RESEARCH ARTICLE

Dynamic Voltage Stability Enhancement in Electric Vehicle Battery Charger Using Particle Swarm Optimization

GOWTHAMRAJ RAJENDRAN[ID]1, (Graduate Student Member, IEEE),
CHOCKALINGAM ARAVIND VAITHILINGAM[ID]1, (Senior Member, IEEE),
KANENDRA NAIDU2, **AHMAD ADEL ALSAKATI**[ID]1, (Graduate Student Member, IEEE),
KAMESWARA SATYA PRAKASH ORUGANTI1, (Graduate Student Member, IEEE),
AND MOHD FAIZAL FAUZAN3

1High Impact Research Laboratory, School of Computer Science and Engineering, Faculty of Innovation and Technology, Taylor's University, Subang Jaya, Selangor 47500, Malaysia
2School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor 40450, Malaysia
3Solar Energy Research Institute, Universiti Kebangsaan Malaysia (UKM), Bangi, Selangor 43600, Malaysia

Corresponding authors: Chockalingam Aravind Vaithilingam (aravindcv@ieee.org) and Mohd Faizal Fauzan
(drfaizalfauzan@ukm.edu.my)

ABSTRACT Electric vehicles (EVs) are poised to lead the transportation sector as the primary choice of automobile due to their efficiency and environmental benefits. EVs with enhanced autonomy and reduced pricing have become feasible in the market, enabling a gradual transition for higher EV penetration. However, electric vehicles require highly efficient and stabilized charging stations in urban areas to ensure the vehicle's charging time is not compromised. In this regard, the Vienna rectifier with a voltage-oriented controller (VOC) plays a significant role in improving the power quality of the utility grid for EV battery charger applications. The low stability of the battery charger's output voltage and current is due to the trial-and-error method used to select the PI controller gains. In order to improve the voltage and current stability, the particle swarm optimization (PSO) technique is used to optimize VOC's PI controller gains. The code composer studio (CCS) platform integrates the PSO technique for EV battery chargers in the experimental setup. The Vienna rectifier with VOC for EV battery charger is implemented using TMS 320F28337 digital signal controller in the test board. Findings indicate that the PSO optimized VOC improves the output voltage and current stability by 12% compared to the existing trial-and-error technique. Furthermore, the proposed system is tested in an experimental setup that provides input current THD to less than 5% for different load variations (up to 1.5kW) to meet the IEEE-519 standards. Results from simulations and experimental setup verify that the proposed PSO-PI controller-based Vienna rectifier significantly improves EV battery chargers' output voltage and current stability.

INDEX TERMS Vienna rectifier, voltage oriented controller (VOC), particle swarm optimization (PSO), electric vehicles, charging stations.

I. INTRODUCTION

Fossil fuels are widely used to power the existing transportation sectors in the modern world, which increases pollution,

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noise, and global warming [1], [2]. Another key issue for the existing transportation industry is the fast depletion of underground petroleum resources due to the overuse of fossil fuels and the rise in fossil fuel prices [3], [4], [5]. The rising cost of fossil fuels, environmental pollution, and the finite lifespan of fossil fuels have motivated automobile makers to

