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COMPARISON OF INVERTERS' PERFORMANCE AS ACTIVE POWER FILTERS WITH UNIFIED CONSTANT-FREQUENCY INTEGRATION CONTROL

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Abstract. Active Power Filter (APF) is well known for its capability of compensating current harmonics in power lines. Vast varieties of APF configurations were proposed for the past few decades, but not many papers consider the expansion capability of APFs. This article presents the comparison of performance for the conventional single level H-bridge inverter and Modular Structured Multilevel Inverter where both are controlled by Unified Constant-Frequency Integration (UCI) control scheme. The latter inverter structure is more flexible to be expanded to suit higher power application. Characteristics of each topology are discussed and the simulation results based on MATLAB/SIMULINK are presented.

Keywords: Active power filter, H-bridge inverter, multilevel inverter, unified constant-frequency integration control, harmonic compensation

Abstrak. Penapis Kuasa Aktif (PKA) terkenal dengan kebolehannya memampas harmonik arus dalam talian kuasa. Pelbagai jenis konfigurasi PKA telah dicadangkan dalam tempoh beberapa dekad yang lalu, tetapi jarang terdapat artikel yang mempertimbangkan kebolehan PKA meningkatkan tahap struktur pembinaannya. Artikel ini akan membandingkan operasi penyongsang biasa yang berbentuk H dengan Penyongsang Pelbagai Aras Struktur Bermodul (PPASB) yang dikawal oleh kaedah kawalan Pengamilan Disatukan Berfrekuensi Tetap (PDBT). Kelebihan struktur penyongsang baru tersebut dapat dipertambahkan peringkatnya untuk kegunaan kuasa yang lebih tinggi. Ciri-ciri setiap penyongsang tersebut akan dibincangkan dan keputusan simulasi berdasarkan MATLAB/SIMULINK juga dicatatkan.

Kata kunci: Penapis kuasa aktif, penyongsang-H, penyongsang pelbagai aras struktur bermodul, pengamilan disatukan berfrekuensi tetap, pemampasan harmonik

1.0 INTRODUCTION

For the past quarter century, application of non-linear loads at the end users is increasing tremendously and caused undesired harmonic problems in the line. Due to this reason, Active Power Filter (APF) has evolved in varying configurations and different control

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strategies to compensate current harmonics and reactive powers in power distribution systems. However, majority of the developed topologies focus to its design of the control schemes and calculation of the reference current for its controller [1, 2]. Recently, more papers research on the power limitation of an APF as the existing topologies mostly meant for low and medium power applications only.

This paper aims at comparing the APF performance achieved by a new control scheme Unified Constant-Frequency Integration control (UCI) [3] in two types of inverters, i.e.: the existing conventional H-bridge inverter and the Modular Structured Multilevel Inverter (MSMI) [4]. This APF system consists of cascaded H-bridge inverters as the power converter. MSMI APF was selected in this comparison because by implementing this APF of topology, more voltage levels can be achieved by expanding its structure, making this APF possible to be implemented in higher ratings power distribution systems.

2.0 DIFFERENT TOPOLOGIES OF UNIFIED CONSTANT-FREQUENCY INTEGRATION (UCI) CONTROLLED ACTIVE POWER FILTERS (APF)

Two types of inverters were selected as APFs with UCI control, they are: the H-bridge inverter which is widely used in active power filtering and the non-conventional MSMI.

2.1 H-bridge Inverter Active Power Filter

A conventional H-bridge inverter is shown in Figure 1. There are two legs in this H-bridge inverter where leg A consists of switches S1, S2, and leg B consists of switches S3, S4.

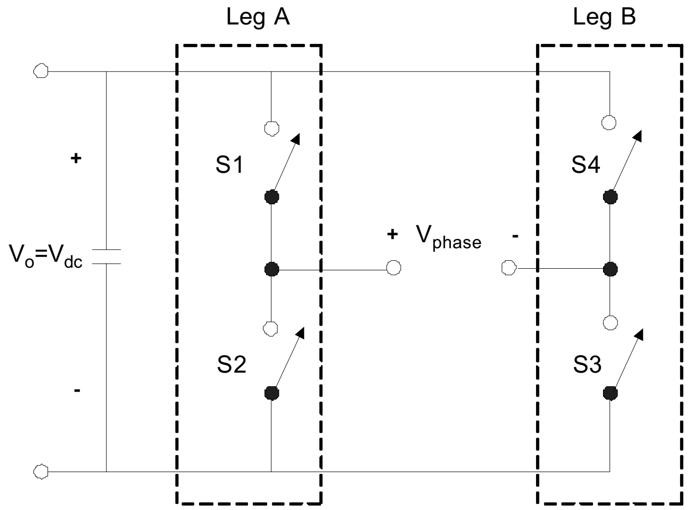

Figure 1 H-bridge inverter

In this research, it acts as a single-phase shunt APF and it is connected in parallel between the nonlinear load and the input supply is shown in Figure 2. The incoming supply is defined as V_g. The dc source for the inverter is obtained from the dc capacitor which is charged by the source during the operation of the inverter switches. Switching operation of this particular inverter is described in depth in [5].

