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Artificial Neural Network-Based Control of Vienna Rectifier for Power Factor Correction and Capacitor Voltage Balancing

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Abstract: This paper uses a modified control approach for a three-phase Vienna rectifier based on hysteresis current control and artificial neural network (ANN) for dynamic power factor correction and improved input current quality. The Vienna rectifier is a high-efficiency device and an ideal solution for medium-power applications that require unidirectional power flow and must adhere to strict power quality regulations. Nevertheless, conventional hysteresis current control has a variable switching frequency, which leads to increased electromagnetic interference (EMI) and a more complicated filter design. Therefore, an adaptive control method based on ANN is proposed, which can adaptively update the hysteresis band and current reference profiles according to real-time operating conditions. The ANN is employed to predict the intended current that will maximize the efficiency of the Vienna rectifier and to balance voltages across capacitors on the DC side under load disturbances. The simulation results confirm that the proposed control scheme achieves a near-unity power factor, low THD of the input currents, and stable DC–link voltage regulation in various dynamic operating conditions. The proposed strategy based on ANN achieves the objective of a future smart-grid interfaced rectifier system with resilience, intelligence, and hardware efficiency.

Keywords: Power factor correction, Artificial neural network (ANN), Vienna rectifier, Capacitor voltage balancing, Total harmonic distortion

Introduction

The rapid increase in the use of nonlinear and dynamic loads such as variable-speed motors, electric car charging stations, uninterruptible power supply, and data centres highlights the necessity for efficient and high-performance AC-DC power conversion systems (Gonçalves et al., 2021). The applications require front-end rectifiers that deliver stable DC voltage while positively influencing the utility grid, primarily through power factor correction and reducing current harmonics. Power Factor Correction (PFC) converters are essential elements of modern power electronics systems striving to adhere to global power quality standards, such as IEEE Std 519-2014 and IEC 61000-3-2 (Gonçalves et al., 2021; Saravana et al., 2018).

Traditional two-level six-switch Voltage Source Rectifiers (VSRs) with high linearity achieved effective Power Factor Correction (PFC) at the cost of increasing complexity, switching losses, and EMI, especially at high power levels (Soeiroet al., 2019). Work (Kolar et al., 2002) proposed the Vienna rectifier to alleviate these limitations and claims it is a high-performance unidirectional half-bridge, three-phase, three-level rectifier topology. The Vienna rectifier is a beneficial solution that reduces the conduction loss of electricity, decreases the voltage stress on components and improves the EMI performance of devices compared to six-switch rectifiers. using half an active device and a paired DC link. Controlling the Vienna rectifier poses significant challenges despite its technical benefits. It requires profound coordination between the adjusted input current and arithmetic voltage at the DC link, preserving a high-power factor across diverse working conditions. Using linear controllers, i.e., PI or PR controllers, is a good solution (Ahmed & Çelik, 2022; Liao et al., 2024). However, these approaches are sensitive to grid voltage distortion, parameter variability, and nonlinear loads. Additionally, they require complex calibration processes and may not be robust to variable operating conditions.

The hysteresis current control is an applicable choice thanks to its easy installation, fast dynamic response, and characteristic disturbance resistance (Aissa, 2017). This is primarily done by maintaining the current in a hysteresis band around the reference waveform, which enables fast corrective switching actions whenever the current moves beyond preset limits (Aissa, 2017). The disadvantage of hysteresis control of variable switching frequency, which makes filter design more complex, increases EMI and may cause uneven thermal stress on the power switches (Aiello et al., 2020).

Since the last decade, some intelligent control techniques have been proposed to tackle this limitation that can enhance these traditional methods. Particularly, (ANNs shown the great promise of nonlinear system modelling, uncertainty quantification, and complex control dynamics learning (Rajendran, 2021; Fekik, 2018). It is unnecessary to have precise mathematical models as ANNs can adapt to variations in grid power, load situations, and component features. Several studies have successfully implemented ANN-based controllers in active power filters, grid-connected inverters, and resonant converters (Bhattacharya & Chakraborty, 2010; Kandasamy & Kanakaraj, 2021; Imanieh & Malekjamshidi, 2011). In (Iqbal et al., 2021), the trainable controller based on a neural network has been utilized to control the reference currents of a shunt active filter adaptively, and it is illustrated that better performance can be obtained in this context than that attained with the classical controller.

