# Variable Parametric Pulse Width Modulation Scheme Applied to Harmonic Current Regulation using Shunt Active Harmonic Filter in Distribution Network

To cite this article: P. Balamurugan and N. Senthil Kumar 2020 *J. Phys.: Conf. Ser.* **1716** 012003

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# Variable Parametric Pulse Width Modulation Scheme Applied to Harmonic Current Regulation using Shunt Active Harmonic Filter in Distribution Network

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**Abstract.** In this paper, an adaptive carrier based pulse width modulation scheme for controlling current output of shunt active harmonic filter (SAHF) is proposed. The control strategy adapts the magnitude of the carrier signal in accordance with the modulation signal so as to generate appropriate pulse width for SAHF for synthesizing desired harmonic current at the point of common coupling (PCC). The technique adapted considers the error magnitude and polarity with the feedback of generated pulse width modulated(PWM) signals. To ameliorate the tracking of reference current, with fast response and defined switching frequency, the variable parametric PWM technique (VP-PWM) is implemented and validated for a distribution network feeding a balanced/unbalanced nonlinear loads. The effectiveness of the proposed strategy is validated using MATLAB/Simulink based simulations and the controller performance metrics are evaluated. The results proves the feasibilityand effectiveness of the proposed control strategy to operate with SAHFin regulating current harmonics in the distribution network.

## 1. Introduction

The problems associated due to harmonics are mitigated by using appropriate filters in the power network. In earlier days, the frequency dependency of reactive elements is utilized to suppress harmonics in a system. The filters employing passive elements like resistor, inductor, and capacitor are referred to as passive filters. The passive filters not only compensate for harmonic distortion reducing THD but also provide reactive power support, power factor correction, voltage profile improvement at certain buses, reducing starting impact and voltage drop of large motors. Well designed passive filters are implemented with high MVAr ratings performing better than synchronous condensers. Despite these advantages, passive filters have drawbacks of fixed compensation, cost, size, volume, resonance at harmonic frequencies aggravating the harmonic voltages/currents, etc. Considerable evolution in the field of high power semiconductor devices/converter and its application for power processing, the quantum of harmonics injected becomes quite more which demands controllable compensation over fixed compensation provided by passive filters. The rapid growth in high-speed switching power devices and high-speed computers leads to the development of alternate power processing circuits to replace conventional passive filters, providing controllable compensation for harmonics. Such a class of filters is

referred to as an active power filter (APF). Active power filters are capable of providing selective compensation and elimination of desired harmonics.

The focus on active power filter research for practical applications since 1970, after the proposal of basic compensation principles with APFs is discussed in [1]. In this work, various combinations of APF and their compensation principles were also discussed. Also, the combination of active power filter and passive filters providing cost-effective compensation was discussed elaborately. The robustness of adaptive controllers under different cases was discussed in [2]with the effect of nonlinearities, signal time delays, and various other factors were considered to validate the robustness of controllers. An adaptive hysteresis band current control strategy was proposed by [3]for switching APF to minimize the current error in the modified synchronous reference frame. A double hysteresis band scheme of current regulation for a single-phase active power filter was implemented by [4]to regulate harmonic distortion at the source level. With double hysteresis band current regulation, the %THD in source current is found to be reduced significantly with fairly reduced switching frequency compared to single hysteresis band current control.

The conventional repetitive controller, while tracking time-harmonic signal with known integer period, error in steady-state is near zero. In the case of the loads with variable frequency harmonics, conventional repetitive control fails to track with zero error and degrades the performance of APF. To overcome this drawback, a fractional-order repetitive controller was proposed employing a Lagrange-interpolation-based fractional delay filter as stated by [5]. This filter approximates fractional delay items with online tuning. A three-level hysteresis regulation scheme was proposed by [6] for a three-phase four-switch active filter utilizing two large capacitors in series for the third phase. The control strategy reduces the switching frequency and switching losses, bu the dc-link voltage needs to be regulated at a very higher value for the compensation, it reduces the switching frequency though.