The function of APF is actually to complete the imperfectness of current in the line caused by nonlinear load, i_{Load} so that incoming supply current, i_g always maintains a sinusoidal waveform. Furthermore, with the implementation of UCI control to H-bridge inverter, this can be done with simple analog circuitry [6].

In the APF system, incoming supply current plays the important role because when deviations occur at the incoming supply current, the changes will be conveyed to the capacitor in the APF and affect the charging of the capacitor. The capacitor voltage value of the APF, V_o will be sent to the controller. Integration of this voltage will take place and the output of the integrator will be compared with a reference signal. The result of comparison is then given to the R-S flip-flops to trigger the inverter switches (S_1, S_2, S_3, S_4).

Operation of this inverter switches will produce unipolar phase voltage when it is connected as shunt APF as depicted in Figure 3 [6], where V_{dc} is the dc voltage supply by the capacitor, T_s is the switching period and d is the duty cycle of the switch.

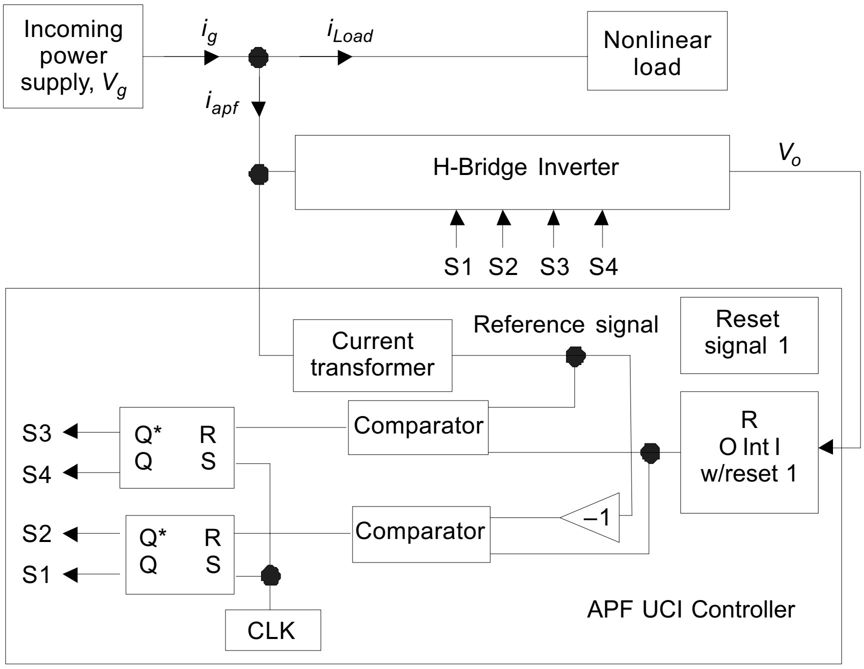

Figure 2 Schematic diagram of single phase APF with UCI controller

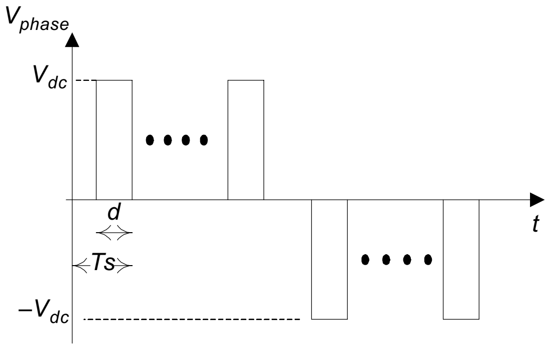

Figure 3 Phase voltage of APF based on operation of H-bridge inverter

2.2 Modular Structured Multilevel Inverter (MSMI) Active Power Filter

MSMI is an inverter structure, which consists of cascaded inverters with Separate DC Sources (SDCs). It is capable in producing phase voltage that is nearly similar to a sinusoidal waveform [7]. Figure 4 illustrated phase voltage waveform of a 5-level MSMI. V_1 is the phase voltage generated by the first H-bridge in the MSMI and V_2 is the phase voltage generated by the second H-bridge in the MSMI. MSMI has this advantage of generating multilevel phase voltage over the standard H-bridge inverter which is only capable of generating square wave phase voltage. By generating the phase voltage in a few levels, the harmonic contents generated by the APF itself can be reduced. This topology also allows expansion of the number of levels, which provides flexibility for higher power applications. This can be done easily without increasing circuit

