

DESIGN OF NOVEL HYBRID SHUNT ACTIVE FILTER FOR THE IMPROVEMENT OF POWER QUALITY IN DISTRIBUTION LINES

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ABSTRACT

This paper deals with the hysteresis current control based hybrid shunt active filter to improve the quality of power in distribution line by minimizing the harmonics. The main harmonic sources of distribution lines are the non linear loads and frequent switching of industrial loads. The non linear loads take discontinuous current and thus it injects harmonics. The switching of loads produces voltage sag and swells which leads to harmonics in the lines. The proposed hybrid shunt active filter is fully characterized by series LC and shunt DC link connected through 3-phase active filter. The disturbances in the supply voltage and load current due to frequent switching of a 5 HP wound induction motor in the 415 V, 50 Hz distribution line are observed using CW240 power quality meter. The same is simulated in MATLAB with and without filter. The simulation results obtained from the proposed method proves that it gives comparatively better THD value.

KEYWORDS— Hysteresis Current Control [HCC], Active Power Filter [APF], Distributed Generators [DG], Distribution Systems [DS], shunt active filters, Voltage Regulation [VR] and Total Harmonic Distortion [THD].

I. INTRODUCTION

Harmonic pollution and reactive power in the power system are the important power quality problems. With the proliferation of non-linear loads in industrial applications and frequent switching of loads in the distribution systems, the compensation of harmonic and reactive power is becoming increasingly concerned. Shunt passive filters have been widely used because of their low cost and low loss. However, the performances of the filters are very sensitive to the power system impedance and series or parallel resonance with the power system impedance may occur. Also, the effective compensation with the variation of the voltage cannot be carried out with passive filters. The filter performance of shunt active power filter does not depend on the power system impedance or any other constant parameters. The

compensation of harmonic and reactive power can be achieved dynamically in the case of APF. The research in this field has been done for many years and researchers proposed several methods of improving THD value up to 4% by eliminating harmonics selectively or reducing it by using different filtering techniques in the active filters. The References papers have reported field test results of active filters intended for installation on power distribution systems. The active filter is characterized by behaving like a resistor for harmonic frequencies, resulting in damping out the harmonic amplification throughout a distribution line. Since the proposed distribution system consists of four distribution lines, installing the active filter on the end bus of each line is effective in harmonic damping. A static synchronous compensator is one of the most effective solutions to regulate the line voltage. However, no literature has addressed the dynamic behaviour of the active filter when it performs both harmonic damping and voltage regulation at the same time. The reactive power flow, the voltage and current variations due to frequent switching of 5 HP wound induction motor in the 415V, 50Hz distribution system are observed using power quality meter and same is verified in the simulation. The novel hybrid shunt active filter is designed and simulated in MATLAB for same application. The simulation results are shown to verify the effectiveness of the active filter capable of harmonic damping.

II. HYBRID SHUNT ACTIVE FILTER FOR A DISTRIBUTION SYSTEM

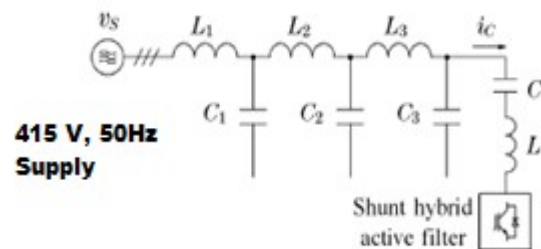


Fig1: A Distribution system with filter [one line circuit]

A. Harmonic Amplification & Damping

The Inductor in the fig 1 is the resultant of a leakage inductance of a distribution transformer to line inductances. The Capacitors are the PFC capacitors installed by consumers. It is observed that the fifth and seventh harmonic voltages present in the system. The “harmonic amplification” is resulting from resonance between the inductance and the capacitance on the line and its effect is more during day time compared to night time. The shunt active filter for damping out harmonic propagation is connected to a distribution system. Fig. 2 shows the simplified Distribution System having a shunt hybrid active filter proposed in this paper. The transformer in the pure filter is replaced by a capacitor in the hybrid filter. The purpose of the capacitor is to impose high impedance to the fundamental frequency so that the fundamental voltage appears exclusively across the capacitor. This means that no fundamental voltage is applied across the active filter.

