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Analyzing the efficacy of LMS-based control algorithms in enhancing power quality in three-phase grid-connected systems

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ABSTRACT

This paper introduces a novel method for controlling shunt active power filters (SAPFs) to improve network efficiency and reduce carbon emissions in the utility sector. It addresses the problem of current harmonics degrading system performance by employing reference current generation based on the least mean square (LMS) algorithm, it decomposes distorted current into fundamental active, fundamental reactive and harmonic components. Traditionally, LMS implementations suffer from poor dynamic response due to uniform learning rates. To overcome this, the method adjusts the learning rates for fundamental active and reactive components separately, improving dynamic response and reducing computational complexity. Extensive analysis validates the effectiveness of this approach under various conditions, demonstrating its superiority in enhancing system performance and reducing carbon emissions in electrical networks.

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1. INTRODUCTION

The urgency to decrease carbon emissions within the utility sector has reached an unprecedented level, necessitating a strategic overhaul in energy generation and distribution systems. A key approach in this effort is the enhanced integration of renewable energy sources into the grid infrastructure. However, alongside renewable energy adoption, optimizing the efficiency of distribution networks and loads can also significantly contribute to carbon emission reduction efforts [1], [2]. The prevalence of non-linear loads, characteristic of modern electrical systems, introduces a host of power quality issues, primarily resulting from the injection of current harmonics into the grid [3], [4].

These current harmonics disrupt the stability of the electrical system. manifesting as voltage distortions, heightened cable heating, underutilization of distribution networks, and degradation of power factor. The cumulative effect of these disturbances results in diminished network efficiency and compromises the longevity and efficiency of connected loads. Consequently, mitigating current harmonics emerges as a critical challenge in ensuring the energy efficient operation of utility networks and associated loads.

Among the arsenal of solutions to tackle power quality issues, shunt active power filters (SAPFs) stand out as effective countermeasures widely documented in literature. SAPFs not only alleviate power quality issues induced by current distortions but also contribute to reactive power compensation, thereby bolstering power factor. Central to SAPF operation is the intricate process of reference current generation, this process requires determining the phase angle of the fundamental grid voltage component and decomposing the load current into its fundamental active, fundamental reactive, and harmonic components [5], [6].

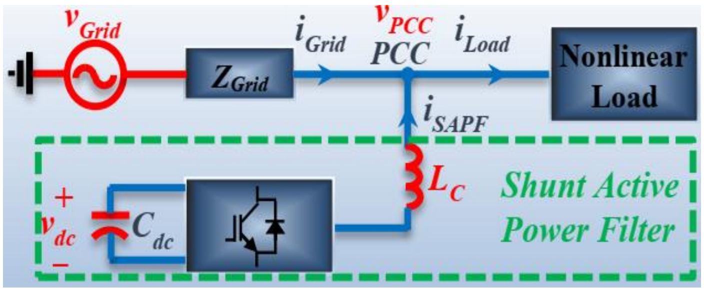
Employing least mean (LM) algorithms for signal decomposition, due to their resilience and adaptive capabilities [7], shows potential in implementing reference current generation. However, the selection of the learning rate in LMS algorithms significantly influences their performance under transient and steady-state conditions. Striking a balance between dynamic response and stability necessitates the adoption of variable learning rate strategies, as reported in existing literature. Nevertheless [8], the computational burden associated with computing individual learning rates for each frequency component remains a challenge. Moreover, alongside fundamental active component extraction, generating the reference current necessitates calculating the phase angle of the fundamental load current component [9]-[11].

This paper presents a new approach for managing shunt active power filters (SAPFs) to enhance network efficiency and lower carbon emissions in the utility sector. It addresses the problem of current harmonics degrading system performance by employing reference current generation based on the LMS algorithm, it decomposes distorted current into fundamental active, fundamental reactive, and harmonic components. Traditionally [12], [13], LMS implementations suffer from poor dynamic response due to uniform learning rates. To overcome this, the method adjusts the learning rates for fundamental active and reactive components separately, improving dynamic response and reducing computational complexity. Extensive analysis validates the effectiveness of this approach under various conditions, demonstrating its superiority in enhancing system performance and reducing carbon emissions in electrical networks [14]-[16].