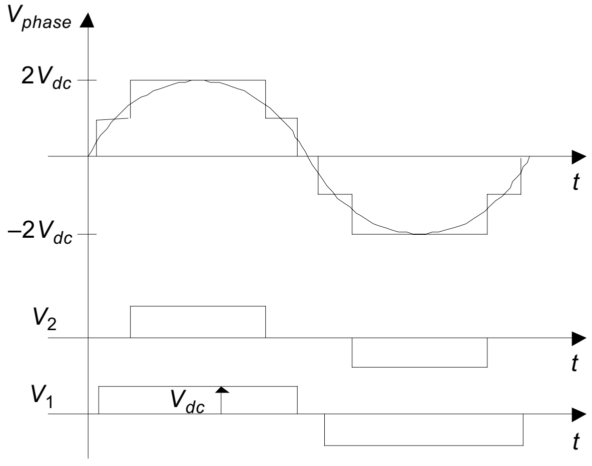

Figure 4 Phase voltage of 5-level MSMI

complexity as the inverter has modularized circuit layout. Furthermore, the cascaded inverter structure helps to reduce voltage stress on switches, as lower voltage will be imposed by the DC side capacitor voltage to each switch or in other words, switches only have to bear on smaller value of voltage.

A 5-level MSMI is shown in Figure 5. For each module of this inverter, the structure and the operation is the same as the H-bridge inverter, where leg A consists of S1, S2 and leg B consists of S3, S4. This inverter will obtain dc voltage from the capacitor of each module, i.e. V_{o1} and V_{o2}.

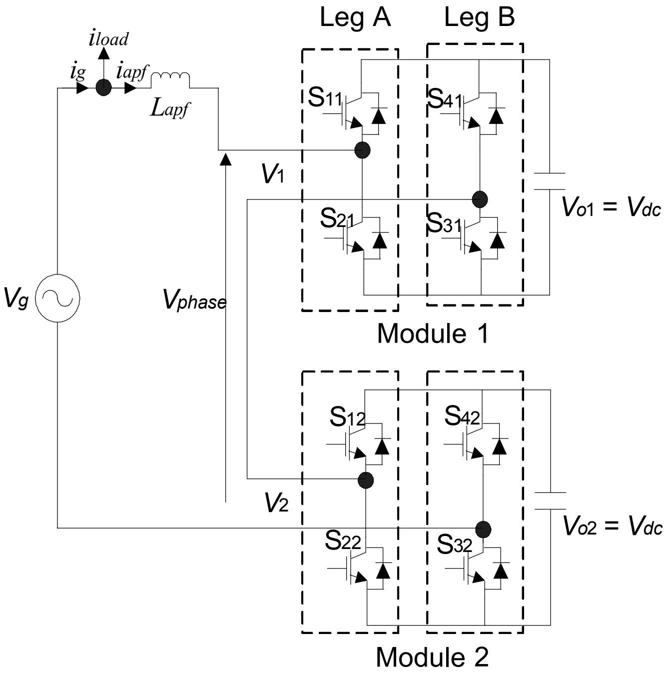

Figure 5 5-level MSMI

The phase voltage of this particular 5-level MSMI is listed in Table 1 which is based on Kirchoff's Voltage Law. Different combination of switch function will produce different value of phase voltage. The inverter level is dependent on the number of different phase voltages produced. The switch function combination will become complicated as the inverter levels increase.

Figure 6 shows the configuration and control block diagram of the proposed APF system. V_{o1} and V_{o2} are the dc voltages of the inverter capacitors. The DC capacitor voltage of each module of the inverter and mains current are sensed into the UCI controller. The capacitor voltage acts as input parameter to the integrator. Through the current transformer, the mains current is compared with the integrated voltage signal from each module of inverter to generate pulses for R-S flip flops for triggering the inverter switches.

Table 1 Switches operation of 5-level MSMI

S11	S21	S31	S41	S12	S22	S32	S42	Vphase
1	0	1	0	1	0	1	0	$V_{o1}+V_{o2}$
				1	0	0	1	V_{o1}
				0	1	1	0	V_{o1}
				0	1	0	1	0
1	0	0	1	1	0	1	0	V_{o2}
				1	0	0	1	0
				0	1	1	0	0
				0	1	0	1	$-V_{o2}$
0	1	0	1	0	1	0	1	$-V_{o1}-V_{o2}$
				0	1	1	0	$-V_{o1}$
				1	0	0	1	$-V_{o1}$
				1	0	1	0	0
0	1	1	0	0	1	0	1	$-V_{o2}$
				0	1	1	0	0
				1	0	0	1	0
				1	0	1	0	V_{o2}

