SHUNT ACTIVE POWER FILTER SIMULATION BASED ON FUZZY LOGIC CONTROLLER AND GENETIC ALGORITHM

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Abstract: *The objective of this paper is to improve the three phase shunt active power filter (SAPF) performance by using the fuzzy logic controller (FLC) for the DC voltage regulation and by evaluation the hysteresis band (HB) based on genetic algorithm (GA). SAPF is used to compensate harmonic and reactive currents which are generated by the non-linear loads in the distribution system. GA and FLC are compared with the conventional methods to verify their positively effectiveness on the SAPF performance. MATLAB/SIMULINK environment is used to simulate the proposed system, SAPF was in compliance with IEEE-519 recommended harmonic std. SAPF achieved a low total harmonic distortion (THD) of the source current which demonstrated the importance of the presented methods.*

Key words: *SAPF, FLC, PI controller, Hysteresis current controller, Genetic algorithm.*

1. Introduction.

The growing use of power electronic equipment produces a large amount of harmonics in the power distribution system due to non-linear loads like diode-rectifiers, static converters and UPSs, etc. Although these devices are economical, reliable and flexible, they may degrade the power quality by creating harmonic currents and consuming of reactive power at the point of common coupling (PCC) of domestic or industrial needs [1].

Harmonics are injected back to the AC main source causing harmonic problems. Among often-cited problems is poor use of the AC source, increase system losses, poor power factor, erroneous operation solid state devices, excessive heating in transformers and motors, significant electromagnetic interference with communication circuits [2]. Harmonics is one of the main power system's disturbances frequently encountered by the utilities and customers. Hence, it's necessary to reduce the dominant harmonics below 5% as specified in IEEE 519-1992 harmonic std [3].

To avoid these harmonics, traditional solutions using passive filters had been used to mitigate harmonics but they were ineffective and inability to adapt to network characteristic variation, resonance with other elements, bulkiness of size and etc. Therefore, recent progress in semiconductor industries has resulted in the several APF topologies not only for harmonics suppression but also for many of power system disturbances. They have some merits like smaller size, precisely controllable and quicker response. APFs may be put in series or in parallel with loads, Active and passive filters may be combined to form the hybrid filters [4]. SAPF based on voltage source inverter (VSI) connected in parallel with the non linear load as an attractive solution to harmonic current problems. Its objective is to inject harmonic currents into the AC system that are equal in amplitude but opposite in phase to the original harmonics. The obtained mains currents are sinusoidal and in phase with the supply voltages, as in figure (1).

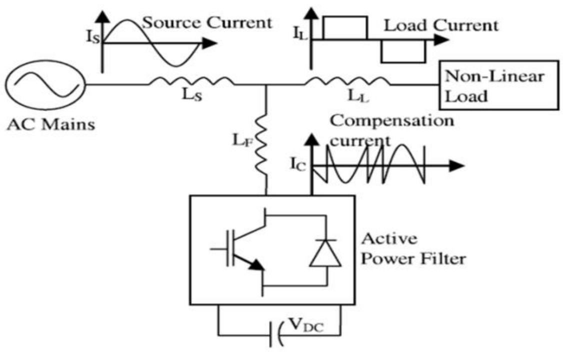

Fig. 1. Shunt active power filter.

This paper deals with SAPF topology that achieved simultaneously harmonic currents elimination and reactive power compensation

[5].The current produced by the SAPF is given by equation (1) [12].

$$I_{f,(compensation)} = I_L - I_S \quad (1)$$

Where I_L is the distorted load current and I_S is the supply fundamental current. Therefore, only the fundamental current would be delivered by the main.

The SAPF performance depends on the technique used to compute the reference of harmonic currents and the control method used to inject the desired current into the line. Several time domain (t-d) and frequency domain (f-d) methods were proposed for the identification of the reference. Generally, t-d methods are more effective for computing references. The t-d method based on p-q theory is followed in this work [6]. For generating the driving signals, a various Pulse Width Modulation-current control (PWM-CC) strategies were proposed but hysteresis current controller (HCC) has the highest rating among other methods and attracted researchers' attention in terms of quick current controllability, easy implementation and is popular for APF applications [14-16]. Here, GA approach is employed to *HB* estimation for HCC [21, 22].

