



ENHANCEMENT OF THE DC BUS VOLTAGE CONTROL OF A SHUNT ACTIVE POWER FILTER THROUGH ROOTED TREE OPTIMIZATION

Ridha Rehouma^{*1}, Laid Zellouma², Yacine Djeghader³, Rabhi Boualaga⁴

^{1,2}LEVRS-Research Laboratory, University of El-Oued, El-Oued, Algeria.
Electrical Engineering departments, University of Souk-Ahras, Souk-Ahras, Algeria.
Department of Physics, National School of Teachers of Bou Saâda, M'sila, Algeria.

¹<http://orcid.org/0000-0001-8201-7962>, ²<http://orcid.org/0000-0002-9682-5490>,
³<http://orcid.org/0000-0002-7097-7808>, ⁴<http://orcid.org/0000-0002-4659-7864>

Email: ridharehouma1989@gmail.com, zellouma13@yahoo.com, yacine.djeghader@univ-soukahras.dz, boualaga.rabhi@ens-bousaada.dz

ARTICLE INFO

Article History

Received: February 10, 2026

Reviewed: April 17, 2026

Accepted: May 17, 2026

Published: June 30, 2026

Keywords:

Active filter
DC Bus Voltage
Harmonics
Power Quality
Root Tree Optimization

ABSTRACT

Simulation results outcomes verify the proposed system's efficiency RTO. The PI controller is employed extensively in this work for controlling the DC-link voltage. Was used the anti-windup controller in this paper may not perform satisfactorily for fast changing load conditions in relation to overshoot, settling delay and undershoot. The DPC of shunt active power filter (SAPF) three phase is a successful approach to guarantee both stability and good performance for the DC link voltage. A new technique is offered in this work enhance the regulation of the DC link voltage using the DPC method. In order to illustrate the performance improvement, the root tree optimization (RTO) is employed to obtain optimal gains value for the windup prevention controller.



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I. INTRODUCTION

Power electronic equipment is ubiquitous in industrial and domestic uses fittings, most of these equipment's are non-linear loads that consumes current that is not sinusoidal causing the distribution network to generate high harmonic currents, the harmonic produced shall cause several disadvantageous effects such as; extra losses in the lines, transformers saturation, and power factor deterioration. Consequently, to tackle the issues outlined above, passive filters were conventionally used to eliminate lower order harmonic currents. Notwithstanding, passive filters have certain drawbacks including; resonance issues, large footprint, and complicated integration into the energy system [1]. Currently, the shunt active power filter gain attention as a good option to eliminate the current harmonics and reactive power resulted by non-linear loads, it has ability to eliminate specific orders of harmonics for the different classes of load. The harmonic currents produced by SAPF is equal in amplitude and in opposite phase to those harmonics produced by non-linear load to restore the grid current to sinusoidal. The choice of intelligent control technique plays a serious role in the functioning of SAPF, various control techniques have been suggested, such as instant active and reactive control [2], direct power control [3], [4]. the latter is similar to the DTC for the induction machine introduced by Noguchi [5]. The main advantages of this technique: no current loop, simple structure and good dynamics and performance. In the DPC technique, the active power of reference is derived from the DC bus voltage, thus importance of DC-bus voltage regulation is crucial. Moreover, it contributes significantly in SAPF performance. Many works in the literature were dedicated in this area to enhance the dynamic response, and many control techniques were developed in this framework such as: fuzzy logic control [6], [7], neural network control [8], sliding mode control [9] Uncertainty in the dynamics of system and sudden changes of operating points could lead the tuning conditions of controller to be insufficient or even invalid, taking as a example the factors of anti-windup PI controller used in the control of DC-link voltage not converging to a satisfactory operating point in a large variety of operating conditions [10], this leads to the conclusion that to get satisfactory results one should optimize the parameters of controller design, hence different optimization methods has been utilized during the tuning of a classical controllers such as Ants colony optimization technique [11], genetic algorithm GA [12], Particle swarm optimization PSO [13], artificial bee colony [14], Ant lion optimizer and grey wolf optimization [15] are employed to optimize the coefficients of PI regulation of the DC link

voltage. Out of them, Rooted tree optimization RTO is a recent metaheuristic optimization technique that imitates desert plants for searching water. The economic load dispatch problem motivated its development and it was experimented on the standard benchmark's functions [16]. The subsequent papers demonstrate the applications of recursive tree optimization algorithm in electrical engineering. In reference [17], the author introduces an algorithm based on rooted tree optimization to enhance the DFIM direct torque control response, thereby minimizing torque ripple and improving motor speed control. In [18] presents a new algorithm to optimize the power control of wind turbine using DFIG through rooted tree optimization algorithm. The proposed algorithm is expected to enhance wind turbine performance by minimizing power losses and improving power factor. Later, the same writer used RTO, high order sliding mode control with super-twisting algorithm based direct torque control to attain better performance in doubly-fed induction power generator [19]. In [20], fuzzy logic-based tree optimization technique is proposed to systematically embed distributed generation (DG) option and distribution static compensator (DSTATCOM) in the power system. The presented algorithm is to be utilized for optimizing DG and DSTATCOM locating and sizing options with an aim to improve power quality and reduce power losses. Here split of DPC methodology is proposed, which is applied for precise control of SAPF three phases. An anti-windup PI controller helps regulating the voltage across DC link. Here the objective is to propose optimized PI controller for maintaining the regulation of DC link voltage in shunt filters using rooted tree optimization. Proposed method should be effective for improving the regulation DC link voltage. The structure of the paper is such that, Section II header and its description and modelling SAPF will be given, followed by RTO algorithm and its implementation for SAPF in Section III, Section IV includes the simulation results and discussion and Section V concludes the paper.