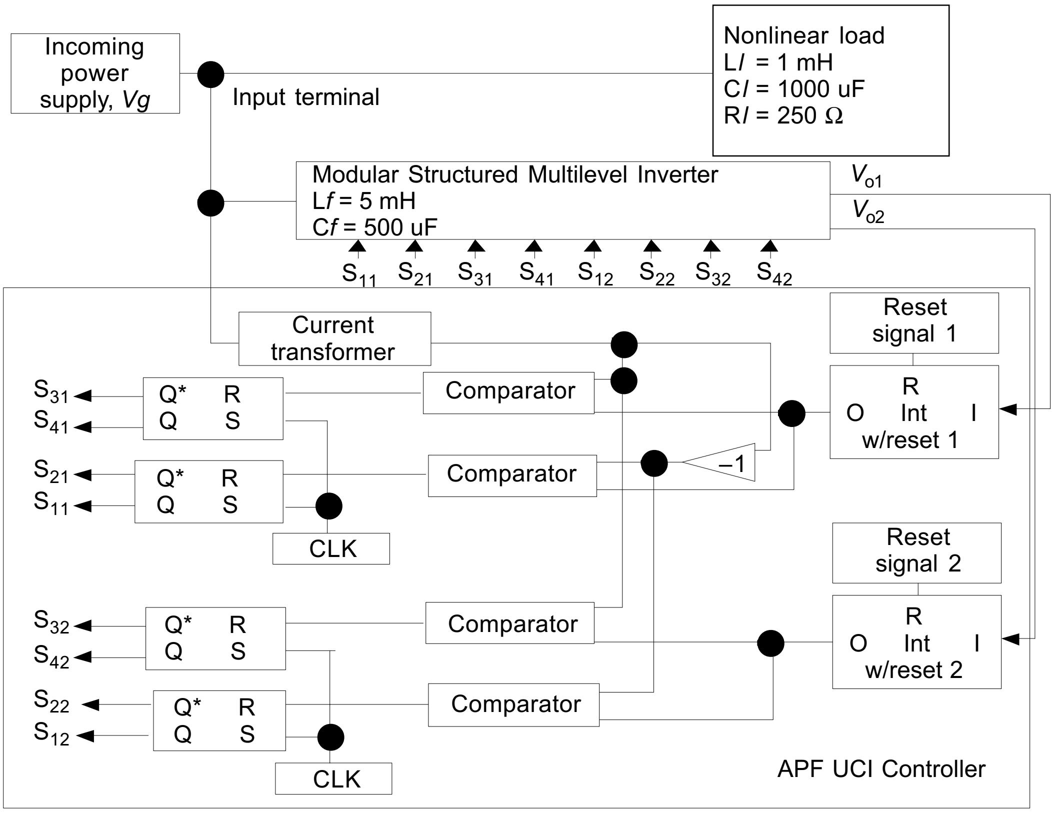

Figure 6 Schematic diagram of single phase MSMI APF with UCI controller

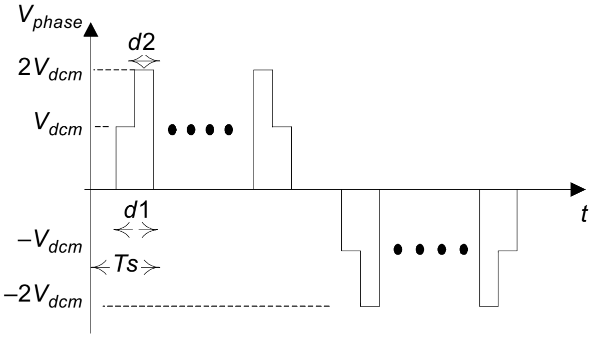

Figure 7 Phase voltage of 5-level MSMI

The phase voltage leveling of this APF at the input terminal is shown in Figure 7, the phase voltage of this APF topology is leveled to: $2V_{dcm}$, V_{dcm}, 0, $-V_{dcm}$, $-2V_{dcm}$ where the notation m is the number of module. The duty ratio of each inverter is denoted by d_m.

3.0 UNIFIED CONSTANT-FREQUENCY INTEGRATION CONTROL

The adopted control scheme, namely UCI controller is a reliable and robust control method based on One Cycle control [8] where compensation of the APF is done in every switching cycle that caused achieving unity power factor possible in the system. To achieve unity power factor, the control goal of the APF is to force the AC current follows the AC input voltage, that is:

$$V_g = R_s \cdot i_g \tag{1}$$

where R_s is the sensing resistor.

Relation between duty ratios of switches, d, input ac voltage, V_{ge}, and DC bus voltage, V_o of the APF is:

$$V_{ge} = V_o(1-d) \quad ; \quad d = d_m \tag{2}$$

where V_{ge} is the input voltage during positive and negative cycle.

