Enhanced performance of electric vehicle Vienna rectifier through soft computing and sliding mode control

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ABSTRACT

The Vienna rectifier (VR) is a component that plays a pivotal role in various power electronics domains. It finds extensive utility in applications that require increased efficiency and minimized harmonic distortion. Some examples of these applications include solar photovoltaic grid-tied inverters, renewable energy systems, and electric motor variable speed drives. However, the ever-evolving system characteristics have spawned problems with the dependability and efficiency of such systems, making them less than ideal in both respects. This research proposes a ground-breaking method by using a three-phase VR model that is enhanced with a modified whale optimization algorithm (MWOA)-infused sliding mode controller (SMC), which is then, incorporated smoothly using the MATLAB/Simulink platform. The efficiency of the proposed system is shown by the construction of a working prototype, which also contributes to this demonstration. The suggested paradigm's enhanced performance is proven numerically and qualitatively via detailed comparisons with present systems.

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1. INTRODUCTION

Vienna rectifier (VR) combines the benefits of both three-phase diode rectifier and active rectifier. The conventional three-phase diode rectifier output voltage is a pulsing voltage with significant ripple. The three-phase active rectifier yields a refined output voltage characterized by its minimal ripple; however, the intricacy and cost of the system are notably heightened. The VR gets around these drawbacks by combining passive and active parts. A near-ideal power factor adjustment is achieved by the VR using three pairs of capacitors and diodes, and an active front-end converter aids in lowering harmonic distortion and enhancing system efficiency. This produces an output voltage of high quality with little power factor and harmonic distortion is nearer unity.

Many different applications, including charging of electric vehicle, telecommunications systems, welding, data centers, and motor drives, use front-end converters with controlled DC output voltage [1]. There is a growing need for power converters with higher voltage and current ratings [2]-[4] for use in applications with high power levels, such as charging electric vehicles (EVs) and welding. Notably, the front-end converter in [5]-[7] employs a unidirectional boost rectifier for motor traction purposes. The VR is an optimal choice for addressing high-power requisites due to its remarkable efficiency, minimized voltage stress, and superior power-to-weight ratio [8]. While proportional-integral (PI) controllers are the prevalent choice for controlling power converters, attaining a linear mathematical model requisite for the PI controller presents challenges. Moreover, parameter fluctuations, nonlinearity, and load disturbances invariably impede the efficient application of the PI controller [9]. Moreover, power factor correction controllers (PFC) [10], direct power controllers (DPC) [11], SMC [12], [13], proportional-integral controllers (PI) [14], voltage-oriented controllers (VOC) [15], along with their amalgamation DPC-SVM [16], [17], stand out as extensively adopted control methodologies for EV charging stations. Notably, voltage-oriented controllers (VOC) are recurrently harnessed as proficient power control mechanisms within active front-end converters, primarily aimed at power factor modulation.

The system's transient analysis can be enhanced by combining a conventional controller and an advanced controller and reduce the input current's overall harmonic distortion when compared to utilizing only one controller. The numerous converters that have been used in the literature can also be employed for low power DC applications. A hybrid controller was utilized in earlier AC/DC converter designs with traditional three-phase regulated rectifiers, which calls for high-rated input and output filters to reduce input current THD [18]. The system's efficiency and power density decreased as a result. To solve this issue, a novel combination of a VR and a PI controller is proposed.

This research article introduces an innovative approach involving the integration of an MWOA-based SMC for the three-phase Vienna rectifier, tailored to cater to high-power requirements. The proposed framework presents a hybridized control configuration, employing the VR under the MWOA-SMC paradigm for EV charging stations. By the advanced transient stability and exceptional Total Harmonic Distortion (THD) of less than 5% achieved at an output voltage of 650 V/90 A, the VR aligns with the IEEE-519 standard. The novel design recommendation distinctly outperforms prevalent AC/DC power converters in high-power scenarios, yielding a substantial reduction in input current THD while simultaneously augmenting power density.

2. METHODOLOGY

Figure 1 depicts a proposed flow diagram for the MWOA-SMC Vienna rectifier. It employs a VR and an SMC based on a MWOA method to maintain consistent output. An illustration of a rectifier circuit employed within the domain of power electronics to facilitate the conversion from AC to DC is embodied by the three-phase Vienna rectifier.

2.1. Three-phase VR modeling

This VR configuration finds pervasive application across industries necessitating not only elevated power efficiency but also minimal harmonic distortion. Its attributes greatly benefit sectors such as data centers, telecommunication systems, EV charging stations, welding power sources, and electric aircraft. Figure 2 depicts integrating a sliding mode, voltage-oriented microcontroller with the three-phase Vienna rectifier.

