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Suppression of Harmonic Resonance in Industrial Power Systems Using Hybrid active filter With Variable Conductance

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Abstract: **-- Unintentional series and/or parallel resonances, due to the tuned passive filter and the line inductance, may result in severe harmonic distortion in the industrial power system. This paper presents a hybrid active filter to suppress harmonic resonance and to reduce harmonic distortion. The proposed hybrid filter is operated as variable harmonic conductance according to the voltage total harmonic distortion; therefore, harmonic distortion can be reduced to an acceptable level in response to load change or parameter variation of the power system. Since the hybrid filter is composed of a seventh-tuned passive filter and an active filter in series connection, both dc voltage and KVA rating of the active filter are dramatically decreased compared with the pure shunt active filter. In real application, this feature is very attractive since the active power filter with fully power electronics is very expensive. A reasonable tradeoff between filtering performances and cost is to use the hybrid active filter. Design considerations are presented, and experimental results are provided to validate effectiveness of the proposed method. Furthermore, this paper discusses filtering performances on line impedance, line resistance, voltage unbalance, and capacitive filters.**

Index Terms:**—Harmonic resonance, hybrid active filter, industrial power system**

NOMENCLATURE

C_{dc} DC capacitor of the hybrid filter.
v_{dc} DC voltage of the hybrid filter.
v_{*dc} DC voltage command.
v_s Source voltage.
i_s Source current.
i_L Load current.
i Filter current.
L_s Source inductor.
R_s Source resistor.
L_f Filter inductor.
C_f Filter capacitor.
R_f Filter resistor
i_* Current command.
SRF synchronous reference frame
e Terminal voltage.
E_{eqd} Terminal voltage in the synchronous reference frame
$e_{eqd,h}$ Terminal harmonic voltage in the SRF.
e_h Terminal harmonic voltage.
ω_h Harmonic frequency in radians.
i_{*h} Harmonic current command.
i_{*f} Fundamental current command.
i_* Current command.
G_* Conductance command
K_p Proportional gain of the tuning control.
K_i Integral gain of the tuning control
K_c Proportional gain of the current controller
THD∗ Voltage total harmonic distortion (THD) command
I_h Filter harmonic current amplitude
$E(s)$ Terminal voltage in the s-domain
$I(s)$ Filter harmonic in the s-domain
$I_*(s)$ Filter harmonic command in s-domain

I. INTRODUCTION

HARMONIC pollution is becoming increasingly serious due to extensive use of nonlinear loads, such as adjustable speed drives, uninterruptible power supply systems, battery charging system, etc. This equipment usually uses diode or thyristor rectifiers to realize power conversion because of lower component cost and less control complexity. However, the rectifiers will contribute a large amount of harmonic current flowing into the power system, and the resulting harmonic distortion may give rise to malfunction of sensitive equipment or interfering with communication systems in the vicinity of the harmonic sources. Normally, tuned passive filters are deployed at the secondary side of the distribution transformer to provide low impedance for dominant harmonic current and correct power factor for inductive loads [1], [2].

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However, due to parameter variations of passive filters, unintentional series and/or parallel resonances may occur between the passive filter and line inductance. The functionality of the passive filter may deteriorate, and excessive harmonic amplification may result [3], [4]. Thus, extra calibrating work must be consumed to maintain the filtering capability.

Various active filtering approaches have been presented to address the harmonic issues in the power system [5]–[7]. The active filter intended for compensating harmonic current of nonlinear loads is the most popular one, but it may not be effective for suppressing harmonic resonances [8]. Bhattacharya and Divan proposed a hybrid series active filter to isolate harmonics between the power system and the harmonic source [9]. A so-called "active inductance" hybrid filter was presented to improve the performance of the passive filter [10]. Fujita et al. proposed a hybrid shunt active filter with filter-current detecting method to suppress the fifth harmonic resonance between the power system and a capacitor bank [11]. A hybrid filter in series with a capacitor bank by a coupling transformer was proposed to suppress the harmonic resonance and to compensate harmonic current [12], [13]. However, this method needs extra matching transformers or tuned passive filters to guarantee filtering functionality.