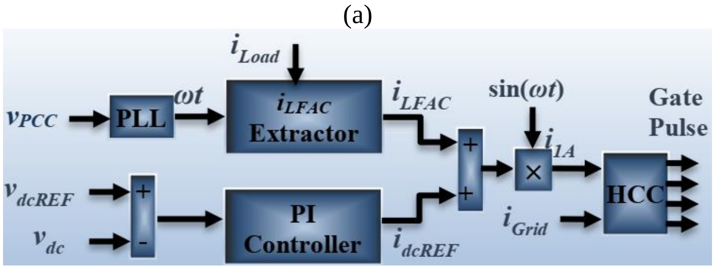
2. FUNCTIONING PRINCIPLES OF SAPFs

The SAPF, situated at consumer premises, serves as a specialized power apparatus designed to alleviate harmonic currents and offset reactive power demands from the load. As illustrated in Figure 1(a), the SAPF consists of a voltage source inverter (VSI) linked to the grid via a coupling inductor L_C, positioned at the point of common coupling (PCC). Within this diagram, key variables include v_{dc}, representing the voltage across the dc-link capacitor, C_{dc}; i_{Grid} grid, denoting the grid-supplied current; i_{SAPF}, indicating the current supplied by the SAPF; and v_{PCC}, representing the PCC voltage. The load's current, i_{Load}, comprises components such as i_{LFAC}, i_{LFRC}, and i_{Lh}. i_{LFRC} and i_{Lh} contribute to power quality degradation through current and voltage distortions, along with diminished power factor [17]-[19]. This detrimental effect can be averted if i_{Grid} equals i_{LFAC}, necessitating i_{SAPF} to match the combined value of i_{LFRC} and i_{Lh}. Effective regulation of i_{SAPF} relies heavily on the reactive current generator.

As shown in Figure 1(b), the reactive current generator scheme comprises several components: a phase-locked loop (PLL) utilized for ωt estimation, an i_{LFAC} extractor responsible for computing i_{LFAC}, a proportional-integral (PI) controller employed to determine the reference DC current i_{dcREF} to regulate v_{dc} at v_{dcREF}, and a hysteresis current controller utilized for generating gate pulses. These gate pulses ensure that i_{Grid} matches i_{LFAC} and i_{SAPF} corresponds to the sum of i_{LFRC} and i_{Lh}, thus facilitating crucial shunt compensation for harmonic current alleviation and reactive power correction [20]-[22].



(a)



(b)

Figure 1. Integrated block diagram of SAPF: (a) power circuit and (b) control system

3. GENERATION OF REFERENCE CURRENT USING THE LMS ALGORITHM

Figure 2 shows a schematic of active power filters (APFs) using the LMS control method. This algorithm's main goal is to create unit templates for each of the three phases (x_{aa}, x_{ab}, and x_{ac}) using the grid voltages that are being monitored (v_{sa}, v_{sb}, and v_{sc}), the necessary grid reference current that is being obtained by feeling the three phases' load currents (i_{La}, i_{Lb}, and i_{Lc}), the magnitude of the grid voltage (V_t), and the direct current voltage (V_{dc}) across the voltage source converter. The switching pulses for APFs are then produced by contrasting the system's measured current with the reference current that was obtained via the algorithm [23], [24].

