DC Side voltage Control Consideration for Single Phase Shunt Active Power Filter for Harmonic and Reactive Power Compensation.

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Abstract:
Shunt Active Power Filter (APF) is widely used to address the harmonic pollution created by nonlinear loads in power system. The APF consists of dual loop, inner current control responsible for shaping the output current of the APF, while DC side voltage control loop is accountable for power balancing. The APF current control is highly demanding due to non-sinusoidal reference and considered vital to obtain desired compensation performance. DC side voltage control too has a pronounced impact on APF's compensation characteristics, if not properly considered. This paper evaluates the various factors that have impact on the performance of the DC side voltage control. A moving average filter is used to eliminate the even harmonics present on capacitor voltage as a result of harmonic compensation before it is fed to comparator and voltage controller. The paper also presents the brief description and design of DC side components of single phase APF. A comparison between PI based and Fuzzy Logic based DC side voltage control is carried out. The analysis and performances are evaluated with simulation results.

Key words: *Active Power Filter, Fuzzy Logic Control.*

1. Introduction

The usage of nonlinear loads in power system has brought about harmonics and other power quality issues. Traditional passive filters are unable to satisfy the required compensation performance hence use of Active Power Filter (APF) to mitigate the harmonics and other power quality issues is gaining momentum. The basic principle of APF is to inject the harmonic components of load current in equal and opposite amount into the power system such that they cancel each other. This way, the source will only be supplying fundamental component of load current and the harmonic components are delivered by the APF maintaining sinusoidal source current [1]. Since APF is only supplying the harmonic contents in the form of reactive/distortion power there is no need for energy storing devices and a reactive element can cater the demand of supplying reactive and distortion power[2]. Shunt APF utilizing Voltage Source Inverter (VSI) is the most popular configuration where APF is connected in parallel to the nonlinear load. Single phase APF has drawn less attention than three-phase due to its limited application. However, using several single phase APF in place of three phase APF can offer several advantages [3]. Single phase APF using VSI has two major parts power stage and control circuit as shown in Fig. 1. Power circuit consists of a Full bridge VSI with capacitor at DC side and interfaced to the grid via inductor. The control subsystem consists of a reference current extraction subsystem, current control subsystem and voltage control subsystem. The reference current subsystem identifies the harmonic and reactive current components present in the load current which is fed to the inner current control loop which ensures that APF generates these current components with minimum error. There will be fluctuation in capacitor voltage due to oscillating reactive power between Non linear load and the APF. In non ideal scenario, owing to losses in parasitic component and switching devices in converter, the active power will also be consumed resulting in slow decrement of capacitor voltage [4]. Hence two factors will cause the change in DC side capacitor voltage: the first one is necessary to realize the compensation performance and the rise and fall of voltage will carry on periodically without affecting the average voltage. However, the second factor will keep on decreasing the voltage of capacitor, to offer the energy losses which will affect the compensation performance. Therefore it necessitates a control mechanism to maintain the capacitor voltage to its pre-specified reference value for reimbursing the losses in the VSI. To realize this, it will draw an active current component from the grid based on the difference between the reference and measured capacitor voltage.

The reference current extraction and current control poses a stringent requirement for obtaining better compensation performance and are considered the pivotal components. However the proper design of passive components and the DC side voltage control is equally important to realize desired compensation characteristics. The major factors used for judgment of performance of APF can be:

(a) The THD and frequency spectrum of line current after the compensation

(b) Dynamic response in case of the load changes

There are 3 factors in DC side of APF structure that has

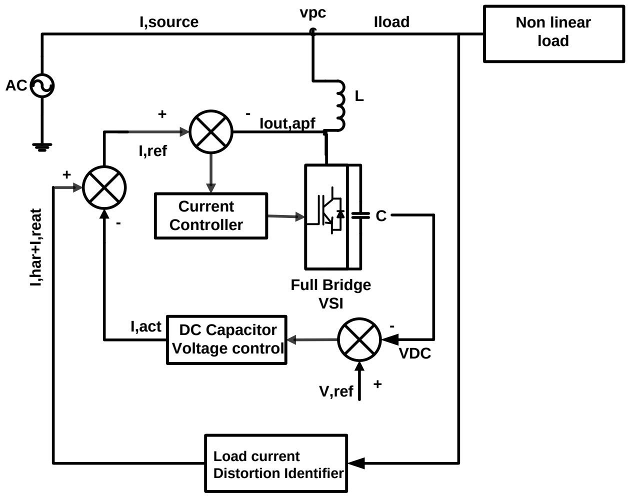

Figure 1: Structure of Shunt Active Power Filter

impact on the compensation performance. The DC side reference voltage, Capacitance used and the control mechanism to maintain capacitor at reference value. The first two are very much fixed during system design and topology selection while the control structure can be adjusted to improvise APF performance. This paper presents the design of the DC side components and parameters in the simplest approach. The use of Moving Average Filter to eliminate the harmonic components from the measured Capacitor voltage and its impact is discussed. The comparative analysis of voltage controller implemented with Proportional Integral controller and Fuzzy Logic Controller is carried out. The discussions presented are validated via simulation results in Matlab.

2. System Description

The DC side capacitor is used as a buffer for reactive power flow which is oscillating between APF and Non linear load. The reactive power flow will charge and discharge the capacitor and it is necessary to avoid serious voltage fluctuations to affect the compensation performance of APF. A proper sizing of capacitor, suitable selection of reference voltage, combined with a well designed control loop will serve to maintain the average DC side voltage and consequently compensation characteristics of APF. [5] Has presented various approaches to design of capacitor and reference voltage in APF. A simpler approach will be considered here for designing parameters of DC side based on following assumptions:

(a) Grid voltage is sinusoidal
(b) The highest harmonic current APF can compensate be I_h present at $f_{h,max}$
(c) Maximum ripple allowed on the DC side capacitor is 7.5% of the reference voltage.

