Harmonic Resonance Reduction using Hybrid Active Filter with Fuzzy Logic Controller in Industrial Power Systems

Murikipudi Pavan Kumar, A.Manjula

Abstract: This paper proposes a hybrid active filter for damping harmonic resonance and reducing harmonic distortion in industrial power systems. The change in load and variation in parameters causes harmonic distortions which are reduced to a considerable level by operating hybrid filter as variable harmonic conductance in accordance with voltage total harmonic distortion. The hybrid filter consists of an active filter and a seventh tuned passive filter connected in series. Therefore the dc voltage and kVA rating are reduced noticeably in comparison with the pure shunt active filter. The simulation study for the proposed method is carried out in Matlab/Simulink software which validates the efficiency. This paper also considers the filtering performances on line resistance, line impedance, capacitive filters and voltage unbalance.

Keywords: Harmonic resonance, Hybrid active filter, Industrial power system.

I. INTRODUCTION

In industrial power systems the power quality is a major concern which might be affected by non linear loads such as rectifiers, diode/thyristor and cycloconverters. And the harmonic pollution is caused by the heavy use of these non linear loads, uninterruptible power supply systems, adjustable speed drives, battery charging system, etc. In order to mitigate these harmonics, passive filters that are tuned are placed at the secondary side of the distribution transformer [1], [2]. But, the problem with the passive filters is that the parameters are varied in passive filters causing the unintentional series/parallel resonances. Consequently several active filtering methods are taken into consideration to tackle the harmonic problems in the power system [3]–[5].

A hybrid series active filter was presented in [6] that separate power system harmonics from the harmonic source and [7] presented a hybrid shunt active filter in which the fifth harmonic resonance is suppressed by the filter current detecting method. The resonance was between the power system and a capacitor bank. But the above filters require extra transformers or tuned passive filters. Therefore a transformerless hybrid active filter was designed to balance both harmonic and fundamental reactive currents [8], [9] also to restrain harmonic resonances in the industrial power system [10], [11].

The authors are with the Indian Railways,
Anurag Group of Institutions, India

The hybrid filter is composed of a seventh-tuned passive filter connected in series with the active filter. This hybrid filter works as a variable conductance in proportion to voltage THD at harmonic frequencies, thus reducing harmonic distortion to an acceptable level for different load changes and variations in power system.

In this paper, a hybrid filter has been designed in Matlab/Simulink software to verify steady-state behavior and transient response whose filtering performance is discussed by the *X/R* ratio and magnified variations of line impedance. Also the filtering deterioration in the power system because of capacitive filters, line resistance and voltage unbalance is discussed. In most of the cases the design of an active power filter is done in such a way that it compensates the harmonic current generated by particular nonlinear load by measuring the load current that is to be compensated [8], [12]. Whereas this paper designs the active filter as a harmonic conductance that suppresses harmonic resonance and distortion by taking voltage and current measurements of inverter into consideration without requiring information of the current of nonlinear loads. Thus, this method can be appropriate in power distribution networks [13].

II. OPERATION PRINCIPLE

Fig 1(a) and (b) depicts a circuit diagram and a control block diagram of HAFU respectively in which a seventh-tuned passive filter is connected in series with the three-phase voltage source inverter. The passive filter compensates harmonic current and reactive power whereas the inverter suppresses harmonic resonances thus improving the filtering performance. HAFU includes harmonic loop, fundamental loop, current regulator, and conductance control which are explained in detail as follows.

A. Harmonic Loop

The HAFU employs as variable conductance at harmonic frequencies to suppress harmonic resonances as follows:

$$i_h^* = G^*.e_h \quad (1)$$

where i^*_h , G^* , e_h denotes the harmonic current command, conductance command, harmonic voltage component respectively . G^*, the conductance command, is a variable gain that provides damping for all harmonic frequencies. e_h is acquired by SRF transformation [9-14], and the fundamental frequency of the power system is fixed by a phase-locked loop (PLL) [15].

