Active Harmonic Filtering Using Multilevel H-bridge Inverter Based STATCOM

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Abstract. — This paper proposed three-phase multilevel cascaded H-bridge inverter (MCHI) based active harmonic filtering (AHF) compensator, or refer to as static synchronous compensator (STATCOM), to minimize the harmonic components in a transmission network. There are three main elements to form a STATCOM, namely: control scheme, modulation technique and inverter topology. In this work, the synchronous reference frame (SRF) based controller is designed and implemented to produce the desired modulating signals (i.e., one for each phase) for the pulse width modulation (PWM) module. For simplicity, the carrier based pulse width modulation (CBPWM) with in phase disposition (IPD) technique is employed to generate the pulse trains and drive the three-phase five-level CHI. On the other hand, two three-phase non-linear loading conditions, which structured by different transformer winding configurations and power rectifier circuits, are utilized to verify the feasibility of the proposed AHF. The effectiveness and the theoretical prediction of the proposed approach is investigated and validated through simulation studies using MATLAB SIMULINK software package.

1. Introduction

Power quality (PQ) problems have been the most significant concerned for the utility companies and the industrial consumers. For instance, low PQ triggers low electrical transmission efficiency (i.e., due to the presence of harmonic frequencies and fluctuations of voltages [1]) which leads to high or wasteful expenditure. These problems exist due to the increase in usage of electrical and electronic appliances, specifically from the non-linear loads like electric arc furnaces, refrigerators, converters, inverter drives, etc. [2]. Nevertheless, there are a few international PQ standards such as IEC 61000, EN 50160 and IEEE 519 series which the utilities or any professions can refer to on the desirable PQ level [3].

As mentioned earlier, harmonic is one of the factors that contribute to poor PQ. Harmonic is defined as the voltage or current with frequencies where the integer multiplies with the fundamental frequency. Harmonics, specifically the negative sequence components (i.e.: 5th, 11th, 17th, etc.), causes unnecessary overheating, low efficiency of equipment [2] and shorten the lifetime of equipment. In addition, the harmonics also result in telephone interference (causes the metering and instrumentation difficulties) and damaging the capacitors [4].

In order to overcome the harmonic problem in the system, the harmonic filter (i.e.: passive filter and active filter) is installed. Passive filter, which has the minimum impedance path for tuning the harmonic frequency, is simple and less expensive. However, it does have some drawbacks. For instance, it can only produce regular compensation, unable to compensate the unbalanced load, has resonance issue of the L-C filter, and is large in size [5].

Due to these drawbacks, active harmonic filter (AHF) is developed to tackle the harmonic issue in the system. There are two different types of AHF which are the series AHF and shunt AHF. The series AHF is typically used to minimize the voltage total harmonic distortion (THD) while the shunt AHF is normally used for compensating the current harmonic for the non-linear loads [6]. On the other hand,
the shunt AHF injects the harmonic current at the point of common coupling (PCC) to compensate the non-linear load current and to produce a sinusoidal current source curves.

Flexible alternating current transmission system (FACTS) devices are the example of advanced AHF that can effectively solve the PQ issues. The FACTS devices example includes the static synchronous series compensator (SSSC), STATCOM, static var compensator (SVC), unified power flow controller (UPFC) and other controllers. The FACTS devices enhance the PQ and reduce the power cost by supplying the inductive or capacitive reactive power to the transmission [7]-[17].

The existence of harmonics due to the incremental of non-linear loads introduces significant issue to power quality problems. This includes waveforms deterioration and distortion with high THD values, where THD indicates more power loss, less transmission efficiency and the high cost of operation. Therefore, the presence of harmonics in power system is critical and should be minimized with AHF. In this project, MCHI based STATCOM is simulated as an AHF.

This paper demonstrated the design of an AHF that can filter out the harmonics and improve THD simultaneously. The selected STATCOM controller, PWM and multilevel inverter (MLI) will be implemented and modelled in Simulink. The planned model is examined based on THD results and the current waveform obtained by the system.