This paper describes a new method of controlling a Vienna-based system that employs a rectifier. integrating artificial neural networks with a current hysteresis regulator. The (ANN) is utilized to regulate the direct current (DC) voltage across the capacitor at the DC side of the Vienna rectifier and to achieve a close unity power factor at the input side, also known as the grid side. The output of the ANN is the reference current integrated with the hysteresis bandwidth. This adaptive control method maintains the switching frequency almost constant while providing better current track performance and lower total harmonic distortion (THD), thus improving the power reliability and quality of the system.

The remainder of the article is divided into five parts, including the introduction in part 1. Part 2 presents the modelling of the Vienna rectifier. Part 3 elucidates the proposed control strategy based on artificial neural networks (ANNs). The subsequent section, part 4, presents the simulation results and associated discussions. Part 5, which discusses the main findings, concludes with the paper.

Modelling of Vienna Rectifier

Circuit configuration of a three-phase, three-level Vienna rectifier as shown in figure 1. This crucial apparatus facilitates effective unidirectional AC to DC conversion while minimizing harmonic distortion and achieving a near-uniform power factor. The following mathematical model may well represent the dynamic performance of this rectifier. The dynamic input phase currents for each phase (e.g., phase a) are regulated by Kirchhoff's voltage law, and their dynamics may be calculated as (Thangavelu et al., 2015), (Monroy-Morales et al., 2016):

$$v_{sa}(t) = R_s i_{sa}(t) + L_s \frac{di_{sa}(t)}{dt} + V_{rec,a}(t) \tag{1}$$

where $v_{sa}(t)$ denotes the source voltage, $i_{sa}(t)$ represents the input current, R_s is line resistance , L_s is the line inductance and $V_{rec,a}(t)$ indicate the voltage at the rectifier input terminal obtained by switching state and DC voltage. The rectifier voltage for each phase can be represented as

$$V_{rec,a}(t) = S_x(t).\frac{V_{dc}(t)}{2}, \ \ S_x \in \{-1, 0, 1\} \tag{2}$$

with $S_x = 1$ represented for upper capacitor connection and $S_x = -1$ denotes the lower capacitor and $S_x = 0$ indicates the neutral point. The Dclink voltage for C_1 and C_2 can be expressed mathematically as (Adhikari et al., 2016), (Zhang et al., 2020):

$$\frac{dV_{c1}(t)}{dt} = \frac{1}{C_1}\left(i_{c1}(t) - \frac{i_{load}(t)}{2}\right) \quad (3)$$

$$\frac{dV_{c2}(t)}{dt} = \frac{1}{C_2}\left(i_{c2}(t) - \frac{i_{load}(t)}{2}\right) \quad (4)$$

Being $i_{c1}(t)$ and $i_{c2}(t)$ are represented by the instantaneous current for both capacitors, upper and lower. While $i_{load}(t)$ does the load draw the current. The equations 1– 4 together define the electrical characteristics of the Vienna rectifier and serve as the foundation for formulating effective control techniques for sinusoidal input currents, balanced capacitor voltages, and regulated output voltage.