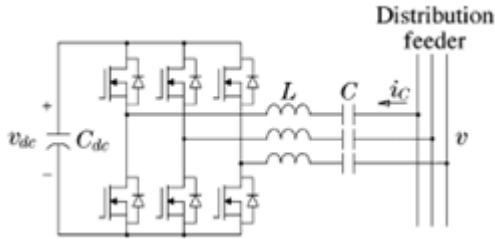


Fig 2. A typical 3 Φ Hybrid Shunt Active filter

Fig 2 shows the detailed power circuit of the hybrid filter, which consists of a three-phase voltage-fed PWM inverter and [switches are named as per their conduction sequence] a series connection of L and C per phase. Note that the tuned frequency of L and C is not the fifth-harmonic frequency but around the seventh-harmonic frequency. The reason is that the seventh-tuned LC filter is less bulky than the fifth-tuned LC filter as long as both filters have the same inductor as L. The dc-bus of the PWM inverter has only a capacitor without external supply, and the dc-bus voltage is controlled by the hybrid filter. The hybrid filter is controlled so as to draw the compensating current i_c from the distribution line.

B. Operating Principle

The compensating current of the hybrid shunt active filter consists of a fundamental component and harmonic components and they are determined by the impedance of the LC filter and are controlled by the active filter. Three-phase voltages and currents are detected at the

installation bus. The harmonic voltage V_h in each phase is extracted from the detected three-phase voltage, and then the harmonic voltage is amplified by a control gain K_v . Thus the harmonic current reference i_{ch} is given by

$$i_{ch} = K_v \cdot V_h \quad (1)$$

The actual harmonic compensating current i_{ch} is extracted from the detected compensating current i_c . Assuming that it is equal to its reference i_{ch} , the hybrid filter behaves as a damping resistor of $1/K_v$ [V/A] for harmonic frequencies. The optimal value of K_v is equal to the inverse of the characteristic impedance of the distribution feeder. With this value, the hybrid filter can damp out harmonic propagation effectively.

III. EXPERIMENTAL SYSTEM [proposed]

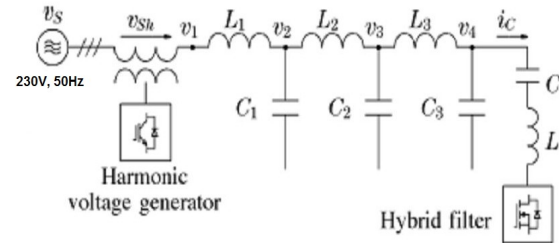


Fig 3: Single line diagram of experimental system

In the experimental the harmonics are generated either by switching the load frequently or by connecting a non linear load. A three-phase power distribution feeder simulator rated at 230 V, 50 Hz, and 20 kW is used for the laboratory experiments. Table I summarizes the line simulator parameters. When a lossless line is assumed, the characteristic impedance of the feeder simulator Z_o can be calculated as

$$Z_o = \sqrt{L/C} \quad (2)$$

A shunt hybrid active filter component values given in the table – II is connected to the bus. The dc-bus voltage of the PWM inverter is controlled to be 40 V. Note that the dc-bus voltage as low as 40 V in the 230-V system corresponds to a dc-bus voltage as low as 1.3 kV. This means that adopting a diode-clamped three-level inverter allows us to use 1200-V IGBTs that are easily available on the market at low cost. Referring to [7], the control gain K_v should be set to the inverse of the characteristic impedance of the feeder.