## 2. Current Harmonic Compensation Principle

The precept of current compensation in a power system feeding a nonlinear load is shown in Figure 1. At PCC, Kirchhoff current law yields $i_s = i_L + i_f$. The current drawn by the nonlinear load is non-sinusoidal. The load current can be resolved using Fourier series to sum of infinite sinusoids whose frequencies are integer multiples of the supply frequency. The load current ($i_L$) is the sum of fundamental component ($i_{L1}$) and harmonic components ($i_{Lh}$). If the filter current is equal to $i_{Lh}$, then the source current becomes the fundamental component of $i_L$.
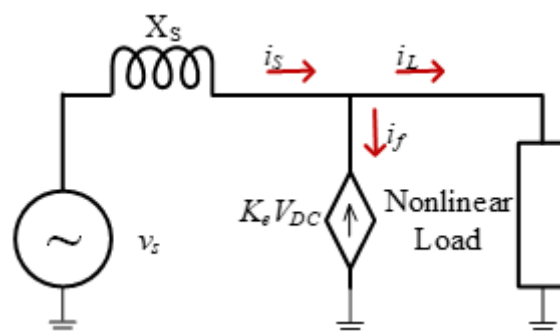


Figure 1: Principle of harmonic compensation.

In this work, *instantaneous real and reactive power theory* proposed by Akagi is employed to generate harmonic current references required for desired compensation. The harmonic current references are computed as in [7] and the same is expressed in equations (1) - (3).

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_r \\ i_y \\ i_b \end{bmatrix} \tag{1}$$

Equations governing the computation of instantaneous active (p) and reactive (q) components of power in $\alpha\beta0$ -domain is expressed in equation 2.

$$p = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{2a}$$

$$q = v_\beta i_\alpha - v_\alpha i_\beta \tag{2b}$$

The compensating currents for the SAHF are computed from equation 5 after separating the average and oscillating components. The currents are calculated as in equation 3.

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{\sqrt{v_\alpha{}^2 + v_\beta{}^2}} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_c^* \\ q_c^* \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_{cr}^* \\ i_{cy}^* \\ i_{cb}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{3}/2 \\ -\frac{1}{2} & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \tag{4}$$

The voltages and currents of a power system at every instant is transformed in to two stationary orthogonal components in $\alpha\beta o$-domain using equation 1. Instantaneous powers drawn by the load is computed in the transformed domain as in equation 2. The compensating powers are selected using higher-order low / high pass filter and the reference currents are computed using equation 4. The computed reference currents are applied to the current controller that produces the necessary duty cycle for the VSC switches after comparing with the actual filter currents $i_f$.

SAHF is connected as a shunt element in a power network performing current compensation. SAHF is a voltage source converter(VSC), in which the dc-link is powered by a fully charged capacitor. The function of SAHF is to synthesis the desired current waveform at its output poles. To achieve perfect compensation, it is vital to maintain the voltage in the dc-link to be stiff magnitude. An additional controller for dc-link is required to regulate/stabilize the dc-link. For constant dc references, the conventional PI controller is sufficient to regulate the dc-link. In SAHF, capacitor powered Voltage Source Converter is used for its simple structure, controllability, cost and flexibility in control. SAHF is switched at high-frequency PWM and hence the output voltage has ripples at switching frequency. Switching frequency harmonics at the output of SAHF are eliminated by using small passive filters. A suitably sized 'L' filter is used to interface SAHF to the grid.

The power circuit of typical VSC with a filter controller is shown in figure 2. IGBT's with anti-parallel diodes form the power switches of VSC. The principle of dc-link voltage control and ac-side current control of the SAHF is achieved simultaneously by controlling the VSC. When the pulses to VSC are being withdrawn, the VSC will act like an uncontrolled bridge rectifier charging the dc-link. Under normal working conditions, when the IGBT is 'ON' dc-to-ac conversion takes place and diode remains 'OFF', whereas when the IGBT is 'OFF' the respective anti-parallel diode will charge the dc-link capacitor. This is regulated by PWM signals to the VSC generated by the filter controller. The filter controller is the heart of the SAHF as it performs the following functions:

