© 2017 IJSRST | Volume 3 | Issue 7 | Print ISSN: 2395-6011 | Online ISSN: 2395-602X
Themed Section: Science and Technology

Mitigation of Harmonic Current Using Active Filter with Fuzzy Control in Distribution System

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ABSTRACT

Maintaining voltages within tolerable limits is of prime importance in distribution system . Voltage distortion due to harmonics is main concern which affects the distribution voltages to fall out of limits. A shunt connected active filter with Fuzzy logic controller is able to suppress harmonic resonance within the distribution facility. However, inherent phase-lagging in digital signal processing of active filter affects its functioning which might induce unintentional harmonic amplification at alternative locations within the feeder . This paper presents an active filter with fuzzy control to suppress harmonic resonance.. The current control is realized by parallel-connected band pass filters tuned at harmonic frequencies to ensure that the active filter functions as an approximately pure conductance. The electrical phenomenon at dominant harmonic frequencies is individually and dynamically adjusted to ensure the damping performance. Additionally, so as to handle the harmonic resonance, the load distributed-parameter model of a radial feeder is developed with considering harmonic damping by variable electrical phenomenon and admittance, separately. Simulation results show that the active filter with fuzzy control will effectively reduce voltage harmonic distortions. Simulation was done by using MATLAB/Simulink software.
Keywords: Active Filter, Harmonic Resonance, Voltage Distortion, Fuzzy Control.

I. INTRODUCTION

Equipment operates satisfactorily for the rating they have designed and they withstand some margin of tolerable limits. Voltage distortion, due to harmonic resonance can affects the performance of distribution equipment in ways such as heating, vibration etc. thus it has received serious concerns in the distribution power system [2], [3], [4], [5], [6]. This scenario becomes significant due to extensive use of nonlinear loads as well as high penetration of inverter-based distributed generation systems. Maximum allowable voltage total harmonic distortion (THD) is 5% and individual voltage distortion is 3% in distribution networks below 69kV. This guideline is also included in IEEE standard for interconnecting distributed resources with electric power systems (IEEE std. 1547.2- 2008). Tuned-passive filters are typically adopted to cope with harmonic issues, but their functionality may suffer from component aging, frequency shifting, or unintentional resonances. They require time to time calibration to maintain their filtering performances.

The shunt active filter controlled as a fixed or variable conductance has been proposed to suppress harmonic resonances in a radial power distribution system [9]. The mismatching between the conductance of active filter and the characteristic impedance of the line may result in unintentional amplification of harmonics due to the harmonic standing waves. This phenomenon is analogous to a “whack-a-mole” amusement for children [10]. As soon as a child whacks a mole appearing from a hole, the mole goes back into the hole. Another mole immediately appears from another hole and this activity is repeated endlessly. Thus voltage harmonics can be well dampened at the installation point of the filter, whereas unintentional harmonic resonances may be excited in the other location of the feeder with no filter installed. In order to approach this issue, a real-time communication system [11], [12] was proposed to coordinate operation of distributed active filters by using droop-control [13], on-line optimization [14], [15], particle swarm optimization [16] or single-frequency tuned algorithm [17]. In a nutshell, the active filter working as harmonic conductance is able to suppress the propagation of harmonic voltage on the feeder. However, instead of conductance, the active filter presents inductive characteristic at harmonic frequencies due to the limited bandwidth of the current control [18]. The phase lagging may be further worsening by the controlling delay of the active filter in the digital system. Thus the harmonic admittance deteriorates the damping performance of the active filter, or even result in the "whack-a-mole" issue.

Various current control methods have been proposed for active power filters. Hysteresis current regulator is simplest, but low-order harmonics resulting from variable switching frequency may become a serious concern [19]. Repetitive control with selectively harmonic compensation is very popular. However, this approach may suffer from heavy computing loading [20]. A shunt active filter with asymmetrical predictive current control was presented for harmonic-resonance suppression in the power system [21], [18], and [22]. In this application, current-tracking capability is very sensitive to parameter variations. Analysis of stability margin of the active filter was discussed in [18]. Recently, resonant controls have been applied for the active power filters. Most of research was simply focused on harmonic current compensating at load side [23], [24], [25], [26], [27], [28].