Another important task in the SAPF control is the maintenance of a constant DC voltage across the VSI capacitor. This is necessary to compensate energy loss associated with the power switches of VSI and to compensate real power that is absorbed from the mains at load transients which tend to DC voltage reduction. This paper proposes a FLC for DC voltage control in order to improve the SAPF dynamics [8, 9].

Finally, the theoretical study is validated through a simulation series with MATLAB-SIMULINK. The reminder of the paper was organized as followed: section (2) describes the SAPF principle, section (3) emphasizes on the proposed control scheme and section (4) gives a summary of the simulation results. Finally in section (5), conclusion and comments are presented.

2. Design and Principle of SAPF.

SAPF is connected in the distribution-grid at PCC through AC filter inductance (L_f) as in figure (1). The harmonic current compensation is achieved by injecting equal but opposite harmonic components. This leads to cancel the original harmonics [5]. The instantaneous source current and source voltage are represented as in equations (2& 3) [8, 10].

$$I_S(t) = I_L(t) - I_f(t) \quad (2)$$

$$V_s(t) = V_m \sin(\omega t) \quad (3)$$

Where, V_m is the peak value of source voltage. The nonlinear load current contains the fundamental and harmonic current components based on Fourier series analysis, it is represented as in equation (4) [10].

$$I_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n) = I_1 \sin(\omega t + \Phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \quad (4)$$

Where ω is the fundamental angular frequency of the load current; Φ_n and I_n are phase shift and amplitude of the n^{th} order harmonic current, respectively. The load power can be computed from source voltage and load current, it is given by equation (5) [10].

$$\begin{aligned} P_L(t) &= V_S(t) * I_L(t) = V_m I_1 \sin^2 \omega t * V_m I_1 \sin \omega t . \\ &\cos \omega t * \sin \Phi_1 + V_m \sin \omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \\ &= P_f(t) + P_r(t) + P_h(t) \end{aligned} \quad (5)$$

Where, P_f, P_r and P_h are the fundamental (active) power, reactive power and harmonic power respectively.

The considered system structure is composed of 3 phase-3 wire network; 3 phase AC supply with line impedance. Non linear polluting load based on a bridge of 6-pulse diode rectifier. The proposed SAPF is based on a 3 phase VSI with an ac 1st order inductance filter, DC-capacitor (C_{DC}) to provide a DC voltage. Each arm of VSI contains 2-pairs of IGBT with anti-parallel diode. The p-q method block is used for reference current detection. DC bus capacitor voltage regulation block is based on FLC technique. HCC is used for switching patterns generation of the inverter.

3. Shunt APF control strategies.

The control system consists of three parts; (1) reference currents extraction method, (2) control of DC voltage, (3) method of switching signals generation.

3. 1. Algorithm of reference current generation.

There are different methods for the reference determination from the distorted line-current which are classified into f-d and t-d approaches. These methods include: Fast Fourier Transformer (FFT), Discrete Fourier Transform (DFT), Recursive DFT and etc, based on f-d but they require a large memory, computation power and are imprecise during the transient conditions. But, the t-d methods require less calculation and are widely followed for the references. The 2-mostly used t-d methods are synchronous reference frame (d-q) and (p-q) theories. In this paper, the reference is generated using the p-q method. This control algorithm is based on the feedback signals of source voltages, load currents and DC voltage [5].

Instantaneous active-reactive power (p-q) theory

This theory is due to (Akagi, Kanazawa and Nabae in1983-84) for applying it to APF control in real-time [5]. It's valid for operation in steady or transitory state. The calculation is simple which involve only algebraic calculation. It's suitable for the SAPF to reference currents calculation. It bases on instantaneous voltage and current in 3 phases - 3 or 4 wire systems. Here, it applies an algebraic transformation “Clarke transformation” of 3 phases - 3 wire system. Voltage and load current in the a-b-c coordinates transformed into the α–β coordinates as in equations (6& 7) [5, 6].

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I\alpha \\ I\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I\ La \\ I\ Lb \\ I\ Lc \end{bmatrix} \quad (7)$$

The instantaneous power is as in equation (8).

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} I\alpha \\ I\beta \end{bmatrix} \quad (8)$$

Where: p & q are the instantaneous real and reactive power respectively. p & q are formed as in equation (9).

$$P = P^{-} + P^{\sim}, \quad q = q^{-} + q^{\sim} \quad (9)$$

Where, $\underline{P^{-}}$: DC component of the real power relates to the fundamental component of the active current.