Equating (1) and (2) results in the control key equation:

$$R_s \cdot i_{ge} = V_o(1-d) \quad ; \quad d = d_m \tag{3}$$

UCI controller will ensure duty ratio for each module of inverter is controlled to satisfy Equation (3) which in turn will satisfy Equation (1) to achieve unity power factor.

Figure 8 shows the relation between integrated APF output voltage and the reference input current which operate the R-S flip-flop.

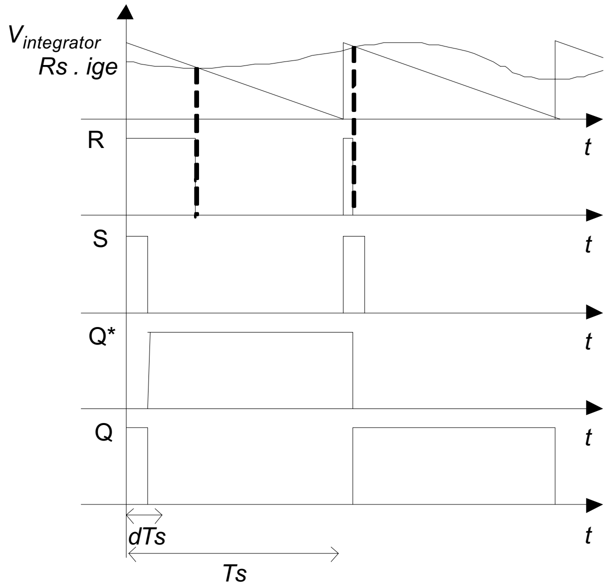

Figure 8 Operation waveform of UCI controller

4.0 RESULTS

The simulation for both types of APF systems based on the simulation parameters are listed in Table 2.

Table 2 APF system simulation parameters

Parameters	Symbol	Value
Line voltage	V_g	220 V_{rms}
Line frequency	f	50 Hz
APF inductor	L_f	5 mH
APF DC-bus capacitor	C_f	500 μF
Switching frequency	f_s	10 kHz
Rectifier resistance load R	R_l	250 Ω
Rectifier DC-link capacitor	C_l	1000 μF
Rectifier smoothing inductor	L_l	1 mH

The typical non-linear load used in this simulation is a diode rectifier with R-C load as shown in the simulation schematic diagram in Figure 9.

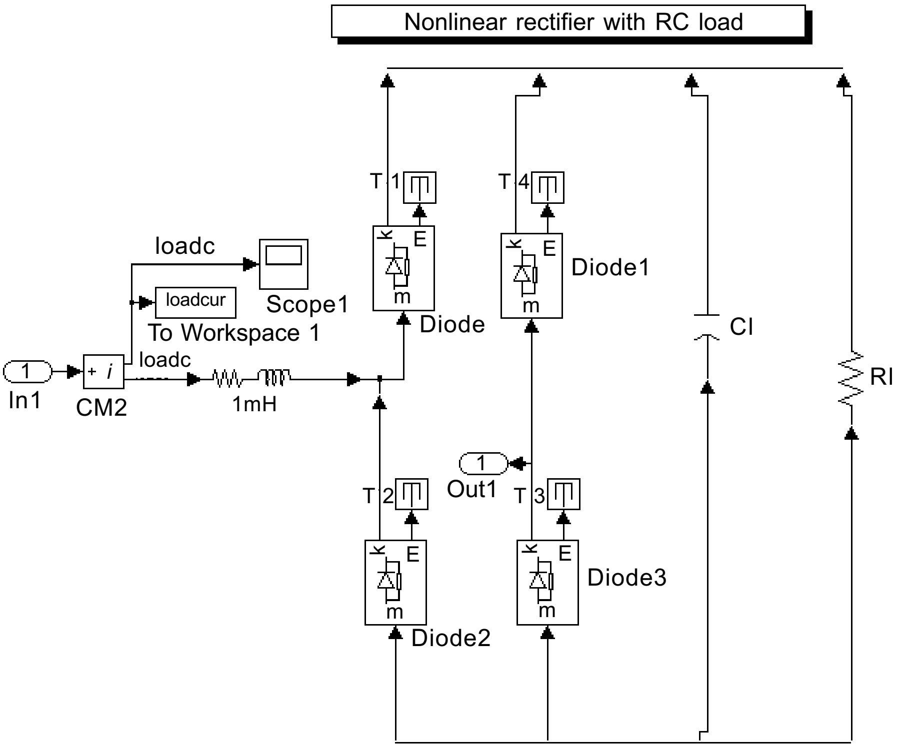

Figure 9 Nonlinear rectifier with RC load

Figure 10 shows the ac input current drawn by the nonlinear load. It is distorted severely and the harmonics content is high where, for the selected load parameters, the THD goes up to 146.74% as in Figure 11.