 (i) Sensing and computation of harmonic reference current generation

 (ii) Regulation of dc-link voltage

(iii)  Tracking of reference current by VSC

(iv)  Generating PWM for VSC

The filter controller incorporates sensors and it's signal conditioning circuits, micro controller or higher generation controller for harmonic computation, current controller, dc-link controller and PWM generator.
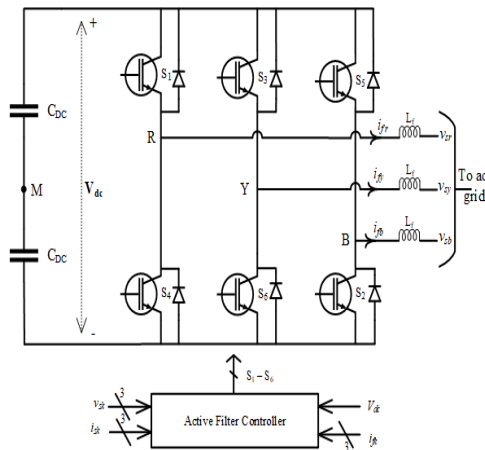


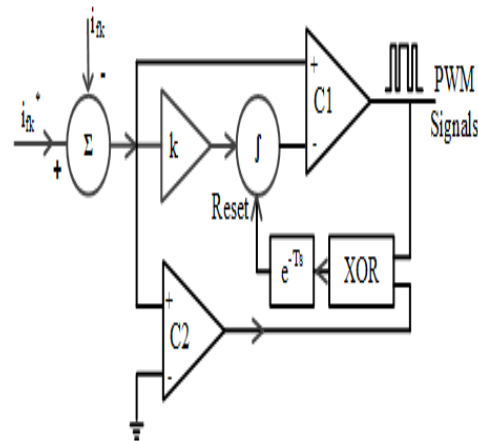Figure 2: Power circuit of capacitor powered VSC based SAHF.



Figure 3: VP - PWM current control.

The active filter controller incorporates two controllers namely for stabilizing dc-link voltage and a controller for regulating ac output current of the VSC. PI controller is best suited for regulating dc quantities that ensure zero steady-state error and exact tracking of reference quantity due to its integral action. The dc-link voltage is to be maintained constant to facilitate the proper functioning of VSC. The dc-link capacitor ($C_{DC}$) value is computed based on the power exchange between the compensator and the dc-link. The voltage magnitude of dc-link is to be fixed ahead than the maximum value of the ac grid voltage.

## 3. Variable Parametric PWM

It is the coalescence of hysteresis control and the triangular carrier modulation technique. VP - PWM control provides faster dynamic response, high fidelity and controllable switching frequency proposed by [8]. The structure of VP - PWM controller is shown in Figure 3.

Comprising of two magnitude comparators, a re-settable integrator, logic circuits, the controller process the error signal with two time-varying parameters gain ($k$) and integrator time ($T_s$). The current error signal is directly transformed into PWM signals by the dual functions namely closed-loop regulation and PWM. If the output current is less than the reference value then, the current error $\Delta i$ generated by the comparator $C_1$ is positive. Also, $\Delta i$ is integrated to generate a triangle wave whose magnitude is proportional to $\Delta i$. This variable amplitude triangular carrier is compared with $\Delta i$ to generate PWM to turn 'ON' the upper switch $S_P$ of the phase-leg. Once the output of the integrator exceeds the current error, the integrator will receive reset command after a time delay $T_s$. Now the switch $S_N$ is triggered to force the output current $i_f$ in the opposite direction. For negative error, comparator $C_2$ is utilized to detect current error polarity by comparing to ground potential, and ensures the validity of PWM generation.

The mathematical interpretation of Figure 3 can be explained based on equation 5.

$$i_f - \frac{1}{T_s} \int_0^{DT_s} i_f dt = i^* - \frac{1}{T_s} \int_0^{DT_s} i^* dt \tag{5}$$

where $T_s$ is the switching period of the filter. The control law in (5) can be deduced as in (6).

$$\int_0^{t_1} k\Delta i_f(t)dt = \Delta i_f(t_1) \tag{6}$$

The parameters '$k$', integral gain parameter and PWM coefficient '$T$' governs the performance of the control scheme interms of better control of switching frequency, current tracking error and switching frequency limits. These parameters determine the switching frequency of SAHF. At fixed $T$, the integral gain decides the switching frequency proportional to the value of $k$. The control strategy embeds the information about modulating signal into the carrier which is unique among the existing conventional PWM schemes. This feature eliminates the need for separate current control loop to limit the violations in current control and hence is a combination of carrier modulation PWM and direct current tracking PWM.