II. SYSTEM CONFIGURATION

II.1. SHUNT ACTIVE POWER FILTER

The overall layout for studied system depicted in figure 1, which consist of three blocks requires: first block is the grid network source, second block is the non-linear load which is a three phase uncontrolled rectifier, inductance L and resistance R, last block: shunt active filter utilized to remove harmonics introduced by non-linear load, DPC employed as control technique of SAPF, the PI controller optimized with Rooted tree optimization in order to control the DC link voltage, the output of PI considered as reference active power.

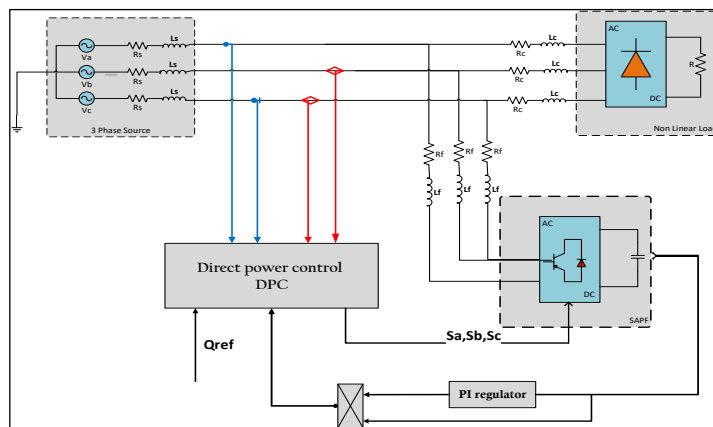


Figure 1: Block Diagram of the studied system.
Source: Authors, (2026).

II.2. THE PRINCIPE OF DPC

DPC is based on considering the active and reactive powers as control variables, its concept is similar to DTC applied for controlling the electrical machine [5]. It only needs the information of grid voltage position and errors of active/reactive power, and then the suitable voltage vector can be chosen from a predefined switching table to minimize both active and reactive power errors, the reference active power delivered from DC-bus voltage and the reference reactive power set to zero for unity power factor. The concept of DPC for SAPF is illustrated in Figure.

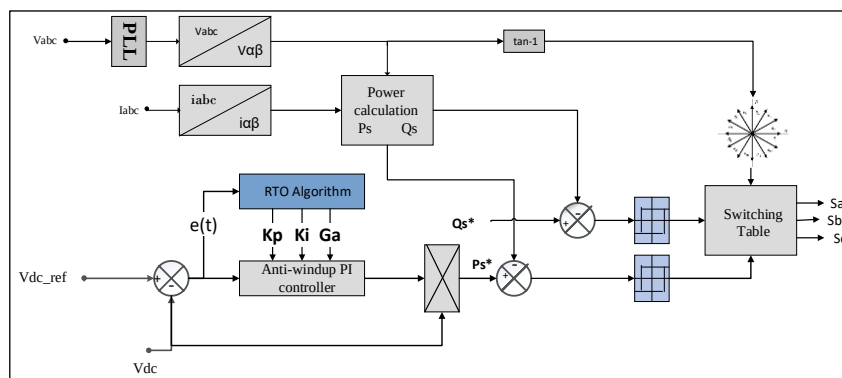


Figure 2: Block diagram of the principle of DPC.
Source: Authors, (2026).

After transformation the voltage and the currents sources to alpha-beta frame, the instantaneous active power can obtained as follow:

$$P_s(t) = V_{sa}.i_{sa} + V_{sb}.i_{sb} \quad (1)$$

$$Q_s(t) = -V_{sb}.i_a + V_{sa}.i_b \quad (2)$$

The information of grid voltage position is necessary to define the switching state. For this reason, the plan of vector space is divided into 12 sectors, these sectors can be defined by this relationship:

$$(n-2)\frac{\pi}{6} < \theta_n \leq (n-1)\frac{\pi}{6}, \quad (3)$$

$$n = 1, 2, \dots, 12$$

Using the components of grid voltage vector in alpha-beta frame, the angle can be obtained as the following expression:

$$\theta = \arctan\left(\frac{V_a}{V_b}\right) \quad (4)$$

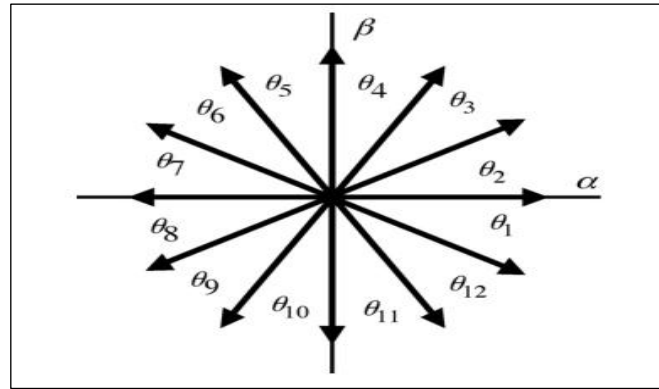


Figure 3: Vector space plane (α , β) divided into twelve sectors.