$\underline{P^{\sim}}$: AC or oscillating component of P that associated with harmonic currents.

$\underline{q^{-}}$: DC component of the reactive power relates to the fundamental component of the reactive current.

$\underline{q^{\sim}}$: AC or oscillating component of q that associated with harmonic currents.

The reference currents in α-β coordinates are as in equation (10).

$$\begin{bmatrix} I*\alpha \\ I*\beta \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix}^{-1} \begin{bmatrix} P\sim \\ q \end{bmatrix} \quad (10)$$

This current is divided into reactive, harmonic current only and the fundamental active current is excluded. Distorted reference currents are calculated from (α-β) to (a-b-c) "inverse Clarke transformation" in relation (11).

$$\begin{bmatrix} I*fa \\ I*fb \\ I*fc \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I*c\alpha \\ I*c\beta \end{bmatrix} \quad (11)$$

p-q theory is only an effective under the mains voltages are purely sinusoidal and balanced condition.

3.2. DC-Link Capacitor Voltage Controller.

Conventional controllers like PI (proportional-integral) and PID (proportional-integral-Derivative) had been used to control the DC capacitor voltage. However, they require precise linear mathematical model of the system and are difficult under parametric variations. Recently, FLC is used in SAPF applications. FLC's advantages over traditional controllers are: no need to accurate mathematical model, more robust and provides more user friendly programming for control purposes due to the employment of linguistic variables [7 - 9].

The DC capacitor voltage is sensed and compared with a desired value. The DC voltage error ($e = V_{DC, ref} - V_{DC, act}$) at the n^{th} sampling instant is used as an input for a suitable regulator for the DC voltage regulation by estimating the reference current magnitude (I_{max}) of the VSI losses. I_{max} is multiplied by the source phase voltage amplitude to generate the required power loss (P_{loss}) of VSI and the system. This is added to the real power of harmonics as in equation (12) based on equation (10) for contribution in reference currents generating [4].

$$P_{ref} = P_{loss} + P^{\sim} \quad (12)$$

3.2.1. PI-controller.

This controller estimates the output as I_{max} and controls the DC voltage. The error (e) passes through it, this controller is eliminating steady state error in the DC voltage. Its transfer function $H(s)$ is defined in figure (2), the equations (13& 14) illustrate this [10, 12, 13].

$$H(s) = K_P + K_I/s \quad (13)$$

$$Output\ (I_{max}) = e * K_P + K_I \int e\ dt \quad (14)$$

Where, K_P is the proportional constant that determines the dynamic response of the voltage control and K_I is the integration constant that determines the settling time.

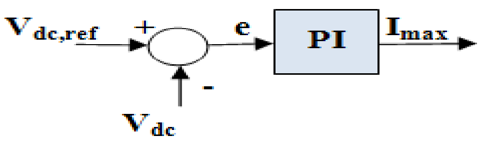

Fig. 2. PI controller function.

3.2.2. The proposed FLC approach.

The FLC concept was proposed in 1965 that was based on a logical system called fuzzy logic. It is much closer in spirit to human thinking and natural language. FLC was deduced from fuzzy set theory. Fuzzy sets boundaries were undefined, ambiguous and useful for approximate systems design [8, 10].

FLC is used for the SAPF in closed loop to control a constant DC voltage, improve the SAPF performance and reduce the *THD* of the current. The (*e*) and its derivation (*de*) are used as inputs for fuzzy process as in figure (3). FLC output (*C de*) is I_{max}. The FLC characterized by: (1) five fuzzy sets in linguistic variables are Negative Large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Large (PL) for each input and output variables, (2) triangular membership function is used for the simplicity, (3) implication using mamdani-type min-operator, and (4) defuzzification using the centriod method[7, 9, 10].

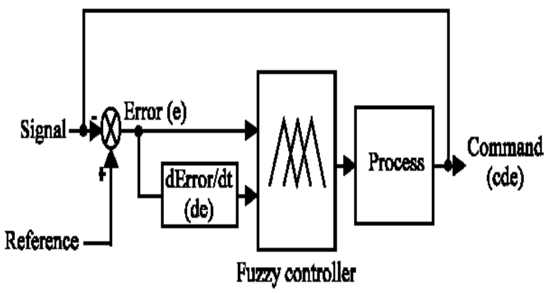

Fig. 3. Operation of FLC.