The paper is organized as follows: Section II presents the formulations for the components needed to structure the AHF. Section III documented, analyzed, and discussed all the simulation results attained from the aforementioned model via MATLAB/Simulink. Finally, the conclusions are summarized in Section IV.

2. Active harmonic filter/STATCOM

Figure 1 depicted the single-line diagram of three-phase power transmission system with the proposed AHF connected at the PCC.

The main element of the transmission line is structured as an inductor $L_s$ and its size is approximated to be 1% of the coupling inductor $L_f$. The non-linear loads are formed by two sets of six-pulse diode rectifiers with different resistive loading conditions and different transformer winding configurations, respectively. In this work, the AHF is constructed with five-level CHI. Comparing MCHI with the traditional voltage source inverter (VSI), large and expensive power transformer can be neglected and replaced by a coupling inductor $L_f$.

2.1. Multilevel cascaded h-bridge inverter

The schematic of three-phase five-level CHI is illustrated in Figure 2. Specifically, to form one single-phase five-level CHI, two identical of H-bridge inverters are required to be stacked in series. Similar to traditional H-bridge inverter, two series-connected switching devices that structured each phase-leg cannot be turned on simultaneously as to avoid its DC-link from short-circuiting.
From Figure 2, the output voltage $v_c$ of CHI should be at least twice than the PCC voltage. The size of the coupling inductor $L_f$ can be found via (1) as follows:

$$L_f = \frac{2v_c - v_{pcc}}{2\pi f_c i_c}$$  \hspace{1cm} (1)

where $f_c$ defines the cutoff frequency of low pass filter (i.e., twice the fundamental frequency) and $i_c$ defines the maximum current flows through $L_f$ in regards to $v_c$.

On the other hand, the DC-link capacitor of each H-bridge cell acts as energy storage element and its size is obtained in (2) as:

$$C = \frac{i_c}{2\pi f_c}$$  \hspace{1cm} (2)

where $V_{pv}$ and $I_{pv}$ are the DC source voltage and DC source current of the boost converter from the PV array, respectively, while $V_{dc}$ and $I_{dc}$ define output voltage and output current generated by the boost converter, respectively.

2.2. Carrier based pulse width modulation technique

In this work, the CBPWM with IPD technique (see Figure 3) is employed to generate all gate pulses for driving the proposed five-level CHI.

![Figure 3. Three-phase five-level CBPWM technique with IPD.](image)
The number of carrier waveforms requires to generate any level of AC voltage waveform using MCHI topology can be found by using (3) as follows:

\[ N_T = X - 1 \]  

(3)

where \( N_T \) is the number of triangular carrier and \( X \) is the desired AC output voltage level.

From Figure 3, the intersection of one modulating waveform with each carrier waveform will produce its respective pulse train to drive each upper switch (e.g., \( Q_{a1} \)) of one single-phase CHI. The aforementioned pulse train will be inverted simultaneously in order to drive the series-connected lower switch (i.e., (e.g., \( Q_{a2} \)).

2.3. Synchronous Reference Frame based Control Scheme

The block diagram of the proposed controller to achieve APF is shown in Figure 4.

The phase lock loop (PLL) is utilized to trace the frequency \( w_t \) of three-phase AC source in order to perform Park’s and Inverse Park’s transformation for three-phase load currents (i.e., \( i_a, i_b, \) and \( i_c \)) and the resultant dq load currents (i.e., \( I_{dq}^* \) and \( I_{ld}^* \)), respectively. Particularly, after the Park’s transformation, the dq load currents (i.e., \( I_{dq} \) and \( I_{ld} \)) are filtered via its respective 2\(^{nd}\) order Butterworth low pass filter (LPF) to separate the AC and DC of load components. The cutoff frequency \( f_c \) of 100 Hz is chosen as band edge frequency in this case to eliminate the higher order harmonic components.