Source: Authors, (2026).

Finally, the appropriate voltage vector can be selected from the following table Table.

Table 1: Classical switching table.

Dp	Dq	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
1	1	V ₅	V ₅	V ₆	V ₆	V ₁	V ₁	V ₂	V ₂	V ₃	V ₃	V ₄	V ₄
	0	V ₃	V ₃	V ₄	V ₄	V ₅	V ₅	V ₆	V ₆	V ₁	V ₁	V ₂	V ₂
0	1	V ₆	V ₁	V ₁	V ₂	V ₂	V ₃	V ₃	V ₄	V ₄	V ₅	V ₅	V ₆
	0	V ₁	V ₂	V ₂	V ₃	V ₃	V ₄	V ₄	V ₅	V ₅	V ₆	V ₆	V ₁

Source: Authors, (2026).

V₁(1,0,0), V₂(1,1,0), V₃(0,1,0), V₄(0,1,1), V₅(0,0,1), V₆(1,0,1), V₇(1,1,1), V₀(0,0,0).

III. DC LINK REGULATION

The regulation of DC-bus voltage is a critical component of the DPC's performance in the SAPF. Typically, the PI controller was suggested to reduce fluctuations and instability by maintaining the DC link voltage constant and adhering to its reference value. The transfer function of the closed loop, which is shown in the figure, is written in the following manner:

$$\frac{V_{dc}}{V_{dc_{ref}}} = \frac{K_p.s + K_i}{C.s^2 + K_p.s + K_i} = \frac{K_p/C(K_i/K_p)}{s^2 + K_p/C.s + K_i/C} \quad (5)$$

By using pole placement theory, the gains of PI regulator are obtained by the following relations:

$$K_p = 2 \cdot \varepsilon \cdot \omega_n \cdot C \quad (6)$$

$$K_i = C \cdot \omega_n^2 \quad (7)$$

In transient time, The PI controller suffers from the large error due to saturation of controller PI controller saturation can be a problem in control systems because it can lead to oscillations, instability. Anti-windup is used to make sure the stability and prevent the oscillations that caused by saturation problem. Anti-windup, high gain has been added to PI controller loop shown in figure 3 to solve the saturation problem and getting better performance in transient state.

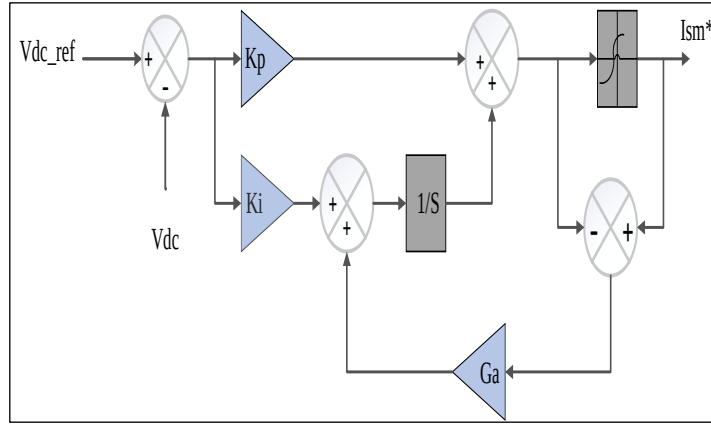


Figure 4: Anti-windup PI Controller for DC voltage regulation.
Source: Authors, (2026).

Rooted tree optimization is new optimization method mimics the behavior of the roots for looking for water, like the other optimization methods the movement of the roots collectively enables them to find the best place of the water. the initial population created randomly from the first node, the root which has highest wetness degree represents the new breakthrough for the second generation while the others which have less wetness degree are deleted or replaced by a new random root [21], [18]. fig 3 show how the roots move for looking water in the desert plants.