Mainly, the three main features of FLC are Fuzzification, Fuzzy Inference Mechanism (Knowledge base) and Defuzzification, as shown in figure (4).

Fuzzification: The conversion process of a numerical variable to a linguistic variable.

Rule Elevator: FLC uses linguistic variables as a control gain. The basic operations of FLC requires AND (∩), OR (U) and NOT (~) for evaluation fuzzy set rules.

Defuzzification: The conversion process of linguistic variable to a numerical variable.

Database: stores the definition of the triangular membership function for the fuzzifier and defuzzifier.

Rule Base: stores the linguistic control rules required by rule evaluator. The 25 rules in this proposed controller are shown in table 1 [11-13]. Example: If (*e*) is NL and (*de*) is NL then (*C de*) is NL. If (*e*) is NL and (*de*) is PS then (*C de*) is NS.

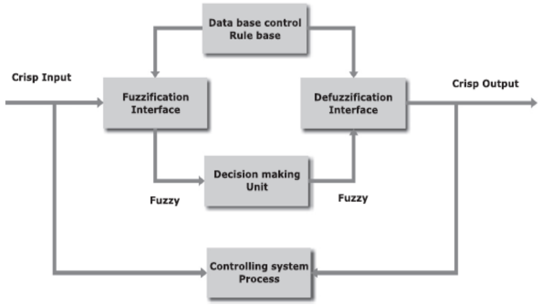

Fig. 4. Block diagram of fuzzy logic controller.

Table 1
Rules base of fuzzy control

		(*e*)				
		NL	NS	ZE	PS	PL
(*de*)	NL	NL	NL	NL	NS	ZE
	NS	NL	NL	NS	ZE	PS
	ZE	NL	NS	ZE	PS	PL
	PS	NS	ZE	PS	PL	PL
	PL	ZE	PS	PL	PL	PL

3.3. PWM-VSI current controller.

The SAPF effectiveness relies on the design and characteristics of the PWM- CC. There are many PWM- current control strategies proposed such as sinusoidal-PWM, PI controller, HCC, Average Current Mode Control and Space Vector PWM, etc. HCC method is discussed here. HB is used to determine the switching signals. The fixed-band HCC is imposed a bang-bang instantaneous control method that draw the output filter current (I_f) to follow its reference current (I^*_f). HCC merits are suitable stability, fast response, high accuracy and simple design more than other methods. However, this control scheme exhibits several unsatisfactory features like uneven switching frequency where it varies within a particular band limit and possible to generate resonance. This unpredictable switching function affects on the filter efficiency [12-18].

Hysteresis current controller

In this approach, the current error is the difference between the reference current and the injected current of the inverter, $e(t) = I^*_f(t) - I_f(t)$. When the current error exceeds the upper limit of the *HB*, the inverter upper switch arm is turned OFF and the lower switch is turned ON. As a result, the current started to decay that is shown in figure (5). When the current error crosses the lower limit of the *HB*, the lower switch is turned OFF and the upper switch is turned ON. So, the current came back into the *HB*. But, no action when the error is inside the limits of hysteresis band.

The switching logic performance as followed.
S (switch state) = 0, if $I_f(t) > I^*_f(t) + HB$, the upper switch is OFF and the lower switch is ON ($S = -V_{DC}$).
S=1, if $I_f(t) < I^*_f(t) - HB$, the upper switch is ON and the lower switch is OFF ($S = +V_{DC}$).

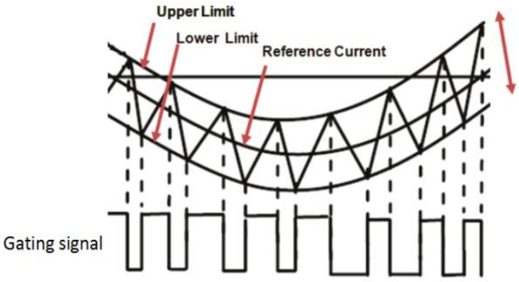

Fig. 5. Diagram of hysteresis current control.

3.3.1. Ingram-Round method for HB design.

In 1997, D.M.E. Ingram and S.D. Round presented the SAPF design controlled by hysteresis method. The details are explained as followed [23].