TABLE 1; Parameters of the feeder simulator

Line inductance	$L_a=L_b=L_c$	0.22Mh
Line Resistance	$R_a=R_b=R_c$	0.02 or 0.05Ω
Line Capacitance	$C_a=C_b=C_c$	350μF

TABLE II; Parameters of the Hybrid Filter

LC Filter [1.3KVA]		
L	2 mH	
C	100 μ F	
Resonant Frequency	f_r	356Hz
Quality Factor	Q	20
DC Bus Capacitor	C_{DC}	4700 μ F
DC Bus Voltage	V_{DC}	40V

III. HCC PRINCIPLE

The bidirectional switches shown in Fig. 2 are controlled with hysteresis current control technique. In the balanced three phase system and unity power factor operation, the three-phase voltages and reference currents are equal in magnitude and displaced by 120° . The switches S_1 , S_3 , and S_5 conduct when corresponding Phase voltage is in positive half cycle and the bidirectional switch is in the switch-off state. Similarly, switches S_4 , S_6 , and S_2 conduct when corresponding phase voltage is in negative half cycle and the bidirectional switch is in the switch-off state. In order to prove the instantaneous power balance between ac source and dc bus, the local average method is adopted [5]–[6]. In fig 4, phase a current i_a is controlled to track the reference current within the window width I_w and same way the other two phases are carried out.

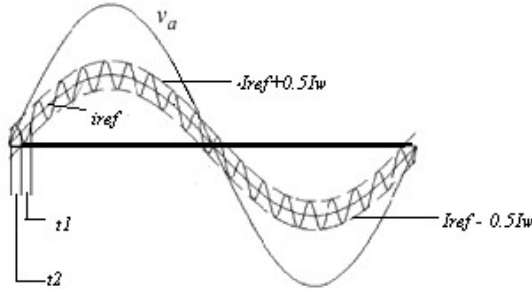


Fig 4. Currents within one switching period

The phase a current being switched between upper and lower bounds to track the reference current (upper trace); Switch S_1 current (mid-trace); bidirectional switch S_a current (lower trace) in the balanced three phase system and unity power factor operation.

A. Operation during the Positive Interval of i_{refa} .

It is explained by taking phase “a” parameters and the other phase parameters are assumed to be same. During $0 < t < t_1$, the supply current i_a flows through the bidirectional switch S_a , rising from $(i_{refa} - 0.5I_w)$ to $(i_{refa} + 0.5I_w)$ and during $t_1 < t < (t_1 + t_2)$, the switch S_a is off and the currents in the input inductor continues to flow through the freewheeling diode $D1$. It is assumed that the time period $(t_1 + t_2)$ is so concise that i_{refa} is considerably constant. From fig.3 Let i_{1a} be the current flowing through the upper switch S_1 and i_{3a} be the current

flowing through the bidirectional switch S_a . The average currents i_{1a} and i_{3a} are

$$i_{1a} = \frac{\int_{t_1}^{t_1+t_2} i_{refa} dt}{t_1+t_2} \approx \frac{i_{refa} t_2}{t_1+t_2} \quad (3)$$

$$i_{3a} = \frac{i_{refa} t_1}{t_1+t_2} \quad (4)$$

When the bidirectional switch S_a is on, the corresponding equation is

$$L \frac{di_a}{dt} = v_a \quad (5)$$

Since the phase a current i_a rises from $(i_{refa} - 0.5I_w)$ to $(i_{refa} + 0.5I_w)$ within time t_1 , hence (5) can be expressed as

$$L \frac{I_w}{t_1} = v_a \quad (6)$$

From (6) t_1 can be expressed as $t_1 = \frac{LI_w}{v_a}$ (7)

When bidirectional switch S_a is switched off and diode D_1 is on, phase a current i_a falls from $i_{refa} + 0.5I_w$ to $i_{refa} - 0.5I_w$ within the transit time t_2

$$L \frac{di_a}{dt} = v_a - 0.5V_{dc} \quad (8)$$

$$\text{From (8) } t_2 = \frac{LI_w}{0.5V_{dc} - v_a} \quad (9)$$

But $0.5V_{dc} > v_a$. Substituting (7) and (9) in (3)

$$i_{1a} = \frac{2V_a}{V_{dc}} i_{refa} \quad (10)$$

B. Operation during the Negative Interval of i_{refa}

During this condition, the phase a voltage is in negative half cycle and the Switch S_1 is reverse-biased and the phase a current will flow through Switch S_4 . It is similar to the operation of positive interval of i_{refa} .