The DC side voltage must be greater than the peak value of grid voltage for APF to be capable to output the compensating current. The output voltage from the converter consists of reactive component and the harmonic components as present in the reference current and components at switching frequency. The current thus generated will cause a voltage drop in the inductor at various frequency components.

$$v_{ind} = v_{out} - v_{grid} \quad (1)$$

$$v_{ind} = L\frac{di_{apf}}{dt} \quad (2)$$

Higher frequency component will cause higher voltage drop across the inductor and for worst case the maximum voltage due to harmonic current and the grid voltage peak can occur at same time as shown in Fig. 2. The minimum required DC side voltage at the instant of peak voltage in grid supply can then be given as (3).

$$V_{DC} > \left(\omega_3 I_3 + \omega_5 I_5 + \omega_{h,\max} I_h\right)\sqrt{2}L + V_{ac,pk} \quad (3)$$

In most practical scenario dominating harmonic current components occur at odd harmonics at 3^{rd}, 5^{th} and 7^{th} and negligible amount at higher frequencies [6]. Higher DC side voltage will improve the current tracking (di/dt) ability but the voltage stress on the switching device will increase. The reference voltage can thus be decided based on worst case scenario the APF will be subjected depending upon the application scenario. For a considerable calculation, we can take 50% of the rated current occurring at 3^{rd}, 35 % at 5^{th} harmonic, 10 % at 7^{th} harmonic and 5 % at h^{th} harmonic. The rated current can be determined based on the output power capacity of the APF system ($I_{rated}= S_{rated}/V_{ac}$).

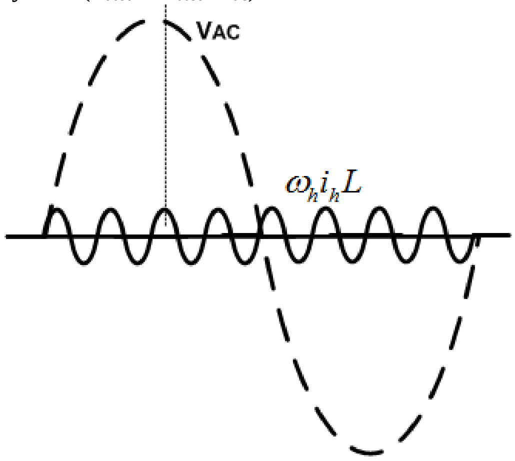

Figure 2: Grid voltage and the voltage drop in inductor due to harmonic component

Maximum ripple in DC side voltage is chosen as criteria for determining capacitance. The maximum transaction of reactive energy occurs when APF is compensating the pure reactive current at rated value. The minimum capacitance should be able to cater the maximum reactive power flow and limit the voltage swing within the allowed range of $V_{DC,min}$ to $V_{DC,max}$.

If the APF is compensating for the inductive load then the output current generated by APF will also be a sinusoidal but out of phase with the grid voltage.

$$V_{grid} = V_{pk}\sin(\omega t) \quad (4)$$

$$i_f = I_{pk}\sin(\omega t - 90) \quad (5)$$

Then reactive energy injected into the grid by APF can be obtained by integrating the voltage and current waveform of the APF over the half cycle.

$$E_{conv} = \int_{\pi/2}^{\pi} V_{pk}\sin(\omega t)\times I_{pk}(-\cos(\omega t))dt \quad (6)$$

$$E_{conv} = \frac{V_{pk}I_{pk}}{2\omega} \quad (7)$$

The reactive energy appears as charge and discharge of capacitor. To supply above energy to grid, the capacitor will discharge causing the decrease in the capacitor voltage. If capacitor voltage drops from $V_{DC,max}$ to $V_{DC,min}$ the energy lost by the capacitor can be obtained as:

$$\Delta E = \frac{1}{2}C(V^2{}_{DC,\max} - V^2{}_{DC,\min}) \quad (8)$$

Equating equations (7) and (8), we get:

$$C \geq \frac{V_{pk}\times I_{c,pk}}{\omega(V_{DC,\max}{}^2 - V_{DC,\min}{}^2)} \quad (9)$$

3. DC Voltage Control Consideration

The APF will enable the source to deliver active power only and it will cater the harmonic and reactive power of the load.

In case of lossless system, the output power from converter will contain only the harmonic and reactive power. To maintain power balance, the input side should also have similar power component present in it. This results in the fluctuation of DC side voltage which though averages to zero in one fundamental mains cycle. Generally the non linear load currents are odd half wave symmetric and periodic in nature [7].

$$i_{load} = \sum_{h=2n+1,n=0,1,2}^{\infty} I_h\sin(h\omega t - \phi_h) \quad (10)$$

If we consider, the mains voltage is pure sinusoidal as in (4), the load power is calculated as (11) composed of real and distortion power.

$$P_l(t) = v_{grid} * i_{load} = P_l + \tilde{p}_l(t) \quad (11)$$

Then, the real power supplied by source (12), and reactive & harmonic power flow from APF is given as (13).

$$P_{src} = \frac{V_{pk}I_1}{2}(1-\cos 2\omega t) \quad (12)$$

$$p_{apf} = P_l(t) - P_{src} = P_f + \tilde{p}_{apf}(t) \quad (13)$$

In ideal case P_f is negligible and the distortion power injected is as below:

$$p_{apf} = v_{grid}\times i_{apf} \quad (14)$$

$$= \frac{V_{pk}I_1\sin 2\omega t.\sin\phi_1}{2} + \frac{V_{pk}I_3}{2}(\cos(4\omega t - \phi_3) - \cos(2\omega t - \phi_3)) + \bullet\bullet\bullet \quad (15)$$

$$p_{apf} = \tilde{p}_2 + \tilde{p}_4 + \bullet\bullet\bullet \quad (16)$$

We can infer there are power components at even harmonics as shown in Fig. 3 and these components should also be present in the DC side too. Though these power averages to zero in a cycle, they will create an ac component of input current that will result in voltage fluctuation of the capacitor.

