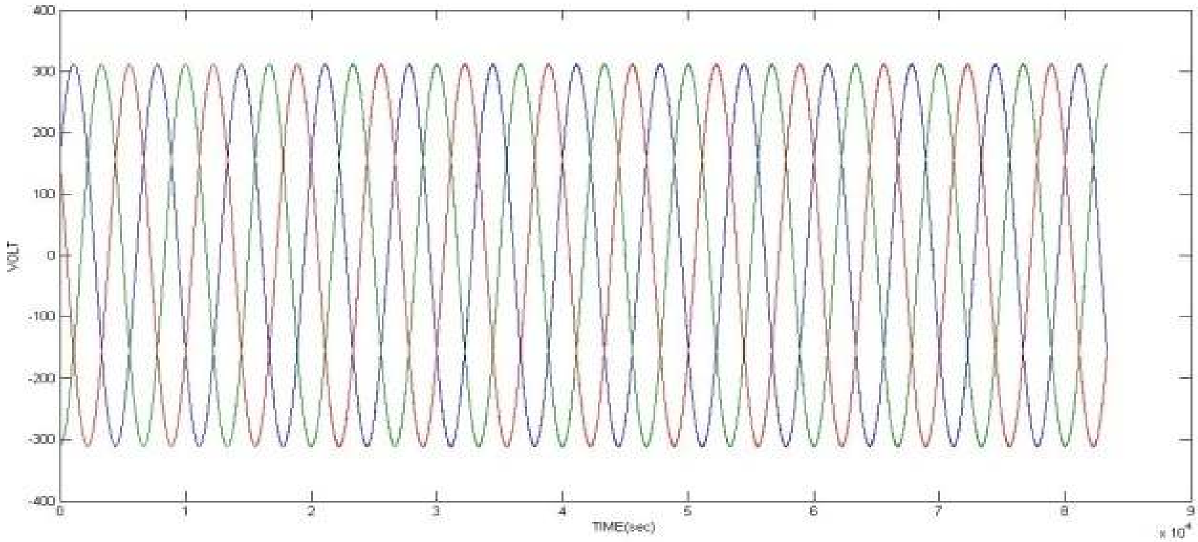
(a) Source current



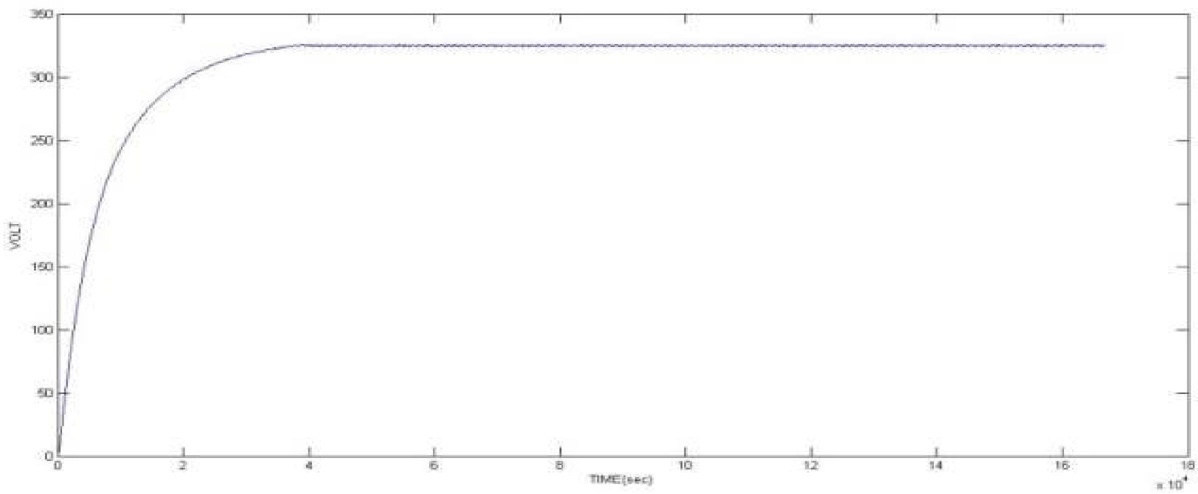
(b) Load current



(c) Source vs load current



(d) Source voltage



(e) Vdc voltage

Fig. 11: Dynamic response of SAPF with under distorted nonlinear load conditions

Ripples rejection of the i_d and i_q current based on the Butterworth filtering is clearly shown in the Fig. 9. Figure 10 shows the reference currents I^*S_a, I^*S_b, I^*S_c, which are the output from the shunt active filter.