Recently, a transformer less hybrid active filter was presented to compensate harmonic current and/or fundamental reactive current [14]. Design consideration of the hybrid filter for current compensation has been extensively studied. A hybrid active filter with damping conductance was proposed to suppress harmonic voltage propagation in distribution power systems . Nevertheless, this method did not consider the resonance between the passive filter and the line inductance. The fixed conductance may deteriorate the damping performances. An anti resonance hybrid filter for delta-connected capacitor bank of power-factor-correction applications was presented . This circuit was limited to three single-phase inverters, and the filtering performance was not considered. In addition, the hybrid active filter was proposed for the unified power quality (PQ) conditioner to address PQ issues in the power distribution system . Several case studies of the hybrid active filter considering optimal voltage or current distortion were conducted in Optimal multi-objective design of hybrid active power filters considering a distorted environment.

In previous work, the authors have presented a transformer-less hybrid active filter to suppress harmonic resonances in the industrial power system. The hybrid filter is constructed by a seventh-tuned passive filter and an active filter in series connection. It operates as a variable conductance at harmonic frequencies according to the voltage THD, so that harmonic distortion can be reduced to an acceptable level in response to load change and power system variation. Since the series capacitor is responsible for sustaining the fundamental component of the grid voltage, the active filter is able to operate with a very low dc bus voltage, compared with the pure shunt active filter. Hence, both the rated kVA capacity and the switching ripples are reduced accordingly. Moreover, the proposed harmonic conductance is able to avoid over current of the passive filter in the case of mistuning parameters. These features will benefit practical applications.

In this paper, we further present designing consideration of the hybrid filter. A prototype circuit of the hybrid filter based on 220-V/10-kVA system has been established to verify theoretic analysis, including steady-state behavior, transient response, and stability analysis. The filtering performance of the hybrid filter is discussed considering X/R ratio and magnified variations of line impedance. We also focus on filtering deterioration due to line resistance, voltage unbalance, and capacitive filters in the power system. In many cases, an active power filter is designed to compensate harmonic current produced by a

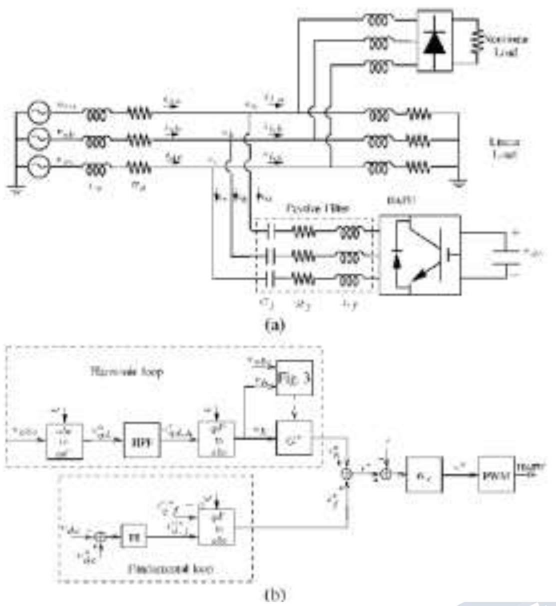

Fig. 1. Proposed HAFU in the industrial power system and its associated control. (a) Circuit diagram of the HAFU. (b) Control block diagram of the HAFU.

Specific nonlinear load, in such a way that it needs to measure the load current to be compensated [14]. In this paper, the active filter is designed as a harmonic conductance to suppress both harmonic resonance and harmonic distortion by using inverter-side voltage and current measurements. Notice that it does not require current information of the nonlinear loads. Thus, this approach can be suitable in power distribution networks in which the loads may be distributed along a feeder . In addition, compensating fundamental reactive power due to unbalanced load is possible, but it is outside the scope of this paper .

II. OPERATION PRINCIPLE

Fig. 1(a) shows a simplified circuit diagram considered in this paper, where Ls represented the line inductance plus the leakage inductance of the transformer. The hybrid active filter unit (HAFU) is constructed by a seventh-tuned passive filter and a three-phase voltage source inverter in series connection. The passive filter Lf − Cf is intended for compensating harmonic current and reactive power. The inverter is designed to suppress harmonic resonances and improve the filtering performances of the passive filter. Fig. 1(b) shows the overall control block diagram of the HAFU, including harmonic loop, fundamental loop, current regulator, and conductance control. A detailed principle will be presented as follows.