$$\tilde{i}_{dc}(t) = \frac{\tilde{P}_{apf}}{V_{DC}} \quad for, (V_{DC} >> \tilde{v}_c \,\&\, I_{DC} \approx 0) \quad (17)$$

$$\tilde{v}_{dc}(t) = \frac{1}{C}\int_0^t \tilde{i}_{dc}(t)dt \quad (18)$$

The fluctuation in the DC side capacitor voltage in general is calculated to be as (19) [2].

$$\tilde{v}_{cap}(t) = \frac{-1}{CV_c}\sum_{n=1}^{\infty}\frac{P_n}{n\omega}\sin(n\omega t + \phi_n) \quad (19)$$

The voltage fluctuation and frequency is function of the magnitude and order of the harmonic to be compensated with higher harmonic current requiring more frequent periodic oscillation of voltage

For a real system, there will be power losses hence an active power flow also occurs consequently resulting in variation of DC component of the capacitor voltage too. The active power flow can occur due to:

(a) Losses in the switch and parasitic component of the converter
(b) Reference current falsely including a fundamental component
(c) Real power exchanged due to source voltage distortion and injected harmonic current at same frequency.

Hence, we can consider the real time capacitor voltage to compose of DC and AC component.

$$v_{dc}(t) = V_{DC} + \tilde{v}_{dc}(t) \quad (20)$$

The ac component has to be filtered out and the DC component has to be maintained near reference value for proper operation of the APF. Thus a voltage controller is eminent to draw required current from the mains to charge the capacitor. The ac component is composed of low frequency terms for compensation of harmonic and reactive current, while the high frequency terms are due to the injected harmonic components at switching frequency and present in negligible amount.

Voltage controller acts on the difference of the sampled instantaneous capacitor voltage and the reference voltage and provides a reference current for inner current tracking loop to bring capacitor voltage closer to reference.

$$v_{err} = (V_{ref} - V_{DC}) - \tilde{v}_{dc} \quad (21)$$

But the controller should not act on ac quantities which are responsible for reactive and distortion power which sum up to zero in one fundamental cycle. If controller acts on these ac fluctuations, the corresponding reference current will also include harmonic components.

For instance, using PI controller the reference peak current is:

$$i_{dc,ref} = K_{p,vl} \times v_{err} + K_{i,vl} \int v_{err}\, dt \qquad (22)$$

If the load current is as (10), then ac component in capacitor voltage is composed of even harmonics.

$$i_{dc,ref}(t) = i_{dc,ref} + \tilde{i}_{dc,ref}(t) \qquad (23)$$

Where, $\tilde{i}_{dc,ref}(t) = \tilde{i}_2(t) + \tilde{i}_4(t) + \bullet\bullet$

The actual current drawn from grid for maintaining capacitor voltage is given in (24)

$$\begin{aligned} i_{ref} &= i_{dc,ref}(t) \times \sin \omega t \\ &= i_{dc,ref} \times \sin \omega t + (\tilde{i}_2(t) + \tilde{i}_4(t)) \times \sin \omega t \end{aligned} \qquad (24)$$

The even harmonic component in capacitor voltage results in inaccurate current estimation and odd harmonics are drawn from the grid resulting in degradation of THD of source current.

$THD\% = \sqrt{\sum_{h \neq 1} \left(\frac{I_h}{I_1} \right)^2} \times 100$ where, I_h is rms value of the harmonic current and I_1 the rms of fundamental

To minimize the voltage fluctuation, we can increase the Capacitance and reference voltage. But, higher voltage requires higher voltage rating of the semiconductor devices which is not practically and economically feasible. Using optimal capacitor and voltage reference, we can opt for the filtering of the generated AC components. Low frequency component poses strict filtering requirement and when APF is compensating the reactive current it will have a power component at twice the grid frequency as shown in Fig.3.

A Low Pass Filter (LPF) can be added to remove the ripple components. Higher order filter are required for better filtering performance, but it will affect the dynamics and make system much slower. In this paper Moving Average Filter (MAF) is used to reject the even harmonic components which can sharply remove the harmonics with less compromise on the system dynamics.

Moving Average Filter

Since LPF dictate the dynamics of the voltage control system, MAF can be used to attain excellent harmonic cancellation with fast transient response. The output of MAF is mean of N continuous samples, obtained as (25), averaging the high frequency component to zero and leaving out only DC components [8].

$$y[k] = \frac{1}{N}(x[k] + x[k-1] + x[k-2] + \bullet\bullet\bullet + x[k-N+1]) \qquad (25)$$

The transfer function of the MAF is given as

$$H(z) = \frac{1}{N}\frac{1-z^{-N}}{1-z^{-1}} \qquad (26)$$

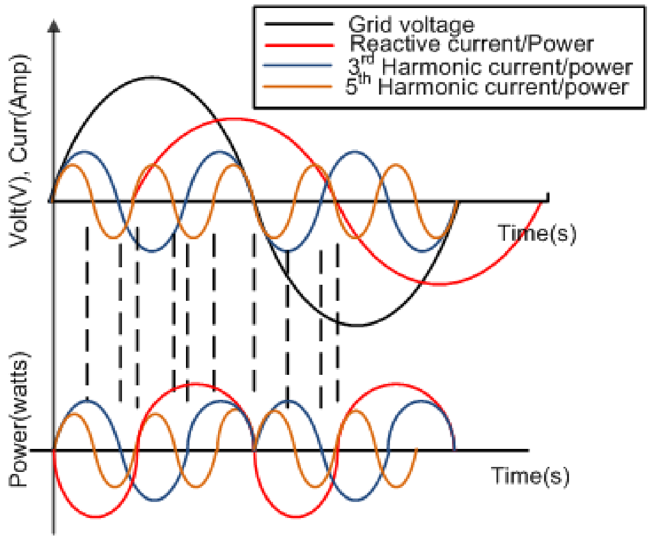

Fig. 3 Ripple in output power of APF when compensating reactive and harmonic current

To attenuate at least 100Hz of frequency the voltage sample should be summed up and averaged at each cycle twice the fundamental frequency. The number of samples required for implementing moving average in period of 10ms with 20kHz sampling frequency is given as (27).

$$N = \frac{T_{prd}}{T_{sam}} = \frac{10 \times 10^{-3}}{(1/20) \times 10^{-3}} = 200 \qquad (27)$$

Fig.4 shows the frequency response and time response of MAF and a 2nd order Butterworth LPF with 25Hz cutoff frequency, MAF provides better attenuation of even harmonics upto half the nyquist frequency and provides good tradeoff between accuracy and speed of response.

