IN A DISTRIBUTION SYSTEM USING ADVANCED CONTROL TECHNIQUE TO SUPRESS THE HARMONIC RESONANCE WITH RESONANT CURRENT

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ABSTRACT - An active filter with resonant current control is proposed in this paper to suppress harmonic resonance. The proposed hybrid filter is operated as variable harmonic conductance according to the voltage total harmonic distortion, so harmonic distortion can be reduced to an acceptable level in response to load change or parameter variation of power system. This harmonic distortion can be reduced by suppressing the harmonic resonance using the hybrid active filter, which is operated as variable harmonic conductance according to the voltage total harmonic distortion. In proposed control method, reactive power compensation is achieved successfully with perceptible amount. 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. A shunt active filter operated as a harmonic conductance is able to suppress harmonic resonance in the distribution power system. Here we are using the fuzzy controller compared to other controllers i.e. the fuzzy controller is the most suitable for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts. By using the simulation results we can analyze that the active filter with the resonant control provides better damping performance compared with other control methods.

Index Terms—Active filter, Fuzzy controller, harmonic resonance, resonant current control

I. INTRODUCTION

Harmonic distortion is mainly due to the tuned passive filter and line inductance which produces resonances in the industrial system. To suppress this above problem hybrid active filter is used. Voltage distortion, due to harmonic resonance between power factor correction capacitors and line inductors, has received serious concerns in the distribution power system [1]. Tuned-passive filters are typically adopted to cope with harmonic issues, but their functionality may suffer from component aging, frequency shifting, or unintentional resonances. Therefore, engineering calibration on passive filters is frequently required 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]. Thus the harmonic admittance deteriorates the damping performance of the active filter, or even result in revival of the “whack-a-mole” issue.

Damping performance of the active filter is also analyzed when different current controls are implemented and when nonlinear loads are deployed at different locations. 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.

The resonant current regulator is composed of various parallel-connected band-pass filters tuned at harmonic frequencies to control the active filter as an approximately pure conductance. The active filter with the resonant current control is proposed in this paper to suppress harmonic resonances in the distribution power system.

OPERATION PRINCIPLE

A simplified one-line circuit diagram of the proposed 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 operates as a variable conductance for different harmonic frequency as given,

\[ i_{abc,h} = \sum G_h \cdot E_{abc,h} \]  

where \( h \) represents the order of the harmonic frequency. The conductance command \( G_h \) is defined as a control gain to dampen harmonic voltage \( E_{abc,h} \). 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.

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**Fig. 1. Active filter and the associated control.**

**A. AFU control**

Harmonic voltage at the different frequency is determined based on the so-called synchronous reference frame (SRF) transformation. The specific harmonic voltage component becomes a dc value after E_{abc} is transformed into the SRF at \omega_h. Accordingly, a low-pass filter (LPF) is applied to separate the dc value and then the corresponding harmonic component E_{abc,h} is obtained when applying reverse transformation. It is worth noting here that a phase-locked loop (PLL) is required to determine system frequency for implementation of SRF. \omega_h should be set as a negative value for negative-sequence component.

**Fig. 2. Tuning control of the conductance command.**

Fig. 2 shows the tuning control for the conductance command \(G^* \) h. As illustrated, \(G^* \) h is determined according to the harmonic voltage distortion \(V_D h\) at the AFU installation point E_{abc}, in which \(V_D h\) is defined as the percentage ratio of the harmonic voltage component \(E_h \) (rms value) to the voltage \(E \) (rms value) by

\[
V_D h = \frac{E_{h,RMS}}{E_{RMS}} \times 100\%
\]

\[
E_{h,RMS} = \sqrt{\frac{1}{T} \int_0^T (E_{ah}(t)^2 + E_{bh}(t)^2 + E_{ch}(t)^2) dt}
\]

\[
E_{RMS} = \sqrt{\frac{1}{T} \int_0^T (E_{ah}(t)^2 + E_{bh}(t)^2 + E_{ch}(t)^2) dt}
\]

The derivation of \(V_D h\) is approximately evaluated by using two LPFs with cut-off frequency at \(\omega_c\), which are to filter out ripple components in the calculation.

The damping ratio \(\xi\) 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. Modelling 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.