In the previous work, the author has presented the resonant current control for the shunt active power filter to dampen harmonic voltage propagation [29]. The resonant current regulators composed of various parallel-connected band-pass filters tuned at harmonic frequencies to control the active filter as an approximately pure conductance [30], [31]. The conductance of each harmonic frequency is designed to be separately and dynamically adjusted to guarantee the damping performance. In this study, the impact of phase lagging on harmonic damping performance is further investigated by using the line distribution-parameter model. Damping performance of the active filter is also analyzed when different current controls are implemented and when nonlinear loads are deployed at different locations. Experimental results from a prototype circuit based on 220V/10kVA system verify theoretical analysis.

II. OPERATION PRINCIPLE

The distribution network is considered as a simplified one-line circuit diagram with active filter and the associated control are shown in Fig.1. The active filter unit (AFU) is installed at the end of a radial line to suppress harmonic resonance. The AFU susceptance is made zero to operate it as a variable conductance for different harmonic frequency as given,

$$i_{abc,h}^{*} = \sum_{h} \mathrm{G}_{\mathrm{h}}^{*} . E_{abc,h} \qquad 1$$

Where h represents the order of the harmonic frequency. The conductance command G^{*}_{h} is defined as a control gain to dampen harmonic voltage $E_{\mathrm{abc,h}}$. As shown in Fig. 1, the control is composed of harmonic-voltage extraction and tuning control, followed by the current regulation and PWM algorithm. Operation principle and design consideration are given as follows.

A. AFU design and control

Synchronous reference frame (SRF) transformation is used to find Harmonic voltage at the different harmonic frequencies. The specific harmonic voltage component becomes a dc value after E_{abc} is transformed into the SRF at ω_{h}. The dc value and then the corresponding harmonic component $E_{\mathrm{abc,\,h}}$ is obtained when applied to a low-pass filter (LPF). It is worth noting here that a phase-locked loop (PLL) is required to determine system frequency for implementation of SRF. ω_{h} should be set as a negative value for negative-sequence component (i.e., fifth) or a positive value for positive-sequence harmonic component (i.e., seventh), respectively. Fig. 2 shows the tuning control for the conductance command G^{*}_{h}. As illustrated, G^{*}_{h} is determined according to the harmonic voltage distortion $\mathrm{VD_h}$ at the AFU installation point E_{abc}, in which $\mathrm{VD_h}$ is defined as the percentage ratio of the harmonic voltage component E_{h} (rms value) to the voltage E (rms value) by

$$VD_h = \frac{E_{h,RMS}}{E_{RMS}} \qquad 2$$

$$E_{h,RMS} = \sqrt{\frac{\int_t^{t+T} (E_{a,h}(t)^2 + E_{b,h}(t)^2 + E_{c,h}(t)^2)}{T}\, dt} \qquad 3$$

$$E_{RMS} = \sqrt{\frac{\int_t^{t+T} (E_a(t)^2 + E_b(t)^2 + E_c(t)^2)}{T}\, dt} \qquad 4$$

The derivation of VD_h is approximately evaluated by using two LPFs with cut-off frequency at ω_c, which are to filter out ripple components in the calculation. . The error between the allowable harmonic voltage distortion VD^*_h and the actual harmonic voltage distortion VD_h is then fed to a PI regulator to adjust the conductance command G^*_h

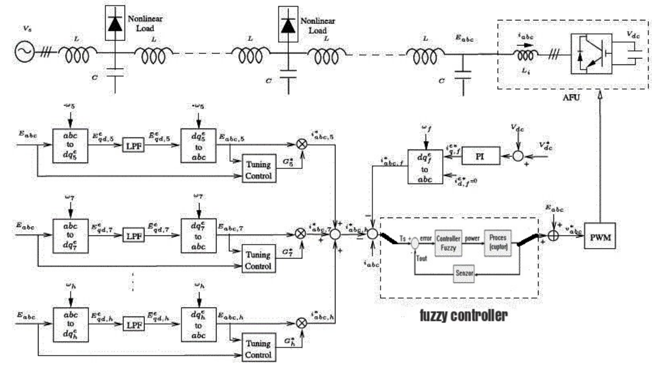


Fig. 1.Block diagram of Active filter with fuzzy control.

