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Performance Analysis of an Active Power Filter Utilizing Cascaded H-Bridge Multilevel Inverter with Unified Constant-frequency Integration Control

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Abstract – *The recent years have seen an increase in non-linear loads that are known to generate harmonics in the source current of an electrical network. To overcome this issue, instead of using passive filters, active power filters (APF) have been introduced to inject harmonic currents of the same amplitude and in the reverse order of the phase current harmonics in the load into the network. In an attempt to improve the effectiveness of APF in source current harmonics compensation, this paper presents the performance analysis on the use of cascaded H-bridge multilevel inverter (CHMI) with Unified Constant-Frequency Integration (UCI) as an APF in a single-phase system. A simulation study conducted using MATLAB/Simulink on the APF has shown improved source current total harmonic distortion (THD) as the CHMI number of output voltage levels is increased.*

Keywords: Active Power Filter (APF), Cascaded H-bridge Multilevel Inverter (CHMI), Unified Constant-Frequency Integration (UCI) Control.

1.0 INTRODUCTION

Recently, the burden of power electronics-based equipment which produces non-linear load is inevitable. The usage of rectifiers, uninterruptable power supplies, motor speed control etc. cause the occurrences of interference in the main electrical distribution system. These power electronics devices produce harmonics or distortion of the supply current even though the efficiency and the reliability of the system is increased by various process control or application tools [1]. To overcome the harmonic-related problems, active power filters (APF) have been introduced [2] and used in the utility and industrial power systems [3]. The APF is introduced to replace conventional passive filters (PF) in many applications due to the drawbacks of the latter when operating with non-linear loads especially below 1 MW [4].

The main advantages of APF are the capability of handling harmonics ranging between fluctuating frequencies and can be operated at a lower order harmonic. The APF will inject harmonic currents of the same amplitude and in the reverse order of the phase current harmonics in the load into the power system. As a result, the APF compensates both reactive power and harmonic currents drawn by the non-linear loads very effectively. The shunt configuration is the most popular in APF applications due to its capability to compensate reactive power [5]. Some product manufacturer refers APF as a power line conditioning device that is able to improve power quality in the distribution network. APF normally utilizes single-phase or three-phase inverters as its main component.

This paper presents the performance analysis on the use of cascaded H-bridge multilevel inverter (CHMI) with Unified Constant-Frequency Integration (UCI) as an APF in a single-phase system. A simulation study is conducted using MATLAB/Simulink on the APF and the results are shown to indicate the overall performance before drawing a conclusion.

1.1 Multilevel Inverters

The first multilevel inverter was introduced in 1981 [6]. The topologies of multilevel inverters can be classified as cascaded H-Bridge multilevel inverter (CHMI), diode-clamped multilevel inverter (DCMI) and flying capacitor multilevel inverter (FCMI). Multilevel inverters in APF application has shown better performance when compared to the use of the conventional three-level inverters [7]. In general, the total harmonic distortion (THD) of a multilevel inverter output voltage decreases as the levels are increased [8]. The most popular multilevel inverter topology is the CHMI because of its robust construction and reliability. Various modified CHMI-based multilevel inverter topologies have been introduced [9]-[12]. With such topologies, the output voltage levels remain the same as the original CHMI but the number of power switches used is greatly reduced.

1.2 Unified Constant-frequency Integration Control

The unified constant-frequency integration (UCI) control has been introduced to improve the performance of an APF by providing a low cost circuitry development and fast switching control loop. The APF with UCI controller is based on the One-Cycle Control (OCC) theory [13]. By using the OCC control technique, most of the conventional voltage sensors and the multipliers in the control loop are extinguished and the control circuitry becomes simple and robust. Basically, a UCI controller requires only two main sensing elements which area current and voltage sensor. The employment of an integrator with reset is the main component. The components such as comparators, clocks and flip-flops are part of the circuit that controls the output of the inverter in the APF. The output of the inverter draws the opposite signal of the reactive current that is produced by the non-linear loads. In this case, many complex measurements and calculations in the conventional APF have been abolished such as the generation of a current reference, multipliers and measurement of the AC line voltage. Figure 1 shows the basic structure of a UCI controller for the control of an APF in a single-phase system.