Voltage-oriented controllers reduce input current harmonic distortion, enhance grid-side input power factor, and remove output DC voltage ripples. Putting three phases into a rotating reference frame, giving it to a control process, and then turning it back into three steps is called "VOC." The VOC technique uses the Clark and Park transformation matrix in (1) and (2) and Figure 3.

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} sin\theta & cos\theta \\ -cos\theta & sin\theta \end{bmatrix} \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} \quad (2)$$

Where, V_{sa}, V_{sb}, V_{sc}- ABC domain source voltage; $V_{s\alpha}$, $V_{s\beta}$, V_0, V_d, V_q – $\alpha\beta_0$ and dq_0 domain source voltages; θ – Operating phase angle in power system.

A similar transition occurs when a three-phase input current is converted. In order to control the Vienna rectifier, the (3) was changed by inverse park transformation. Once the reference voltages $V_{q,ref}$ and $V_{d,ref}$ have been obtained, the gate pulses can be derived.

$$\begin{bmatrix} v_{\alpha,ref} \\ v_{\beta,ref} \end{bmatrix} = \begin{bmatrix} sin\theta & -cos\theta \\ cos\theta & sin\theta \end{bmatrix} \begin{bmatrix} v_{d,ref} \\ v_{q,ref} \end{bmatrix} \quad (3)$$

The three-phase quantities are transformed into stationary two-phase quantities using the Clark transformation. The two-phase stationary quantities are transformed into the synchronous reference frame via a process known as park transformation. The revolving reference frame is transformed into the two-phase stationary quantities via inverse park transformation and then converted in to three-phase quantities.