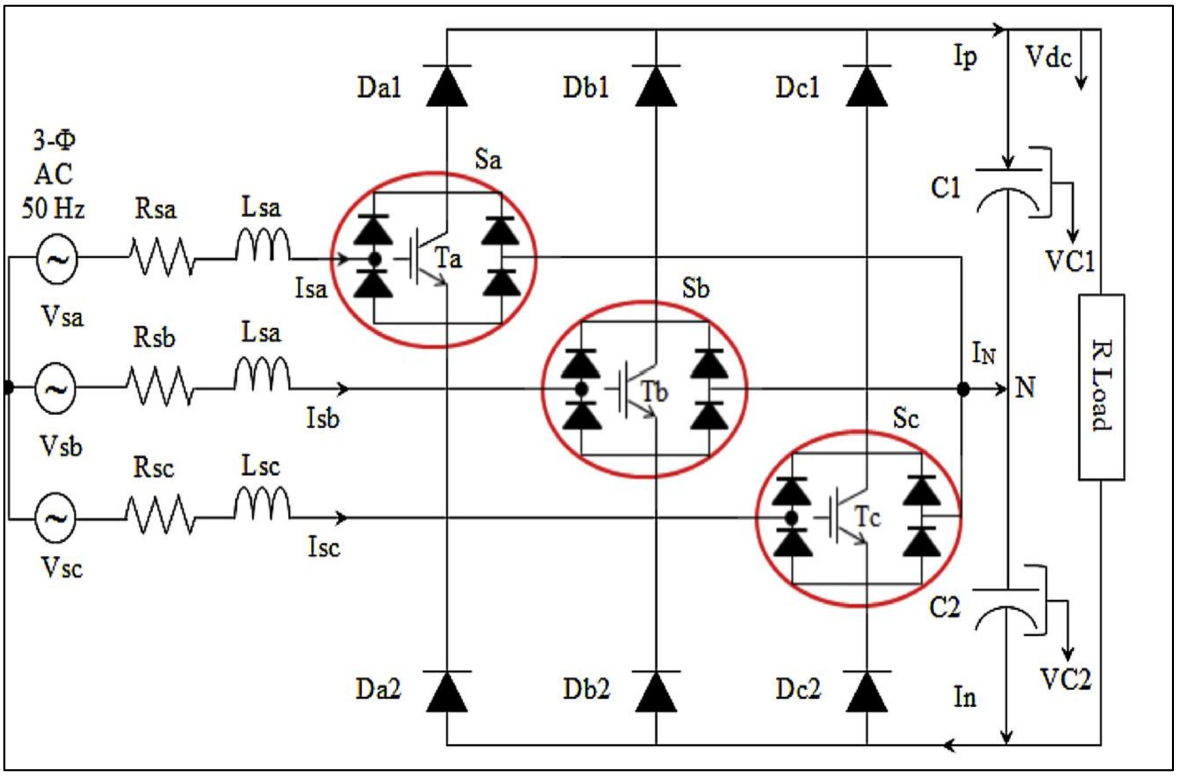

Figure 1. Schematic of 3 Ø Vienna rectifiers.

Proposed Control Strategy

Figure 2 shows the Vienna rectifier's control architecture, which includes hysteresis current regulation and an advanced proportional-integral (PI) control system with an artificial neural network. In this case, the primary goals are maximum power factor correction, optimal current THD, and consistent DC-link voltage management throughout operating modes. This proposal places Intelligent PI Controllers on the rectifier's phases A, B, and C to regulate the voltage of DC-link. Controllers receive the reference DC voltage V_{dc}^* and the voltages V_{dc1} and V_{dc2} of the two DC-link capacitors. An (ANN) in the PI controller dynamically alters controller gains to compensate for disturbances, grid imbalances, and load variations.

This step produces the reference DC-side current component I_d^* for sinusoidal current reference production. This part is the base. To obtain the unity power factor, scaling I_d^* with the instantaneous phase voltages Ua*, $Ub\,*$, and $Uc\,*$ generate the reference phase currents I_{sa}^*, I_{sb}^*, and I_{sc}^*. A compensating current, I_c^*, is provided in reference to achieve voltage balance between the divided DC capacitors. An accurate reference current that meets power distribution and capacitor voltage balancing criteria is generated. The reference and absolute phase currents are then controlled using hysteresis current controllers. These controllers maintain a hysteresis range for immediate inaccuracy. Each hysteresis controller outputs a switching signal (S') representing the current phase. This architecture allows a unidirectional Vienna rectifier to operate precisely, offers the user control over current flow, and assures safe switching.