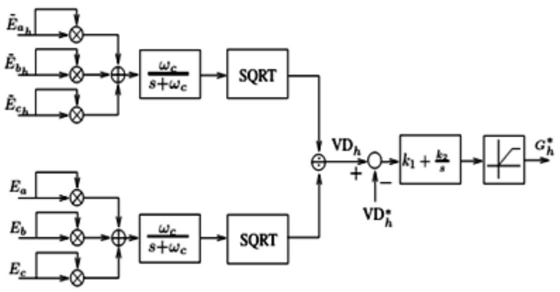


Fig. 2. Tuning control of the conductance command

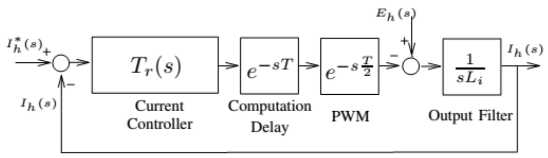


Fig. 3. Current control block diagram of the proposed AFU.

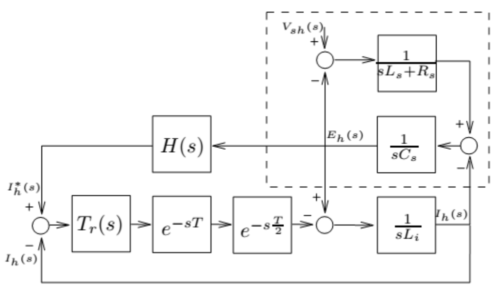


Fig. 4. Voltage control block diagram of the proposed AFU in the distributed power system.

The total current command is the summation of fundamental current command $i^*_{abc,}f$ and all harmonic current commands $i^*_{abc,}\ h$ which is equal to the product of the harmonic voltage and its corresponding conductance command. $i^*_{abc,}f$ shown in Fig.1 is the in-phase fundamental current command generated by a PI control to control the dc voltage V_{dc} of the AFU. In order for the active filter to guarantee current tracking capability, the resonant current regulator is realized by:

$$T_r(s) = k_p + \sum_h \frac{2K_i \xi w_h s}{s^2 + 2\xi w_h s + w_h^2}$$

where k_p is a proportional gain and k_i , h is an integral gain for individual harmonic frequency, respectively. The current control is tuned to resonate at harmonic frequencies ω_h, so that various narrow gain peaks centered at harmonic frequencies are introduced. The damping ratio ξ is designed to determine the selectivity and bandwidth of the current control. Accordingly, the voltage command V_{abc}^* is obtained for PWM to synthesize the output voltage of the active filter.

B. Modeling of Control

Nomenclature used in this section is given as:

- $V_{sh}(s)$: harmonic voltage at the source terminal
- $E_h(s)$: harmonic voltage at the installation location of the active filter
- $I_h(s)$: harmonic current of the active filter
- $I^*_h(s)$: harmonic current command of the active filter

Line voltage	11.4 kV
Line frequency	60 Hz
Feeder length	9 km
Line inductance	1.55 mH /km (4.5 %)
Line resistance	0.36 Ω /km (1.2 %)
Line capacitance	22.7 µF / KM (11.1 %)
Characteristic impedance, Z_0	8.45 Ω
Wavelength of 5th harmonic, λ_5	17.8 km
Wavelength of 7th harmonic, λ_7	12.7 km

Table 1: parameters of given power line

Fig. 3 shows current control block diagram for each phase. Digital signal processing delay and PWM delay are included, where T represents a sampling period. Hence, current loop stability and current tracking capability can be simply evaluated by using bode plots of open-loop and closed-loop transfer functions. Fig.4 shows the block diagram for harmonic damping analysis. The distribution network is replaced with a second order resonant tank (L_s, C_s, R_s) as indicated by the dashed box. Here, the resonant tank is tuned to amplify the harmonic voltage $E_h(s)$. Note that the scheme of harmonic detection at ω_h is equivalent to a single-side band pass filter in the stationary frame. The transfer function H(s) can be expressed as shown in fig.(4), where ω_h is the harmonic frequency and T_{LPF} is time constant of the low-pass filter, which is used to filter out the dc component in the rotational reference frames. Thus the damping performance of the AFU can be evaluated by the harmonic-voltage magnification $\frac{|E_h(s)|}{|V_{sh}(s)|}$ shown in Fig. 4.

$$H(s) = G^{*}{}_{h}\frac{(s-jw_h)T_{LPF}}{1+(s-jw_h)T_{LPF}} \qquad 5$$

III. HARMONIC RESONANCE

Parameters of a sample feeder are given in TABLE I. In this section, harmonic resonance along the feeder was found by evaluating the line distributed-parameter model. Harmonic voltage can amplified if harmonic standing wave is generated [10]. The active filter is assumed to be installed at the end of the line (x = 9). Considering both feeder and damping impedance provided by the filter.