B. Fundamental Loop

At the fundamental frequency the passive filter is capacitive and extracts fundamental principal current from the grid, positioned on the d-axis. And the proposed inverter generates fundamental voltage on the d-axis in phase with the fundamental principal current. Hence, the dc bus voltage control is accomplished by real power exchange with

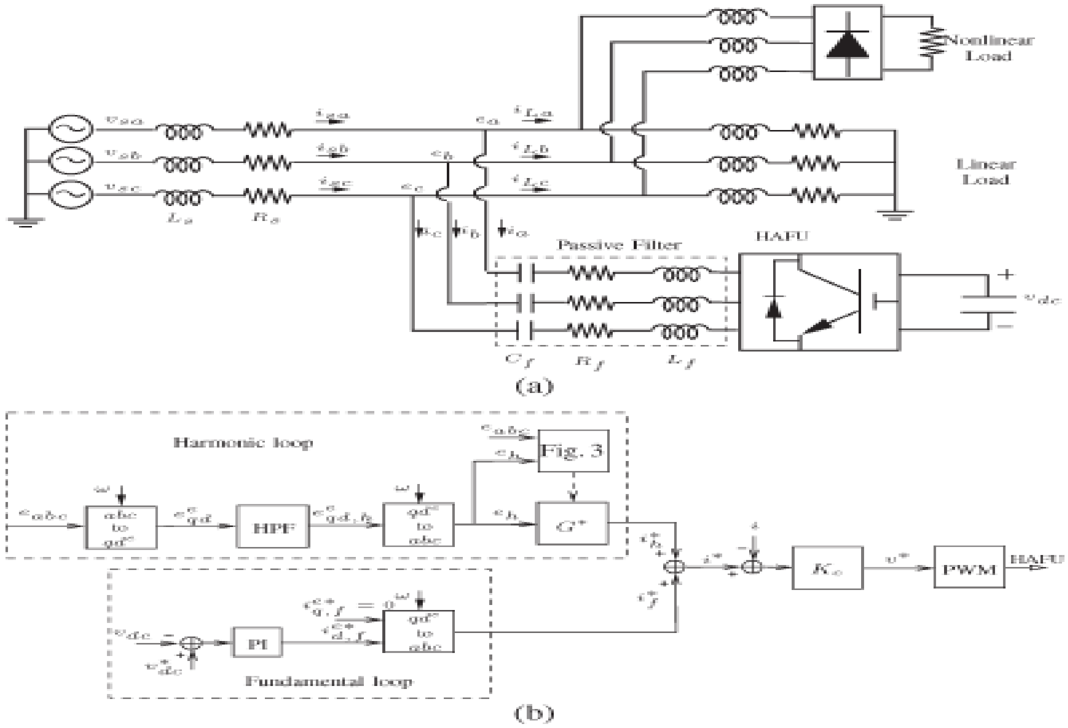


Fig. 1. Proposed HAFU in the industrial power system and its associated control. (a) Circuit diagram of the HAFU. (b) Control block diagram of the HAFU.

the grid. Thus, in three phase system, the fundamental current command i^*_f is obtained by the application of the inverse SRF transformation and the current command $i^{e*}_{d,f}$ is attained by a proportional–integral (PI) controller.

The compensating current of HAFU [13] causes voltage drop on passive filter as shown in (2), where the maximum harmonic current is denoted by I_h and voltage drop on R_f, the filter resistance is ignored. A large filter capacitor is intended to determine the reactive power compensation of the passive filter at fundamental frequency. Hence the dc voltage v^*_{dc} can be determined. The compensating current must be limited to an extent that ensures the operation of the hybrid filter without undergoing saturation, i.e.,

$$v_{dc} > 2\sqrt{2}\sum_h \left|\frac{1}{j\omega_h C_f} + j\omega_h L_f\right| . I_h \quad (2)$$

C. Current Regulator

The current command i^* is composed of i^*_h and i^*_f and the voltage command v^* is derived by the current command $i*$ and the measured current i, with a proportional controller as shown:

$$v^* = K_c.(i^* - i) \quad (3)$$

where K_c represents proportional gain. Fig. 2 shows the closed model of the current control.

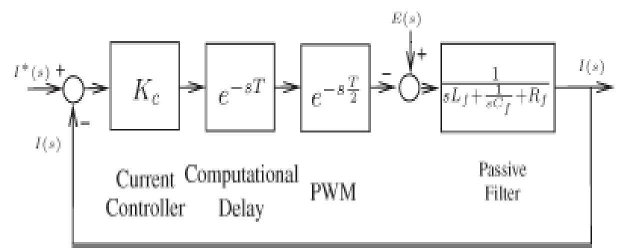


Fig. 2. Closed-loop model of the current control.