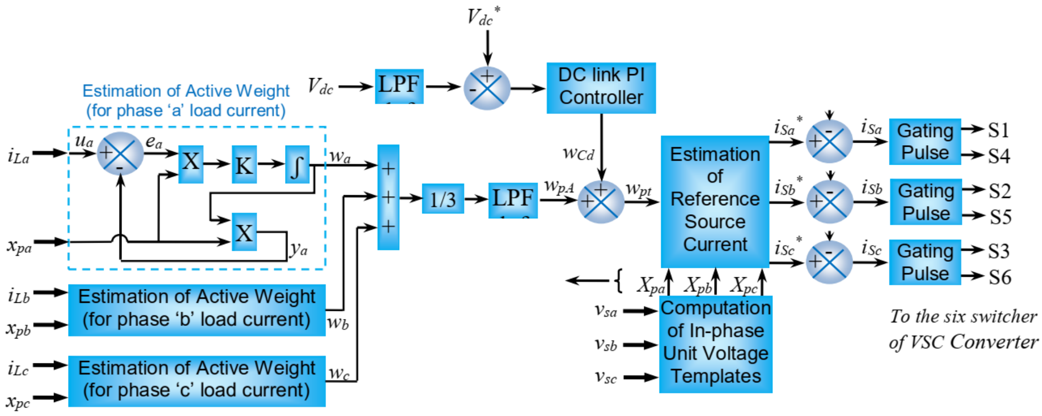


Figure 2. Schematic illustration of an LMS-based control algorithm

At first, each of the three phases' active or in-phase voltage unit templates, namely x_{aa}, x_{ab}, and x_{ac}, can be computed utilizing the grid voltage magnitude (V_t). These unit templates, denoted as x_{pa}, x_{pb}, and x_{pc}, are synchronized with the three-phase grid voltages v_{sa}, v_{sb}, and v_{sc}, respectively, and are expressed mathematically as (1).

$$x_{pa} = \frac{v_{sa}}{V_t}, x_{pb} = \frac{v_{sb}}{V_t}, x_{pc} = \frac{v_{sc}}{V_t} \quad (1)$$

The three-phase instantaneous supply voltages (V_t) have the following magnitudes as (2).

$$V_t = \sqrt{\frac{3}{2}(v_{sa}^2+v_{sb}^2+v_{sc}^2)} \quad (2)$$

Where the three-phase voltages are instantaneously as (3).

$$\begin{cases} v_{sa}(t) = V_m \sin \omega t \\ v_{sb}(t) = V_m \, sin\left(\omega t - \frac{2\pi}{3}\right) \\ v_{sb}(t) = V_m \, sin\left(\omega t - \frac{4\pi}{3}\right) \end{cases} \quad (3)$$

Each active weight component associated with the three phases is calculated using three distinct units. These units receive the load current as an input. By multiplying the phase template x_{pa} for phase $'a'$ with the appropriate weight component, a specific result is obtained. The difference between the input and output signals is defined as the error signal. Furthermore, the total output derived from multiplying the unit template by the error plus gain represents the active component of the load current for a given phase. The (4) illustrates this time-domain process for phase 'a'.

$$e_a(t) = i_{La}(t) - y_a(t) \quad (4)$$

Where output

$$y_a(t) = w_a(t).x_{pa}(t)$$

$$w_a = k \int_0^t e_a(t).x_{pa}(t)dt$$

Similarly, the active weight components for phase $'b'$ and phase $'c'$ (w_b and w_c) can also be determined. To ensure that the source current remains balanced, the average of the active weights across all three phases is denoted as w_{pA}, is calculated. The numerical representation of this value is as (5).

$$w_{pA}(t) = \frac{w_a + w_b + w_c}{3} \quad (5)$$

The direct current (DC) link voltage of the voltage source converter is detected in comparison with a reference direct current voltage to obtain an error signal. Subsequently, this error signal is inputted into a proportional plus integral (PI) controller for the DC bus voltage, yielding the direct current loss weight component (w_{cd}) [25]. The formulation for this relationship is outlined in (6) and (7).

$$w_{cd}(k+1) = w_{cd}(k) + k_p[v_{dd}(k+1) - v_{dd}(k)] + k_i \,.\, v_{dd}(k+1) \quad (6)$$