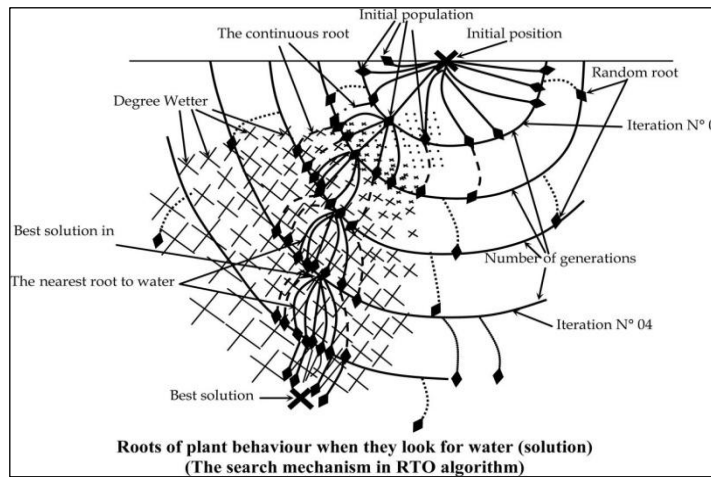


Figure 5: Behavior of the roots of the desert plants searching for water.
Source: Authors, (2026).

It is the rate which represents the number of members among the total number of populations that should be collect in the water place (best solution), the new generation of the nearest root to water is given by:

$$x^{new}(i, It + 1) = x^{best}(It) + c_1 \times D_w(i) \times randn \times l / (N \times It) \quad (8)$$

here It is the iteration number, $x^{new}(It + 1)$ becomes the new candidate for the iteration $(It + 1)$, $x^{best}(It)$ is the best solution from the previous generation, where i is the candidate number, N is the population scale, l is the high limit for the param, and $randn$ is normal random number in $(-1,1)$.

III.1 RATE OF THE CONTINUOUS ROOT IN ITS ORIENTATION (RC)

The Roots which collected near the water from the previous generation continue its orientation to create a new generation given by the following relationship:

$$x^{new}(i, It + 1) = x(i, It) + c_2 \times D_w(i) \times rand \times (x^{best}(It) - x(i, It)) \quad (9)$$

Where $x(It)$ is the previous candidate for the iteration It and $rand$ is random number between $[0,1]$

III.2 RATE OF THE RANDOM ROOT (RR)

here It is the iteration number, $x^{new}(It + 1)$ becomes the new candidate for the iteration $(It + 1)$, $x^{best}(It)$ is the best solution from the previous generation, where i is the candidate number, N is the population scale, l is the high limit for the param, and $randn$ is normal random number in $(-1,1)$. This rate represents the number of roots among the total number of populations that they propagate randomly in research field also they replace the root deleted from the previous generation the new population of random roots is given by:

$$x^{new}(i, It + 1) = x_r(It) + c_3 \times D_w(i) \times randn \times l/It \quad (10)$$

Where $x_r(It)$ is individual randomly selected from the previous generation, c_1, c_2, c_3 are adjustable parameters RN, Rc, Rr are planned according the studied problem which its convergence influenced by this variables. In order to adjust the optimal gains of the anti-windup controller of the DC link using rooted tree optimization must be following these steps:

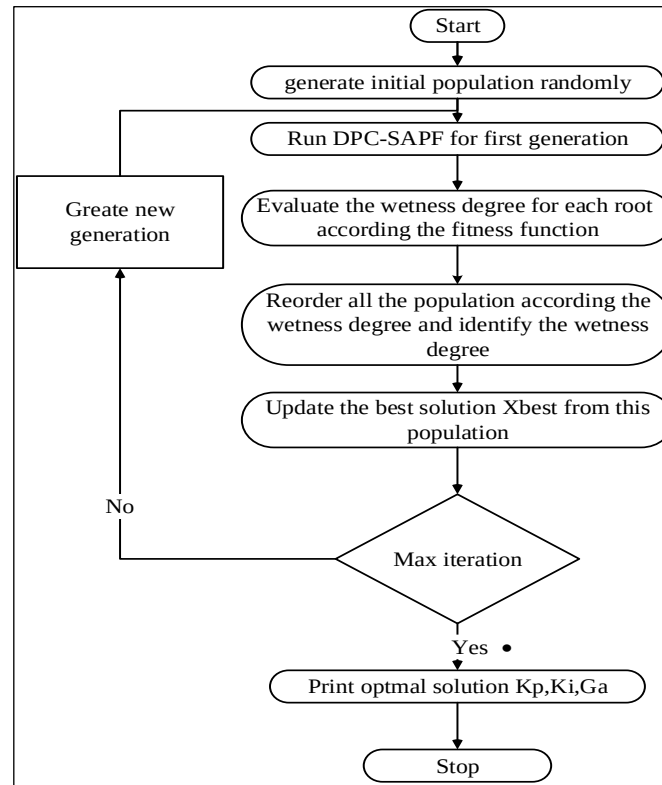


Figure 6: Flowchart of RTO algorithm.
Source: Authors, (2026).