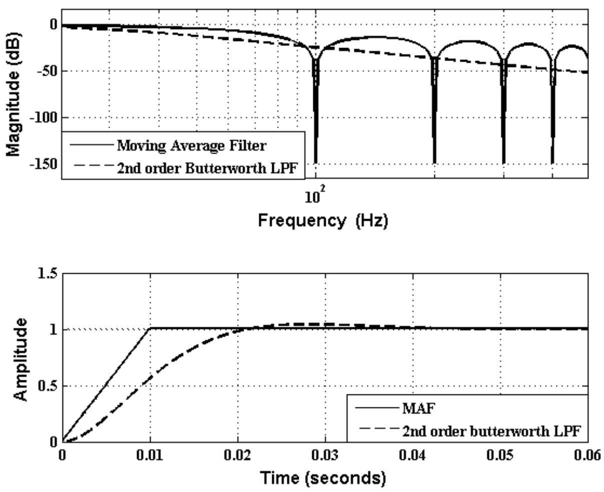

Fig. 4 Frequency domain and time domain characteristics of MAF and 2nd order BWLPF

The moving average filter can be approximated as a first order LPF with cutoff frequency and time constant given in (28) and (29) [9].

$$f_c = \frac{0.443}{N \times T_{sam}} \tag{28}$$

$$\tau = \frac{1}{2\pi f_c} \tag{29}$$

The transfer function of LPF is then

$$G_{ma}(s) = \frac{1}{\tau s + 1} \tag{30}$$

The characteristics of moving average filter and its approximate first order LPF closely matches as shown in Fig 5.

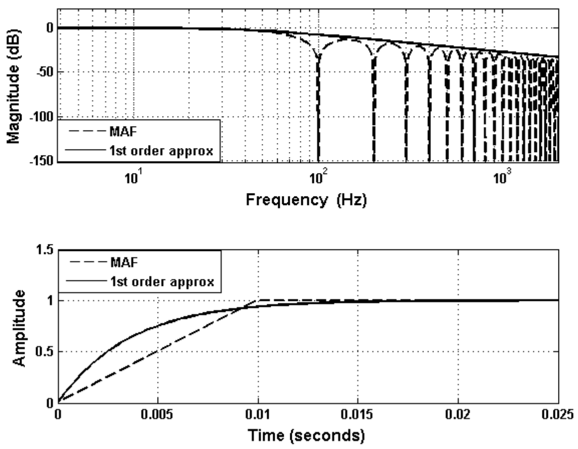

Fig.5 Bode plot and step response of MAF and its first order approximation

4. DC Voltage Control

The aim of the controller is to adjust the capacitor voltage to its reference value. We consider and compare two controllers for the cause, Proportional Integral and Fuzzy Logic Controller.

4.1 Proportional Integral Controller

Application of linear control techniques requires development of the system's mathematical model to facilitate the design of controller. The transfer function needed for analysis is regarding how the current injected or drawn by the APF affects its DC side voltage. For modeling the system transfer function, consider a lossless system then the average output power of APF should be equal to average input power provided from the DC side capacitor.

$$P_{AC} = v_{grid} \times \hat{i}_f \tag{31}$$

Where v_{grid} and i_f are the RMS values of the source voltage and the output APF current.

$$P_{DC} = V_{dc} \times I_{dc} \tag{32}$$

Let the DC side voltage consists of small fluctuation $\tilde{v}_{dc}$ over the reference value V_{DC}. Using the relation between capacitor voltage and current we have:

$$P_{DC} = (V_{DC} + \tilde{v}_{dc}) \times C \frac{d(V_{DC} + \tilde{v}_{dc})}{dt} \tag{33}$$

For lossless system

$$P_{DC\_inp} = P_{AC\_out} \tag{34}$$

Since $V_{DC} >> \tilde{v}_{dc}$ we can approximate (34) using (31) and (33) as

$$\frac{d\tilde{v}_{DC}}{dt} = \frac{v_{grid}\, \hat{i}_f}{CV_{DC}} \tag{35}$$

Converting (35) to laplace domain

$$\frac{\tilde{v}_{DC}}{\hat{i}_f} = \frac{v_{grid}}{sCV_{DC}} \tag{36}$$

PI control algorithm is the most common control algorithm widely used in power converter applications. The controller offers simpler implementation and ease in tuning. The proportional constant (Kp) is responsible for the speed of the response while the integral constant (Ki) ensures steady state accuracy in tracking DC signals. These gains can be designed based on the dynamic response requirement and generally, dc voltage control loop need not be too fast [10].

$$G_{pi}(s) = K_p + \frac{K_i}{s} \tag{37}$$

The voltage control loop block diagram with PI controller is shown in Fig. 6, where $G_{ma}(s)$ is transfer function of MAF and $G_{eq}(s)$ is equivalent transfer function of inner current control loop.

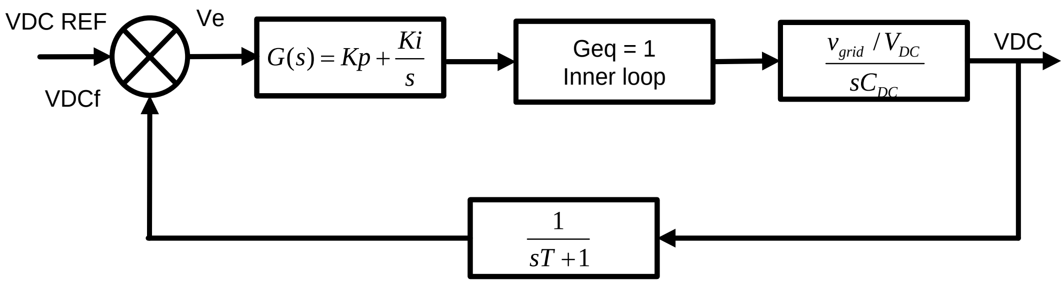

Fig. 6 DC side voltage control loop structure

The uncompensated and compensated open loop voltage gain is given in (38) and (39) and the bode plot is shown in Fig. 7

$$G_{vl,gn} = G_{eq}(s) \times G_{vi}(s) \times G_{ma}(s) \quad (38)$$

$$G_{vc,gn} = G_{vl,gn}(s) \times G_{pi}(s) \quad (39)$$

The controller acts on voltage difference and determines the amplitude of current component required to maintain the capacitor to a specified voltage (40). The sinusoidal current in phase with grid voltage is calculated as (41) which is current required or to be rejected depending on measured capacitor voltage.

