Modular Structured Multilevel Inverter with Unified Constant-Frequency Integration Control for Active Power Filters

N. A. Azli
Power Electronics and Drives Group (PEDG)
ENCON Department, Universiti Teknologi Malaysia
Johor, Malaysia
naziha@ieee.org

P. Y. Lim
Electrical Engineering Department
Sabah Polytechnique
Sabah, Malaysia
pylim@hotmail.com

Abstract— **The increasing use of power electronics based loads in recent years has resulted in the generation of harmonic and reactive currents to the common point of coupling at which the loads are connected to. Besides the commonly used passive filters, active power filters (APFs) are gaining interest lately in canceling the reactive and harmonic currents from the nonlinear loads to ensure that the resulting total current drawn from the main incoming supply is sinusoidal. This paper presents a non-conventional inverter topology known as the Modular Structured Multilevel Inverter (MSMI) as an active power filter. With the MSMI, the harmonic content generated by the APF can be reduced as it can produce more levels of voltage than conventional inverters. Additionally, it can reduce the voltage and current ratings of the power devices used while providing the convenience for future expansion in order to achieve higher power ratings for the APF system. A Unified Constant-Frequency Integration (UCI) control technique is adopted for the MSMI APF which features constant switching frequency operation and simple analog circuitry. To demonstrate the capability of the proposed APF system, simulation results of a single-phase MSMI APF with UCI controller is presented and its performance analyzed.**

Keywords-Active power filter, current harmonics compensation, modular structured multilevel inverter, unified constant-frequency integration control

I. INTRODUCTION

The usage of power electronics based loads is increasing rapidly in recent years. The harmonic and reactive currents produced by these nonlinear loads to the common coupling point at which they are connected to have caused low power factor, low efficiency and harmful electromagnetic interference to neighborhood appliances. Furthermore, contamination of voltage and current waveforms caused by the increasing usage of power semiconductor switches in wide range of applications in distribution network, especially in domestic and industrial loads have gained more attention from the power quality researchers. This has brought the emergence of harmonic suppression concerns of many researchers and vast numbers of active power filter (APF) configurations with different control techniques have been explored and proposed to overcome these problems. The shunt APF is the most common method being employed to produce harmonic current component that cancels the harmonic current from a nonlinear load so that the AC main current remain sinusoidal. In general, the performance of an APF depends on the inverter topology and the pulse width modulation (PWM) control method imposed on the power switches.

The PQ theory [7], linear current control, digital deadbeat control and Hysterisis control [9] are some examples of control methods for APFs that have been previously reported. These proposed control approaches require sensing of the input voltage and load current followed by the calculation of the harmonic reactive component of the load in order to generate the reference current for controlling the inverter. The switching of the inverter power devices are controlled in such a way as to produce a current that is equal to the amplitude and opposite in direction of the reactive current of the nonlinear load. These control methods require fast and real-time calculations which in turn require several high precision analogue multipliers or high speed DSP chip with fast A/D converter that yields high cost, complexity and low stability [3].

To reduce the problems related to these control methods, work has been done to develop an APF system with Unified Constant-Frequency Integration (UCI) controller [2],[3] that is based on the theory of one cycle control [1]. The UCI controller employs an integrator with reset port as its core component to control the duty ratio of an APF to ensure that under any condition, the AC inlet draws sinusoidal current. With this control method, calculation of the current reference is no longer necessary, which greatly simplifies the control circuit.

The existing APF with UCI controller is so far suitable for low power range utilization only. This paper proposes the integration of a UCI controller with a Modular Structured Multilevel Inverter (MSMI) as an APF which will generate harmonics current that cancels the harmonics current from a nonlinear load in order to form better sinusoidal incoming supply. MSMI has the advantage of reducing the voltage stress in each of its switching device in high power applications. Furthermore, the modularized circuit layout of an MSMI allows easy expansion of the APF structure itself [10]. This will be convenient if expansion of an APF is required to meet higher power level demand, such as in a power transmission line. Simulation results of a single-phase MSMI APF with UCI controller is presented in this paper for the purpose of demonstrating its capabilities. This is followed by some analysis on the performance of the proposed APF system. The simulation study however can easily be extended to a three-phase configuration in future.