The main objective of the H-bridge inverter in an APF is to produce the reactive and harmonic current in reverse order as required by the non-linear load. As a result, the net current drawn from the AC source is always purely sinusoidal with a fundamental active power supplied to the non-linear load. Figure 2 depicts the basic single-phase full-bridge shunt APF which consists of two arms. Arm A consists of switches S_1 and S_2 while arm B consists of switch S_3 and S_4. All power switches in both arms are connected in series. C_1 is a DC capacitor that acts as a DC source to the APF. It will be charged by the source during the operation of the inverter power switches. Referring to Figure 1, R_1 and R_2 are the voltage divider that measures the voltage difference in capacitor C_1 and sends the feedback signal to the UCI controller when the charging process of C_1 is changed. The voltage across C_1 fluctuates according to the changes in the source current. This is due to the non-linear load characteristic that influences the perfectness of the source current waveform in the system.

CT is the current sensor that measures the disturbance in the AC supply current in the system while *VT* is the voltage sensor that senses the DC voltage difference at the APF.

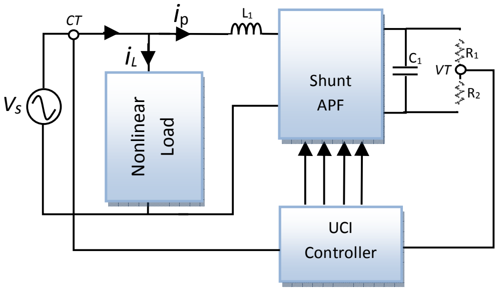


Figure 1: Basic structure of UCI in a single-phase shunt APF

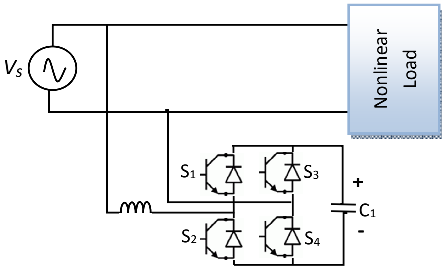


Figure 2: Single-phase full-bridge shunt APF

1.3 UCI Control in a Single-Phase APF System

The application of UCI control in active power filtering has extensively been studied as presented in [14]. In a single-phase APF system, UCI control has shown good performance and is able to operate in steady-state and dynamic conditions [15]. In a single-phase system, the basic configuration that utilizes a full-bridge inverter connected in parallel with two series resistors is as shown in Figure 1. The difference in the charging voltage in C_1 is because of the occurrences of harmonic in the closed loop system. In short, for the basic single-phase system, the UCI control only requires a single current sensor to sense the main current and a voltage sensor at the output side to measure the difference in the value of the capacitor voltage V_c. Figure 3 depicts the equivalent circuit of a single-phase APF system. In this case, i_s is the source current and R_s is a current sensing resistor. R_e is the equivalent resistor that is used to emulate the non-linear load with the APF for main supply current.

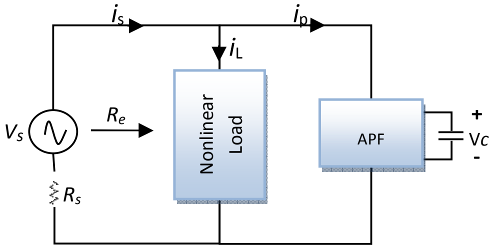


Figure 3: The equivalent circuit with resistor R_e

From the equivalent model for inductor current and voltage waveform as explained in [15], the relationship between V_s and V_c are given as follows;

$$V_c = \frac{1}{1-2D} . V_s \tag{1}$$

The control goal of the APF is supposed to be;

$$V_s = R_e * i_s \tag{2}$$

Where $D = T_{on} / T_s$ is the duty ratio, $T_s = 1/f_s$ is the switching period and f_s is the H-bridge inverter switching frequency.