## 4. Simulation of VP-PWM based Current Control of SAHF

The performance investigation of VP-PWM based current controller for SAHF application, is implemented and simulated in MATLAB/Simulink environment. The impact of harmonic current regulation is analyzed with balanced nonlinear load essentially a three-phase uncontrolled bridge rectifier. The Simulink implementation of SAHF is shown in Figure 4. The simulation parameters of SAHF for the test system with distortion free source voltage is given in Table 1. [9]
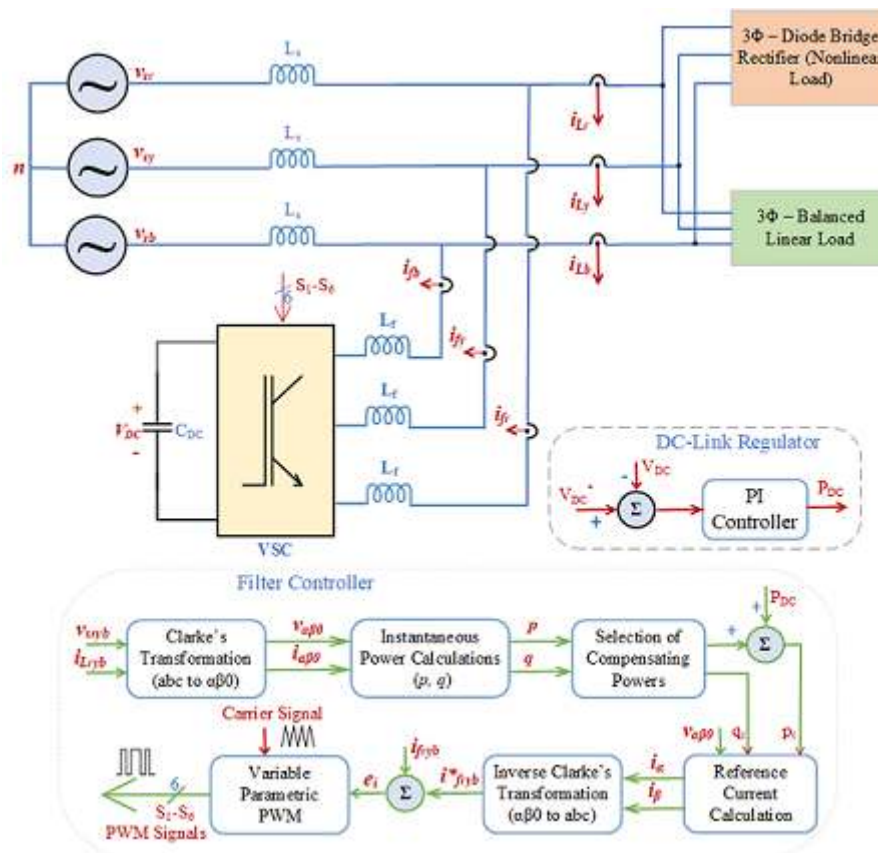


Figure 4: Simulink implementation of VP-PWM regulated SAHF.

Table 1: Parameters of the Test-System Considered for Simulation.

| Parameters | Values |
|---|---|
| Source Parameters | |
| Source Voltage ($V_s$) | 440 V, RMS, $3\phi$ |
| Frequency ($f_s$) | 50 Hz |
| Line resistance ($R_s$) | $0.1\Omega$ |
| Line inductance ($L_s$) | 12mH |
| Load Parameters | |
| Three Phase uncontrolled bridge rectifier | R = $30\Omega$, L =15 mH |
| Three Phase Linear load | P = 500W, Q = 50VAr |
| Filter Parameters | |
| DC Link voltage ($V_{DC}$) | 700V |
| DC Link capacitor ($C_{DC}$) | 400 $\mu$F |
| Interface Inductor ($L_f$) | $0.1\Omega$, 5 mH |



a. Source voltage.