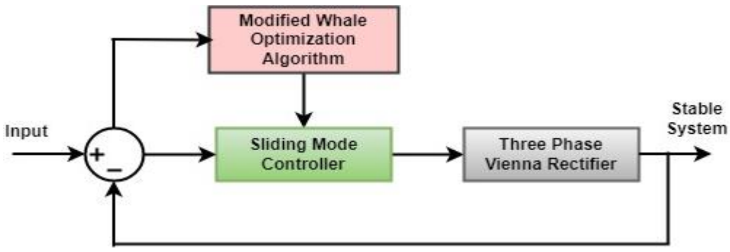


Figure 1. MWOA-SMC VR system design

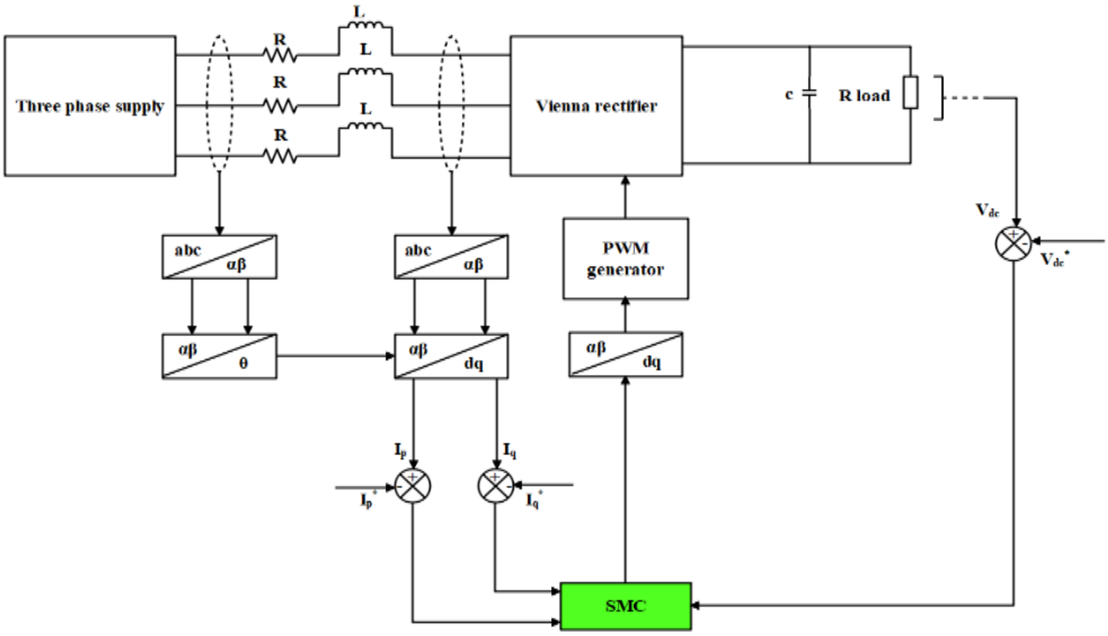


Figure 2. Block diagram of three-phase VR controller

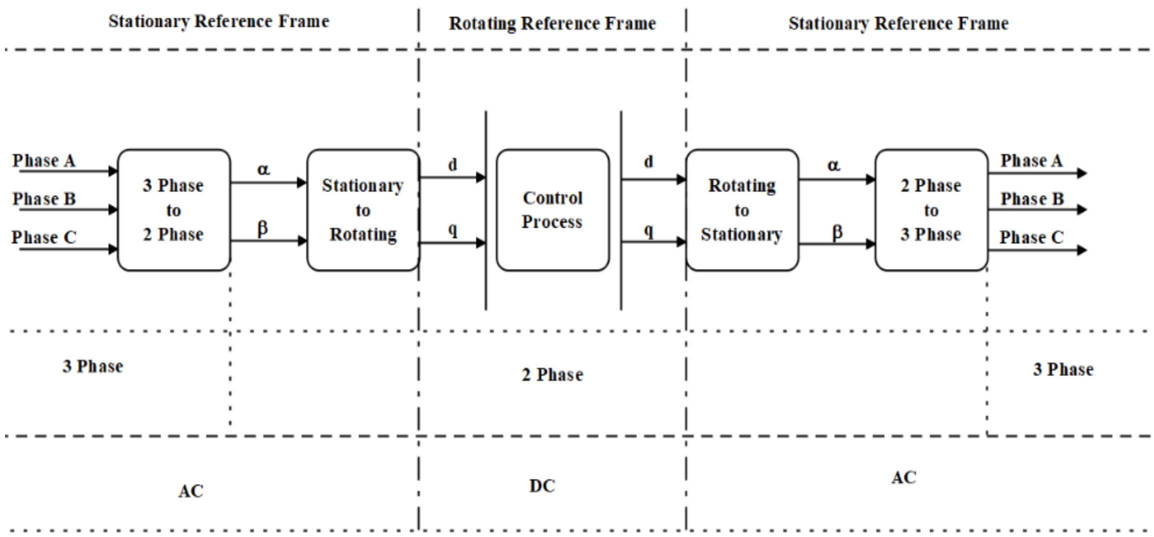


Figure 3. Transformation of VOC using Park's and Clark's methods

2.2. Modeling of SMC

When employed in engineering applications, a SMC is a form of control system that offers resilience against various system disruptions and uncertainties. The primary goal of the SMC is to establish a sliding surface, which serves as a dynamic border between the system's intended conduct and its undesirable behavior. The correctness of the system model, the decision made on the sliding surface, and the control rule all affect how well the SMC works. Numerous engineering disciplines, including robotics, aircraft, power systems, and automotive control, have used the SMC [19]. Figures 4(a) and 4(b) depict the SM controller's construction and sliding surface and switching function s(t) are (4)-(6).

$$s(t) = k_1 \frac{d}{dt} e(t) + k_2 e(t) \tag{4}$$

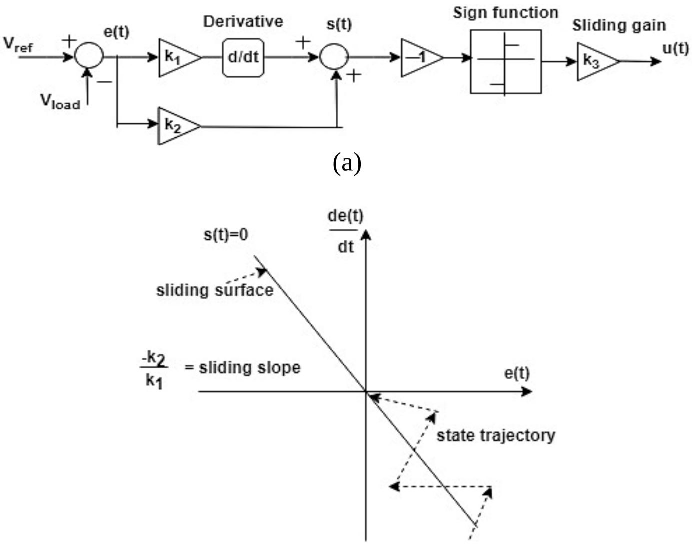
While s(t) = 0

$$\frac{d}{dt} e(t) = -\frac{k_2}{k_1} e(t) \tag{5}$$

e(t)- tracking error; k_1 and k_2 –sliding slope gain. The sliding mode controller control law is given by equation $u(t) = -k_3 sgn\big(s(t)\big)$ or

$$u(t) = \begin{cases} -k_3 if s(t) \geq 0 \\ k_3 if s(t) < 0 \end{cases} \tag{6}$$

k_3- sliding gain sgn ( ) – sign function. In SMC, gain of the switching function (k_1 and k_2) and sliding function (k_3) are calculated by MWOA.