Where

$$v_{dd}(k+1) = v_{dc}^*(k+1) - v_{dc}(k+1) \quad (7)$$

The parameters k_p and k_d represent the proportional and integral gains utilized in the direct current (DC) voltage controller. Meanwhile, $v_{dd}(n+1)$ denotes the discrepancy between the reference DC voltage and the measured value of the DC bus voltage. Consequently, the total active weight component can be derived by combining the average active weight component with the DC loss component, as described in (8).

$$w_{pt} = w_{pA} + w_{cd} \quad (8)$$

One way to get the reference grid currents for all three phases is to multiply the total active weight components by the appropriate unit templates for that phase. This method is shown as (9).

$$i_{sa}^* = w_{pt} \,.\, x_{pb}, i_{sb}^* = w_{pt} \,.\, x_{pb}, i_{sc}^* = w_{pt} \,.\, x_{pc} \quad (9)$$

After that, the reference grid currents for each phase are compared with the actual grid currents. Subsequently, a 10-kHz triangular carrier wave is used as a reference signal, and each of these current discrepancies is assessed independently against it. Based on this analysis, six pulses (S1 to S6) are discovered. These pulses serve as the gate signal for the six switches of the three-arm voltage source converter.

4. SIMULATION RESULTS AND DISCUSSION

In this section, we delve into the simulation outcomes of the envisioned active filters utilizing the MATLAB/Simulink platform. The results exhibit the resultant source voltage and current subsequent to the filtering stage, with simulation time spanning from t=0 sec to t=0.5 sec. Notably, the LMS algorithm generates a pulse following 0.04 sec, facilitating the generation of a compensated waveform for the source current. Comprehensive details regarding the parameters of the proposed system are elucidated in Table 1.

Table 1. Parametrs systeme

Parameters	Value
Single phase AC supply	100 V, 50 Hz
Line impedance	0.1 + j0.00015
C_{dc}	35 µF
v_{dcREF}	220 V
L_C	15 mH

The three-phase source voltage is depicted in Figure 3, and the non-linear load current for the three phases is shown in Figure 4. In Figure 5, the harmonic spectrum is displayed prior to correction. The nonlinearity of the currents is reduced to the appropriate level following the application of the SAPF, as seen in Figure 6. Figure 7 shows the SAPF current, which balances the harmonic currents from the non-linear load. Figure 8 shows a spectrum analysis following the shunt active power filter's application. The self-supported DC bus voltage is further displayed in Figure 9.