Figure 4 shows the schematic diagram of a UCI control for an APF in a single-phase system. V_c is the voltage difference at the APF capacitor. The purpose of the PI controller is to maintain the DC voltage value which has been stored in the capacitor and produce the output error voltage, V_m. The error V_m is then integrated and the output is compared with the V_m - $R_s * i_s$ value. All switches SW1, SW2, SW3 and SW4 are turned on and off when the clock pulse is fed to the flip-flop as a set S signal. The switching process repeats in every switching cycle within the duty ratio D. The overall control process satisfies the control goal of an APF as follows;

$$2DV_m = V_m - R_s * i_s \tag{3}$$

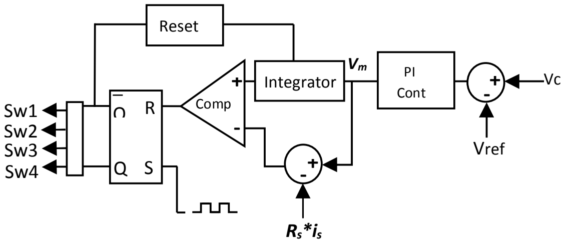


Figure 4: The structure of UCI in single-phase shunt APF

2.0 METHODOLOGY

In this work, a CHMI-based APF with UCI control in a single-phase electrical network has been designed. The APF should produce a nearly sinusoidal supply current with the lowest possible percent THD. To achieve the objective of the work, the methodology of the work has been designed with three major tasks. The first task is to analyze the imperfectness of the source current waveform which is drawn by typical non-linear loads in a single-phase power system. As in Figure 5, the non-linear load considered in this work is an RC load which is coupled with a rectifier. The main AC source is set to 240 V_{rms}. Figure 6 depicts the MATLAB/Simulink model of a single-phase system feeding the non-linear load. The second task involves the development of the simulation model of the conventional 3-level H-bridge inverter followed by the 5-level and 7-level CHMI. The third phase relates to the design and development of the UCI switching control strategy. Figure 7 shows the simulation model of a 5-level CHMI APF with UCI control. Figure 8 specifically shows the UCI control structure for the 5-level CHMI APF.