(a)

(b)

Figure 4. SM controller: (a) structure and (b) sliding surface

2.3. WOA controller design and tuning

2.3.1. Whale optimization algorithm (WOA)

The WOA is a kind of optimization software that takes its cues from the natural world and is modeled after the method that humpback whales use to hunt. In 2016, Seyedali Mirjalili was the one who presented the idea for the first time. The bubble-net feeding method is a specific and unusual hunting strategy used by humpback whales. They swim around the prey and create a specific bubble on a path that forms a circle or a nine shape.

2.3.2. Modified whale optimization algorithm (MWOA)

Within MWOA [20], [21], target prey is the best option for a solution. Two correction factors, CF_1 and CF_2, with respective values of 2.5 and 1.5, are used to adjust the search agent during the search in order to get around this restriction. The revised equations are now in (7) and (8).

$$\vec{D} = \left|\vec{C}.\vec{X}^*(t) - \vec{X}(t)\right|/C_{F1} \quad (7)$$

$$\vec{X}(t+1) = (\vec{X}^*(t) - \vec{A}.\vec{D})/C_{F1} \quad (8)$$

Where X^* and X represents the location of the best solution and the position vector, t represents the iteration that is now being performed, A and C represent the coefficient vectors, a value between 0 and 2 is used, and r is a random integer between 0 and 1.

Similarly, a correction factor is included in the exploitation phase; however, in this instance, it refers to the spiral updating position as in (9).

$$\vec{X}(t+1) = (\vec{D}' \ .e^{bl}. \ cos(2\pi l) + \vec{X}^*(t))/C_{F2} \quad (9)$$

Whales swim simultaneously in the two directions mentioned above when they are hunting. For the two approaches mentioned above, a 50% probability is used to update whale positions given in (10).

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A}. \ \vec{D} & if \ p < 0.5 \\ \vec{D} \ . \ e^{bl}.cos(2\pi l) + \vec{X}^* & if \ p \geq 0.5 \end{cases} \quad (10)$$

The metric for the separation between the whale and its prey is $D^{'} = \vec{X}^* - \vec{X}(t)$ (best solution), and b [1, 1], p [0, 1] and *l* [-1, 1]. The correction factors from (11) and (12) are used to adjust the search agents' locations in the present MWOA technique. Equations are considered as (11) and (12).

$$\vec{D} = \left|\vec{C}. \ \vec{X}_{rand} - \vec{X}\right|/C_{F1} \quad (11)$$

$$\vec{X}(t+1) = (\vec{X}_{rand} - \vec{A}. \ \vec{D})/C_{F2} \quad (12)$$

$\vec{X}_{rand}$ - current iteration random whales. The symbol || represent the absolute values. Finally, note the following conditions:
- |A| $>$ 1 WOA algorithm exploration to find a global solution rather than a local one.
- $\left|\vec{A}\right| < 1$ Adjust the search agent position

3. PROPOSED SYSTEM

Figure 5 (see Appendix) illustrates the integration of a three-phase supply alongside a VR configured with MWOA-SMC for an EV charging system, comprising the core components of the proposed framework. The modified WOA-SMC VR has several advantages over traditional control strategies, such as better transient response, faster dynamic response, and improved accuracy. It is commonly used in applications where high performance and high reliability are required, such as in renewable energy systems, electric vehicle charging systems, and power supplies for high-tech equipment. The core operations of the Modified WOA-SMC VR encompass three fundamental tasks:
- Ensuring the stabilization of the DC output voltage at a predefined magnitude.
- To give a power factor of unity, input harmonic distortion must be controlled, and the voltage must be kept in phase with it.
- WOA aids in bringing the utility grid's power factor closer to unity and lowering the THD input current to below 5% in order to comply with IEEE 519 requirements.