Voltage base	220 V
Current base	52.5 A
Impedance base	2.42 Ω
Conductance base	$0.413\ \Omega^{-1}$

Table 3: Base values

IV. FUZZY INFERENCE SYSTEM

Fuzzy logic block is prepared using FIS file in MATLAB 7.8.0.347(R2009a) and the basic structure of this FIS editor file as shown in Fig. 5. This is implemented using following FIS (Fuzzy Inference System) properties:

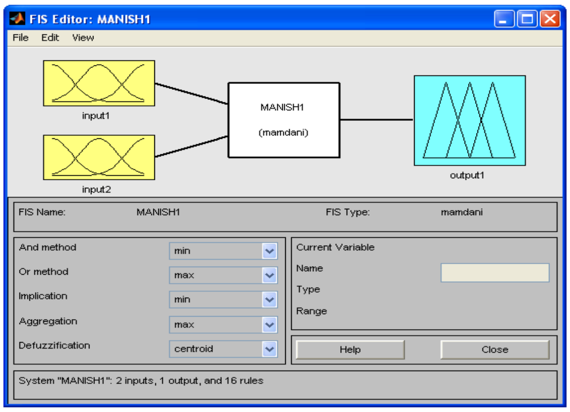


Fig.5. Fuzzy Inference System

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables. The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

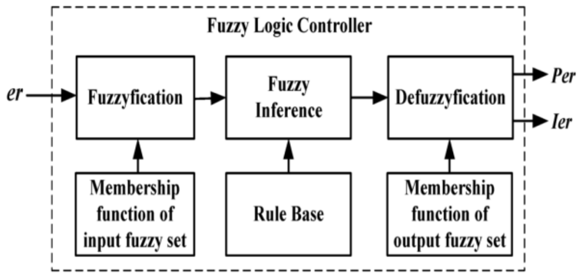


Fig.6. Fuzzy logic controller

A. Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The Partition of fuzzy subsets and the shape of membership *CE (k) E (k)* function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z

NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

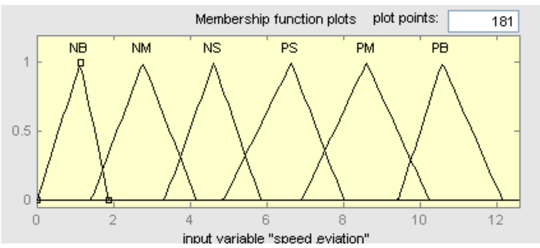
Table 2: Fuzzy Rules

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular *E (k)* input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E\ (k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \qquad (6)$$

$$CE\ (k) = E\ (k) - E\ (k-1) \qquad (7)$$

C. Inference Method: Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.



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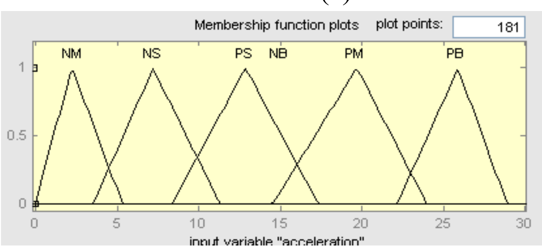

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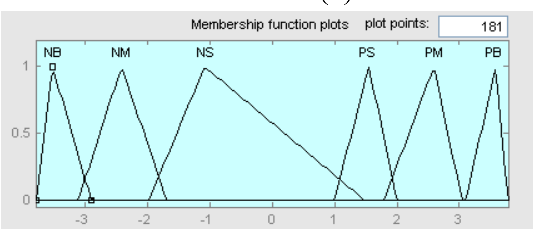


Fig.7. (a). Membership functions for error
(b). Membership functions for change in error
(c)Membership functions for output

B. Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output. The set of FC rules are derived from

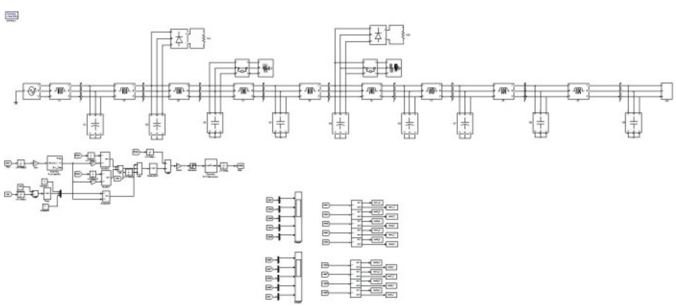
$$u=-[\alpha E + (1-\alpha)*C] \qquad (8)$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable.