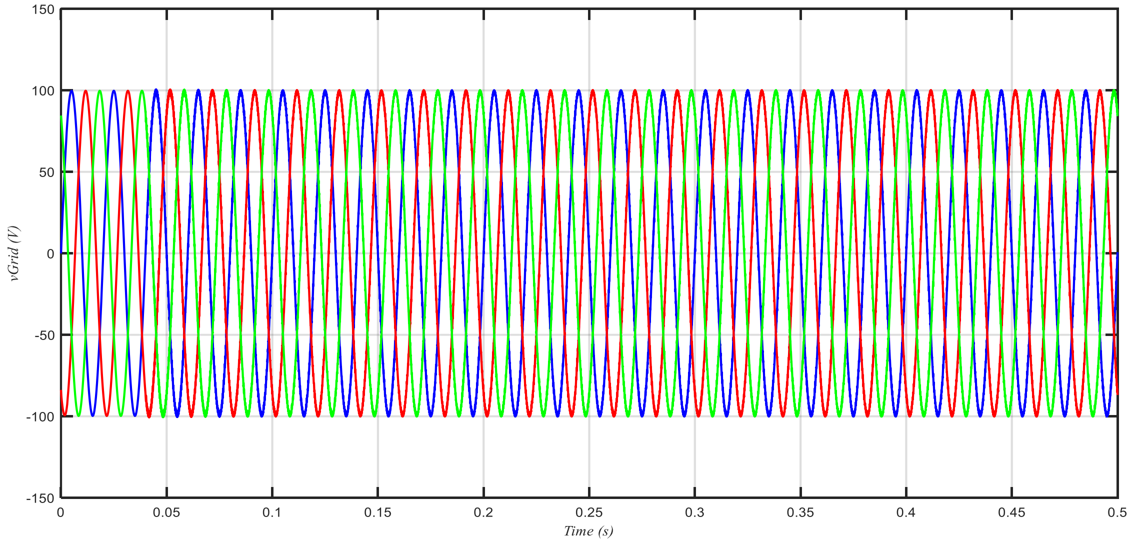


Figure 3. Three-phase source voltage

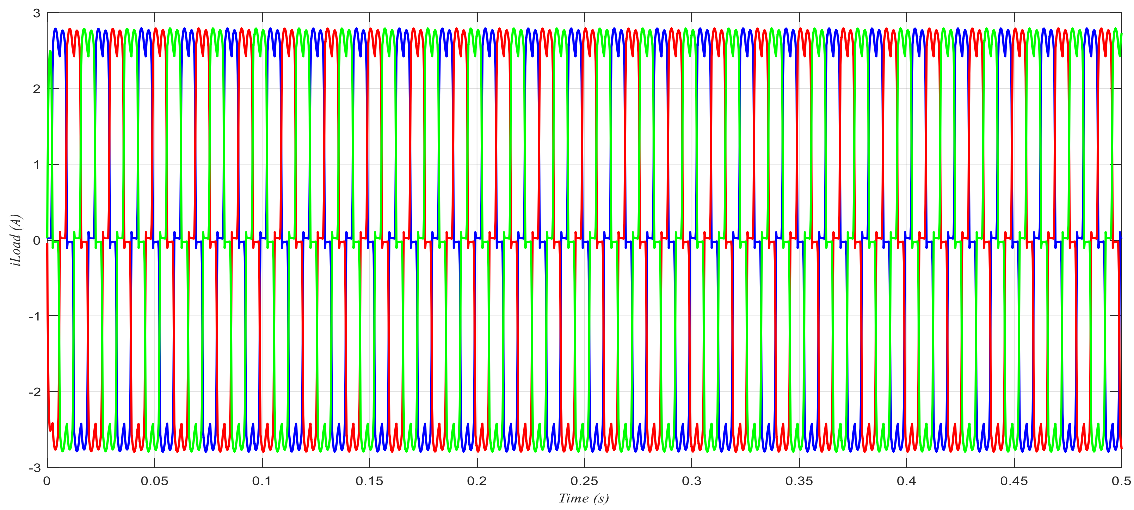


Figure 4. Supply source current without filtering stage

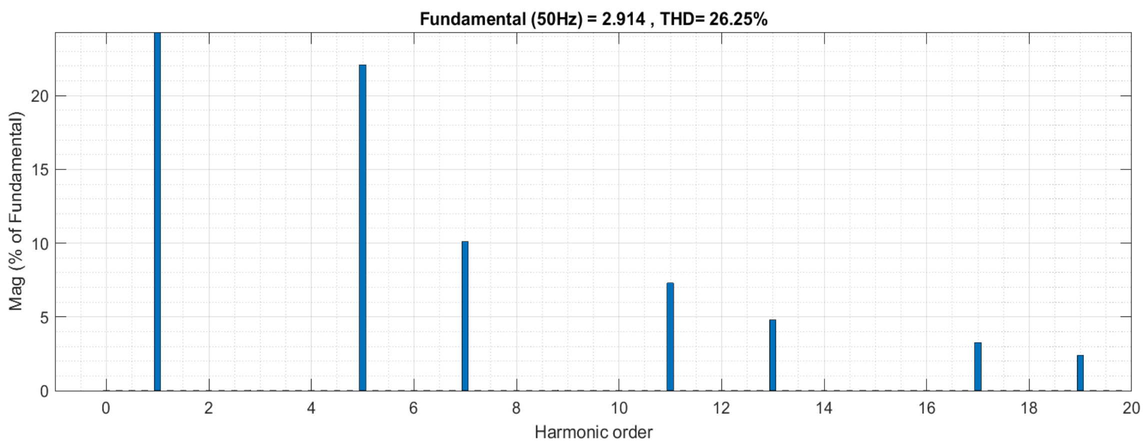


Figure 5. THD before filtering stage

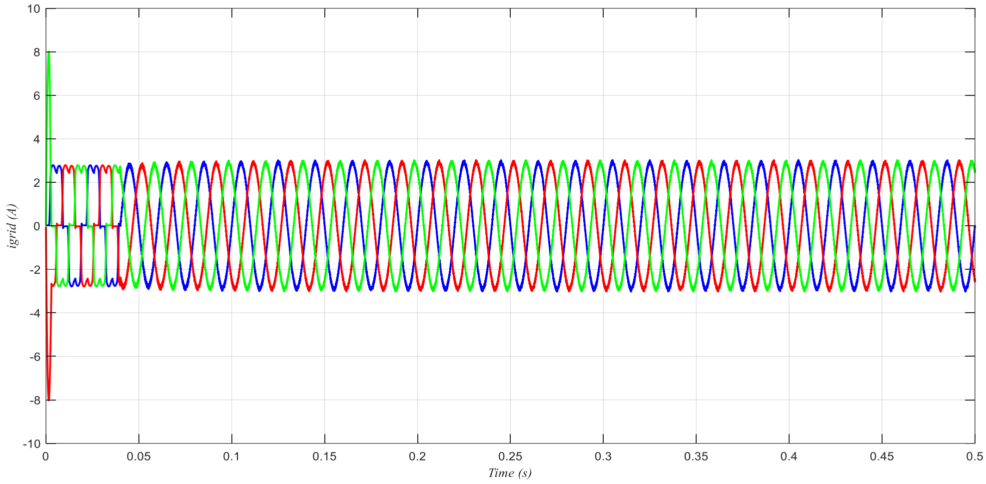


Figure 6. Source current of three phase after compensation

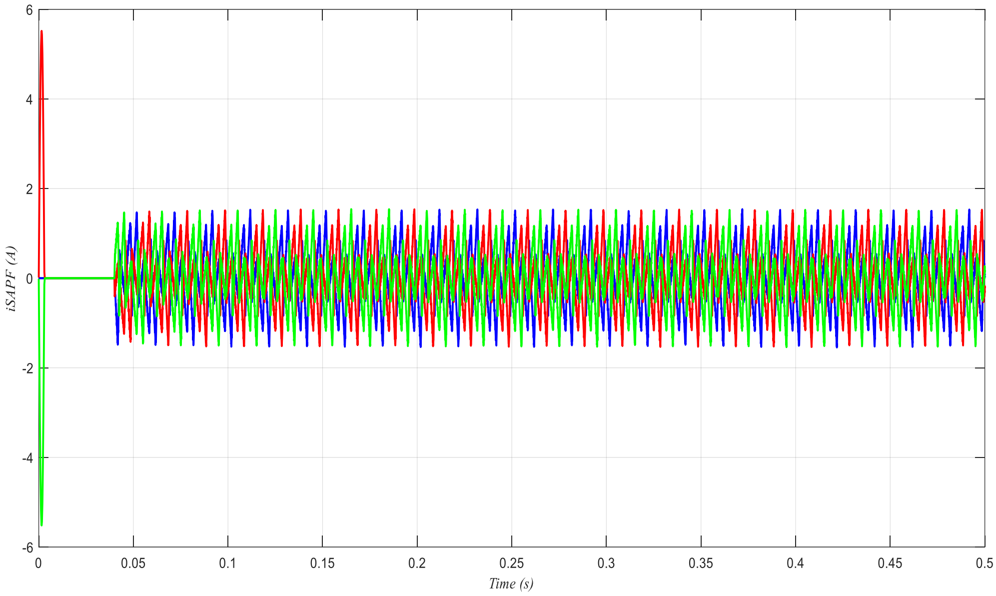