<u>Step 1</u>: Calculate the maximum value of di_c^* / dt by equations (15& 16).

$$I_{h,\,max}(t) = A\sin 2\pi ft \tag{15}$$

$$(di_f^* / dt)_{max} = A2\pi f \tag{16}$$

Where: $I_{h\,(max)}(t)$ is the maximum current for each harmonic components, A is the harmonic current amplitude, f is the frequency of the harmonic current.

<u>Step 2</u>: Determine L_f by equation (17).

$$L_f\,(max) = \frac{V_{DC} - V_S}{max\left(di_f^* / dt\right)} \tag{17}$$

Where: V_s = the maximum voltage value of the source. Note that, the maximum value of di^*_f/dt is from Step 1 and V_{DC} shall be always designed higher than V_s.

<u>Step 3</u>: Determine *HB* by equation (18).

$$HB = \frac{2V_{DC}}{9L_f F_{sw}} \tag{18}$$

Where: F_{sw} is the switching frequency.

3.3.2. Principle of GA.

There are three main processes for GA operations. The 1st is ***'Selection'***. This process will select the population in the searched system to be the parent for the next generation. The 2nd process is ***'Genetic operation'*** to search the better solutions for each generation by using the crossover and mutation techniques. The final process is ***'Replacement'***. The offspring from the genetic operation process will replace the previous population in which it may replace the whole or some part of population [19].

The suitable GA parameters are necessary for problems optimization and to achieve the best solution. The parameters needs to identify are a number of chromosomes, a genetic operation (selection process), a crossover method, a crossover probability, a mutation method and a probability value of mutation .The criterion of selecting these parameters for SAPF design is to minimize the fitness value, here is *HB*.

The proposed GA for HB design

GA search is applied to determine the appropriate *HB*. The SAPF parameters for searching are V_{DC}, L_f and F_{sw}. *HB* is defined as the fitness value that can be determined from the objective function. The GA will try to search the best SAPF parameters by simulation tries to achieve the minimum *HB*. The searching steps of as followed.

<u>1</u>: Define the boundary of parameters. The upper and lower limits of V_{DC}, L_f and F_{sw} are set to [400 - 700 V, 0.7 - 1.5 mH and 20 - 50 KHz] respectively.

<u>2</u>: The chromosomes for the population encoding scheme are set to be the real value [20, 21].

<u>3</u>: The population size equals to 50 chromosomes.

<u>4</u>: Define the initial population by random within the search space of parameters.

<u>5</u>: The maximum number of generation for searching is set to 100.

<u>6</u>: The selection process is tournament method. The uniform mutation (probability = 0.08), the scattered crossover (probability = 0.8) [22, 23].

4. Simulation results and Discussion.

The performance of the proposed control strategy was evaluated through MATLAB/ SIMULINK of Simpower system environment and Fuzzy toolbox.

4.1. System parameters and Filter specifications.

The considered main parameters are: $V_{L\text{-}L}$ (rms) = 380V, F_{Supply} = 50Hz, R_S = 5mΩ, L_S = 1μH. The AC line before the load is L_L = 0.4mH, R_L= 5mΩ. SAPF parameters are C_{DC} = 13mF, $V_{DC,\ ref}$ = 650V. PI controller gains are K_P = 2, K_I = 0.5. FLC gain is according to fuzzy operators. The uncontrolled diode rectifier load is R_{DC} = 6.7Ω, L_{DC} = 20mH.

4.2. Simulation results.

Figure (6) shows the deformed source current waveform by harmonics before filtering. FFT for harmonics analysis notifies that the *THD* is 25.32% as in figure (7).

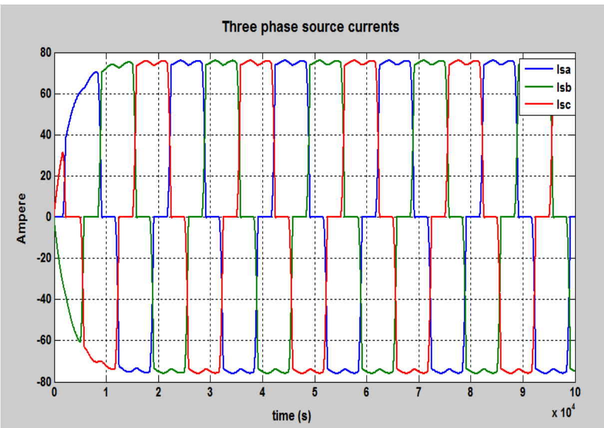

Fig. 6. Three phase distorted source current.