Reference current from shunt active filter:

System performance: In the current simulation AHPF were used in Butterworth filter with cut off frequency $f_c = f/2$. Simulation results are obtained for different voltage conditions like sinusoidal, non-sinusoidal with different main frequencies. Simulation is carried out for instant active and reactive current theory (id- iq) with Space Vector Pulse Width Modulation (SVPWM). The THD of source current is a measure of the effective value of harmonic distortion and can be calculated as per 18 in which $i1$ is the RMS value of fundamental frequency component of current and in represents the RMS value of nth order harmonic component of current as follows:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} \mathrm{i_n}^2}}{i_1} \quad (18)$$

Figure 11 shows the dynamic response of SAPF with under distorted nonlinear load conditions.

It is observed from the simulation that the THD is minimized from load current THD 20.3% to source current THD 1.82% mainly due to the self tuning of PI controller using BFO (Fig. 12).

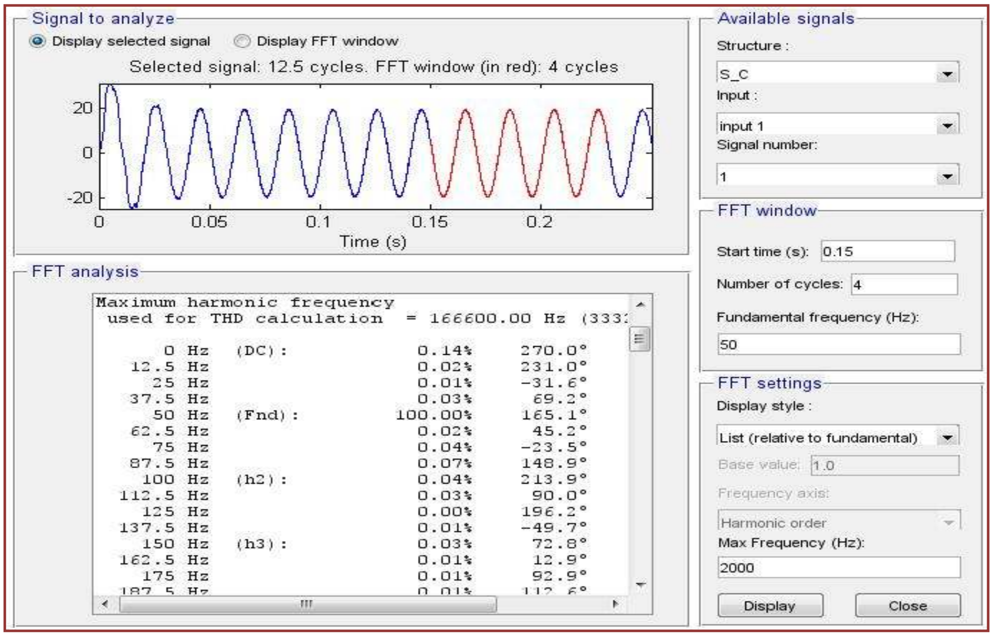


Fig. 12: Harmonic frequency analysis result

Table 3: THD Comparison

S. No	Approaches	THD (%)
1	Tang *et al*. (2012)	3.49
2	Rahmani *et al*. (2009)	3.10
3	Bhattachary and Chakraborty approach (2011)	4.50
4	Proposed SVPWM and I_d-I_q control strategy	2.02
5	Proposed BFO based SAPF	1.82

Table 3 shows the performance of the proposed approach based on THD. It is observed from the table that the proposed SVPWM and $\mathrm{i_d} - \mathrm{i_q}$ control strategy provides significant performance with THD of 1.82%.

CONCLUSION

This study proposes an optimal BFO based self tuning the PI controller to eliminate line current harmonics and compensate reactive power. BFO algorithm has been observed to produce significant optimization results. In this approach, this BFO approach optimizes the parameters such as proportional gain (k_p), integral gain (k_i) and saturation limit to determine the PI control parameters for a better performance. The results of simulations of the proposed optimized SAPF control technique based on BFO are observed to be very effective with higher harmonic suppression. The proposed approach is simulated in MATLAB and the performance of the proposed approach is compared with other existing technique. It is observed from the results that the proposed BFO based SAPF approach attains lesser a THD of 1.82%. This is mainly due to the effective optimization of BFO in finding the optimal fitness function and finding optimal parameters k_p, k_i and saturation limits. This BFO based SAPF proves to be a significant approach in reducing the ripple current harmonics.

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