IV. THE OPTIMIZATION PROBLEM

To determine the coefficients of the anti-windup PI controller in case of parameters variation and system nonlinearity, the need of exact mathematical model for the studied system arises. hence, the control of DC link voltage can be enhanced by optimization the coefficients of anti-windup PI controller using a new metaheuristic technique called rooted tree optimization. the parameters values of PI anti-windup K_p , K_i and G_a will be evaluated off-line by RTO method through minimization the fitness function. The objective of this paper is to keep the DC-link voltage to track its reference with no undershoot and overshoot, power ripples reduction and THD minimization. Therefore, the cost associated with the objective function that is to be minimized is considered as DC-bus voltage instantaneous error $e(t)$ and instantaneous THD_i of current supply [22].

$$ITAE = \int t \cdot e(t) dt \quad (11)$$

$$IAE = \int |e(t)| \cdot dt \quad (12)$$

$$ISE = \int e(t)^2 \cdot dt \quad (13)$$

Whereas

$$J(t) = e(t) + THD \quad (14)$$

Table 2: Parameters of the RTO.

Parameters	Value
RTO size	20
Number of maximum iteration	20
$C_1=C_2=C_3$	2
$R_r=R_n$	0.3
R_c	0.4
Dim	3

Source: Authors, (2026).

V. SIMULATION RESULTS

Simulations will be implanted in MATLAB/Simulink environment for both proposed DPC RTO and conventional DPC for SAPF, the results are compared in order to check the efficiency of proposed approach. the parameters of studied system are mentioned in appendix. firstly, the system runs without harmonics compensation and the SAPF are connected at 0.2 s. To examine the effectiveness of DPC based on the gains obtained by RTO algorithm under load variation, the non-linear load increased from 24Ω to 28Ω at 0.4 s and then returned to 24Ω again at 0.6 s. The gains of anti-windup PI controller obtained by RTO are tuned off-line, the parameters of RTO algorithm is illustrated in Table 2. Figure (7) represents the variation of fitness function for RTO, it is clear that the fitness function takes minimum value at the iteration 6, the variations of the parameters (K_p , K_i and G_a) is shown in figure (8), it can be seen that the best values are: $K_p=0.13$, $K_i=4.45$ and $G_a=200$. A comparative analysis will be carried out between both approaches SAPF system control to validate the efficiency of proposed method, the DC-link voltage for both controllers is depicted in figure 9, proposed method has outperformed the conventional controller, DC-link voltage DPC-RTO follow the reference value (120 V) quickly as compared to conventional case and the overshoot and undershoot during load change fluctuation are very small as compared to conventional controller which provide considerable value as shown in (9-b). According to figure 10, It can be seen that active power at the start-up of DPC-RTO reaches a maximum of (559.9 W) is higher than conventional PI (516.8 W), Also DPC-RTO presents significant power ripples compared to the conventional one. moreover, the THD of DPC-RTO (2,15 %) is higher than conventional case (1.35%) as shown in figure 13.

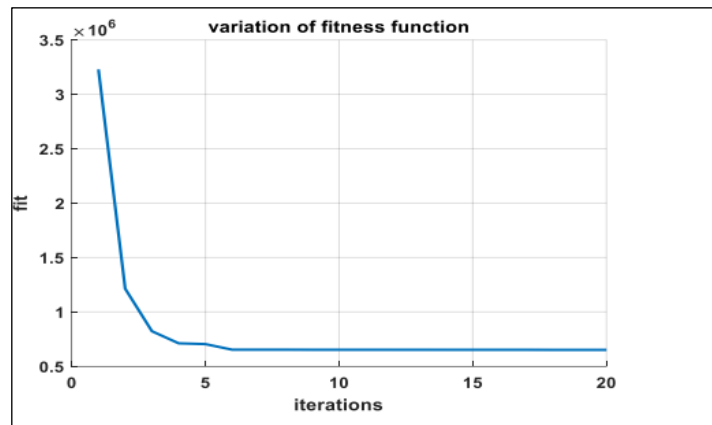


Figure 7: variation of fitness function.

Source: Authors, (2026).