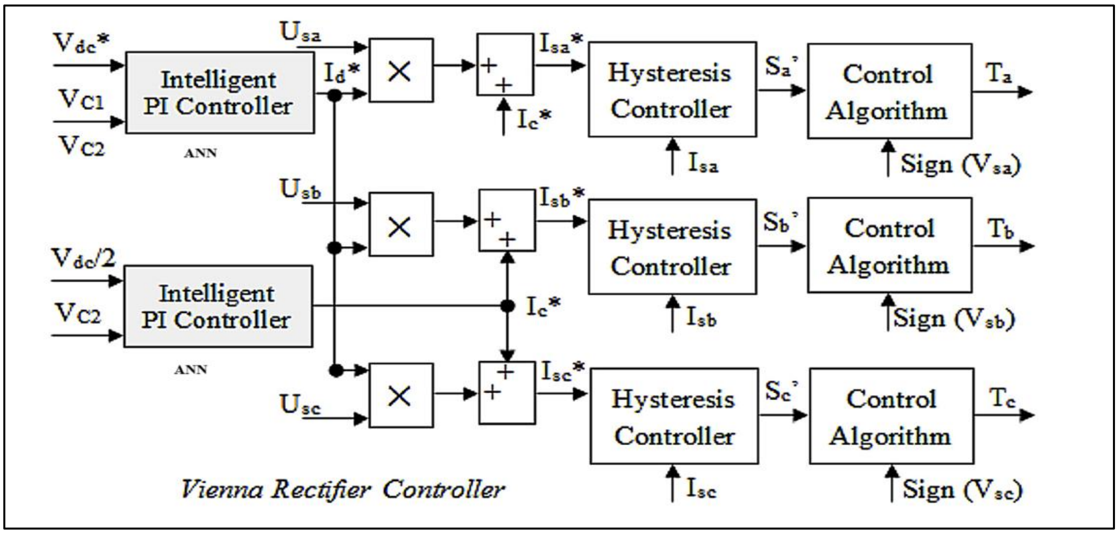

Figure 2. Control strategy of PFC-based Vienna rectifier.

The ANN Proposed Controller

An ANN voltage controller is a type that regulates the output voltage of Vdc to a constant value of $Vdcref$. Figure 3 shows that 100 hidden layers are used. $Vdcref$ is compared to the actual value Vdc, the error obtained is used as the input layer. The predicted output from the ANN controller is used as the output layer. The ANN current controller is trained to control the current component id to their reference value, idref.

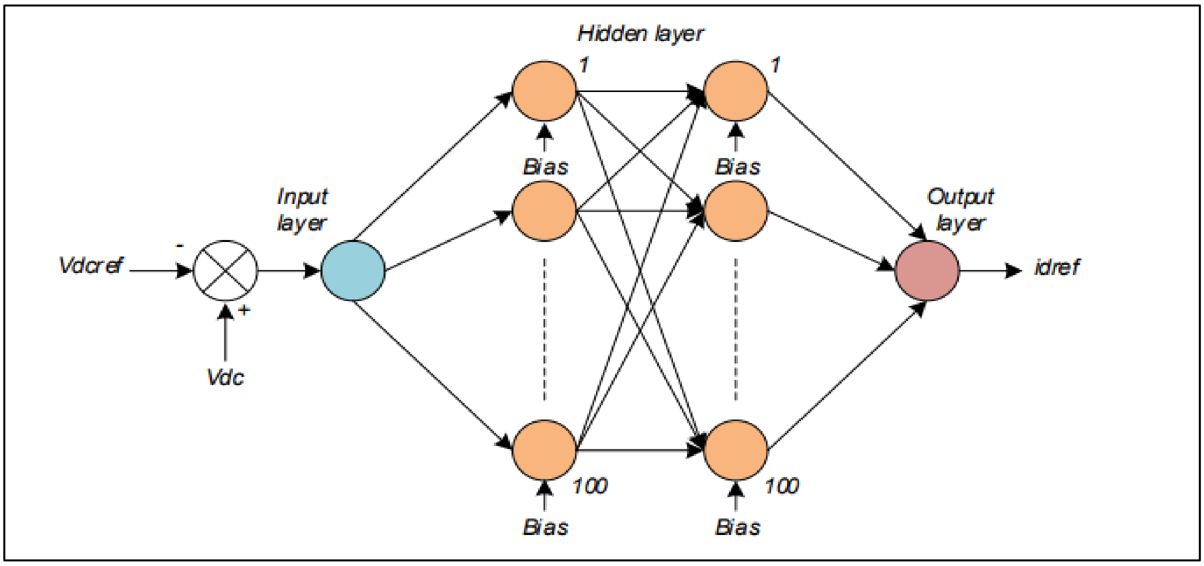

Figure 3. The proposed controller for DC-link voltage is based on the ANN approach.

System Objective

The primary aim of this paper is to propose control strategy to attain a unity power factor and to balance voltage of the upper and lower capacitors. This is done to achieve a pure sinusoidal waveform devoid of harmonics. This objective can be expressed mathematically as

$$v_{sa}(t) = V_m \sin \omega t \tag{5}$$

with V_m is the peak amplitude voltage, and ω is the angular frequency of the grid.