Similar to expression (10), i_{2a} is also calculated as

$$i_{2a} = \frac{2V_a}{V_{dc}} i_{refa} \quad (11)$$

Similarly the phase b and phase c currents can be obtained as

$$i_{1b} = \begin{cases} \frac{2V_b}{V_{dc}} i_{refb} & (i_{refb} \geq 0) \\ 0 & (i_{refb} < 0) \end{cases} \quad (12)$$

$$i_{2b} = \begin{cases} 0 & (i_{refb} \geq 0) \\ \frac{2V_b}{V_{dc}} i_{refb} & (i_{refb} < 0) \end{cases} \quad (13)$$

$$i_{1c} = \begin{cases} \frac{2V_c}{V_{dc}} i_{refc} & (i_{refc} \geq 0) \\ 0 & (i_{refc} < 0) \end{cases} \quad (14)$$

$$i_{2c} = \begin{cases} 0 & (i_{refc} \geq 0) \\ \frac{2V_c}{V_{dc}} i_{refc} & (i_{refc} < 0) \end{cases} \quad (15)$$

The sum of the upper diode currents i_{1a} , i_{1b} , i_{1c} gives the upper dc link currents i_1 and the sum of the lower diode currents i_{2a} , i_{2b} , i_{2c} gives the lower dc link currents.

The total instantaneous dc power p_{dc} is

$$p_{dc} = \frac{i_1 V_{dc}}{2} + \frac{i_2 V_{dc}}{2} = V_a i_{refa} + V_b i_{refb} + V_c i_{refc} \quad (16)$$

Without considering the losses for a balanced three phase system with unity power the instantaneous power can be expressed as

$$p_{dc} = 3V_p I_{ref} = p_{ac} \quad (17)$$

The reference supply current under unity power factor can be obtained as

$$i_{ref} = \frac{V_{dc}}{3V_p} I_{dc} \quad (18)$$

Thus whenever there is any variation on the load the reference current can be adjusted by the output power estimator and dc link voltage regulator, the ac side neutral current i_{n1} can be zero in magnitude and expressed as

$$i_{n1} = \sqrt{2} I_{ref} \left[\sin \omega t + \sin \left(\omega t - \frac{2\pi}{3} \right) + \sin \left(\omega t + \frac{2\pi}{3} \right) \right] \quad (19)$$

Substituting i_{ref} in i_1 and i_2 and summing them the injection current i_{n2} is obtained. Thus i_{n2} consists of the sum of the currents through three bidirectional switches, and is given as

$$i_{n2} = i_2 - i_1 = \frac{2I_{dc}}{3} \sin(3\omega t) \quad (20)$$

Thus the expressions 18, 19 and 20 are used to calculate the amount of current to be injected in order to minimize the harmonics. The same can be implemented in simulation model.

IV. TEST RESULTS

A 5HP induction motor is connected to the three phase 415V, 50Hz distribution system through a switch. The motor is switched on and off frequently to monitor the voltage sag and swell, current variations and reactive power flow. During the test period the waveforms of load current and voltage also monitored using **Yokogawa CW240 power quality analyser**. The results of them are given below and are taken by using print screen option in the instrument.