A. Harmonic Loop

To suppress harmonic resonances, the HAFU is proposed to operate as variable conductance at harmonic frequencies as follows:

$$i_h^* = G^* \cdot e_h \qquad (1)$$

Where i ∗ h represents the harmonic current command. The conductance command G ∗ is a variable gain to provide damping for all harmonic frequencies. Harmonic voltage component eh is obtained by using the so-called SRF transformation [9], where a phase-locked loop (PLL) is realized to determine the fundamental frequency of the power system . In the SRF, the fundamental component becomes a dc value, and other harmonic components are still ac values. Therefore, harmonic voltage component eeqd,h can be extracted from eeqd by using high pass filters. After transferring back to a three-phase system, the harmonic current command i∗h is obtained by multiplying eh and the conductance command G∗, as shown in (1).

B. Fundamental Loop

In this paper, the q-axis is aligned to a-phase voltage. Since the passive filter is capacitive at the fundamental frequency, the passive filter draws fundamental leading current from the grid, which is located on the d-axis. The proposed inverter produces slight fundamental voltage on the d-axis, which is in phase with the fundamental leading current. Therefore, the control of dc bus voltage is able to be accomplished by exchanging real power with the grid. Thus, the current command ie∗ d,f is obtained by a proportional–integral (PI) controller. The fundamental current command i∗f v in the three-phase system is generated after applying the inverse SRF transformation.

Equation (2) shows the harmonic voltage drop on the passive filter due to the compensating current of the HAFU , where Ih represents the maximum harmonic current of the active filter, and the voltage drop on filter resistance Rf is neglected. As can be seen, a large filter capacitor results in the reduction of the required dc

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voltage. On the other hand, the filter capacitor determines reactive power compensation of the passive filter at the fundamental frequency. Thus, the dc voltage $v*$ dc can be determined based on this compromise. Note that the compensating current should be limited to ensure that the hybrid filter operates without undergoing saturation,
i.e.,

$$v_{dc} > 2\sqrt{2}\sum_{h}\left|\frac{1}{j\omega_h C_f} + j\omega_h L_f\right| \cdot I_h. \qquad (2)$$

C. Current Regulator

The current command $i*$ is consisted of $i*\ h$ and $i*\ f$. Based on the current command $i*$ and the measured current i, the voltage command $v*$ can be derived by using a proportional controller as follows:

$$v^* = K_c \cdot (i^* - i) \qquad (3)$$

where Kc is a proportional gain. According to the voltage command $v*$, space-vector pulse width modulation (PWM) is employed to synthesize the required output voltage of the inverter. Fig. 2 shows the model of the current control. The computational delay of digital signal processing is equal to one sampling delay T, and PWM delay approximates to half sampling delay $T/2$. Hence, the proportional gain Kc can be simply evaluated from both open-loop and closed-loop gains for suitable stability margin and current tracking capability.

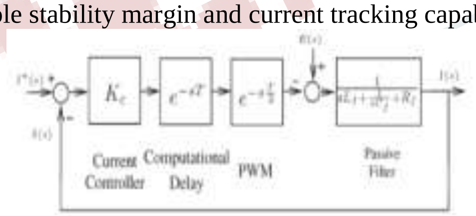

Fig. 2. Closed-loop model of the current control.

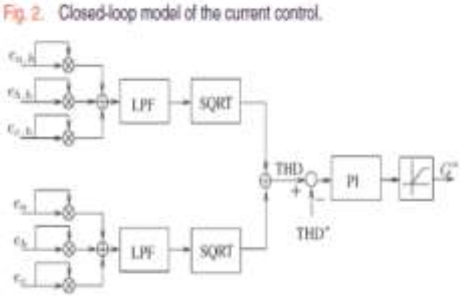

Fig. 3. Conductance control block diagram.