b. Source current.
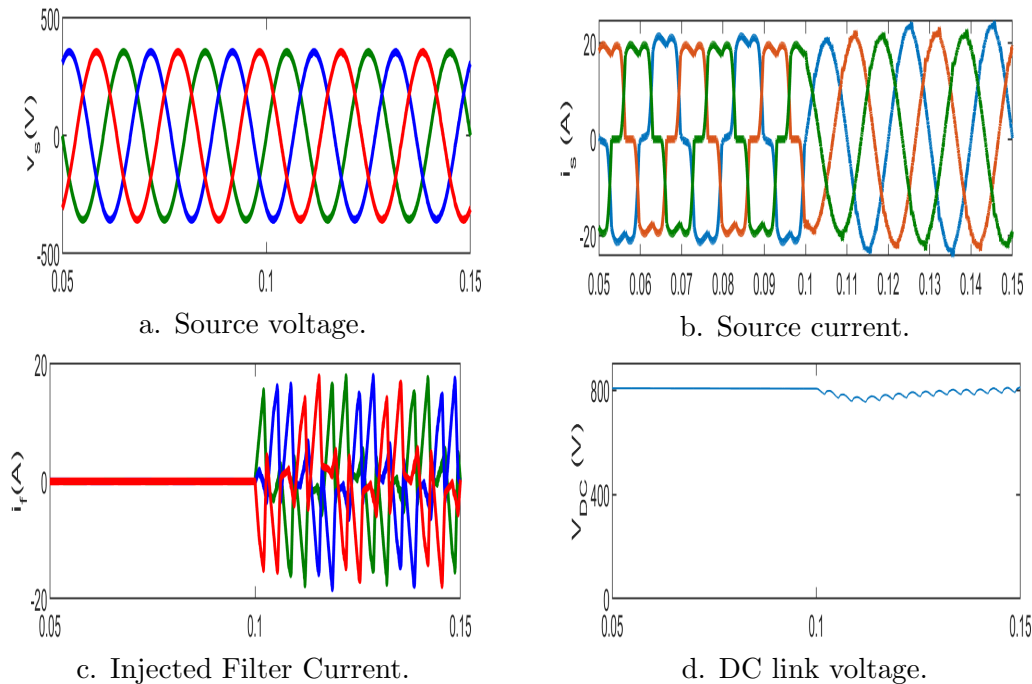
c. Injected Filter Current.

d. DC link voltage.

Figure 5: Simulated waveforms for balanced nonlinear load.

The simulated waveforms of three-phase source voltages, source currents, injected filter current and dc-link capacitor voltage are shown in Figure 5. The source current before time t = 0.1 $s$ is non-sinusoidal. At time t = 0.1 $s$, SAHF is switched 'ON', to compensate for harmonics in source current. The source current undergo transients for the duration of half-cycle in individual phases. In less than one cycle duration of supply voltage, the source currents has become sinusoids and in phase with respective phase voltage at source. SAHF injects current at harmonic frequency as required by the load ($i_{Lh}$) for it's operation. The source is now relieved from delivering harmonic currents and is delivering the real power requirement of the load and losses of SAHF. Hence the power factor at source is near unity.

The harmonic elimination in source current is analyzed and the effectiveness of the proposed

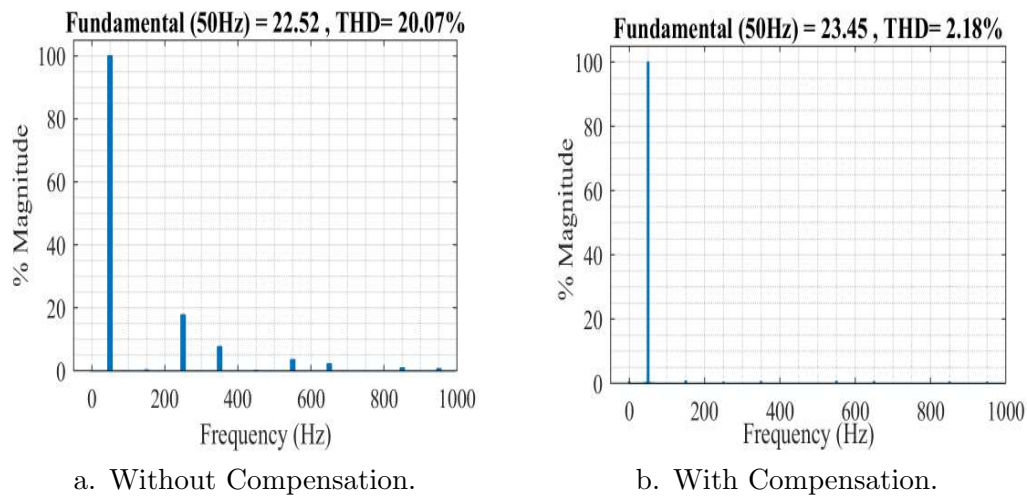a. Without Compensation.                    b. With Compensation.