Figure 7. Filter current of three phase

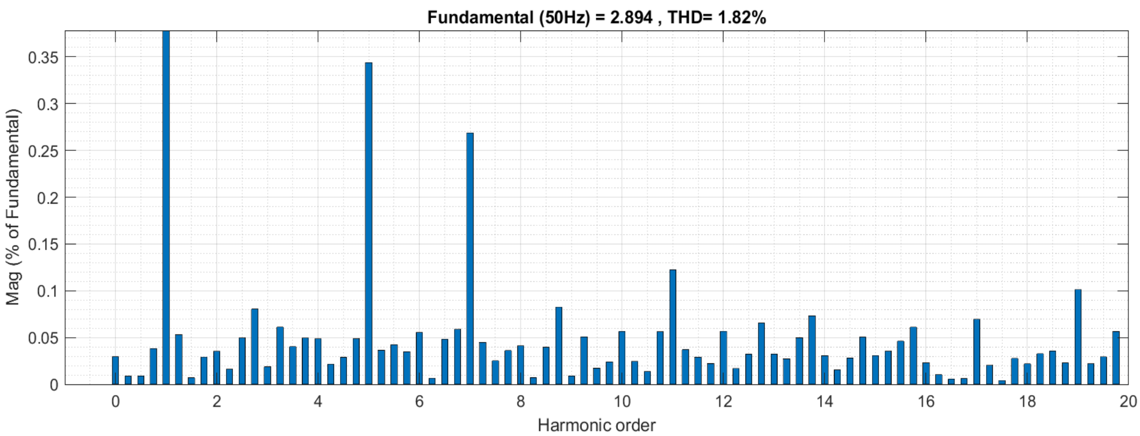


Figure 8. THD after filtering stage

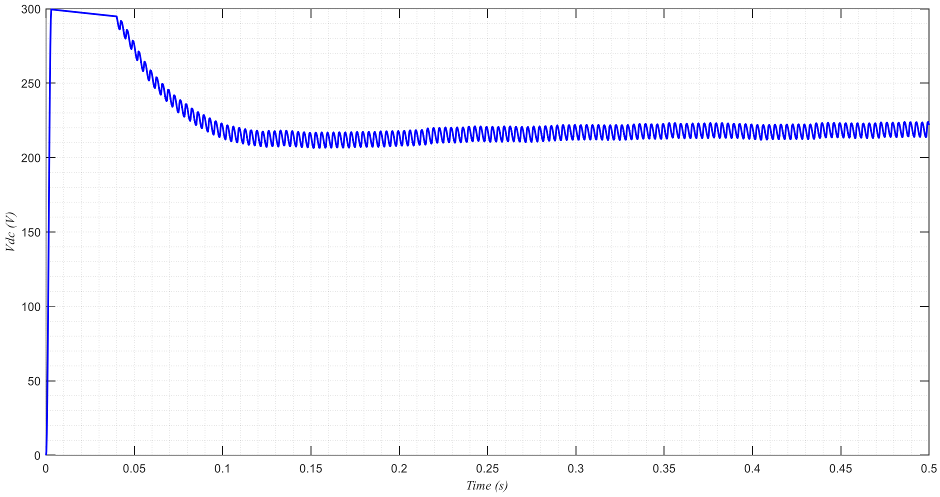


Figure 9. DC link capacitor voltage

5. CONCLUSION

The paper elucidates an LMS-based SAPF aimed at mitigating line current harmonics originating from nonlinear loads within the system. By employing a PI controller to generate switching pulses utilizing V_{dc} reference and C_{dc} voltage for the power circuit, the effectiveness of the approach is established and validated through simulation outcomes. Consequently, the proposed system demonstrates its efficacy in curtailing harmonic content in power lines to comply with IEEE standards' permissible limits.

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