II. System Structure And Operation Of The Msmi

An MSMI is an inverter structure consisting of cascaded H-bridge inverters with Separate DC Sources (SDCs). This topology allows expansion of the number of levels (nl), which provides the flexibility in increasing to a higher voltage level. This can be done easily as the inverter has modularized circuit layout. Furthermore, the cascaded inverter structure helps to reduce voltage stress on the power switches, as lower voltages will be imposed by the DC side capacitor voltages on the switches. Fig. 1 shows the structure of a 5-level MSMI APF.

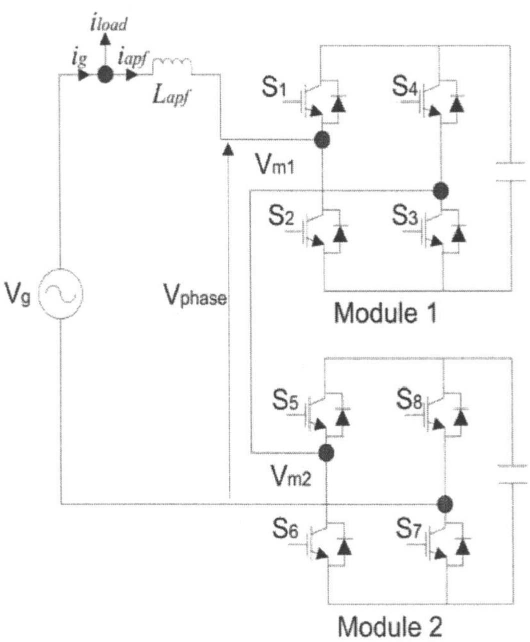

Fig. 1. Single-phase 5-level MSMI APF system

When the MSMI is implemented as an APF, an inductor is typically required at the input connection. The inductor voltage of the APF is listed in Table I based on Kirchoff's Voltage Law where by each of the module's DC supply V_{dc} is denoted as V_{o1} and V_{o2} for module 1 and module 2 respectively. Fig. 2 shows the phase voltage leveling of the APF at the input terminal, which are: $2V_{dc}$, V_{dc}, 0, $-V_{dc}$, $-2V_{dc}$. The duty ratio of each inverter module is denoted by d_m where m = 1, 2, 3 ... nl.

Fig. 3 shows the configuration and control block diagram of the proposed APF. The sensed parameters in this case are the DC capacitor voltage of each MSMI module V_{o1} and V_{o2} and the mains current. Through the current transformer, the mains current will be compared with the integrated voltage signal from each MSMI module to generate pulses for the R-S flip-flops for triggering of the inverter power switches. The comparator output will trigger the flip-flops to differ the state based on Table II, which will in turn switch ON and OFF the corresponding inverter switches.

The operation waveform of the UCI controller for the MSMI is shown in Fig. 4. The waveform shows that when the integrated voltage reaches $R_s.i_{ge}$ as defined by (9), the input port R of the flip-flop will be given an input signal by the comparator. The signal for port S however is provided by the clock. The switching signals at port Q and Q* are generated based on the needs of compensation. This process of compensation will repeat in every switching cycle when the integrators are triggered by the reset signals.

TABLE I: SWITCHING FUNCTION TABLE

S1	S2	S3	S4	S5	S6	S7	S8	V_L=V_g-V_o
1	0	1	0	1	0	1	0	V_g -2V_{dc}
				1	0	0	1	V_g -V_{dc}
				0	1	1	0	V_g -V_{dc}
				0	1	0	1	V_g
1	0	0	1	1	0	1	0	V_g -V_{dc}
				1	0	0	1	V_g
				0	1	1	0	V_g
				0	1	0	1	V_g +V_{dc}
0	1	0	1	0	1	0	1	-V_g -2V_{dc}
				0	1	1	0	-V_g -V_{dc}
				1	0	0	1	-V_g -V_{dc}
				1	0	1	0	-V_g
0	1	1	0	0	1	0	1	-V_g -V_{dc}
				0	1	1	0	-V_g
				1	0	0	1	-V_g
				1	0	1	0	-V_g+V_{dc}