Figure 6: Harmonic spectrum of source current in 'r'-phase.

compensation principle is supported by the harmonic spectrum as shown in Figure 6 for the source current computed before and after compensation for one phase. From t = 0 to 0.1 $s$, the spectrum of $i_s$ has dominant $5^{th}$ and $7^{th}$ order harmonics along with higher order harmonics. The %THD in the source currents is computed to be 20.07%. In the spectrum of $i_s$ after t = 0.1 $s$, the source current has only the fundamental component of load current ($i_{L1}$) and the dominant harmonics are eliminated by SAHF. With compensation, the %THD is computed to be 2.18%.



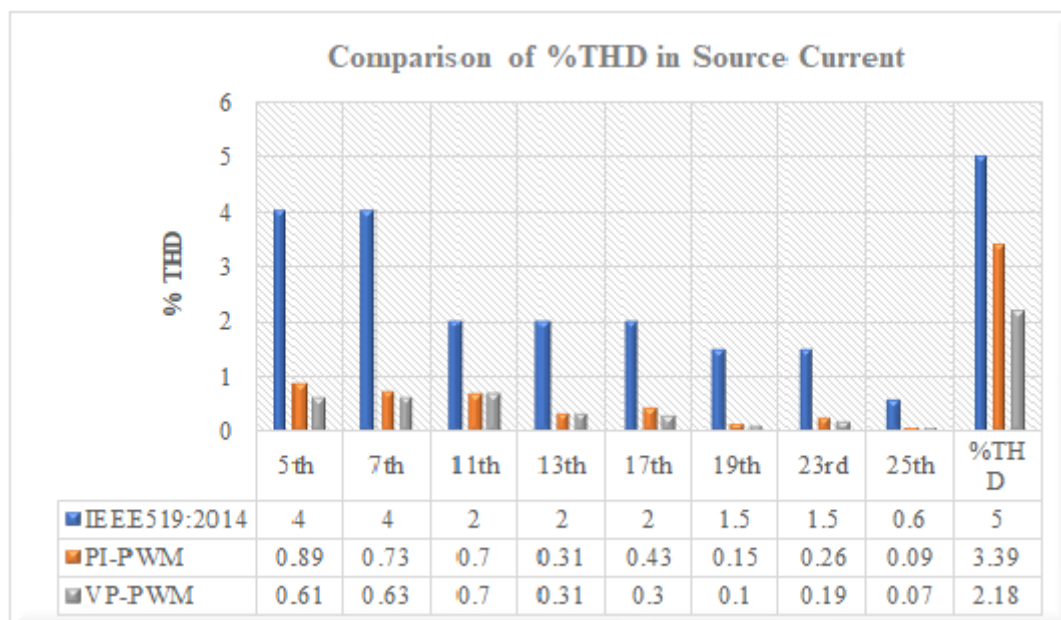| | 5th | 7th | 11th | 13th | 17th | 19th | 23rd | 25th | %THD |
|---|---|---|---|---|---|---|---|---|---|
| IEEE519:2014 | 4 | 4 | 2 | 2 | 2 | 1.5 | 1.5 | 0.6 | 5 |
| PI-PWM | 0.89 | 0.73 | 0.7 | 0.31 | 0.43 | 0.15 | 0.26 | 0.09 | 3.39 |
| VP-PWM | 0.61 | 0.63 | 0.7 | 0.31 | 0.3 | 0.1 | 0.19 | 0.07 | 2.18 |

Figure 7: Comparison of harmonic current regulation performance of SAHF with PI and VP-PWM current control.

The harmonic regulation of PR regulator is compared with the performance of conventional PI controller and IEEE519:2014 recommendations for permissible harmonic distortion levels for

distribution voltage level (120V - 69 kV). The individual harmonic component magnitudes and THD are compared in Figure 7. The results of comparison are appealing that the individual harmonic levels and THD are far less than IEEE519:2014 recommendation and with that of the PI controller. The SAHF is directly coupled to the network without any interface transformer at PCC. The harmonic compensation in this case is best effective compared to the transformer coupled SAHF wherein the transformer inductance plays a vital role in switching frequency harmonic attenuation. The control effort of VP-PWM controller is compared with PI-PWM based current control for the similar operating conditions is evaluated based on integral time absolute error (ITAE) and integral square error (ISE) for various operating conditions. The performance comparison for both the controllers are presented in Figure 8, from which it is inferred that the proposed VP-PWM current controller performs better with minimal control effort the PI-PWM current controller.