4. DESIGN OF PASSIVE COMPONENT

The DC output voltage ripples are reduced by the capacitor which can be calculated by using (13).

$$C = \frac{1}{3}\left(\frac{P_{ac}}{4*f*(v^2-(v-\Delta v)^2}\right) \quad (13)$$

Where f = Grid frequency; P_{ac} = Input power; and v = Change in input voltage. The inductor (14) will reduce the harmonics in the switching frequency. Required inductance can be calculated by using the (14).

$$L_i = \frac{\frac{V_{bus}}{2}}{4*F_{sw}*\Delta i_{pp_{max}}} \quad (14)$$

5. RESULT AND DISCUSSION OF PROPOSED SYSTEM

The simulation was carried out with the assistance of a MATLAB 2016-Simulink application. A VR with VOC's-SMC optimization using the MWOA has been modeled using MATLAB Simulink. It was determined whether or not the recommended controller was effective for high-power. The proposed solution improves the system's stability, reduces harmonics in the input source current, and increases the grid side power factor. In Table 1, you see a depiction of the simulation parameter [25]. The MWOA-VR-SMC simulation diagram and prototype are shown in Figure 6 and Figure 7.

Table 1. Parameters used

Parameter	Proposed system (VR-SMC)	Parameter	Proposed system (VR-SMC)
Input inductance	5 mH	Switching frequency	12 kHz
Input resistance	5 Ω	RMS source voltage	440 V
Resistor load	20 Ω	SMC: K_1, K_2, K_3	K_1=592.2; K_2=21.6; K_3=11.7
DC link capacitor	220 µF	MWOA: Population size, r, d	Population size=50; r=0 to 1; d=3
Source frequency	50 Hz		

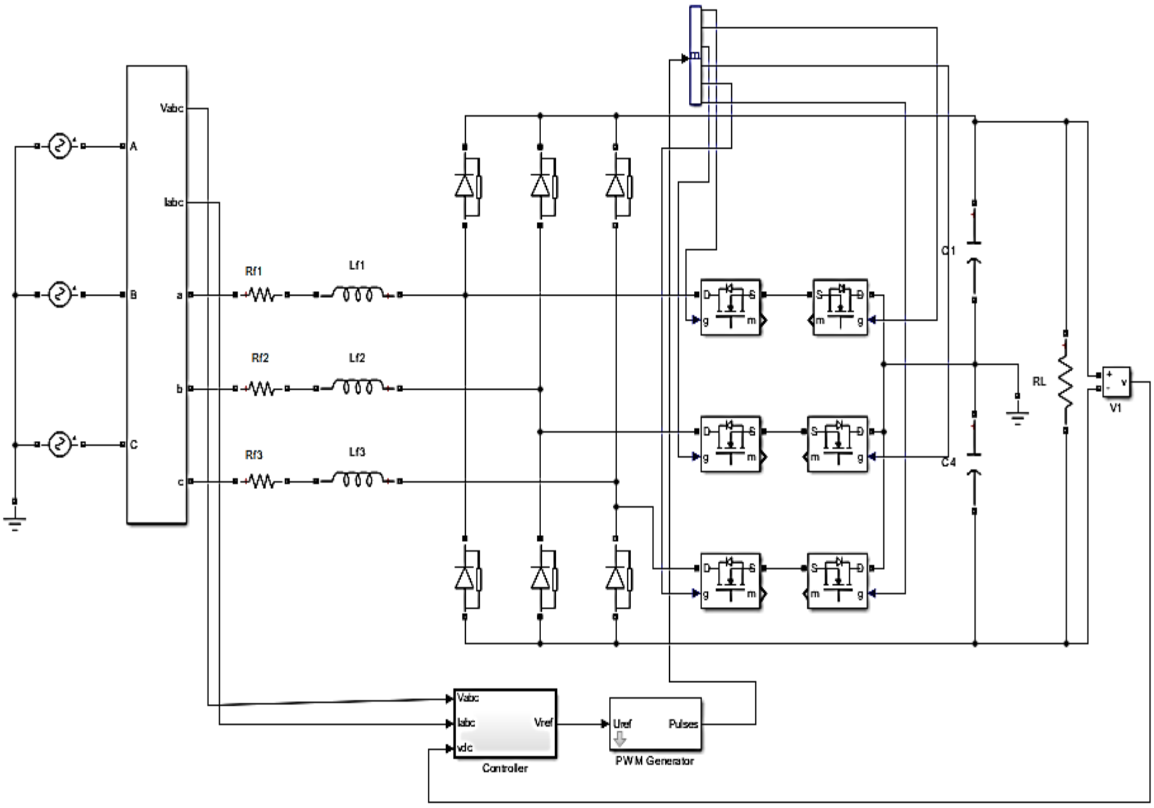


Figure 6. Simulation circuit of VR with MWOA-SMC

Figure 7. Experimental setup of VR with MWOA-SMC

The input voltage waveform shown in Figure 8 for a 440 V source voltage. The output voltage and current waveform for fast charging station are shown in Figure 9 for 440 V input voltage and it gives 650 V DC output voltage reaches steady state at the settling time of 0.014 seconds. Figure 10 presents the total harmonic distortion (THD) values for both the input voltage and input current with output voltage of 650 V.