V. SIMULATION STUDIES

The active filter with the fuzzy control is simulated by using the alternative transient program (ATP). Fig. 8(a) shows the considered lumped feeder that is arranged with similar per unit value to TABLE I in the previous section. All parameters are given as follows. The harmonic resonance caused by higher order harmonics (>8) is rare in the distribution system, so the resonant current control includes fifth and seventh resonant terms only [3].

• Power system: 3φ, 220 V (line-to-line), 20 kVA, 60 Hz. Base values are listed in TABLE II.



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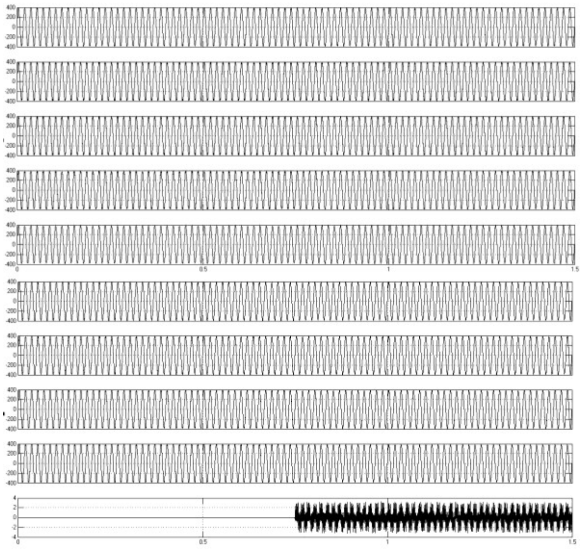

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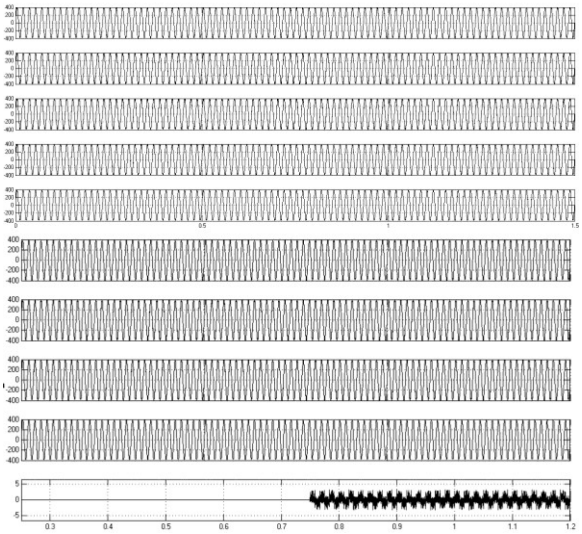


(c)

Fig. 8. (a). Simulation circuit configuration .simulation results when (b) AFU is off (c) AFU is on

- Line parameters: L=3.1 %, C=13.7 %.
- Nonlinear loads: NL1 and NL2 are constructed by three phase diode-bridge rectifiers, and consume real power 0.25 pu, respectively.
- Linear loads: Both linear loads are initially off. LL1, LL2 are rated at 0.1 pu (pf=1.0), 0.09 pu (pf=0.9), respectively.
- Tuning control: k1=100, k2=2000, ωc=62.8Rad/s, VD∗ h=3.0%.
- The AFU is implemented by a three-phase voltage source inverter with PWM frequency 10 kHz

A. Steady-state results

Fig. 8(b) shows bus voltages are severely distorted before the AFU is initiated. For example, voltage THDs at bus 3 and bus 9 are 5.6% and 6.1%, respectively. Fig.9 illustrates voltage VD_5, VD_7 on each bus. We can observe cyclic amplification of voltage distortion along the line

	G^*_5	G^*_7
NLs at Bus 2,5	1014 pu	1.28 pu
NLs at Bus 3,7	1.19 pu	0.32 pu
NLs at Bus 4,6	3.15 pu	1.23 pu