$$i_{dc,ref} = K_{p,vl} \times v_{err} + K_{i,vl} \int v_{err} dt \quad (40)$$

$$i_{ref,fd} = i_{dc,ref} \times sin(\theta) \quad (41)$$

Sinɵ is the synchronizing signal, in phase with the grid voltage.
This reference current is added up with the APF reference current and final net reference current (42) is fed to the inner current control loop

$$i_{ref,tot} = i_{har,react} - i_{ref,fd} \quad (42)$$

The controller is desired to have high gain at low frequency for steady state accuracy and non interference at high frequency to maintain filtering behavior of APF intact. The bandwidth of the controller must be selected carefully. Higher Bandwidth will cause the reference current from outer loop to include components at undesirable harmonic components and could interact with the compensation system. If bandwidth is too low, it might lead to bigger variation of DC link voltage [4]. Furthermore, the MAF has characteristics similar to that of LPF and introduces pole at (1/2πτ) pressing a limitation of maximum crossover frequency.

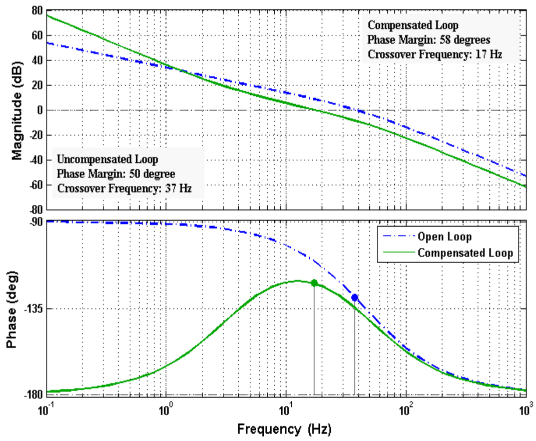

Fig. 7 Outer voltage Loop gain before and after compensation

The crossover frequency of outer voltage control loop (f_{CV}) has to be limited well below line frequency and generally recommended within 1/5th to 1/4th of fundamental frequency of grid voltage (f_1)[11]. Since the current control loop has large bandwidth (f_{CL}), the gain of current control loop within the frequency range of interest of outer voltage control loop is quite high. Hence the equivalent closed loop transfer function of inner current control loop is approximated as unity as it does not influence the voltage control characteristics.

4.2 Fuzzy Logic Controller

The performance of linear control depends on mathematical model for design of controller parameters which in turn is derived using simpler approximation of the system. The dynamic response tends to be poor due to limitation applied on the bandwidth of the voltage control loop.
Intelligent control tries to emulate characteristics of the human intelligence and the system can be controlled without mathematical model of the system. Fuzzy logic is one of the well proven approaches which relies mostly on the human understanding of the system's behavior and allows ease in tuning and control of the performance. The use of fuzzy logic controller in the APF application has also seen tremendous rise due to nonlinear nature of power converters, unavailability or difficulty in derivation of exact model [12-13]. The other well known advantage includes ability to work with imprecise inputs, more robust, and insensitive to parameter variations.
The Capacitor voltage is allowed to vary between V±ΔV, hence accordingly the output current has to be varied to retain the cap voltage at V. To determine the current needed for the purpose fuzzy logic controller depends upon the understanding of the system working rather than on mathematical model. The fuzzy logic controller works on linguistic reasoning, IF condition THEN action based rule [14]. The control structure of the fuzzy logic controller is shown in Fig. 8 which consists of four stages (a) Fuzzification (b) Knowledge Base (c) Inference mechanism (d) Deffuzzification [15]. The fuzzy logic controller is characterized as below:

(a) Seven fuzzy sets for each input and output using triangular and trapezoidal membership functions
(b) Fuzzification using continuous universe of discourse
(c) Implication using Mamdani's 'min' operator.
(d) Defuzzification using the 'centroid' method.

Fuzzy control is implemented based on the deviation of the capacitor voltage and the trend it is following, which are obtained as below:

$$V_{err} = V_{ref} - V_{cap}$$
$$\Delta V_{err} = V_{err}[n] - V_{err}[n-1] \quad (43)$$

The system was designed with a view to limit the voltage fluctuation within ±ΔV volts. The maximum current the APF can demand from the source in a instant depends on the power rating of the converter. Usually the DC side current changes would be more during the load changes and the time required to reach the desired voltage depends