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. Since high-order harmonics seldom excite resonances, the distribution network is replaced with a second order resonant tank (Ls, Cs, Rs) as indicated by the dashed box. Here, the resonant tank is tuned to amplify the harmonic voltage $E_h(s)$. Thus the damping performance of the AFU can be evaluated by the harmonic-voltage magnification $|M_h(x)|$ shown in Fig. 4.

$$H(s) = \frac{v_{ih}(s)}{v_{sh}(s)} = \frac{1}{sC_s + \frac{1}{sL_s}} \frac{1}{sL_L + \frac{1}{sC_C}}$$  \hspace{1cm} \text{(3)}$$

**II. HARMONIC RESONANCE**

In this section, the line distributed-parameter model is applied to evaluate harmonic resonance along the feeder. A sample feeder given in TABLE I can amplify harmonic voltage if harmonic standing wave is generated \[10\]. The active filter is assumed to be installed at the end of the line ($x = 9$) with equivalent harmonic admittance $Y_h$ given in (5), where $\theta_h$ represents the lagging angle.

$$Y_h = |Y_h| < \theta_h$$  \hspace{1cm} \text{(4)}

The voltage magnifying factor $M_h(x)$ in (6) represents harmonic amplification along the feeder.

$$M_h(x) = \frac{|v_h(x)|}{|v_{sh}|}$$  \hspace{1cm} \text{(5)}

The suffix $h$ denotes the order of harmonics, $v_h(x)$ is the harmonic voltage at position $x$ ($0 \leq x \leq 9$), and $v_{sh}$ is the harmonic voltage source ($v_{sh} = v_h(0)$).

Note that $M_h(x)$ can be formulated by using standing wave equations considering both feeder and damping impedance provided by the filter.

**A. Harmonic conductance**

Fig. 5 shows $M_h$ along the line when the active filter is modelled as a purely harmonic conductance, i.e. $\theta_h = 0 \degree$. $M_5$ shows no amplification in case of no active filtering ($|Y_h| = 0$).

$$R_h = \frac{v_h(x)}{v_{sh}}$$  \hspace{1cm} \text{(a)}$$

However, $M_7$ is strongly amplified due to seventh harmonic resonance as shown in Fig.5(b). This results from the standing wave of seventh harmonics.

**Harmonic admittance**

Fig. 6 and Fig. 7 show $M_5$ and $M_7$ when the active filter is modelled as harmonic admittance $|Y_h|$ with $\theta = -45 \degree$ and $\theta = -90 \degree$, respectively.

$$M_h(x) = \frac{|v_h(x)|}{|v_{sh}|}$$  \hspace{1cm} \text{(b)}$$

(a) The magnifying factor of the fifth harmonic.

$$M_h(x) = \frac{|v_h(x)|}{|v_{sh}|}$$  \hspace{1cm} \text{(a)}$$

(b) The magnifying factor of the seventh harmonic.

Fig. 5. The magnifying factor along the radial line if the active filter is modelled as $|Y|$ with $\theta = 0 \degree$.

However, $M_7$ is strongly amplified due to seventh harmonic resonance as shown in Fig.5(b). This results from the standing wave of seventh harmonics.
(b) The magnifying factor of the seventh harmonic. Fig. 6. The magnifying factor along the radial line if the active filter is modelled as \( |Y| \) with \( \theta = -45^\circ \).

As observed, increasing \( |Y_h| \) can enhance the damping capability at the end of the line only, but may result in the "whack-a-mole" issue.

(a) The magnifying factor of the fifth harmonic.

(b) The magnifying factor of the seventh harmonic. Fig. 7. The magnifying factor along the radial line if the active filter is modelled as \( |Y| \) with \( \theta = -90^\circ \).

. Fig. 7 shows voltage distortion near the middle segment of the line becomes much more significant in case of \( \theta = -90^\circ \). Therefore, the active filter operating as harmonic admittance may not effectively suppress harmonic resonances, or even induce other harmonic resonances at other locations on the feeder.

TABLE I
PARAMETERS OF AGIVENPOWERLINE

<table>
<thead>
<tr>
<th>Line voltage</th>
<th>11.4 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Feeder length</td>
<td>9 km</td>
</tr>
<tr>
<td>Line inductor</td>
<td>1.55 mH/km (4.5 %)</td>
</tr>
<tr>
<td>Line resistor</td>
<td>0.30 Ohm/km (1.2 %)</td>
</tr>
<tr>
<td>Line capacitor</td>
<td>22.7 μF/km (11.1 %)</td>
</tr>
<tr>
<td>Characteristic impedance, ( Z_0 )</td>
<td>8.145 Ω</td>
</tr>
<tr>
<td>Wavelength of 5^{th} harmonics, ( \lambda_5 )</td>
<td>17.8 km</td>
</tr>
<tr>
<td>Wavelength of 7^{th} harmonics, ( \lambda_7 )</td>
<td>12.7 km</td>
</tr>
</tbody>
</table>

III. FUZZY LOGIC CONTROLLER

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, mathematical modeling of the system is not required in FC.

Fig. 8. Fuzzy logic controller

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.

TABLE I: Fuzzy Rules

<table>
<thead>
<tr>
<th>Change in error</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NM</td>
</tr>
<tr>
<td>NB</td>
<td>PB</td>
</tr>
<tr>
<td>NM</td>
<td>PB</td>
</tr>
<tr>
<td>NS</td>
<td>PM</td>
</tr>
<tr>
<td>Z</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>PM</td>
<td>PS</td>
</tr>
<tr>
<td>PB</td>
<td>Z</td>
</tr>
</tbody>
</table>

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. 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

\[ E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \]  
\[ CE(k) = E(k) - E(k-1) \]

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.