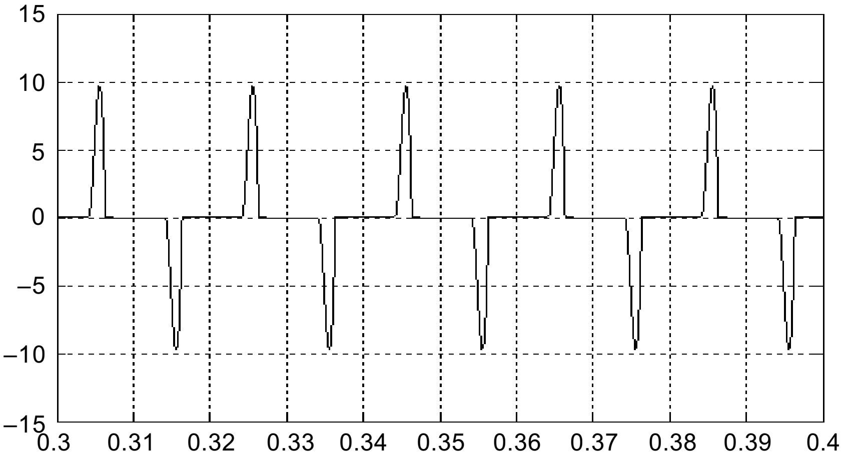

Figure 10 Waveform of highly distorted source current caused by diode rectifier with RC load