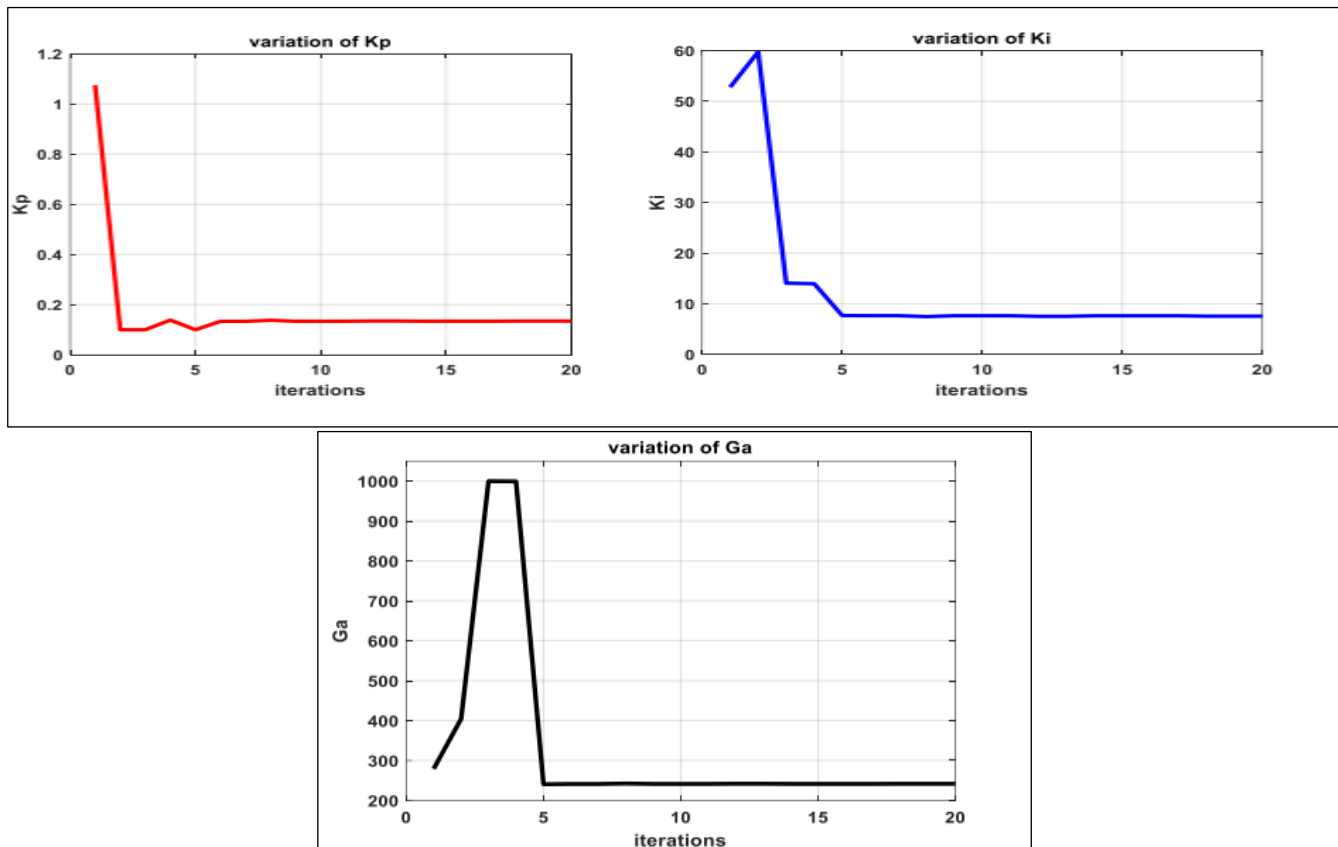


Figure 8: variation of the parameters: K_p , K_i and G_a .

Source: Authors, (2026).

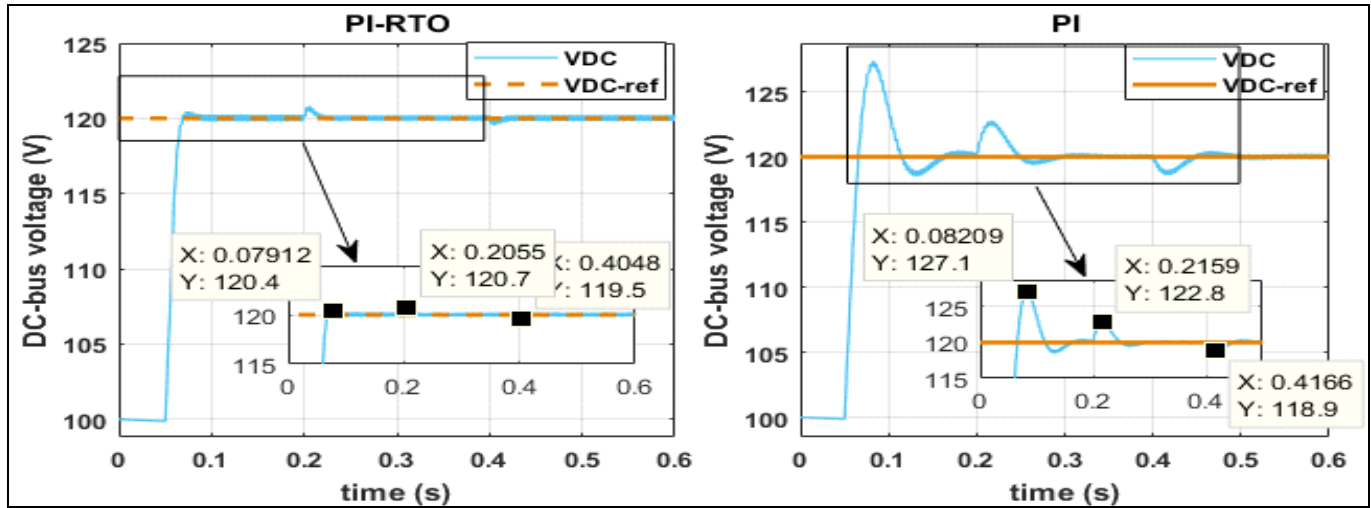


Figure 9: simulation results of DC-link voltage under load variation: (a) PI conventional, (b) RTO-PI.
Source: Authors, (2026).