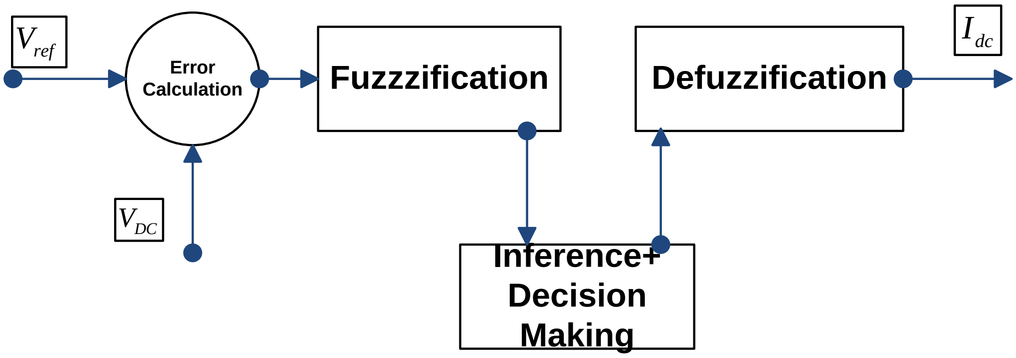

Fig. 8 DC voltage control structure using Fuzzy Logic controller

on the current drawn/rejected, during each control action. The crisp data input's are converted to linguistic variables using the membership functions (Fuzzification). The membership function for the error input and its variation are shown in Fig. 9 The determination of the membership function depends on the experience and knowledge of the system and can be optimized. The triangular membership function provides simplicity and ease in implementation. The rule base and inference mechanism deduces a conclusion based on the rule base and the linguistic values obtained from fuzzification. The defuzzification process converts the linguistic output from the rule base to the numerical data which is the peak of the reference current. The output membership function is shown in fig. 10. The rule-base which assists in decision making and consequently the control action is given in Table 1, where NS, NM, NL, ZE, PS, PM and PL are linguistic codes.(Negative Small, Negative Medium, Negative Large, Zero, Positive Small, Positive Medium and Positive Large)

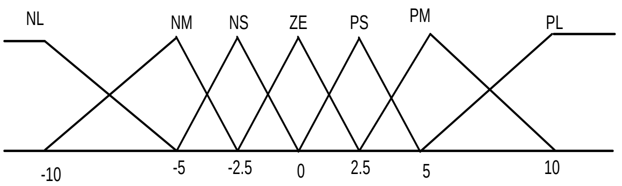

Fig. 9 (a) Membership function for the input variable (Verr)

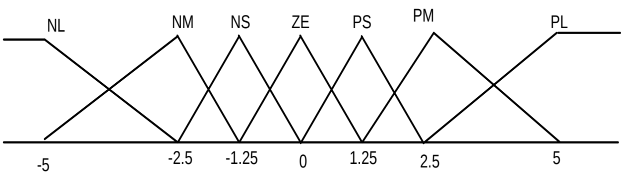

Fig. 9 (b) Membership function for the input variable (ΔVerr)

5. Simulation Results

To evaluate the design of energy storage component and the performance of the system the simulation is carried out in MATLAB/SIMULINK. Nonlinear load consisting of uncontrolled rectifier and APF are connected in parallel with the Grid. The harmonic extraction is carried out using fundamental dq SRF method [16].The reference current is composed of combination of sinusoidal components at different frequencies hence poses a stringent demand. Various current control techniques has been used like Proportional Integral, hysteresis and other linear and nonlinear control methods [4]. The choice of controller and its parameters has influence on the tracking speed and error. Unipolar modulation is used to generate the switching patterns. The parameters used for the simulation study is given in table 2. The circuit is simulated first using PI controller and then with FLC keeping all other parameters and scenario constant.

Table 1: Rule Table for Fuzzy Logic Controller

de/e	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

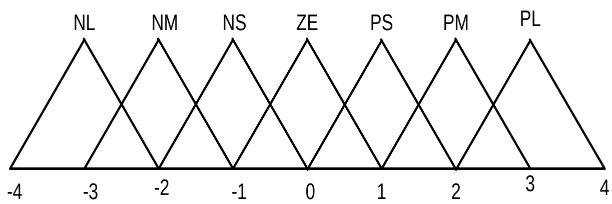

Fig 10. Membership Function for the output variable (I_{out})

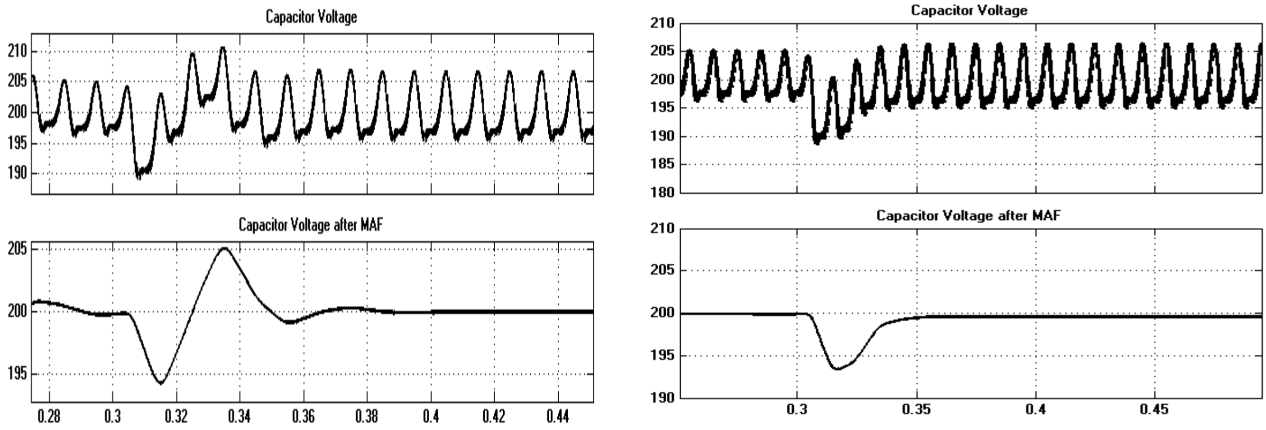

Fig. 11 Capacitor voltage before and after MAF using (a) PI and (b) FLC

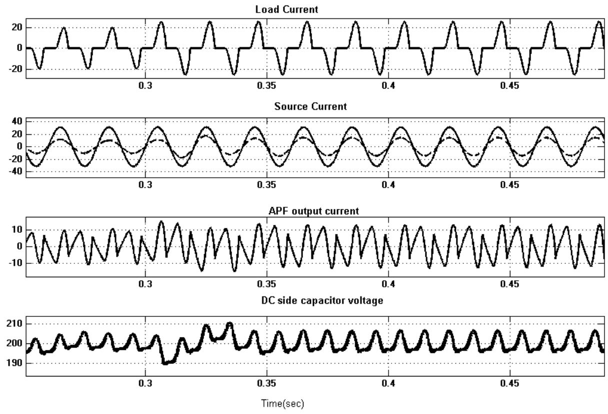

Fig. 12. Load current, source current, APF current and Capacitor voltage with PI controller

Table 2: Parameters used for the simulation study

Parameters	***Values***
Grid	110v @ 50Hz
Rated Current	15.4 @ 15% safety factor
DC side reference voltage	200V
DC side capacitor	1800µF
Interface Inductor(Li)	1.75mH
Grid Inductance	0.1e-4mH
Switching Frequency	10KHz

A. Dynamic Load condition

In practice, non linear loads are time variant in nature hence dynamic performance in such scnerios is very important [17] Fig. 11 shows the DC side output before and after the Moving Average Filter for both cases, using PI controller and FLC, with load change at t=3s.