Table 4: AFU CONDUCTANCE COMMANDS

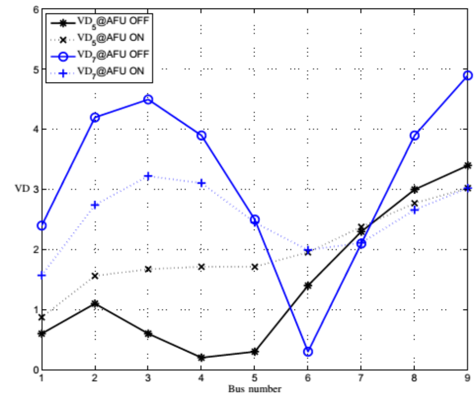
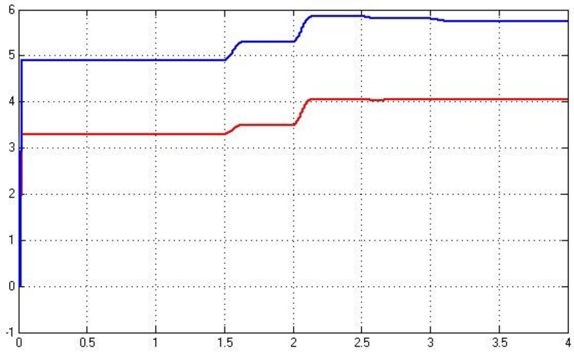


Fig. 9. VD_5 and VD_7 on all buses before and after the AFU is in operation.

and seven harmonic resonance is dominant. This result confirms the previous analysis by harmonic distributed-parameter model. After the AFU starts in operation, Fig. 8(c) shows voltage distortion is clearly improved. Voltage THD at bus 9 is reduced from 5.91 % to 2.80%, which contains 3.0% fifth harmonics and 3.0% seventh harmonics. The blue curves of Fig. 9 demonstrate that both VD_5 and VD_7 become more uniform along the line. At the steady state, the AFU is operated at G^*_5 = 1.14 pu and G^*_7 = 1.28 pu with rms current 0.06 pu



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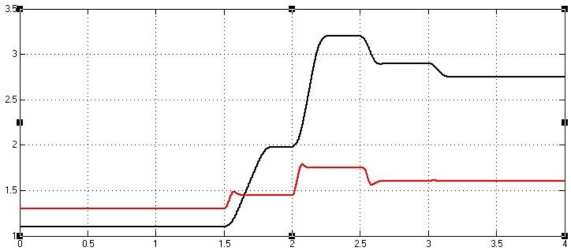

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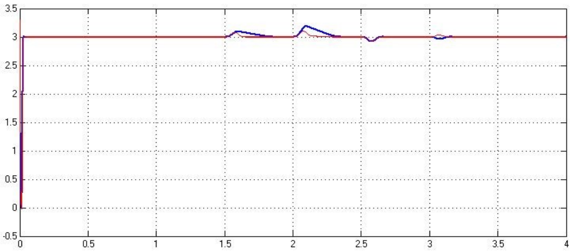


(c)

Fig. 9. AFU transient behavior (NL1, NL2 are increased at t=1.5 s, t=2.0 s, respectively, and then LL1, LL2 are turned on at t=2.5 s, t=3.0 s, respectively.) (a) Harmonic-voltage distortion when the AFU is OFF. (b) Active filter conductance commands. (c) Harmonic-voltage distortion when the AFU is ON.

A. Voltage damping analysis

Harmonic suppression capability of the AFU with fuzzy control is evaluated in this section which is evaluated based on Fig. 4 considering AFU control, including phase lagging and current control. The resonant tank (C_s=717uF, L_s=200uH, R_s=0.1) is tuned to amply seventh harmonic voltage. Fig.8 shows that seventh harmonic voltage is reduced and controlled by harmonic conductance after the AFU is turned on.

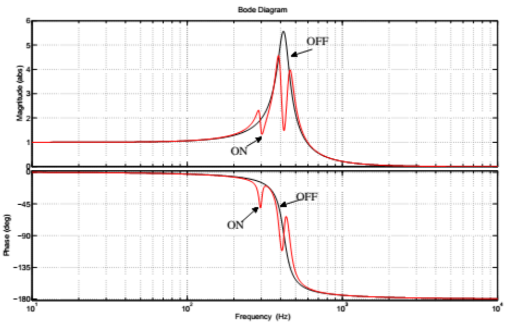
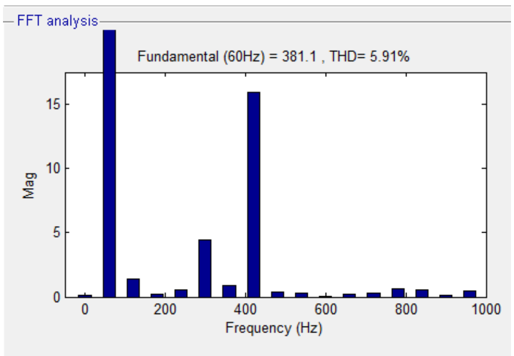


Fig. 10. Frequency characteristics of harmonic amplification.