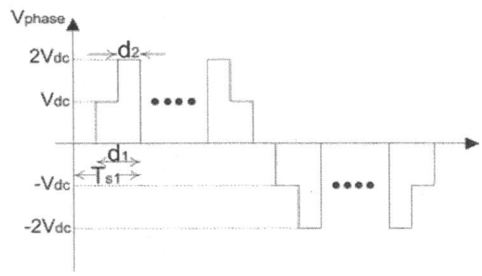

Fig. 2. Generalized waveform of the phase voltage for unipolar operation

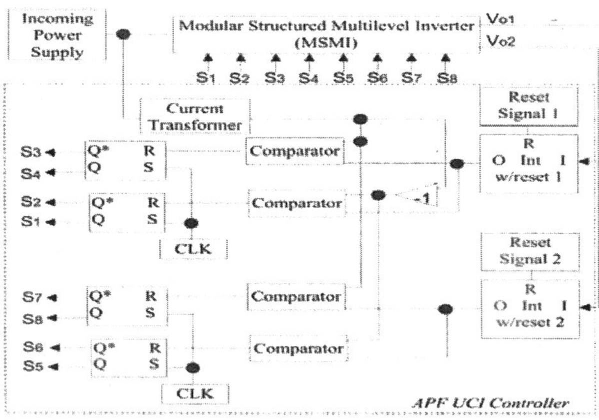

Fig .3. Block Diagram of the proposed structure of the single phase MSMI APF with UCI controller

TABLE II: R-S FLIP-FLOP FUNCTION TABLE

R	S	Q(t+1)	Where,
0	0	Q(t)	Q(t+1) = Present output of flip-flop Q(t) = Previous output of flip-flop
0	1	1	Activated output = 1
1	0	0	Deactivated output =0
1	1	x	Do not care output = x

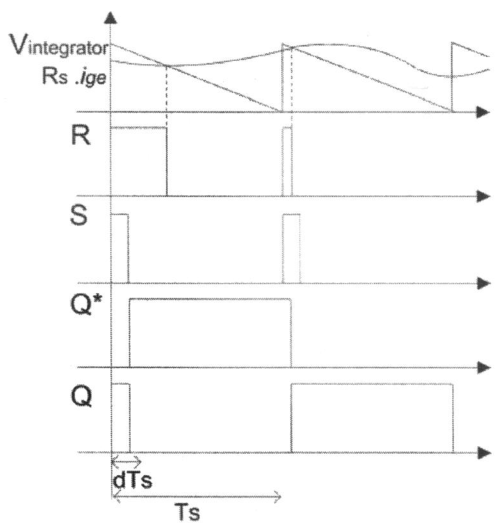

Fig.4 Operation waveform of the UCI controller

The control key equations for the UCI controller are derived for the MSMI based on [3]. During the positive half cycle $V_g>0$, S_1 is always in the ON position. The inductor voltages are given as follows:

for $0<t<dT_s$ (1)

$$V_L(OFF)=V_g-V_o=\begin{cases}V_g-V_{dc}, & d=d_1\\ V_g-2V_{dc}, & d=d_2\end{cases} \quad (2)$$

for $dT_s<t<T_s$

In constant frequency operation, the average inductor voltage-second is approximately balanced during each switching cycle, thus giving,

$$V_L(ON)\cdot dT_s+V_L(OFF)\cdot(1-d)T_s=0 \quad (3)$$

By substituting (1) and (2) into (3),

$$V_g\cdot dT_s+(V_g-V_o)\cdot(1-d)T_s=0 \quad \text{when } V_g>0 \quad (4)$$

Similarly for the negative half cycle,

$$V_g\cdot dT_s+(V_g+V_o)\cdot(1-d)T_s=0 \quad \text{when } V_g<0 \quad (5)$$

By definition,

$$V_{ge}=\begin{cases}V_g,\\ -V_g,\end{cases} \text{ and } i_{ge}=\begin{cases}i_g,\\ -i_g,\end{cases} \text{ for } \begin{matrix}V_g>0\\ V_g<0\end{matrix} \quad (6)$$