D. Conductance Control

Fig. 3 shows the proposed conductance control. The harmonic conductance command $G*$ is determined according to the voltage THD at the HAFU installation point. The voltage THD is approximately calculated by the control shown in Fig. 3. Here, two low-pass filters (LPFs) with cutoff frequency fLP = 20 Hz are realized to filter out ripple components . The error between the allowable THD∗ and the measured THD is then fed into a PI controller to obtain the harmonic conductance command $G*$. The allowable distortion could be referred to the harmonic limit in IEEE std. 519-1992. Note that PI parameters need to be tuned for required response and stability. For example, the proportional gain can be tuned for transient behavior, and the integral gain is responsible for suppressing the steady-state error. The bandwidth should be lower than one-tenth of the cutoff frequency of the current loop to assure stable operation. This way, the HAFU is able to dynamically adjust $G*$ to maintain harmonic distortion at an allowable level.

III. ANALYSIS OF FILTERINGPERFORMANCE

The filtering performance of the HAFU has been addressed in by developing equivalent circuit models, in which both harmonic impedance and harmonic amplification are considered. The frequency characteristic of the passive filter is changed by the proposed harmonic conductance to avoid unintentional resonances. Here, we will concentrate on the damping performance with variation of line impedance Ls, line resistance Rs, and THD∗ . Voltage unbalance and filter capacitors in the power system are also considered.

A. Ls on Damping Performances

Fig. 4 shows voltage THD for various values of Ls. The fifth harmonic voltage is severely amplified at Ls = 0.3 mH (2.3%), as shown in Fig. 4(a). This resonance is alleviated if Ls is not equal to 2.3%. However, voltage distortion is still significant due to harmonic voltage drop on Ls. After the HAFU isstarted, Fig. 4(b) shows voltage distortion is maintained at 2% by increasing $G*$, as shown in Fig. 4(c). It is worth noting that the HAFU is operated at anti-resonance mode, i.e., $G*$ = 0, if Ls is less than 2.3% for NL1. This means that the voltage distortion is less than 2%. At that time, a lower THD∗ command is needed to further reduce the current distortion of is.

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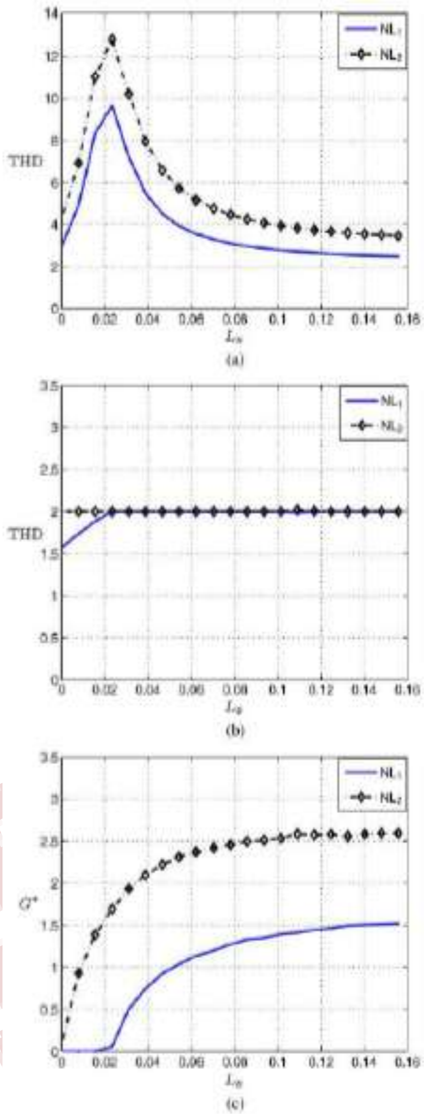

Fig. 4. Voltage THD (%) and the required G∗ (p.u.) with varying line impedance Ls (p.u.). (a) Voltage THD at e when the HAFU is off.(b) Voltage THD at e when the HAFU is on. (c) G∗ when the HAFU is on.