LIST					LOAD1 INST.					2010/09/29 12:32:51				
U1	232.8	V	I1	4.08	A	WIRING	3P4W							
U2	229.8	V	I2	4.12	A	LOAD	1							
U3	227.5	V	I3	4.38	A	U	600V	x	1.00					
Uave	230.0	V	Iave	4.19	A	A	20A	x	1.00					
P	2.64	kW	PA	-24.2	°	PLL	U1 50Hz							
Q	-1.18	kvar	f	49.63	Hz	INTER.	100ms							
S	2.89	kVA												
PF	-0.912													

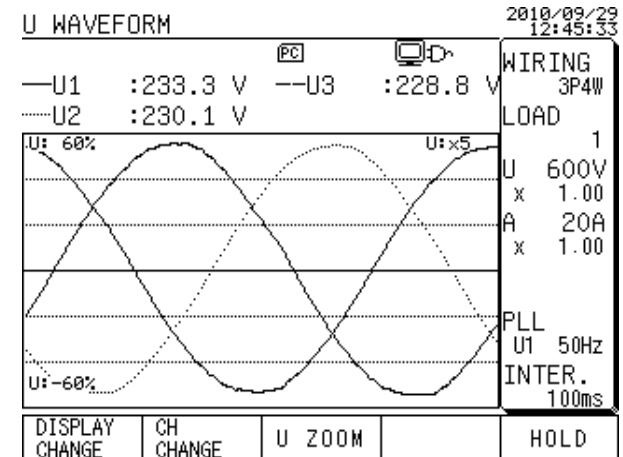
The above readings are the values of supply voltage, motor current, real and reactive power, power factor and frequency under normal condition. All of the values indicate that the variations are within the acceptable limit.

The below table gives the vales of voltage sag and swell occurred during the motor switched on.

VOLT.QUALITYEND							ALL	2010/09/29 12:43:53
							18/100	
Date	Time	Itm	CH	IO	RMS	Period		
▲09/29	12:43:12.208	Swe	1	I	233.4 V	00:00:00.000		
09/29	12:43:12.208	Dip	1	I	233.4 V	00:00:00.000		
09/29	12:43:12.208	Swe	2	I	229.8 V	00:00:00.000		
09/29	12:43:12.208	Dip	2	I	229.8 V	00:00:00.000		
09/29	12:43:12.208	Swe	3	I	228.7 V	00:00:00.000		
09/29	12:43:12.208	Dip	3	I	228.7 V	00:00:00.000		
09/29	12:43:18.899	Swe	1	O	46.5 V	00:00:06.691		
09/29	12:43:18.899	Int	1	I	46.5 V	00:00:00.000		
09/29	12:43:18.899	Swe	2	O	45.9 V	00:00:06.691		
09/29	12:43:18.899	Int	2	I	45.9 V	00:00:00.000		
09/29	12:43:18.899	Swe	3	O	46.0 V	00:00:06.691		
09/29	12:43:18.899	Int	3	I	46.0 V	00:00:00.000		
▼09/29	12:43:19.279	Swe	1	I	127.1 V	00:00:00.000		

The voltage has gone to minimum of 45V from 230V for a moment and attains to its normal value. This phenomenon leads to a harmonic injection according to the Fourier analysis

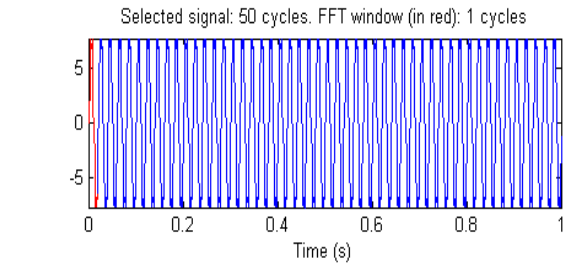
The current waveforms are much deteriorated from the supply voltage waveforms which clearly indicate the harmonics due to switching of loads. Hence in the distribution system the harmonic sources are the non linear loads and switching of industrial loads. These are taken as a case for simulation and the results are obtained shows the scope of the paper.



V. CONTROLLER DESIGN

The load current samples are fed to the PLL to generate their fundamentals and are transferred from three phase to two phase quantities. The ripples are filtered by LPF and then they are transformed to three phase quantities. This reference current(i_{refa} , i_{refb} , i_{refc}) is added with the load current i_a , i_b & i_c by comparator. The error generated is then sending to the HCC. The hysteresis current controller (HCC) generates pulses based on the current window width (I_w).

and their types. Hence a dynamic filtering system is required to reduce the harmonics.