The combination of (4), (5) and (6) yields the relationship between duty ratios of the switches, input AC voltage and DC bus voltage of the APF.

$$V_{ge}=V_o(1-D) \quad (7)$$

For the system with nonlinear loads, unity power factor can be achieved by connecting an APF to the AC inlet. The control goal of the APF is therefore to force the AC current to follow the AC input voltage, that is,

$$V_{ge}=R_s\cdot i_{ge} \quad (8)$$

where R_s is the sensing resistance.

Equating (8) and (7) results in the control key equation,

$$R_s\,.\,i_{ge}=V_o(1-D) \quad (9)$$

The duty ratio for each level of the MSMI is controlled to satisfy equation (9) which in turn will satisfy equation (8) to achieve unity power factor.

III. Simulation Results

To demonstrate the compensation capability of the MSMI APF with UCI controller, a diode rectifier with RC load is connected at the AC mains inlet by using simulation tools to observe the distorted AC current waveform. Fig. 5 shows the severely distorted ac input current drawn by the nonlinear load. The Total Harmonic Distortion (THD) for such contaminated current is undoubtedly large (146.96%) as displayed in Fig. 6.

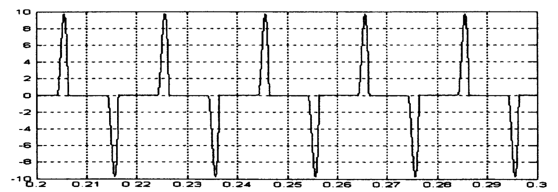

Fig.5 Distorted source current caused by a diode rectifier with RC load

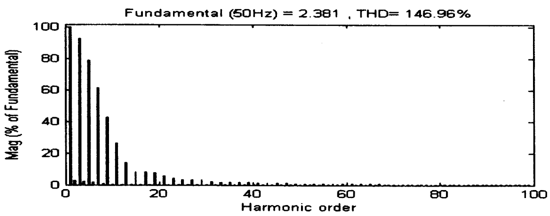

Fig.6 Harmonic current components without compensation

By connecting the shunt MSMI APF in between the incoming supply and the nonlinear load, the harmonic problem can be mitigated. The compensation current from the APF as shown in Fig. 7 will compensate the distorted source current waveform.

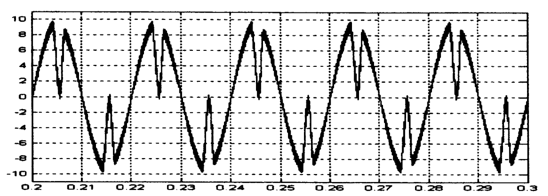

Fig.7 Compensation current produced by MSMI APF

After being compensated by the proposed configuration of the MSMI APF, the current waveform drawn from the AC incoming supply is now nearly similar to a sinusoidal wave shape with slight distortion as shown in Fig. 8. The THD of AC mains current after compensation is greatly reduced (about fifteen times) from 146.96% to 9.84% as in Fig. 9.

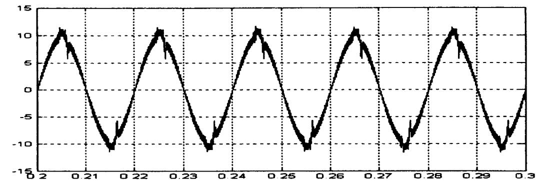

Fig.8 Source current waveform after compensation

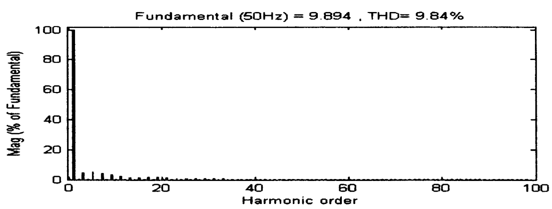

Fig.9 Harmonic spectrum of the source current after compensation

Fig.10 is the phase voltage of the MSMI APF, which indicates 5 levels of voltage including the reference level. The waveform is closer to sinusoidal compared to the conventional single stage APF that produces square wave voltages.