The second aim of the proposed control is to balance the voltage across the capacitor of the DC side of the Vienna rectifier, and this objective can be expressed as:

$$\frac{V_{dc1}}{2} = \frac{V_{dc2}}{2} \tag{6}$$

In order to investigate these two objectives, the ANN-based controller is combined with the hysteresis controller.

Results and Discussions of the Simulation

This section presents the simulation of the proposed control based on ANN for power factor correction and balancing capacitor voltage using Matlab/Simulink. for illustrate the efficiency of the ANN-based control scheme in assuring power factor correction (PFC) of the Vienna Rectifier, the simulation results displayed in Figures 4 to 8 are provided. Figure 4 shows the waveforms of the phase input voltage and current so that the input current is virtually sinusoidal and in close phase with the voltage. This demonstrates that the power factor operating is close to unity.

As shown in figure 5 the DC link voltages at the upper and lowest capacitors (vdc1 and vdc2) are well balanced with low ripple, showing the ANN voltage symmetry control capabilities. Figure 6 demonstrates that the total DC link voltage quickly recovers from the transitory impacts of an increase in load and stabilizes at roughly 650 V after the initial start-up. This occurs shortly after the initial start-up. The fact that a quick change in load power from about 27 kW to 45 kW at 0.5 s is efficiently controlled without impacting the system's stability is demonstrated by Figure 7, which provides evidence for this assertion. Figure 8, which demonstrates that the power factor of each input phase always approaches 0.999, even during transient periods, supports this fact. Based on these results, the ANN controller can provide stable voltage regulation, balanced capacitor voltages, and improved power quality, substantiating its appropriateness for dynamic and nonlinear power electronic applications.

Table 1. Specifications of the proposed system.

Description	Value
Maximum power	45 kW
Grid side phase voltage	220V
DC-link voltage	650V
Grid frequency	50Hz
Switching frequency	100 kHz
Filtering inductor	0.4 mH
Resistance of inductor	0.04Ω