**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

\[ u = (\alpha E + (1-\alpha)C) \]  

**IV. SIMULATION RESULTS**

In order to demonstrate harmonic damping performance, the active filter with the proposed control is simulated by using the alternative transient program (ATP).

- 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.
- Current control: \( k_p=25, k_i,5=100, k_i,7=100, \xi=0.01 \).
- Tuning control: \( k_1=100, k_2=2000, \omega_c=62.8 \text{Rad/s}, VD^* h=3.0\% \).
- The AFU is implemented by a three-phase voltage source inverter with PWM frequency 10 kHz.

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**Additional Details**

- Power system: 3φ, 220 V(line-to-line), 20 kVA, 60 Hz. Base values are listed in TABLE II.
- Line parameters: L=3.1 %, C=13.7 %.
TABLE II
BASEVALUES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage base</td>
<td>220 V</td>
</tr>
<tr>
<td>Current base</td>
<td>52.5 A</td>
</tr>
<tr>
<td>Impedance base</td>
<td>2.42 Ω</td>
</tr>
<tr>
<td>Conductance base</td>
<td>0.413 Ω⁻¹</td>
</tr>
</tbody>
</table>

(c) Harmonic voltage distortion when the AFU is on.

Fig. 13. VD5 and VD7 on all buses before and after
the AFU is in operation.
distortion along the line is cyclically amplified and
seven harmonic resonance is dominant. This result
confirms the previous analysis by harmonic
distributed-parameter model. After the AFU starts in
operation, Fig. 12(c) shows voltage distortion is
clearly improved.

**Transient behavior**

Fig. 14(a) shows transient responses of
distortion when the AFU is off. Accordingly,
G*5 and G* 7 are decreased at t=2.5 s, t=3.0 s,
respectively. Fig. 14(c)

shows VD5, VD7 can be clearly maintained at 3%
after short transient.

**B. Current-loop analysis**

Fig. 15 shows the open-loop and closed-loop bode
plots of the AFU current control. In Fig.15, there are
magnitude peaks at both fifth and seventh harmonic
frequencies as well as phase-leading compensation
for the resonant current control. Therefore, the AFU
is able to function as an approximately pure
conductance at fifth and seventh harmonic
frequencies.
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Fig. 16. Comparison of voltage THD for different current controls. TABLE III summarizes conductance commands and AFU currents.

<table>
<thead>
<tr>
<th></th>
<th>$G_5$</th>
<th>$G_7$</th>
<th>RMS current</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p=50$</td>
<td>1.89 pu</td>
<td>1.04 pu</td>
<td>7.8%</td>
</tr>
<tr>
<td>$k_p=25$</td>
<td>3.39 pu</td>
<td>0.90 pu</td>
<td>12%</td>
</tr>
<tr>
<td>$k_p=25, k_q=100$</td>
<td>1.14 pu</td>
<td>1.28 pu</td>
<td>6%</td>
</tr>
</tbody>
</table>

C. Voltage damping analysis

Fig. 17 shows that seventh harmonic voltage is reduced and controlled by harmonic conductance after the AFU is turned on. This test can verify AFU effectiveness.

D. Nonlinear loads at different locations

In this section, the damping performance of the AFU is evaluated when nonlinear loads are connected to different locations.

(b) Nonlinear loads are at bus 4 and bus 6. Fig. 18. Harmonic damping performances when nonlinear loads are connected to different buses.

Fig. 18(a), Fig. 18(b) demonstrate voltage distortion on all buses when nonlinear loads at bus 2, 5, bus 3, 7, bus 4, 6, respectively. TABLE IV lists the corresponding $G_5^*$ and $G_7^*$, respectively.

<table>
<thead>
<tr>
<th></th>
<th>$G_5^*$</th>
<th>$G_7^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLs at Bus 2, 5</td>
<td>1.14 pu</td>
<td>1.28 pu</td>
</tr>
<tr>
<td>NLs at Bus 3, 7</td>
<td>1.19 pu</td>
<td>0.32 pu</td>
</tr>
<tr>
<td>NLs at Bus 4, 6</td>
<td>3.15 pu</td>
<td>1.23 pu</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

The proposed Active filter is operated as variable harmonic conductance according to the voltage total harmonic distortion, so harmonic distortion can be reduced to an acceptable level in response to load change or parameter variation of power system. By using the fuzzy controller for a nonlinear system allows for a reduction of uncertain effects in the system control and improve the efficiency. The active filter with the resonant current control is proposed in this paper to suppress harmonic resonances in the distribution power system. In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. This harmonic distortion can be reduced by suppressing the harmonic resonance using the active filter, which is operated as variable harmonic conductance according to the voltage total; harmonic distortion. Damping performance of the active filter is discussed when nonlinear loads are located at different buses. The current 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. Both current loop and voltage loop are modelled to illustrate current-tracking capability and damping performance of the active filter.

REFERENCES


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