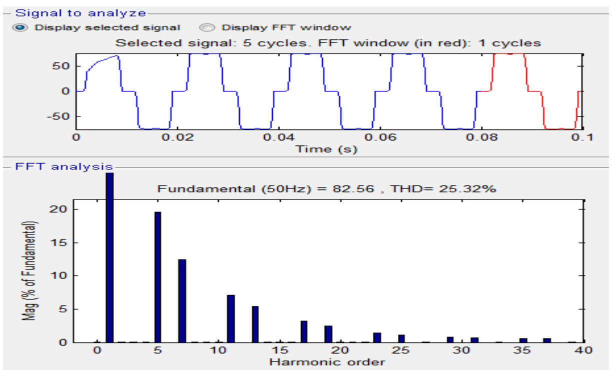

Fig. 7. THD of source current analyzed by FFT.

Parameters of SAPF based GA and Ingram-Round methods are showed in the table 2.

Table 2
SAPF Parameters according to design methods

	Ingram-Round	GA
L_f (mH)	1.2	1
$V_{DC,ref}$ (volt)	650	650
F_{sw} (KHz)	25	50
***HB* (A)**	4.814	2.917

According to HB values which were deduced from the stated method in table 2, SAPF was simulated under PI and FLC to regulate the DC voltage with each method as shown in table 3 and table 4.

Table 3
THD of the source current and V_{DC} based PI controller

	Ingram-Round	GA
%THD	2.96	1.95
V_{DC} (volt)	620	648

THD of the supply current as in table 3 based PI controller for Ingram-Round and GA methods are plotted in FFT analysis spectrum as in figures (8, 9). It's clear that the source current after filtering is sinusoidal and the *THD* of it is better in case of GA than the other one. Because the *THD* of the source current is reduced from 25.32 % to 1.95 % with GA method but the *THD* is reduced from 25.32 % to 2.96 % with Ingram-Round method. In case of PI controller, the DC voltage is measured as mentioned in table 3.

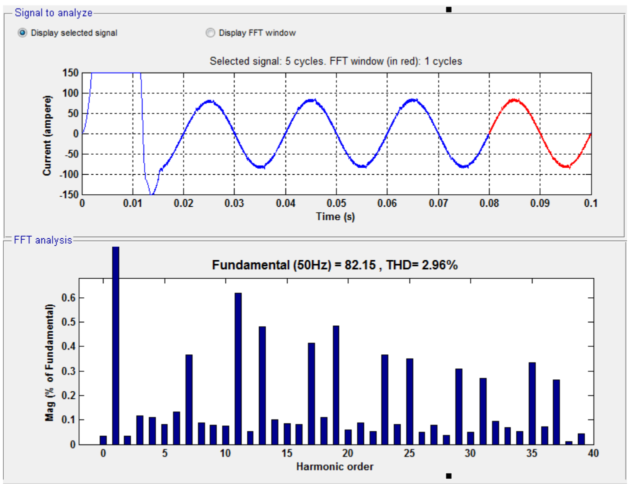

Fig. 8. Source current analyzed by FFT (Ingram-Round).

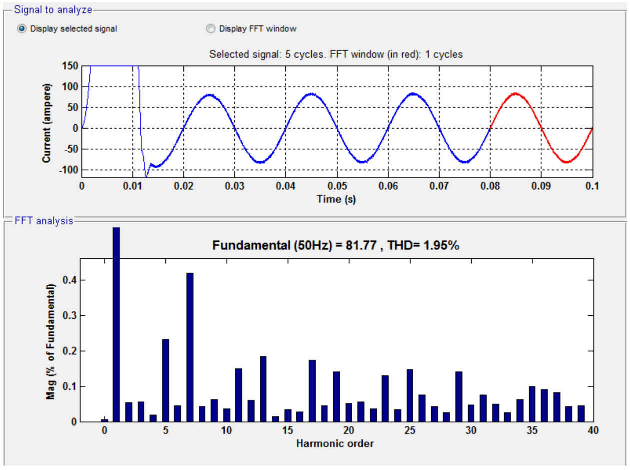

Fig. 9. Source current analyzed by FFT (GA).