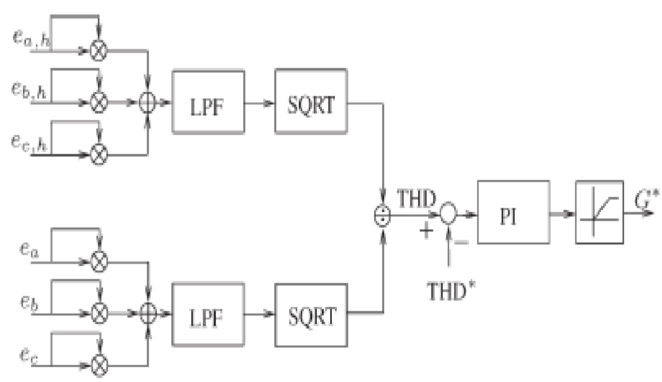


Fig. 3. Conductance control block diagram.

D. Conductance Control

The block diagram of the proposed conductance control is depicted in Fig. 3. The harmonic conductance command G^* is determined by the voltage THD.

TABLE I
SIMULATION PARAMETERS

Power System	220 V(L-L), 60Hz, VD_5=0.7%, VD_7=0.5%
Transformer	220/127V, 10kVA, impedance 5%
Resistive Load	2kW(20%)
Nonlinear load	NL_1=1.8kW(18%), NL_2=2.8kW(28%)
Passive filter	L_f=1.0mH(7.8%), C_f=150µF(27%), Q_f=20
Switching frequency	10kHz
Sampling frequency	20kHz
Current control	k_c=5V/A
DC voltage control	k_p=1A/V, k_i=100A/(V.s).v_{dc}^* =50V
Tuning control	k_p=1A/V, k_i=500A/(V.s). THD^*=2.0% f_{HP}=10Hz, f_{LP}=20Hz

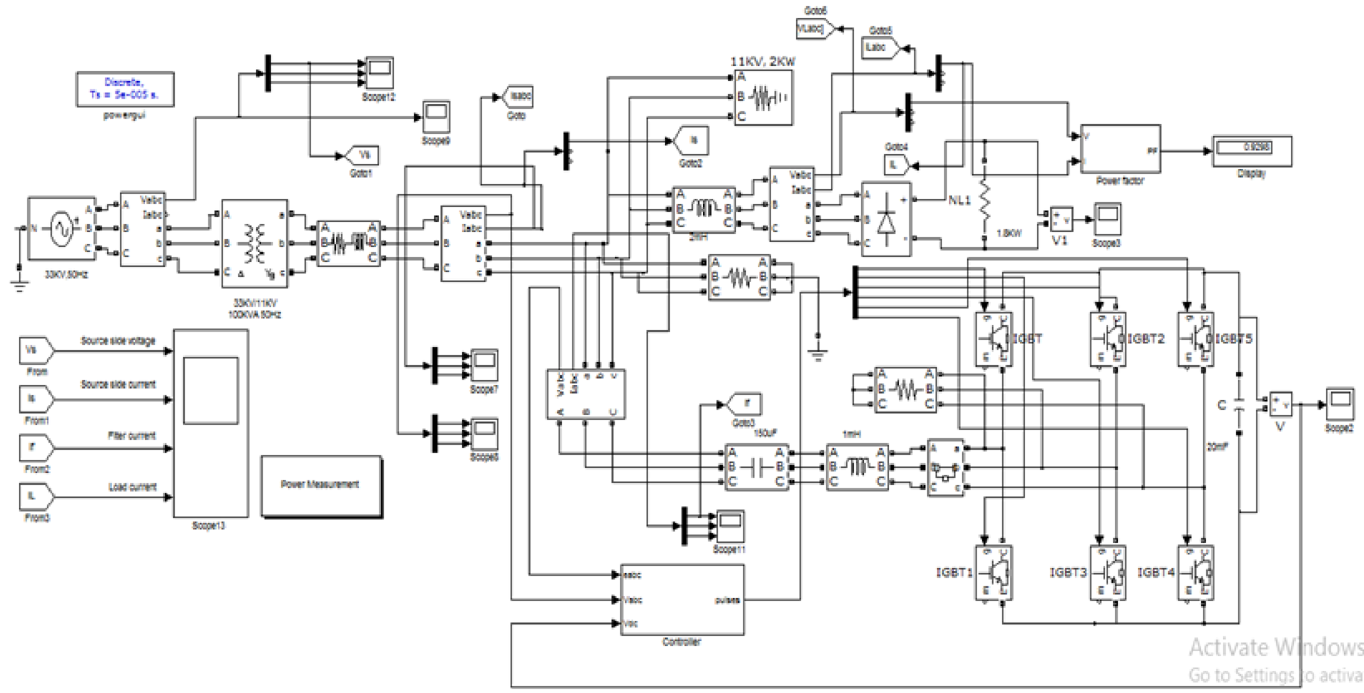


Fig 4. Simulink block diagram of HAFU

It is obtained by giving the error between the allowable THD^* and the measured THD to a PI controller. The PI parameters need to be tuned for required response and stability.