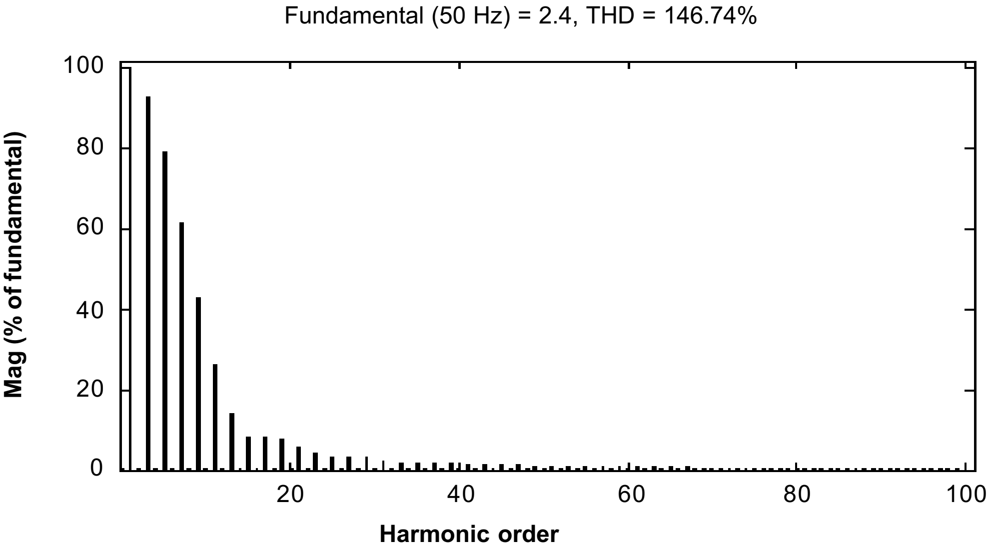

Figure 11 Harmonic components of source current without compensation

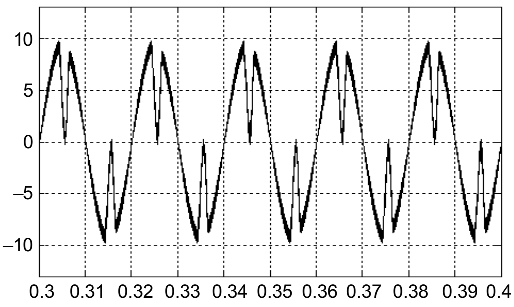

Figure 12 Current of H-bridge inverter APF for compensation

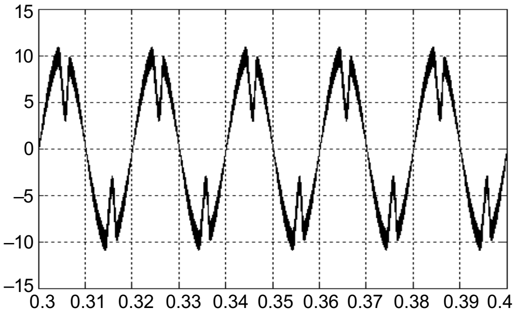

Figure 13 Compensation current produced by MSMI APF

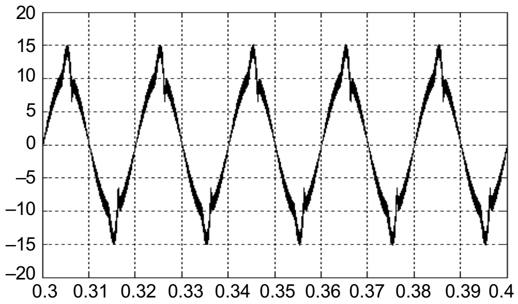

Figure 14 Waveform of source current after compensated by H-bridge inverter

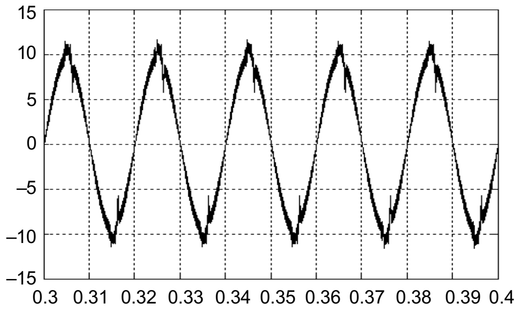

Figure 15 Source current waveforms after compensated by MSMI APF

Both of the compensation current produce by H-bridge inverter and MSMI APF are shown in Figures 12 and 13 respectively. Figures 14 and 15 are the source current waveforms after compensation were done by two different topologies of APF system.

After the distorted source current is compensated by H-bridge inverter APF, the THD of source current is 13.51% and the harmonic spectrum of the source current is shown in Figure 16. On the other hand, the THD is greatly reduced to 6.61% by the compensation of MSMI APF as in Figure 17, this displays an encouraging result. Figures 18 and 19 depicted the phase voltage produced by H-bridge inverter and MSMI respectively, and as mentioned in the previous section, the H-bridge inverter phase voltage is square whereas the MSMI phase voltage is leveled to 5 level of dc voltage.

The contents of Column 2 in Table 3 present the odd harmonics components contents of the source current without compensation, whereas Column 3 and 4 show H-bridge Inverter APF compensation and the proposed MSMI APF compensation respectively. Even harmonic contents are not shown as they are negligibly small for

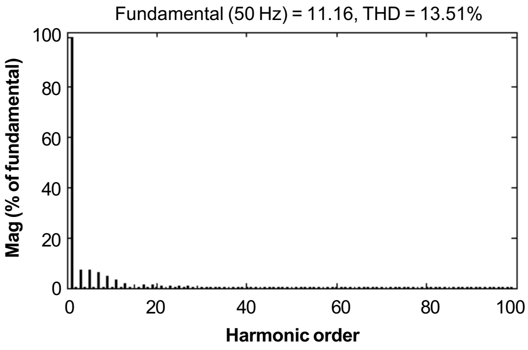

Figure 16 Harmonic spectrums of source current after compensated by H-bridge inverter APF