Specifically, for the depicted scenario, the THD values stand at 2.13% for the input current and 1.09% for the input voltage, given an output voltage of 650 V and an input voltage of 440 V. This particular approach demonstrates its suitability for high-power applications by effectively mitigating harmonics, resulting in minimal distortion. Additionally, this strategy ensures that the power factor on the grid side remains at unity, contributing to efficient power utilization.

The proposed MWOA-SMC-based VR has undergone comprehensive experimental testing to achieve a consistent and stable DC voltage output while maintaining low total harmonic distortion (THD) in the input current. Notably, the system successfully complies with the stringent IEEE-519 standard due to its input current THD, which remains below the prescribed threshold of 5%. To gauge the efficacy of the approach, Table 2 provides a comparative analysis, juxtaposing the THD performance of the proposed methodology against various alternative strategies.

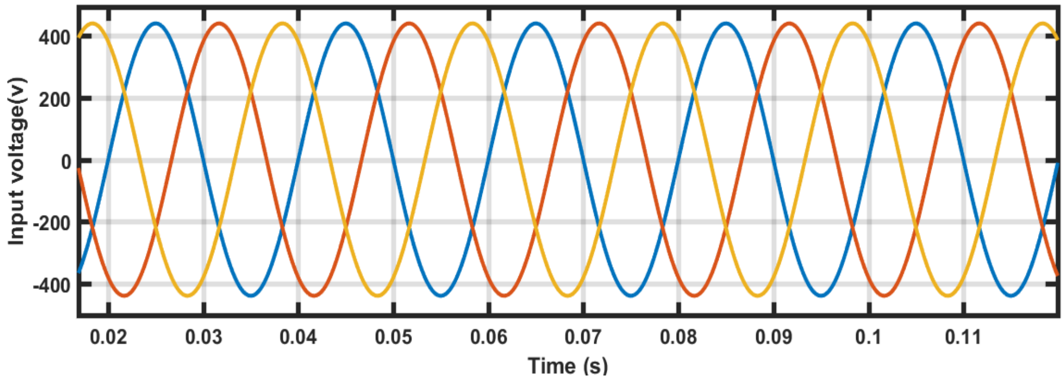


Figure 8. Input voltage waveform for VR-MWOA-SMC with 440V_{AC}

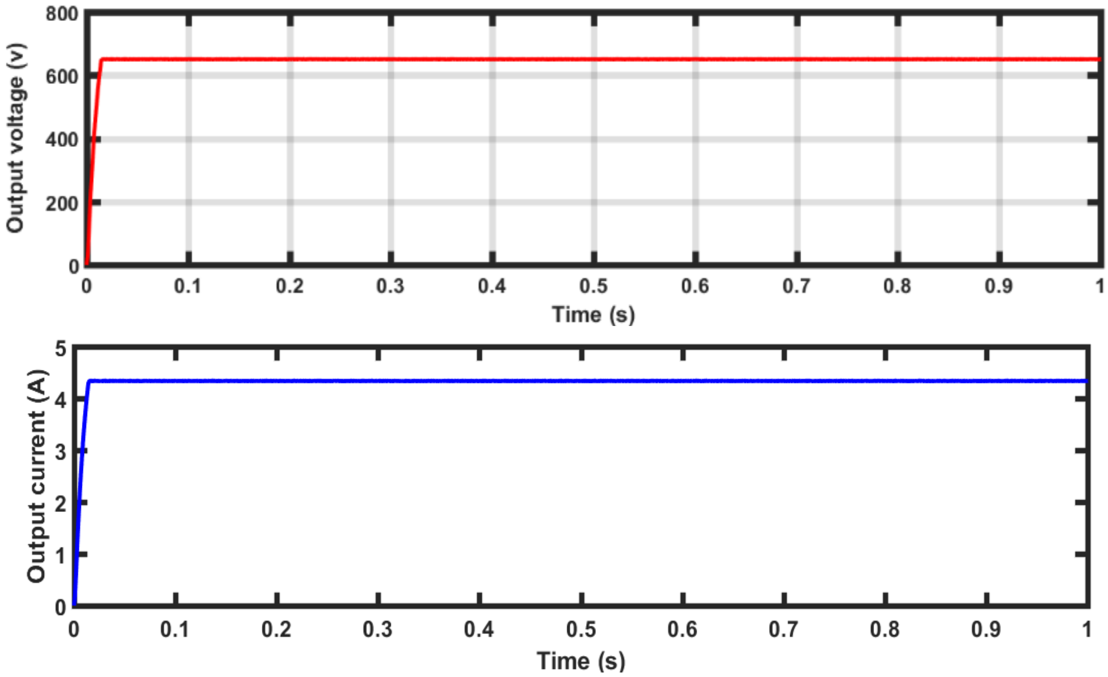


Figure 9. DC output voltage and current for VR-MWOA-SMC with 440V_{AC} and 650V_{DC}