TABLE II
BASE VALUE

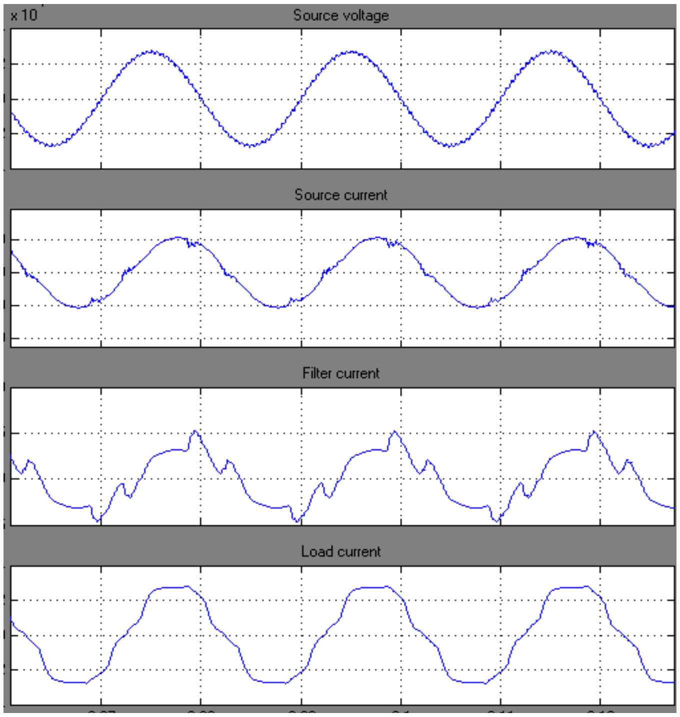
Voltage	220V
kVA	10kVA
Impedance	4.84Ω
Conductance	0.207 Ω^{-1}

IV. Simulation Results

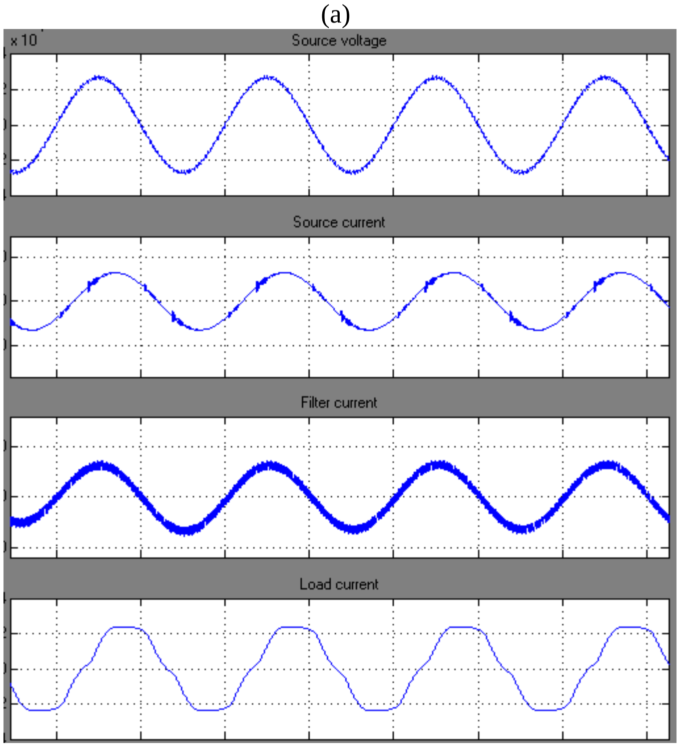
The simulink block diagram of HAFU is depicted in Fig. 4. The simulation parameters according to per unit system (Table II) are given in Table I. The voltage distortions of fifth and seventh are denoted as VD_5 and VD_7 respectively. C_F and L_F represents filter capacitor and filter inductor, C_F compensates inductive load whereas L_F enables the LC filter to be resonant at seventh order harmonic frequency. The HAFU is OFF means the upper three switches are turned on and lower three switches are turned off implying the inverter's three phases are short circuited. Here the HAFU acts as a pure passive filter.