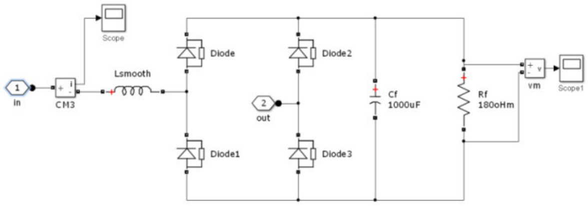


Figure 5: The non-linear load representation

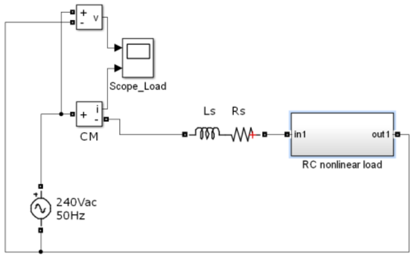


Figure 6: A single-phase system with non-linear load

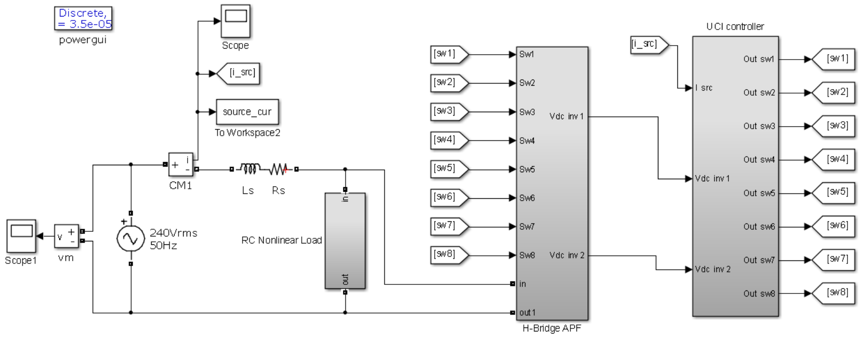


Figure 7: Simulation model of a single-phase 5-level CHMI APF with UCI control

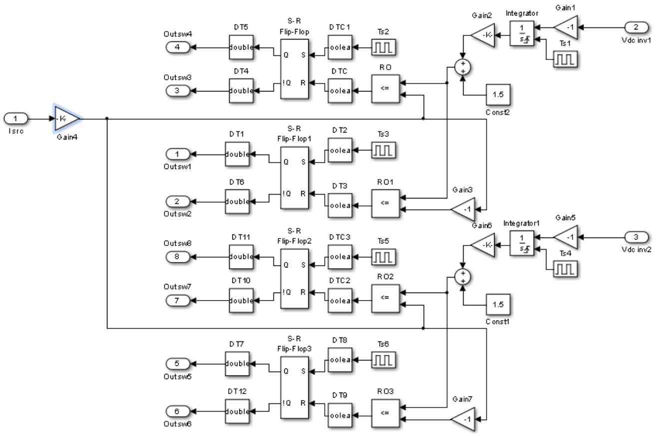
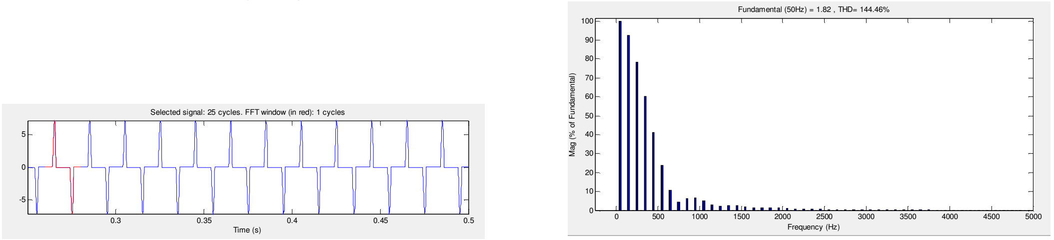


Figure 8: UCI control structure for the 5-level CHMI APF

3.0 RESULTS AND DISCUSSION

Figure 9(a) and (b) depict the source current waveform and its harmonic spectra respectively for a single-phase system feeding non-linear loads. The THD of the source current is 144.46%, as indicated by Figure 9(b).



(a) (b)

Figure 9: Single-phase system feeding non-liner loads (a) Source current (b) Harmonic spectrum

Table 1 is derived from the simulation study conducted on three different inverter configurations as active power filters with UCI control. For comparison purposes, three different configurations are considered namely the conventional 3-level H-bridge inverter and the non-conventional 5-level and 7-level CHMI. Using the 3-level H-bridge inverter as an APF, the supply current has tremendously reduced from 144.46% (without filter) to 14.88%. This involve the use of four power switches. By doubling the number of power switches with the 5-level CHMI configuration, further reduction of about 4% is achieved in the supply current THD. With the 7-level CHMI, although the number of power devices has increased from 4 to 12, the supply current THD is reduced by about 7%. This indicates that by increasing the number of output voltage levels in the CHMI, the supply current THD can be reduced. In other words, although the supply voltage is feeding a non-linear load, the supply current can remain as a sinusoid. In general, further decrease in the supply current THD is possible if the CHMI output voltage levels is increased. Of course, this would require more number of power switches but with the availability of other multilevel inverter topologies that can achieve high number of output voltage levels with less number of power switches, the concept is feasible and can be further explored.

Table 1: Performance comparison on different APF inverter configurations

APF	Number of power switches	Number of DC Capacitors	Source current THD
3-level H-bridge	4	1	14.88%
5-level CHMI	8	2	10.90%
7-level CHMI	12	3	7.63%

4.0 CONCLUSION

This paper has presented a performance analysis on the use of cascaded H-bridge multilevel inverter (CHMI) with Unified Constant-Frequency Integration (UCI) as an APF in a single-phase system. Based on the results obtained from the simulation study conducted, the 5-level and 7-level CHMI with UCI control is found to improve the APF performance in terms of effectiveness in source current harmonics compensation. This is confirmed by the reduction in the source current THD as the CHMI number of output voltage levels is increased in comparison to the use of the conventional 3-level H-bridge inverter. However, by using the CHMI configuration, the power switches count is increased which in turn can increase the size and cost of the overall APF system. The concept of increasing the inverter output voltage in improving the performance of an APF can be further explored to include the utilization of circuits with manageable number of power switches.

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