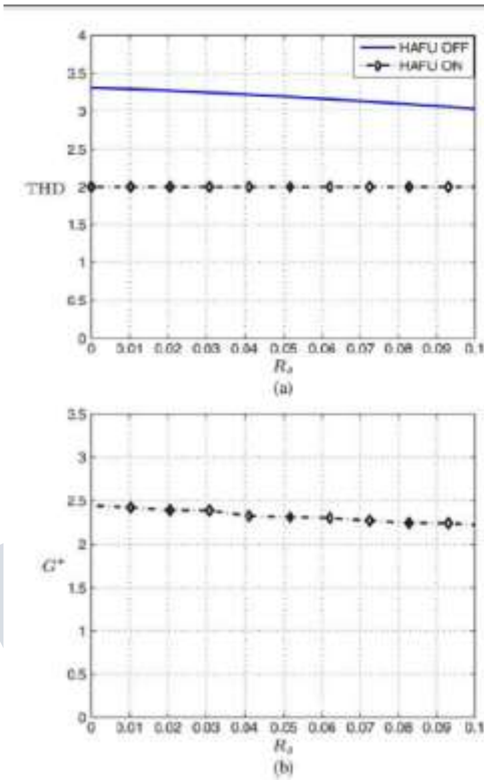

Fig. 5. Voltage THD (%) and the required G∗ (p.u.) with varying line resistance Rs (p.u.). (a) Voltage THD at e. (b) G∗ when the HAFU is on.

B.Rs on Damping Performances

In the low-voltage system, the *X/R* ratio becomes lower, and line resistance on damping performances must be taken into consideration. Fig. 5(a) shows voltage distortion with varying *Rs* for NL2. Since increasing *Rs* could help in reducing voltage distortion, the required conductance to maintain voltage distortion at 2% is accordingly reduced, as shown in Fig. 5(b). From this observation, the HAFU could provide effective damping capability, although *Rs* is as large as 10%.

C. Determination of THD∗

According to IEEE std. 519-1992 , voltage THD is limited to 5%, and individual distortion should be below 4%. Thus, THD∗ is set in the range of 3% and 5%. If *vs,h* and *Rs* are neglected, voltage THD at *E*, due to harmonic current load *Ih*, can be expressed as follows:

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$$\mathrm{THD} = X_{\mathrm{pu}} \sqrt{\sum_h (h \cdot I_{h,\,\mathrm{pu}})^2}. \tag{4}$$

X represents the series impedance of both *Ls* and leakage inductance of transformer. Here, we will consider three cases in Table I to illustrate how to determine voltage THD∗, where only the fifth and seventh harmonics are considered. In the first one, the fifth harmonic is dominant; therefore, THD∗ lower than 0.2*X*pu is a sufficient condition to confirm with the harmonic limit. If the fifth and seventh harmonics have the same distortion, THD∗ = 0.22*X*pu is acceptable. When the seventh harmonic becomes critical, THD∗ = 0.32*X*pu works in the third case. Therefore, the first case is the critical one to determine the required THD∗. Note that THD∗ should be reduced to enhance filtering capability in the case of low system-impedance.

TABLE I
CALCULATION OF THD*

	$I_{5,pu}$	$I_{7,pu}$	THD
Case 1	0.04	0.03	$0.2X_{pu}$
Case 2	0.035	0.035	$0.22X_{pu}$
Case 3	0.03	0.04	$0.32X_{pu}$

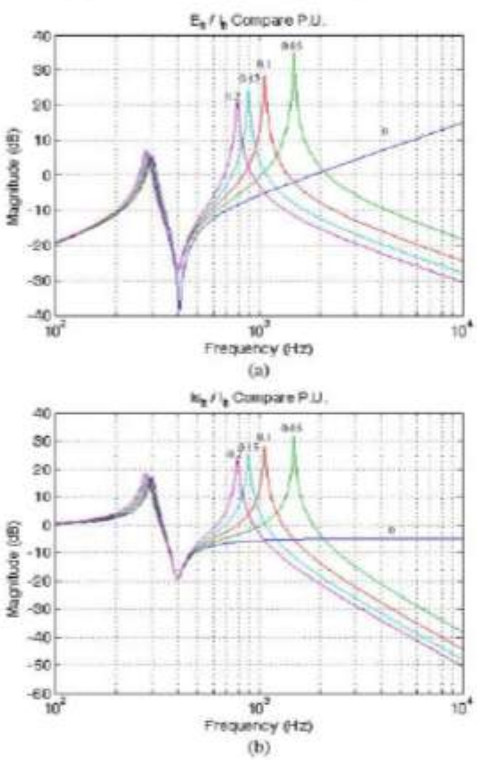

Fig.6. Harmonic amplification considering different passive filter capacitorsCe (0.05, 0.1, 0.15, and 0.2 p.u.). (a) Harmonic impedance. (b) Source current amplification.