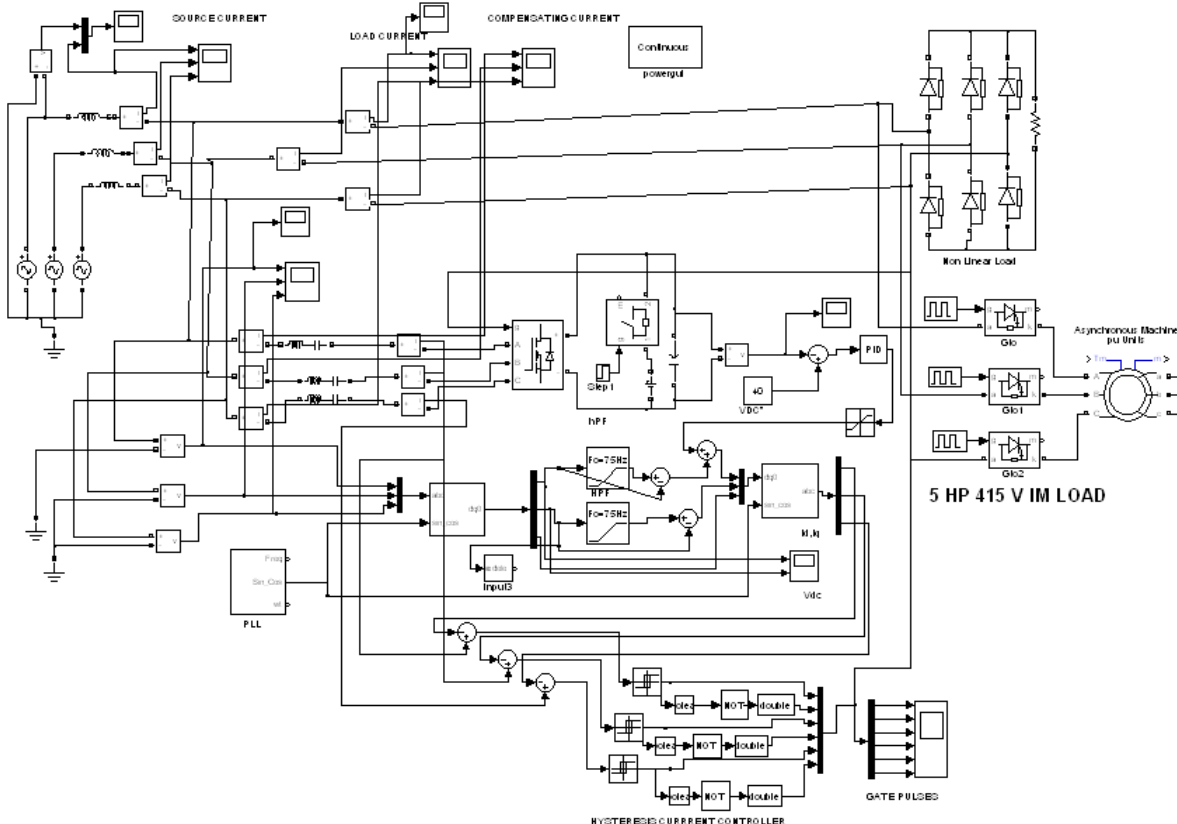
- FFT analysis

Fundamental (50Hz) = 7.822 , THD= 22.91%

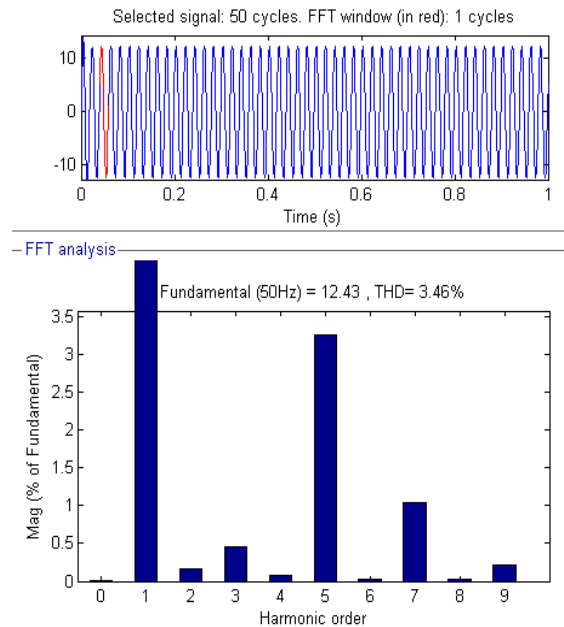
Harmonic order	Mag (% of Fundamental)
0	0.5
1	22.91
2	1.5
3	2.0
4	1.2
5	21.5
6	1.5
7	7.0
8	1.5
9	4.0

FFT window of load current without filter

VI. SIMULATION MODEL



The HCC based hybrid shunt active filter is connected to the distribution system and simulated. The THD value has reduced to as low as 3.46%. The result is given below.



VIII. CONCLUSIONS

The harmonic pollutions in the 415V, 50Hz distribution system due non linear loads and the switching of industrial loads are analysed with the simulation and measured results. The HCC principle and its implementation are explained with mathematical proof. The dynamically produced triggering pulses for the hybrid shunt active power filter fetches good results for this method. The results of this method can be validated and it will be the future scope of this study.

IX. REFERENCES

- [1]. Experimental Study and Comparison of Hybrid Active Filter with Parallel Active Filter, Xiao Xiangning, Xu Yonghai, Liu Hao, Ma Yulong Department of Electrical Engineering, North China Electric Power University, Beijing China 102206
- [2]. Power System Harmonic Analysis Using State-Estimation Method for Japanese Field Data, Norikazu Kanao, *Member, IEEE*, Mitsunori Yamashita, Hikoni Yanagida, Munehisa Mizukami, Yasuhiro Hayashi, *Member, IEEE*, and Junya Matsuki, *Member, IEEE* TRANSACTIONS ON POWER DELIVERY, VOL. 20, NO. 2, APRIL 2005