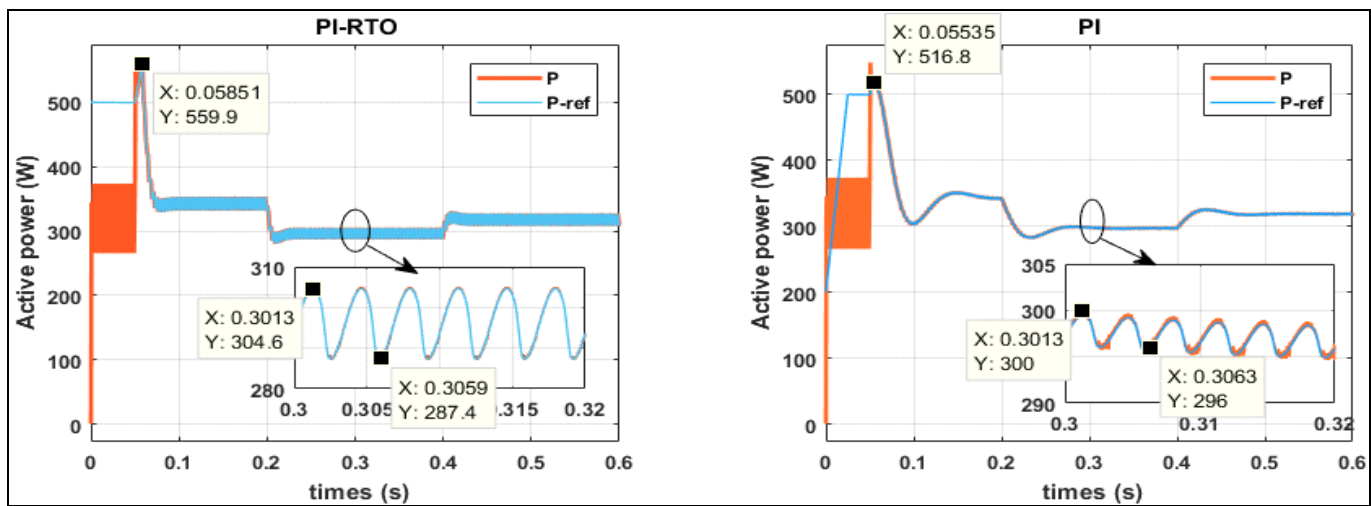


Figure 10: simulation results of active power under load variation: (a) PI conventional, (b) RTO-PI.
Source: Authors, (2026).

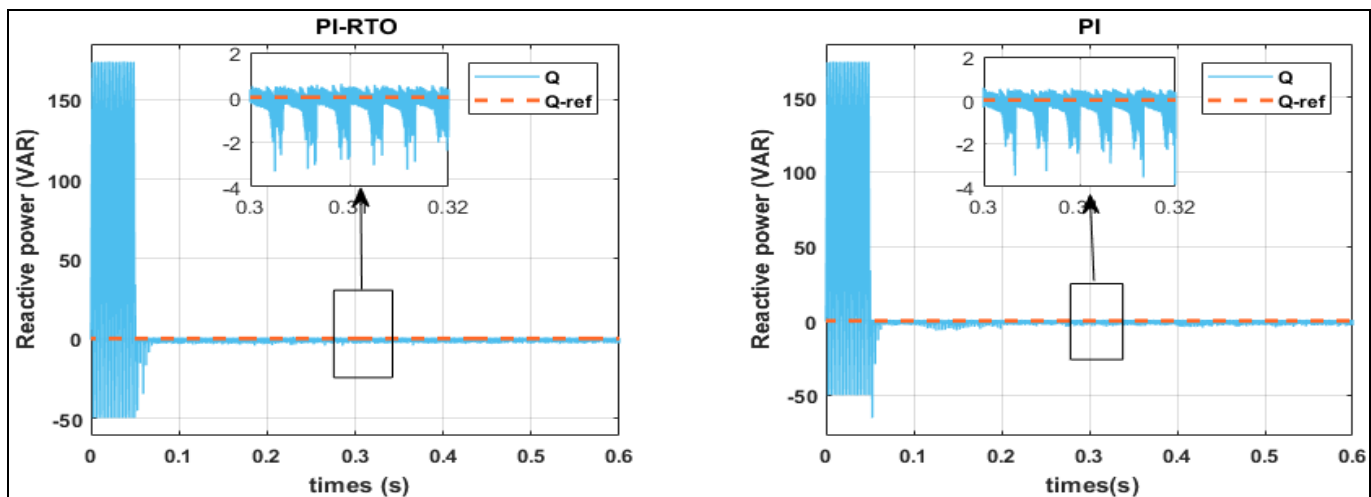


Figure 11: simulation results of reactive power under load variation: (a) PI conventional, (b) RTO-PI.
Source: Authors, (2026).