**Performance Comparison of VPPWM with PI Controller**

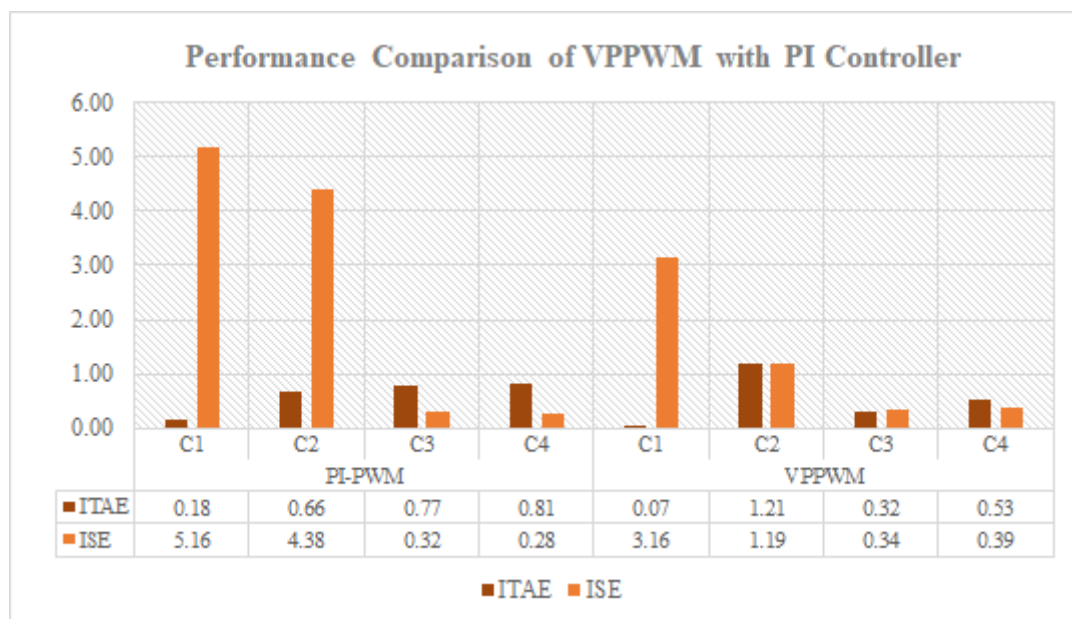| | PI-PWM | | | | VPPWM | | | |
|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C1 | C2 | C3 | C4 |
| ITAE | 0.18 | 0.66 | 0.77 | 0.81 | 0.07 | 1.21 | 0.32 | 0.53 |
| ISE | 5.16 | 4.38 | 0.32 | 0.28 | 3.16 | 1.19 | 0.34 | 0.39 |

Figure 8: Comparison of controller performance of VP-PWM with PI current control.

The operating conditions considered are balanced nonlinear load (C1), step increase in balanced nonlinear load (C2), unbalanced nonlinear load (C3) and single-phasing condition at the supply (C4). The performance of the controller is evaluated in terms of %THD in post compensated source current, rms magnitude of source current, and ISE,ITAE for the controller. The performance of VP-PWMcurrent control is significant among all the operating conditions considered under balanced sinusoidal supply voltage condition.

## 5. Conclusion

Variable parametric PWM based current control of SAHF is discussed in this paper. The proposed controller for SAHF is implemented and validated for its harmonic current regulation performance in a distribution power network using simulations. The effectiveness of the controller was analyzed for dynamic operating conditions like unbalanced loads and single-phasing loads in addition to prove its adaptaility. The performance of VP-PWM controller was evaluated based on ITAE for its better steady-state response and is compared with the performance of PI current controller. The performance of VP-PWM dominates PI current control in terms of reduced THD, reduced harmonic current for the same operating conditions.

Also the evaluation metric for the controller is found to be satisfactory with SAHF operation. The total harmonic distortion of the source current is achieved well below the recommended guidelines of IEEE519:2014.

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