A. Three-Phase Load

Fig. 5 shows the grid voltage e, the source current i_s, the filter current i, and the load current i_L for NL_1 = 1.8 kW. The HAFU acts as passive filter when it is OFF. The fifth harmonic distortion on grid voltage, source current, filter current and load current is shown in Fig. 5(a). This distortion occurs when resonant frequency between passive filter and line inductance is near to the fifth harmonic frequency.



(a)



(b)

Fig. 5. Line voltage e, source current i_s, load current i_L, and filter current i in the case of NL_1 initiated. X-axis: 5 ms/div. (a) HAFU is off. (b) HAFU is on.

As shown, the filtering performance of the passive filter is lost and results in unnecessary harmonic current on i_s or harmonic voltage on e. The presence of leakage inductance of the transformer could result in shifting of resonant frequency towards the lower frequency. Once the HAFU is ON, the harmonic distortion gets improved as in Fig. 5(b).

TABLE III

HARMONIC DISTORTION FOR NL1 = 1.8 kW. (a) VOLTAGE DISTORTION OF e. (b) CURRENT DISTORTION OF i_s. (c) CURRENT DISTORTION OF i_L. (d) CURRENT DISTORTION OF i

(a)

	THD	HD_5	HD_7	HD_{11}	HD_{13}
HAFU OFF	2.9%	2.7%	0.1%	0.5%	0.4%
HAFU ON	2.0%	1.6%	0.9%	0.5%	0.4%

(b)

	THD	HD_5	HD_7	HD_{11}	HD_{13}
HAFU OFF	8.5%	8.2%	1.7%	0.3%	0.2%
HAFU ON	4.8%	3.7%	2.8%	0.4%	0.4%

(c)

	THD	HD_5	HD_7	HD_{11}	HD_{13}
HAFU OFF	9.1%	7.3%	4.3%	2.8%	1.6%
HAFU ON	9.1%	7.7%	3.4%	2.5%	1.5%

(d)

	THD	HD_5	HD_7	HD_{11}	HD_{13}
HAFU OFF	27%	25%	9.2%	3.7%	2.3%
HAFU ON	12%	8.9%	6.7%	3.7%	2.0%

When HAFU is started the seventh harmonic voltage distortion is increased, due to the emulsion of conductance for all harmonic frequencies. And the increase in fifth harmonic component of load current i_L is also observed because of the enhancement of the fifth voltage distortion on e. The results show that the proposed HAFU can suppress harmonic resonances and decrease harmonic distortion.

B. Single-Phase Load

The filtering performance is also considered for single phase non linear load which is formed by the addition of smooth dc capacitor to the three phase diode rectifier setup. The non linear load is associated with a-phase and b-phase resulting in the generation of third order harmonic current between them. From Fig. 6, it is clear that the harmonic current is augmented between the source current i_s and the filter current i. When HAFU is started, the harmonic resonance is suppressed and the current distortion is reduced as in Fig. 7. Table IV summarizes the values. The third order harmonic distortion may not be suppressed inefficiently because the passive filter is tuned at the seventh-order harmonic frequency for single-phase nonlinear load. Whereas it might be improved when passive filter is tuned at fifth-order harmonic frequency.