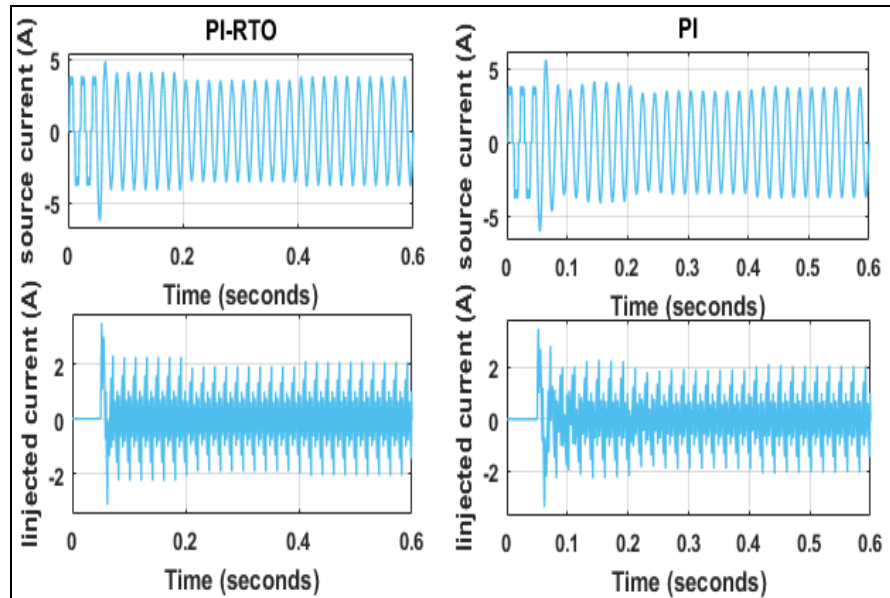
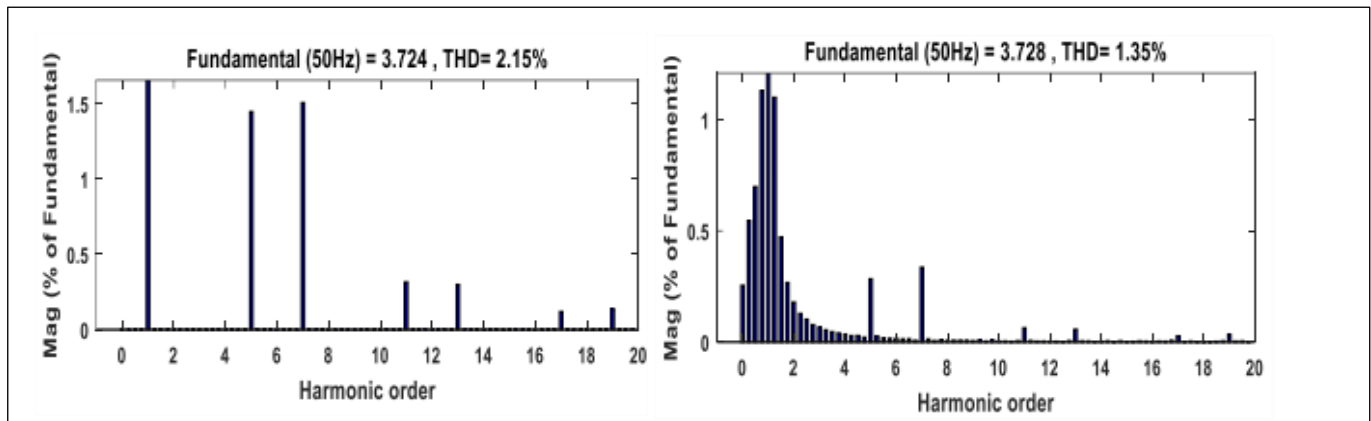


Figure 12: simulation results of source current under load variation: (a) PI conventional, (b) RTO-PI.
Source: Authors, (2026).



(a) (b)
Figure 13: simulation results of spectrum of harmonics of source current : (a) RTO-PI , (b) PI.
Source: Authors, (2026).

VI. CONCLUSIONS

In this paper, RTO algorithm are applied to improve the efficiency of DPC for 3-phase SAPF, the conventional technique is contrasted with the results. In light of the simulation results, it is possible to infer that rooted tree optimization is an effective method for optimizing the parameters PI controller of the DC link voltage in shunt active filters. Compared with the classical PI controller, rooted tree optimization provides better regulation and control of the DC link voltage in various operating conditions, including when the load changes.

VII. AUTHOR'S CONTRIBUTION

Conceptualisation: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Methodology: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Investigation: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Discussion of Results: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Writing – Original Draft: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Writing – Review and Editing: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Resources: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Supervision: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

Approval of the Final Manuscript: Ridha Rehouma, Laid Zellouma, Yacine Djeghader, Rabhi Boualaga.

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APPENDIX:

The parameters of the studied system are:

Source: $V_s=57\text{ V}$, $R_s=0.45$, $L_s=2.5.10^{-3}\text{ H}$, $f=50\text{ Hz}$. **Load:** $R_L=24\text{ and }28\ \Omega$. **SAPF:** $R_f=0.5\ \Omega$, $L_f=4.10^{-3}\text{ H}$, $C=1100\ \mu\text{F}$.