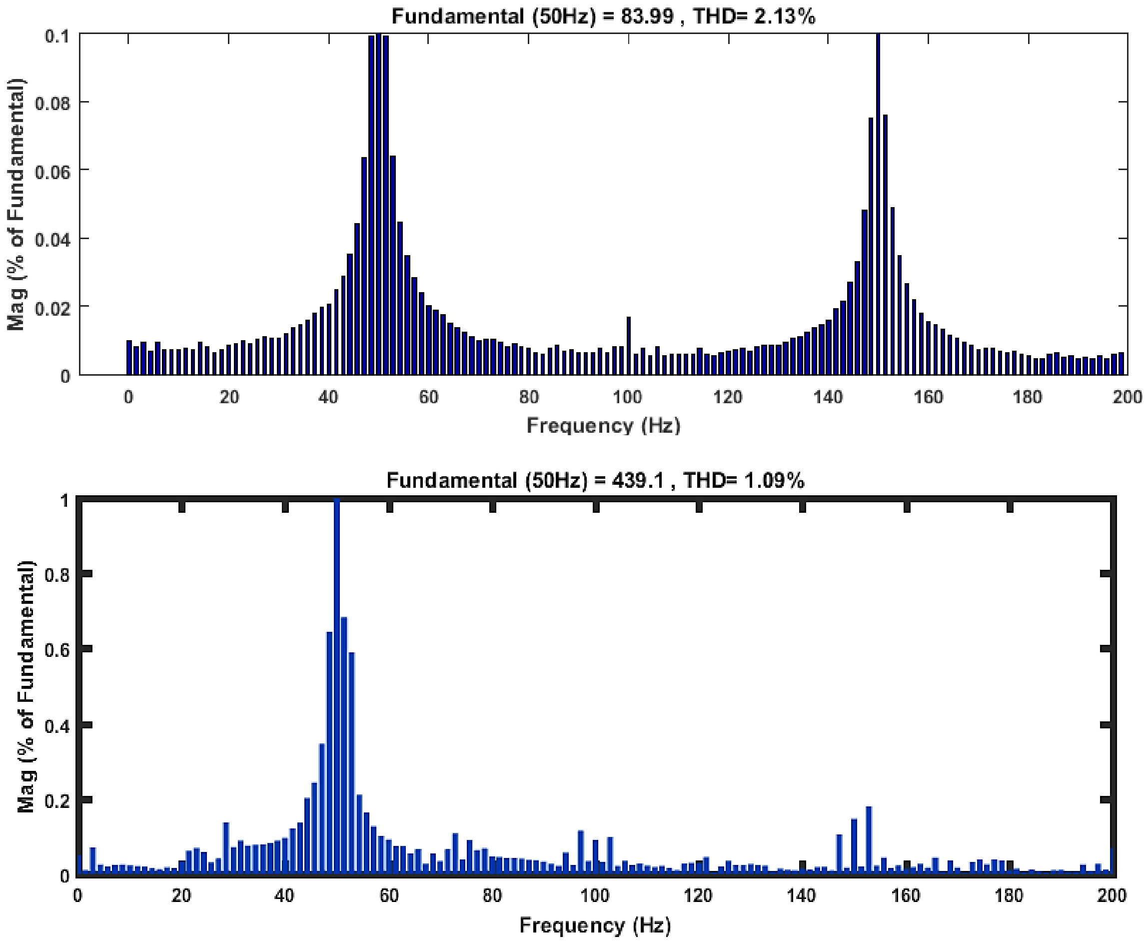


Figure 10. THD for input current and voltage for VR-MWOA-SMC

Table 2. Comparison result

Power controller	% THD	Application
DPC controller [22]	6.4	Regulate grid voltage in inverter applications
PFC controller current controller [23]	6.22	EV charging applications.
Direct power controller [24]	4.6	Wind energy applications
PSO-PI VR [25]	2.47%	High power uses include welding power supplies and DC fast charging stations.
Proposed system (MWOA- SMC VR)	2.13%	