In the other hand, *THD* of the supply current as in table 4 based FLC for Ingram-Round and GA methods are plotted in FFT analysis spectrum as in figures (10, 11). Also, the source current after filtering is sinusoidal and the *THD* of it is more perfectly sinusoidal with GA. the *THD* of the source current is reduced from 25.32 % to 0.89 % with GA method and from 25.32 % to 1.68 % with Ingram-Round method. In case of FLC, the DC voltage is as showed in table 4. The voltage is nearly constant accurately with FLC but is not accurately constant with PI controller.

Table 4
THD of the source current and V_{DC} based FLC

	Ingram-Round	GA
%THD	1.68	0.89
V_{DC} (volt)	616	646

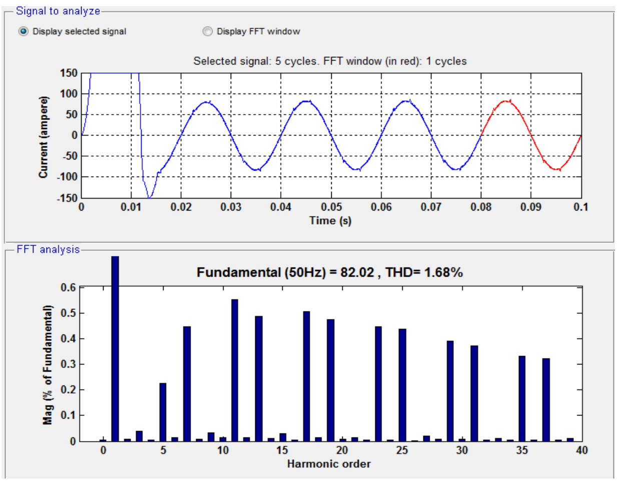

Fig. 10. Source current analyzed by FFT (Ingram-Round).

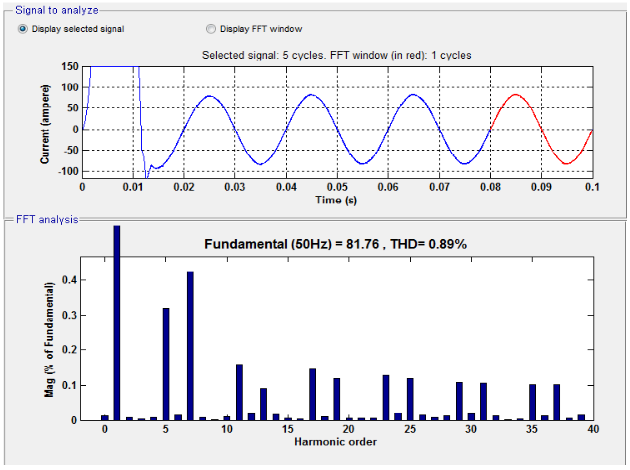

Fig. 11. Source current analyzed by FFT with FLC (GA).

In the Truth, the DC voltage value has an important effect on the *THD* of the source current reduction.

4.3. Simulation results of load transient.

At transient case, R_{DC} of the DC load is changed from 6.7 Ω to 10 Ω. The results were explained in table 5.

Table 5
The simulation results at transient case

parameters	Ingram–Round	GA
Controlled DC voltage based PI controller		
%THD	3.84	2.76
V_{DC} (volt)	623	650
Controlled DC voltage based FLC		
%THD	1.06	0.99
V_{DC} (volt)	617	647

The simulation results showed a fair controlling of DC voltage and a perfect filtering of harmonic currents at steady and transient case of the load.

5. Conclusion.

Accurately, the GA is an interested optimization technique to select and optimize the *HB* value more than the traditional Ingram-Round method. The results were manifested a proportional relationship between *HB* value and the *THD* of the source current.

Also, the controlled DC voltage has an effect on the filtering process positively. FLC was reliable for DC voltage regulation and improving the SAPF performance. The advantages of FLC in the case study are high performance and better dynamic behavior more than PI controller to optimize the energy storage and adjust a constant voltage of the

DC capacitor.

Eventually, the optimized *HB* by GA with the controlled DC voltage by FLC facilitated harmonics and reactive power compensation. The source current waveform became purely sinusoidal after filtering and in phase with the source voltage waveform. Moreover, minimization of the *THD* of the source current is achieved based on IEEE std. 519-1992. Whereas, the *THD* of he source current is reduced from 25.32% to 0.89%.

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