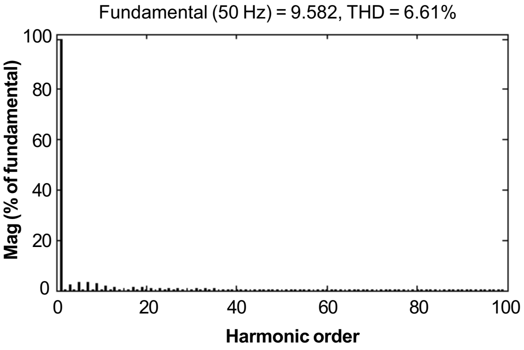

Figure 17 Harmonic spectrums of source current after compensated by MSMI APF

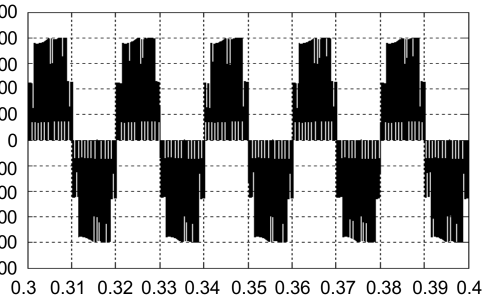

Figure 18 Phase voltage of H-bridge inverter APF

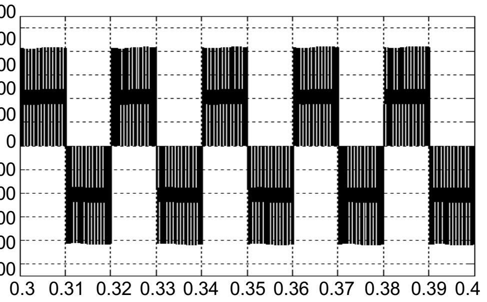

Figure 19 Phase voltage of MSMI APF

Table 3 Comparison of source current harmonic components

h	Source current without compensation [%]	Compensated with H-bridge inverter APF [%]	Compensated with MSMI APF [%]
3	92.51	7.18	2.22
5	78.83	6.96	3.14
7	61.30	6.13	3.00
9	42.79	4.81	2.50
11	26.12	3.24	1.78
13	13.82	1.86	1.11
15	8.25	1.19	0.94
17	7.90	1.20	1.02
19	7.46	1.19	1.04
21	5.81	0.97	0.94
23	4.02	0.69	0.80
25	3.26	0.58	0.64
27	3.27	0.59	0.52
29	3.03	0.56	0.50
31	2.43	0.46	0.60
33	1.91	0.36	0.66
35	1.79	0.34	0.60
37	1.78	0.35	0.39
39	1.60	0.31	0.11
41	1.31	0.26	0.20
43	1.15	0.23	0.41
45	1.14	0.23	0.48
47	1.10	0.22	0.41
49	0.97	0.20	0.27

the analysis. The harmonic number is represented by alphabet '*h*' as in the first column. From the table, high contents of current harmonics can be observed in the second column where there is totally no compensation by APF; this is obvious especially for those low frequency harmonics. These significant low frequency harmonics contribute to the intolerable distortion of current at the main supply.

The harmonic contents are mitigated mildly with the compensation of an H-bridge inverter APF. The low frequency harmonics now appeared to be in lower percentage. Compared to the H-bridge inverter APF, the MSMI APF has effectively compensated the harmonics current, where more reduction of harmonic percentage can be found as listed in the forth column of the table.

Despite some of the high frequency current harmonics in the forth column of Table 3 are higher in percentage compared to the third column, it does not affect much to the total harmonic distortion as the difference between them are considered quite small. The harmonic spectrums results shown in Figure 17 indicates that almost twenty two times (i.e.: 146.74% divide by 6.61%) of THD reduction can be achieved by the compensation of MSMI APF compared with the H-bridge inverter APF which managed to achieve only eleven times (146.74% divide by 13.51%) lower THD of the distorted source current without any compensation. Therefore, it can be said that the performance of an MSMI APF is better than the H-bridge inverter APF system when both are implementing the same control technique.

5.0 CONCLUSION

Since power electronics related equipment has been widely used in the recent years, the voltage and current waveform contamination of power system is more serious than before. To curb the harmonics problems from rampant, harmonic limitation has been imposed to the customers. Therefore, emergence of APF is definitely an effective solution for either industrial or residential end users and from low to high power applications. Its capability to operate over wide load range without affecting the system performance makes it a meaningful solution for harmonic problems for those existing and installed equipment in a building.

As can be observed from the simulation results, MSMI APF has all the performance of conventional APF with addition benefits. The capability of the MSMI APF with UCI controller undoubtedly provides a flexible solution for power quality control. Due to the simplicity of the circuitry, this configuration of APF is applicable and is very suitable to serve the utilities and industrial production purposes, as their high power applications usually suffer the most from harmonic problems. Furthermore, MSMI also promise voltage stress reduction of the inverter switches.

As a conclusion, MSMI APF has inherited robust and reliable characteristics and has shown satisfactory performance in the mitigation of harmonic current problems which may become a remedial solution in harmonics for high power systems in future.

REFERENCES

[1] Akagi, H., A. Nabae, and S. Atoh. 1986. Control Strategy of Active Power Filters Using Multiple Voltage-source PWM Converters. *IEEE Trans. Ind. Applicat.* IA(22): 460-465.

[2] Peng, F. Z., H. Akagi, and A. Nabae. 1990. A New Approach to Harmonic Compensation in Power Systems – A Combined System of Shunt Passive, Series Active Filter. *IEEE Trans. Ind. Applicat.* 26: 983-990.

[3] Luowei, Z. and K. M. Smedley. 2000. Unified Constant-frequency Integration Control of Active Power Filters. *APEC2000*. 406-412.

[4] Azli, N. A. and A. H. M Yatim. 2001. Modular Structured Multilevel Inverter for High Power AC Power Supply Applications. ISIE 2001. IEEE International Symposium on Industrial Electronics. 2: 728-733.

[5] Hart, D. W. 1997. *Introduction to Power Electronics*. New Jersey: Prentice Hall.

[6] Chongming, Q., K. M. Smedley, and F. Maddaleno. 2001. A Comprehensive Analysis and Design of a Single Phase Active Power Filter with Unified Constant-Frequency Integration control. IEEE 32nd Annual Power Electronics Specialists Conference, PESC. 3: 1619-1625.

[7] Peng, F. Z., J. W. McKeever, and D. J. Adams. 1997. Cascade Multilevel Inverters for Utility Applications. Industrial Electronics, Control and Instrumentation, 23rd International Conference. 2: 437-442.

[8] Cuk, S. and K. M. Smedley. 1995. One-cycle Control of Switching Converter. *IEEE Transactions on Power Electronics*. 10(6): 625-633.