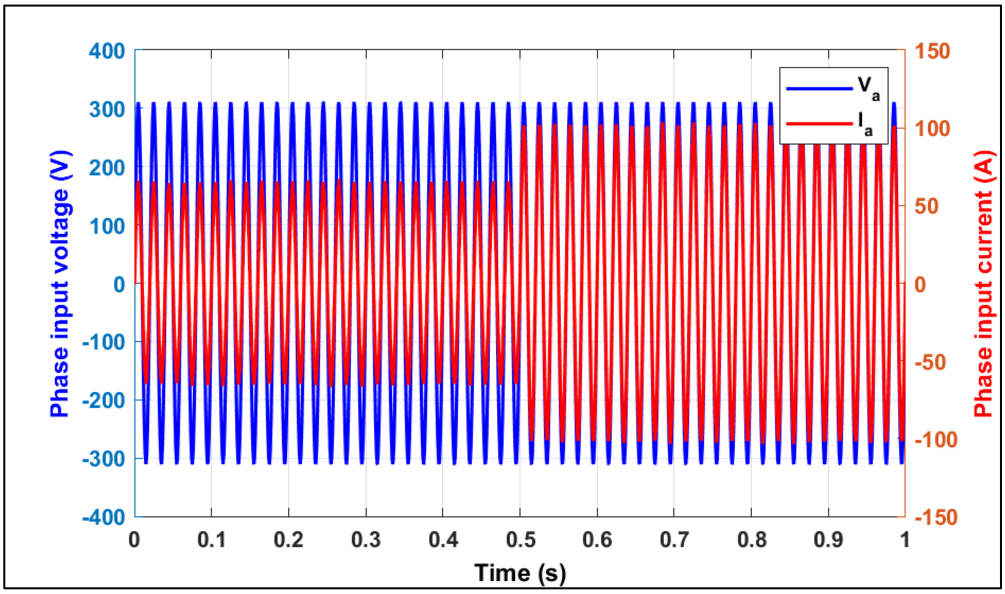

Figure 4. Input voltage and current on the grid side phase waveforms

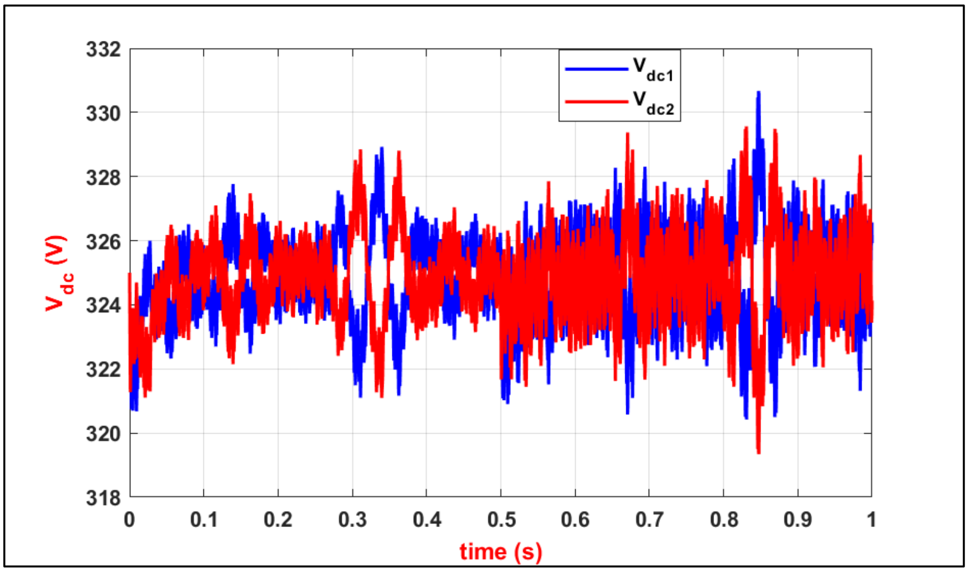

Figure 5. Response of voltage of DC link across the upper, lower capacitors

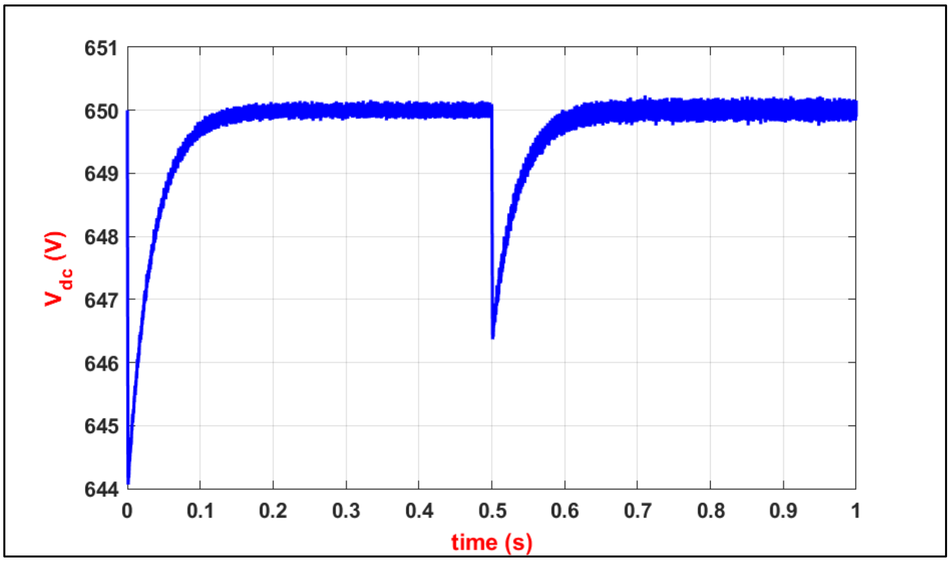

Figure 6. Total DC link voltage response

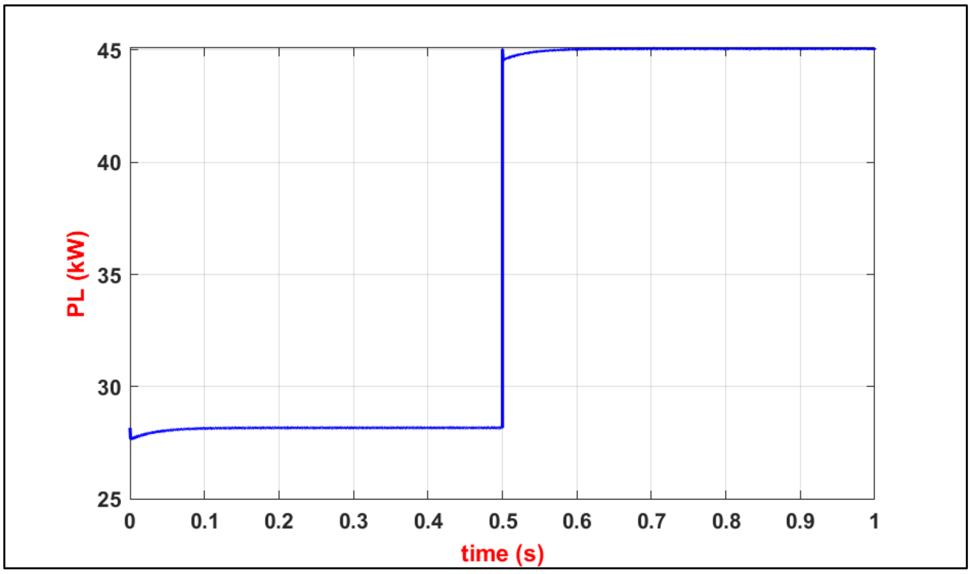

Figure 7. Load power response

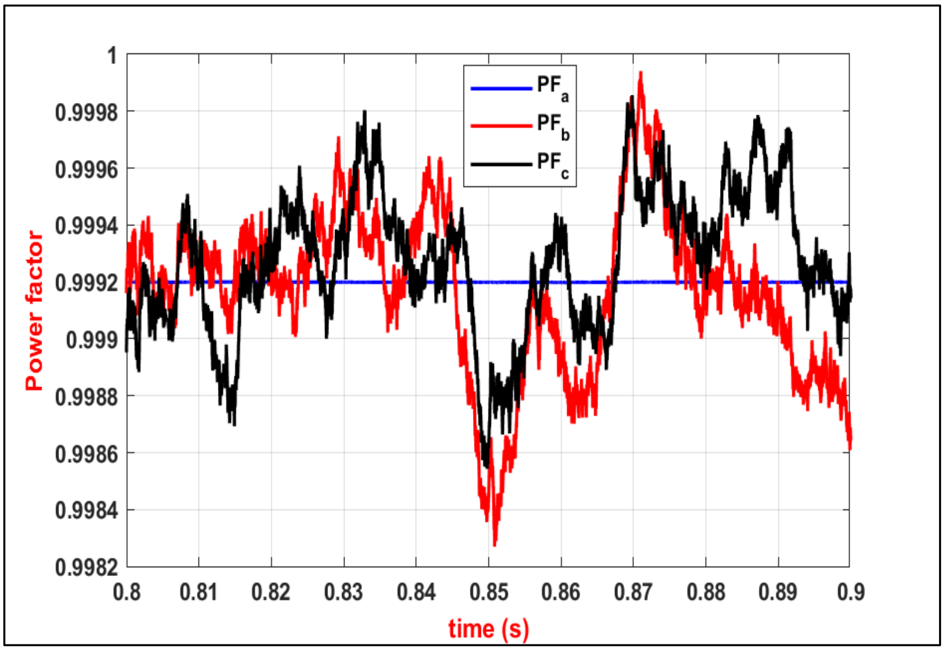

Figure 8. The power factor for each phase of the input side

Conclusion

This study presents a modified hybrid control approach for a Vienna rectifier that integrates the rapid dynamic response of hysteresis current management with the adaptive learning capabilities of an artificial neural network (ANN). The Vienna rectifier is acknowledged for its reduced number of switches, less voltage stress, and three-level output. It is especially suitable for medium-power front-end AC–DC conversion applications with good power quality. Integrating ANN into the control loop enables the system to provide real-time modifications of the hysteresis band and reference current shaping, addressing the primary limitation of traditional hysteresis controllers-namely, the changeable switching frequency.

Simulation results indicate that the proposed ANN-based hysteresis control enhances current tracking, diminishes total harmonic distortion (THD) of input currents by almost 0.97%, and achieves near-unity power factor under steady-state and transient situations. The control technique is highly resilient to grid fluctuations, load variations, and system nonlinearities. The Vienna rectifier, equipped with an adaptable and sophisticated control architecture, is a viable choice for high-performance power converter systems in future smart grids, electric car charging stations, and industrial automation processes. Subsequent activities include assessing hardware implementation feasibility, real-time validation of digital controls, and evaluating performance under high power throughput.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The author states that there is no conflict of interest.

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