Fig. 12 shows the compensation performance of APF when PI is used in the outer voltage control loop while Fig 13. shows the performance of the APF, when FLC is used. In both cases, the steady state performance is comparable and the THD of load current is seen to be decreased from 61% to 2.6~2.7%. However, the difference lies in the transient state. Fig. 14 shows the Harmonic spectrum and THD of the source current for these two scenarios in the 2nd fundamental cycle after load change. The corresponding comparision is presented in table 3.

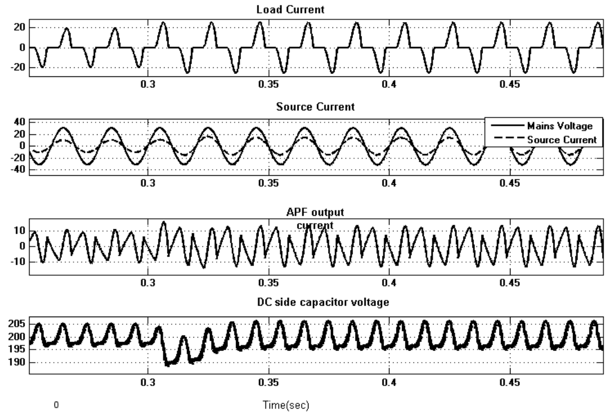

Fig. 13. Load current, source current, APF current and Capacitor voltage with FLC controller

Table 3. APF compensation performance in transient state

Parameter	***FLC***	***PI***
Steady State THD	2.6%	2.7%
THD in 1st cycle of load change	8.32%	11.2%
THD in 2nd cycle after load change	3.72%	8.52%

B. Dynamic Supply Conditions

Studies on APF dynamics are generally considerd only with load changes, however in small rating standalone power system, supply voltage fluctuation may occur frequently causing concern for APF performance[18]. The instantaneous active and reactive/harmonic power exchanged between the SAPF and grid is given as

$p_p = v_{grid} i_p$ and, $p_c = -v_{grid} i_c$

$$v_{grid} i_p(t) - R[i_p^2(t) + i_c^2(t)] - \frac{1}{2}\frac{d}{dt}[i_p^2(t) + i_c^2(t)] = V_{dc}(t) i_{dc}(t)$$

Where, ip and ic are active and compensation (reactive & harmonic) contents of the output APF current, R and Li

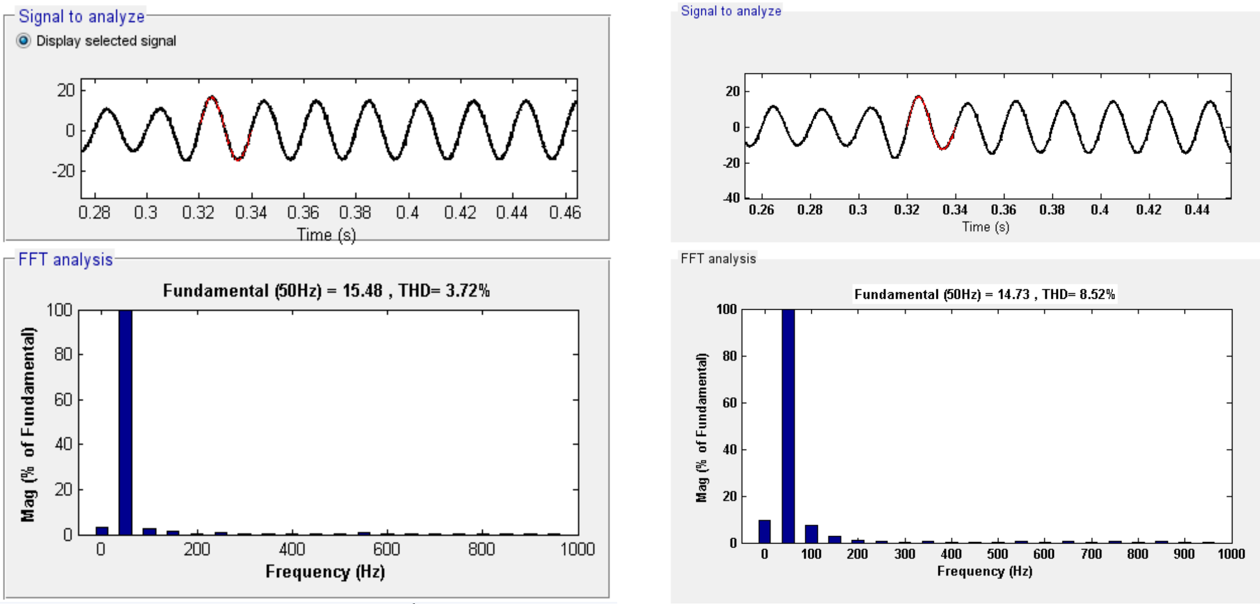

Fig 14. THD of the source current in 2nd fundamental cycle post load change with (a) FLC (b) PI controller

are resistance and inductance responsible for power loss in the system. When, there is fluctuation either in grid voltage or in compensation current, it will cause change in power balance equation and consequently changes will be seen across DC capacitor voltage unless some mechanism is used to counter it. Furthermore, the model developed in (36) is based on assumption v_{grid} is constant and controller is designed accordingly.