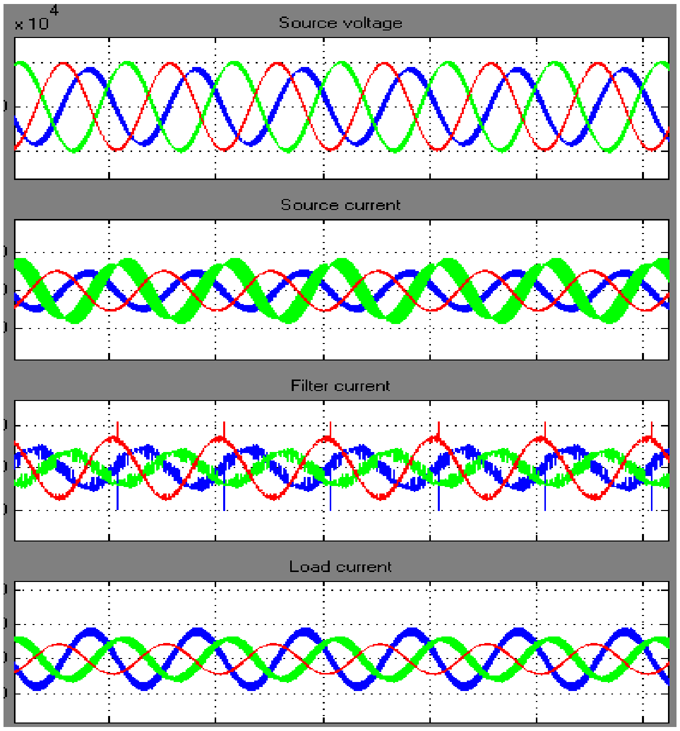


Fig. 6. HAFU is off for single-phase nonlinear load. (a) Source voltage. (b) Source current. (c) Filter current. (d) Load current.

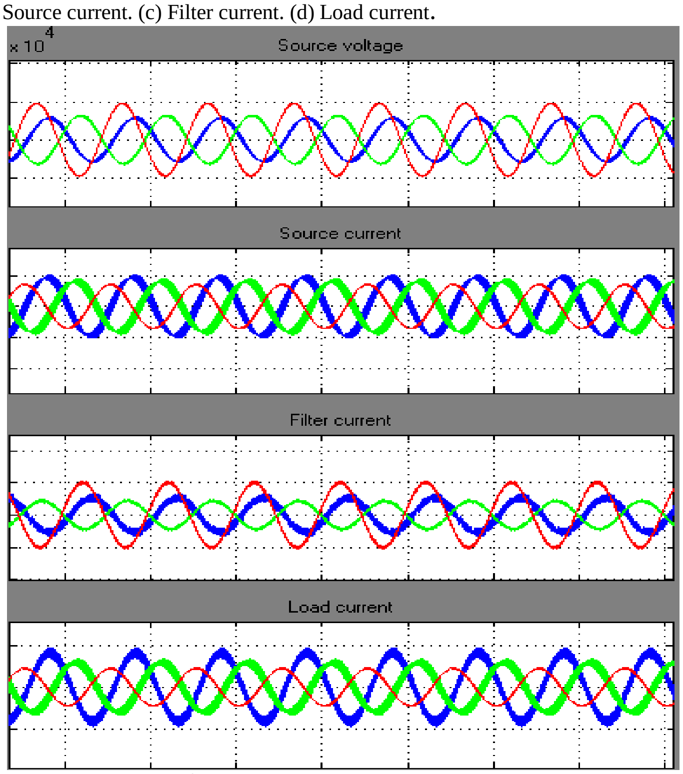


Fig. 7. HAFU is on for single-phase nonlinear load. (a) Source voltage. (b) Source current. (c) Filter current. (d) Load current.

TABLE IV
HARMONIC DISTORTION FOR SINGLE-PHASE NONLINEAR LOAD. (a) VOLTAGE DISTORTION OF *e*. (b) CURRENT DISTORTION OF i_s. (c) CURRENT DISTORTION OF i_L. (d) CURRENT DISTORTION OF *i*

(a)

	e_{ab}	e_{bc}	e_{ca}
HAFU OFF	6.3%	4.1%	2.4%
HAFU ON	4.1%	2.6%	1.8%

(b)

	i_{sa}	i_{sb}	i_{sc}
HAFU OFF	19%	28%	3.8%
HAFU ON	12%	16%	2.5%

(c)

	i_{La}	i_{Lb}	i_{Lc}
HAFU OFF	13%	13%	1.2%
HAFU ON	13%	13%	1.2%

(d)

	i_a	i_b	i_c
HAFU OFF	22%	25%	6.4%
HAFU ON	11%	12%	4.7%

V. Conclusion

In this paper the Hybrid Active Filter Unit (HAFU) was proposed that suppresses harmonic resonances in industrial power systems. It consists of passive filter tuned at seventh harmonic and an active filter connected in series at the other side of the distribution transformer. The filtering function of the passive filter was improved by using active filter as variable harmonic conductance. Thus the harmonic resonances can be suppressed, and the harmonic distortion can be maintained at an acceptable level during change in load and line impedance variations of the power system. The simulation results validate the efficiency of the proposed method.

VI. References

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