B. Nonlinear loads at different locations

The damping performance of the AFU is evaluated when nonlinear loads are connected to different locations. Fig. 9, Fig. 12(a), Fig. 12(b) demonstrate voltage distortion on all buses when nonlinear loads are connected at bus 2, 5, bus 3, 7, bus 4, 6, respectively. TABLE IV lists the corresponding $G*_5$ and $G*_7$, respectively. As shown, VD_7 can be suppressed for all cases after the AFU is on. However, VD_5 may increase in the middle segment of the line with increasing G∗5. Fig. 9 shows both VD_5 and VD_7 can be well suppressed when nonlinear loads are at bus 2, 5. When nonlinear loads are changed to bus 3, 7, Fig. 12(a) shows the damping performance is not clear due to slight distortion. In case of nonlinear loads at bus 4, 6, large fifth harmonic conductance ($G*_5$=3.15 pu) is required to reduce fifth voltage distortion. This results in serious fifth harmonic resonance as shown in Fig. 12(b). Therefore, the termination-installation active filter may unintentionally induce fifth harmonic resonance due to the”whack-a-mole” issue if large $G*_5$ is adopted. This problem might be resolved by using multiple active filters, for example distributed active filter systems [13].



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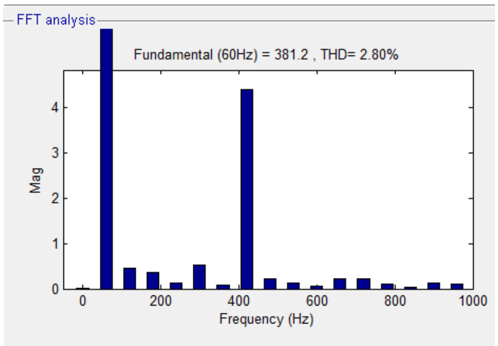
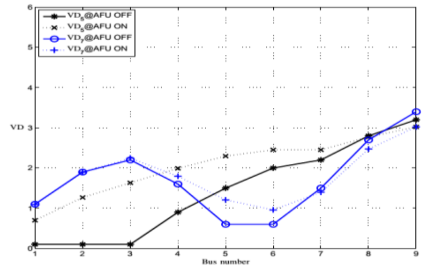
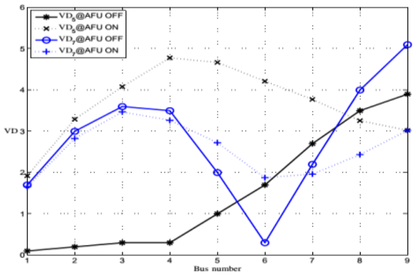


(b)

Fig. 9. (a). total harmonic distortion (a) when PR controller is employed (b). when fuzzy controller is employed



(a) Nonlinear loads are at bus 3 and bus 7.



(b) Nonlinear loads are at bus 4 and bus 6.

Fig. 12. Harmonic damping performances when nonlinear loads are connected to different buses.

VI. CONCLUSION

The active filter with the Fuzzy logic Control (FLC) is proposed in this paper to suppress harmonic resonances in the distribution power system. The fuzzy control is implemented by various parallel band-pass filters tuned at harmonic frequencies so that the active filter can operate as an approximately pure harmonic conductance. Harmonic distortion by this control is drastically reduced .in order to cope with load change and system variations in distribution system a separate and tuning conductance for different harmonic frequency is also realized. The contributions of this paper are summarized as follows. Due to controlling delay, the damping active filter may unintentionally induce harmonic resonance at other locations in the feeder. This phenomenon is analyzed by using harmonic distributed-parameter model. Based on simulations the fuzzy control is able to suppress harmonic resonance effectively. We can observe drastic change in results with fuzzy control when compared to proportional resonant current control. Multiple active filters might provide more effective performance compared to the termination installation one.

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