Fig 15 and 16 shows the performance of the DC side voltage control loop with PI controller and FLC when the grid voltage changes at time t=0.3s. The voltage is changed from 110V rms to 100v rms. The transient performance shown by the FLC is far superior to that shown by the PI controller, which is indicated by the THD of the source current in 2nd fundamental cycle after the grid voltage changes in Fig. 17.

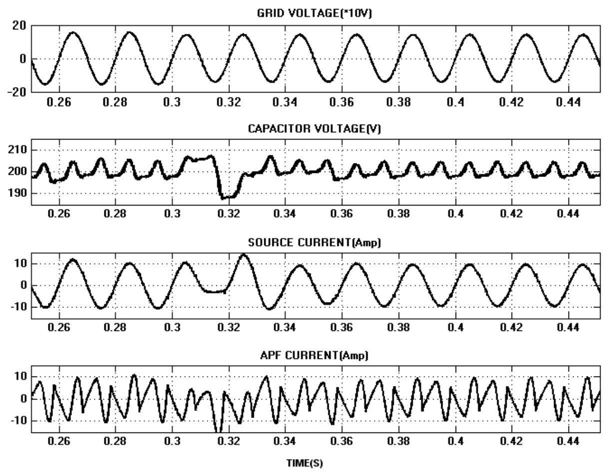

Fig 15. Grid voltage, capacitor voltage, source current and APF current with PI controller.

The comparision between these two control techniques in event of grid voltage fluctuation is presented in table 4.

Table 3. APF compensation performance in transient state

Parameter	***FLC***	***PI***
THD in 1st cycle of source change	15.48%	27.56%
THD in 2nd cycle of source change	5.75%	12.16%
THD steady state post change	3%	3.6%

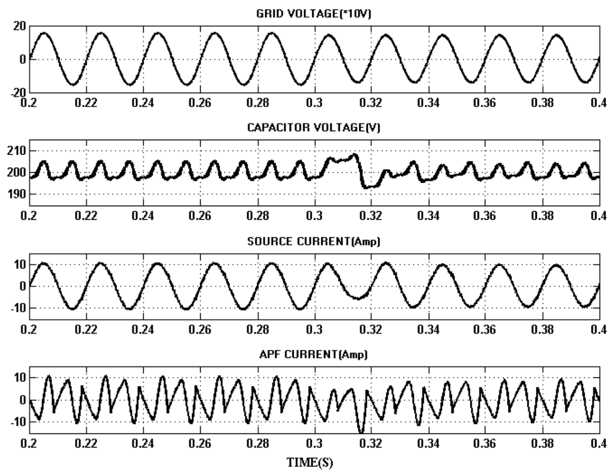

Fig 16. Grid voltage, capacitor voltage, source current and APF current with FLC controller

6. Conclusion

In this paper various facets of DC side and its voltage control subsystem is discussed. A simple approach to determination of DC side parameters is presented. The use of Moving Average Filter provided excellent elimination of the unwanted frequency components from the capacitor voltage. The APF functions as multi-converter providing DC current to capacitor (rectifier) and providing the harmonic and reactive load current to load (inverter). The performance of DC side voltage loop control is also equally important to realize desired compensation characteristics from the APF. The control

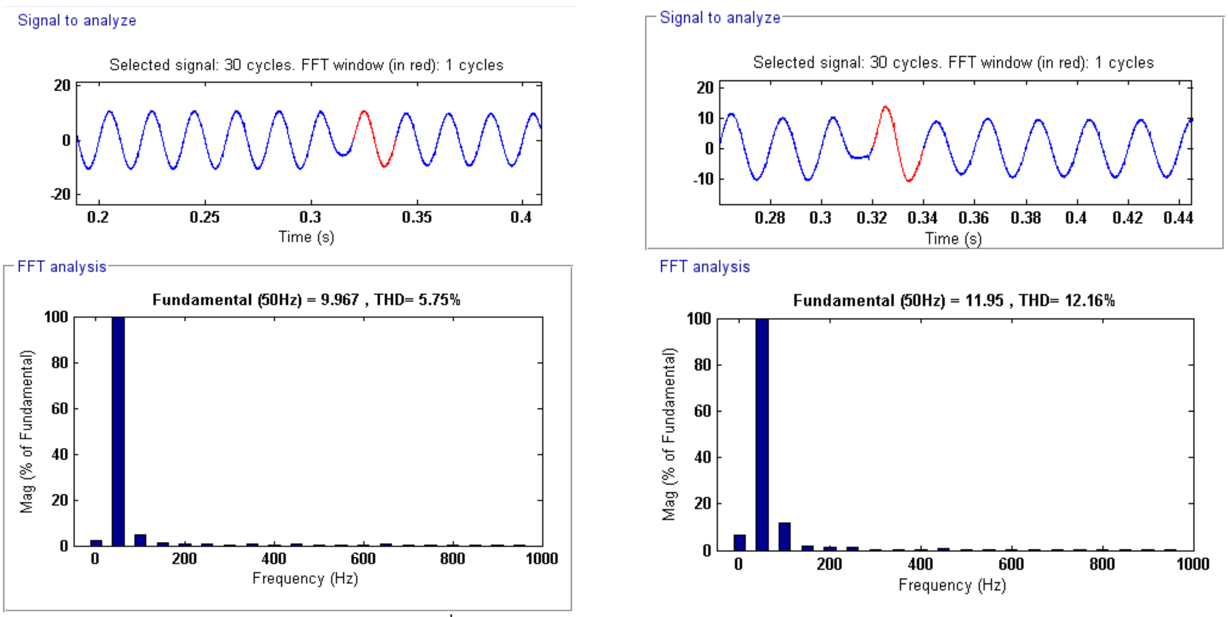

Fig 17. THD of the source current in 2nd fundamental cycle post source change with (a) FLC (b) PI controller

of capacitor voltage using Fuzzy Logic Controller provided faster response and good regulation during load change and grid voltage fluctuation than traditional PI controller. The simulation result demonstrated the improvement in THD of source current exhibiting excellent dynamic behavior of the Fuzzy Logic Controller.

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