6. CONCLUSION

This research introduces a novel approach involving a SMC designed for a three-phase VR, and its optimization is achieved through the application of the MWOA. This advanced controller architecture aims to enhance the system's performance and stability. The entire model of the proposed three-phase VR, equipped with the MWOA-SMC controller, is meticulously simulated and realized using MATLAB software through a Simulink model. The experimental validation of this approach yields promising results, notably showcasing a remarkably low input current THD measurement of 2.13%. The strategy employed not only ensures the reduction of harmonic distortion in the input current but also effectively maintains the utility grid's power factor near unity. The paramount objective of the Vienna rectifier, underpinned by the MWOA-SMC controller, is to generate a DC output voltage of 650V accompanied by an output current of 85A. Impressively, this operation is executed while upholding a unity power factor at the mains and strictly adhering to the stipulated input current THD requirement of less than 5%. These stringent operational parameters are aligned with the critical specifications mandated for the operation of EV fast-charging stations or welding power applications and the guidelines outlined in the IEEE-519 standards.

APPENDIX

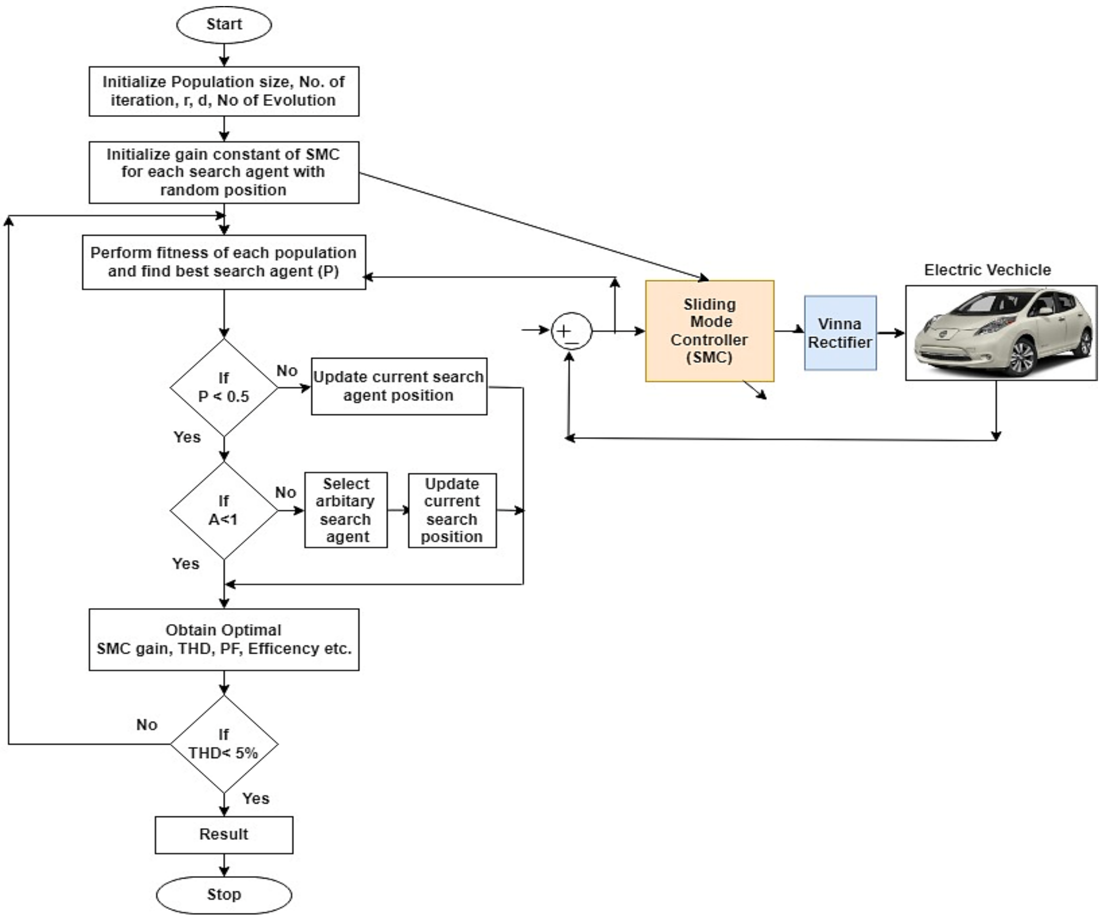


Figure 5. Proposed three-phase VR MWOA-based SMC

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