From Figure 4, the proportional integral (PI) controller is utilized in DC voltage controller to ensure minimal steady-state error of DC voltage component from each H-bridge cell under dynamic conditions. The average of total DC-link voltages \( V_{dc\_Total} \) can be further illustrated in (4) as follows:

\[ V_{dc\_Total} = \frac{1}{3}(V_{dca\_Total} + V_{dcb\_Total} + V_{dcc\_Total}) \]

(4)

where \( V_{dca\_Total}, V_{dcb\_Total}, \) and \( V_{dcc\_Total} \) define the summation of two DC capacitor voltages at phase A, phase B, and phase C of five-level CHI, respectively.

The resultant output signal of PI controller is expressed as:

\[ I_{DC} = K_p(V_{dc}^* - V_{dc\_Total}) + K_i \int (V_{dc}^* - V_{dc\_Total}) \, dt \]

(5)

where \( K_p \) and \( K_i \) represent the gain of proportional and integral controller, respectively. Each aforementioned gain value is obtained via the PI auto tune feature from Simulink to fulfill the design requirement and obtain the desired outcomes.

Lastly, after the inverse Park’s transformation, the resultant abc load currents (i.e., \( i_a^*, i_b^*, \) and \( i_c^* \)) are subtracted with AHF currents (i.e., \( i_{ac}, i_{cb}, \) and \( i_{cc} \)) to obtain the modulating waveform for each phase of the five-level CHI as defined below:
\[
\begin{bmatrix}
    i_{ca}^* \\
    i_{cb}^* \\
    i_{cc}^*
\end{bmatrix}
= \begin{bmatrix}
    i_{ta}^* \\
    i_{tb}^* \\
    i_{tc}^*
\end{bmatrix}
- \begin{bmatrix}
    i_{ca} \\
    i_{cb} \\
    i_{cc}
\end{bmatrix}
\]

(6)

3. Simulation results
The proposed three-phase five-level CHI based AHF is illustrated as a single-line diagram shown in Figure 5. The total simulation period is 1 s with both of the DC load A and DC load B connected to PCC at 0.5 s. From these loading conditions, the effectiveness of the proposed AHF is tested under two THD conditions caused by different transformer winding configurations as well as the non-sinusoidal current draw by the six-pulse diode rectifiers.

![Figure 5](image)

**Figure 5.** Single-line diagram of the proposed AHF with the associated SRF based control scheme.

The parameters of the source, load, and AHF components used in this paper are tabulated in Table I below:

**Table 1.** Three-phase power system parameters.

| Parameter                  | Value | Unit |
|----------------------------|-------|------|
| Grid apparent power \(S\)  | 100   | kVA  |
| Nominal apparent power \(S\) | 25    | MVA  |
| Source voltage \(v_s\)      | 4160  | V_{rms} |
| Source inductor \(L_s\)     | 0.01  | mH   |
| Fundamental frequency \(f\) | 50    | Hz   |
| Switching frequency \(f_{sw}\) | 100  | kHz  |
| Coupling inductor \(L_f\)   | 1     | mH   |
| DC capacitor \(C\)          | 22.99 | mF   |

Without AHF, the current waveforms at source side will be similar to load side as shown in Figure 6; leading to poor THD due to existence of harmonic components. With AHF, the harmonic filter currents (i.e., \(i_{ca}, i_{cb},\) and \(i_{cc}\)) are produced to minimize the harmonic content at the source side (i.e., \(i_{sa}, i_{sb},\) and \(i_{sc}\)). Referring to proposed design, the performance of AHF in producing filter currents are illustrated in Figure 7(b). As AHF injects harmonic currents at PCC, the source currents are being compensated and thus became sinusoidal (see Figure 8(b)). From Figure 7, it was observed that AHF took only 4 ms to track the changes of load currents after 0.5 s.
Figure 6. Simulation result of three-phase AC load (a) voltages $v_l$ and (b) currents $i_l$.

Figure 7. Simulation result of three-phase AC AHF (a) voltages $v_c$ and (b) currents $i_c$.

Figure 8. Simulation result of three-phase AC source (a) voltages $v_s$ and (b) currents $i_s$. 