- [3]. Natchpong Hatti, *Student Member, IEEE*, Kazunori Hasegawa, and Hirofumi Akagi, *Fellow, IEEE* "A 6.6-kV Transformerless Motor Drive Using a Five-Level Diode-Clamped PWM Inverter for Energy Savings of Pumps and Blowers" IEEE Transactions on power electronics, vol. 24, no. 3, march 2009
- [4]. Ali I. Maswood, *Senior Member, IEEE*, and Fangrui Liu, *Student Member, IEEE* "A Unity Power Factor Front-End Rectifier with Hysteresis Current Control" IEEE trans. on energy conversion, vol. 21, no. 1, march 2006

[5]. B. R. Lin, "High power factor AC/DC/AC converter with random PWM," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 35, no. 2, pp. 935–944, Jul. 1999

- [6]. Norikazu Kanao, *Member, IEEE*, Mitsunori Yamashita, Hikoni Yanagida, Munehisa Mizukami, Yasuhiro Hayashi, *Member, IEEE*, and Junya Matsuki, *Member, IEEE* "Power System Harmonic Analysis Using State-Estimation Method for Japanese Field Data" IEEE transactions on power delivery, vol. 20, no. 2, April 2005
- [7]. Anshuman Shukla, *Student Member, IEEE*, Arindam Ghosh, *Fellow, IEEE*, and Avinash Joshi "Hysteresis Current Control Operation of Flying Capacitor Multilevel Inverter and Its Application in Shunt Compensation of Distribution Systems" IEEE Transactions on power delivery, vol. 22, no. 1, January 2007



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