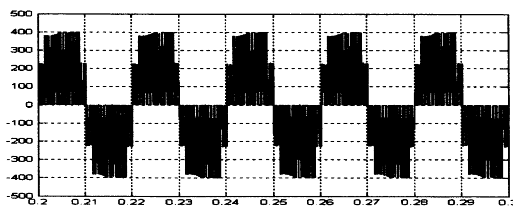

Fig.10 Phase voltage of the 5-level MSMI APF

IV. Conclusion

Harmonics limitations have been imposed to customers in recent years due to the widely used power electronics related equipment that seriously contaminate voltage and current waveforms in the power system. Thus the emergence of APFs is definitely an effective solution for either industrial or residential end users. Furthermore, the MSMI APF with UCI controller performs current compensation in the manner of cycle by cycle, so that the compensated net current matches the input voltage closely, thus a unity power factor can be achieved. The simulation results have shown the capability of the MSMI APF with UCI controller in providing a flexible solution for power quality control particularly at high power levels. Further analysis however can be made by extending the MSMI APF to a three-phase system or increasing the number of levels in its phase voltage.

References

[1] S. Cuk and K. Smedley,. "One-cycle Control of Switching Converter",*Proc of Power Electronics Specialist Conference PESC 1991*, pp.888-896.

[2] L. Zhou, and K. Smedley. "Unified Constant-frequency Integration Control of Active Power Filters", *Proc of Applied Power Electronics Conference APEC2000*, pp.406-412.

[3] C. M. Qiao, K. M. Smedley, and F. Maddaleno, "A Comprehensive Analysis and Design of a Single Phase Active Power Filter with Unified Constant-frequency Integration Control", *Proc of 2001 IEEE 32nd Annual Power Electronics Specialists Conference PESC*, Vol. 3, pp.1619-1625, June 2001

[4] J. Lai and F. Z. Peng, "Multilevel Converters-A New Breed of Power Converters." *IEEE Transactions on Industry Applications*, Vol. 32, No.3, pp.509-517, 1996

[5] P. M. Bhagwat and V. R. Stefanovic, " Generalized Structure of a Multilevel PWM inverter." *IEEE Transactions on Industry Applications*, Vol.19, No 6, pp. 1057-1069, Nov/Dec 1983

[6] A. Nabae, A., Takahashi,I. and H. Akagi, . "A Neutral Point Clamped PWM Inverter." *IEEE Transactions on Industry Applications*, Vol. 17, No. 5, pp. 518-523, 1981

[7] M. T. Haque, "Single Phase PQ Theory for Active Filters". P*roc of 2002 IEEE Regional Conference on Computers, Communications, Control and Power Engineering TENCON '02*, Vol. 3, pp.1941-1944, 2002

[8] D. W. Hart, "*Introduction to Power Electronics*" New Jersey: Prentice Hall, 1997, p. 308

[9] S. Buso and L. Malesani, "Comparison of Current Control Techniques for Active Filter Applications" *IEEE Transactions on Industrial Electronics*,Vol. 45. No. 5 October 1998

[10] N. A. Azli and A. H. M. Yatim," Modular Structured Multilevel Inverter For High Power AC Power Supply Applications", *Proc of IEEE International Symposium on Industrial Electronics ISIE 2001*, Vol. 2, pp. 728 – 733, June 2001

[11] M. G. Lopez, L. T. Moran, J. C. Espinoza and J. R. Dixon, "Performance Analysis of a Hybrid Asymmetric Multilevel Inverter for High Voltage Active Power Filter Applications", *Proc 29th Annual Conference of the IEEE Industrial Electronics Society IECON'03*, pp. 1050-1055, November 2003