By implementing the proposed SRF based control scheme, the resultant dq load currents (i.e., $I_{ld}^*$ and $I_{lq}^*$) extracted from the loads (i.e., $i_{la}$, $i_{lb}$, and $i_{lc}$) is shown in Figure 9. Through inverse Park’s transformation, these resultant currents (i.e., $i_{la}^*$, $i_{lb}^*$, and $i_{lc}^*$) are compared with the harmonic filter currents (i.e., $i_{ca}$, $i_{cb}$, and $i_{cc}$) in order to obtain the modulating waveforms (i.e., $i_{ca}^*$, $i_{cb}^*$, and $i_{cc}^*$) for the CBPWM technique to determine the switching instants of three-phase five-level CHI. The aforementioned modulating waveforms are depicted in Figure 10.

![Figure 9. Simulation result of the resultant dq load currents (a) $I_{ld}^*$ and (b) $I_{lq}^*$](image)

![Figure 10. Simulation result of the resultant modulating waveforms $i_c^*$](image)

To attain THD of one single-phase current waveform, the Fast Fourier Transform (FFT) analysis tool from Simulink is utilized to capture its spectrum as depicted in Figure 11 and Figure 12. From Figure 11, the FFT spectrum illustrates that high THD value from three cycles of phase A load current $i_{la}$ (i.e., 20.47%) is being measured due to the high amplitude of low odd order harmonics (i.e., 5th, 7th, 11th, 13th, 17th, and 19th). However, with AHF connected at the PCC, THD of phase A source current $i_{sa}$ is successfully reduced to 8.45% as shown in Figure 11(a).

Similar observation is elaborated in Figure 12 with both the load A and load B connected to the PCC, where THD of source current $i_{sa}$ is reduced by 41.41% when compared with THD of load current $i_{la}$. Relevant information at other phases is tabulated in Table II. It is worth to note that the highest compensation rate obtained in this proposed design is 58.72%.

Relevant information at other phases is tabulated in Table II. It is worth to note that the highest compensation rate obtained in this proposed design is 58.72%.
Figure 11. Simulation result of FFT phase A spectrum with load A for (a) source current $i_{sa}$ and (b) load current $i_{la}$ at 0.4 s.

Figure 12. Simulation result of FFT phase A spectrum with load B for (a) source current $i_{sa}$ and (b) load current $i_{lb}$ at 0.5 s.

| Time (s) | Load current THD, $I_{LT,HD}$ (%) | Source current THD, $I_{S,THD}$ (%) | Compensate percentage (%) ($= \left| \frac{I_{S,THD} - I_{L,THD}}{I_{L,THD}} \right| \times 100\%$) |
|---------|----------------------------------|-------------------------------------|-----------------------------------------------|
| 0.4     | Phase A: 20.47, Phase B: 20.47, Phase C: 20.47 | Phase A: 8.45, Phase B: 8.45, Phase C: 8.45 | Phase A: 58.72, Phase B: 58.72, Phase C: 58.72 |
| 0.5     | Phase A: 4.72, Phase B: 4.72, Phase C: 4.72 | Phase A: 3.04, Phase B: 3.07, Phase C: 3.04 | Phase A: 35.59, Phase B: 34.96, Phase C: 35.59 |

4. Conclusions
The presence and continuously increased of non-linear loads in high voltage electrical power systems are alarming the industries and electrical utilities which makes it become a major concern in this day and age. Therefore, removing harmonics is a vital aspect in every transmission and distribution system which can be accomplished by applying the AHF. STATCOM is the common inverter based
compensator device from the FACTS family that acts as AHF to eliminate these undesirable harmonics. In this paper, three-phase five-level CHI is chosen as the inverter topology for STATCOM. Comparing MCHI with the traditional VSI, large and expensive power transformer can be neglected and replaced by using a coupling inductor to improve THD from the source side. The SRF based controller and CBPWM technique are used to drive the MCHI. The MATLAB/Simulink software is used to verify the outcome of the proposed AHF system. From the results, it is noticeably the source current is sinusoidal because the AHF injects the necessary harmonic currents at the PCC to mitigate the harmonics produced by the non-linear loads. In addition, THD values of source current are lesser when compared to the load current.

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