D. Capacitive Filters

In power electronic equipment, LPFs or electromagnetic interference (EMI) filters are usually installed at the grid side of the inverter to alleviate switching ripples into the power system. Since these filters present capacitive characteristics, harmonic resonances may unintentionally occur . This scenario becomes much more significant in the so-called micro grid system because a large number of output filters installed by the inverter-based distributed generators may participate in resonances . Fig. 6 shows harmonic impedance and source current amplification for different capacitors *Ce* installed at the power capacitor chip. As can be seen, *Ce* shifts the resonant frequency and induce another high-frequency resonance, which may result in serious harmonics. Simulation results in Fig. 7 show that amplification of *Eh* and *is,h* can be effectively suppressed by the proposed hybrid filter. Note that the filtering capability is dependent on the bandwidth of the HAFU.

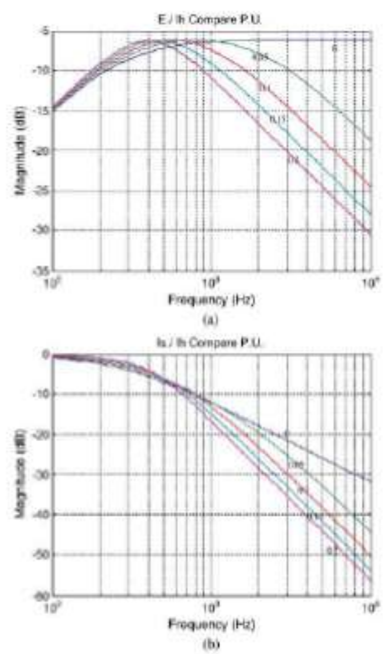

Fig. 7. Damping performances for different passive filter capacitors Ce (0.05, 0.1, 0.15, and 0.2 p.u.) with G∗ = 2.0 p.u. (a) Harmonic impedance. (b) Source current amplification.

E. Voltage Unbalance

The voltage unbalance in a low-voltage system is usually significant due to high line impedance and uneven distribution of single-phase loads . Large unbalance may cause second-order harmonics in executing SRF control of the HAFU. In this sense, we need to add a band-rejected filter tuned at the second-order harmonic frequency in Fig. 1 to reduce this unwanted component. We also can use second-order generalized-integrator-based methods to separate negative sequence component in the proposed control. It is worth nothing that unbalanced voltage or unbalanced current is possible to be compensated by the proposed HAFU. In this case, the HAFU has to generate fundamental negative-sequence voltage. This issue is open for further research.

V. CONCLUSION

This paper presents a hybrid active filter to suppress harmonic resonances in industrial power systems. The proposed hybrid filter is composed of a seventh harmonic-tuned passive filter and an active filter in series connection at the secondary side of the distribution transformer. With the active filter part operating as variable harmonic conductance, the filtering performances of the passive filter can be significantly improved. Accordingly, the harmonic resonances can be avoided, and the harmonic distortion can be maintained inside an acceptable level in case of load changes and variations of line impedance of the power system. Experimental results verify the effectiveness of the proposed method. Extended discussions are summarized as follows.

- ♣ Large line inductance and large nonlinear load may result in severe voltage distortion. The conductance is increased to maintain distortion to an acceptable level.
- ♣ Line resistance may help reduce voltage distortion. The conductance is decreased accordingly.
- ♣ For low line impedance, THD∗ should be reduced to enhance
- ♣ filtering performances. In this situation, measuring voltage distortion becomes a challenging issue.
- ♣ High-frequency resonances resulting from capacitive filters is possible to be suppressed by the proposed method.
- ♣ In case of unbalanced voltage, a band-rejected filter is needed to filter out second-order harmonics if the SRF is realized to extract voltage harmonics.

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