investigate alternative sources such as natural gas, hydrogen gas, and biofuel for automobile applications. Among the different technological advancements, electric vehicles (EVs) have received considerable interest as an innovative means of transportation and are rapidly integrating into the existing transportation system [6], [7]. The average efficiency of an internal combustion engine vehicle (ICE) is 25%, which indicates that only 25% of the fuel is converted to usable energy, and the other 75% is lost due to heat and friction losses. In comparison, an electric vehicle has an average efficiency of 80% [8], but it has practical limitations in terms of overall mileage and refueling time compared to an ICE vehicle [9]. The limited range of EVs due to battery performance poses a significant challenge to their widespread adoption. Battery performance seems to be influenced only by battery technology, but actual battery usage and charging methods also have a significant impact. From this perspective, the battery charger's efficiency is critical to the battery's overall performance [10]. Power electronic converters play an important role in ensuring the EV battery charger maintains high efficiency and stable performance. It has various parameters such as input current total harmonic distortion (THD), power factor, voltage regulation, and filter design. These parameters are significantly high during nonlinear operating conditions. In order to avoid nonlinear operating conditions, various control techniques are proposed to guarantee that the stability of the system is maintained within the limited boundaries under different operating conditions. Even more importantly, due to the nonlinear operating conditions in the EV battery chargers, the input current harmonics are increased, resulting in a low input power factor. Conventional controllers and energy-efficient converters are widely used to reduce the input current THD less than 5% to meet the IEEE-519 standards and improve the power factor nearly unity at the utility grid for EV battery chargers. In this regard, the Vienna rectifier with a VOC has been chosen to provide input current THD of less than 5% and improve the power factor to near unity for EV battery chargers [11], [12], [13]. The VOC's PI controller is highly dependent on the existing trial-and-error method to achieve a stable output voltage and current. However, the stability of the output voltage and current is decreased due to the trial-and-error method. As a result, the system operates with lower level of reliability under different load conditions.

PI controllers are commonly available and known for their simplicity and adaptability [14], [15], [16], and due to PI controller's effectiveness, numerous design techniques have been introduced apart from the commonly used Ziegler and Nichols technique [17]. Furthermore, to improve the performance of the PI controller, many tuning guidelines for the structure, control modes, system model properties, and anti-windup approaches of the PI controller are extensively developed [18], [19], [20], [21], [22]. The PI controller's optimal for providing solutions in the power industry control system is to significantly reduce the issues encountered by the system parameters such as

integral square error (ISE), integral absolute error (IAE), rise time (t_r), starting time (t_s), and peak overshoot (M_P) [23], [24]. The reduction in these system parameters helps to improve the stability of the system. In this regard, the researchers and designers always choose the new algorithm that has less complexity, uses fewer parameters, and is more efficient than the existing algorithms [25]. The existing trial-and-error method of PI controller tuning techniques is inflexible, unstable, and complex. As a result of the lack of knowledge of mathematical models and trial-and-error methods, the robustness of the PI controller is reduced, resulting in poor controller performance. In order to address the periodic errors in the output voltage, sliding mode controllers (SMC) are implemented in rectifier systems for different load variations. As a result, the total harmonic distortion at the input current is maintained at less than 5% to meet the IEEE-519 standards with linear and non-linear loads [26].

Evolutionary computing techniques, artificial neural networks (ANN), and fuzzy logic are used to design the optimized PI controllers. Due to the fast development of computer power, the PI controller based on a computer is designed within a short period. The tuning strategies based on the optimization technique are more efficient than the existing trial-and-error method due to their independence from system dynamics and PI control structure [27], [28], [29]. Heuristic algorithm-based optimization strategies used in control engineering are one of the powerful ways of solving control issues in a wide range of situations [30], [31], [32], [33], [34], [35], [36]. These algorithms are particularly useful in process control due to their simple structure, enhanced optimization, and fast response. They are more effective at solving complex optimization problems with many dimensions than conventional optimization approaches. Because of their adaptability, these algorithms are well-suited to contemporary classical design methodologies. Regardless of the model order, these algorithms serve as a critical tool for developing classical and modified structured controllers for an unstable process model class. The genetic algorithm (GA) [37] and particle swarm optimization (PSO) technique [38] are the two key strategies commonly used in controller design applications for optimization. Due to the intensive study of various algorithms, the PSO technique has significantly been improved for numerous industrial applications. As a self-tuning algorithm, the PSO technique uses the Objective Function (OF) provided to assist the algorithm in identifying the optimum K_p, K_i, and K_d values for the process. As a typical criticism of nature-inspired design approaches and bio-inspired metaheuristics, it is often argued that they both need modifications or adjustments in parameters prior to optimization. The classical PSO technique, on the other hand, contains fewer heuristic variables than the GA technique, making it more straightforward for optimization. Therefore, the PSO technique is selected to optimize VOC's PI controller in this study as a simpler technique.

This study mainly focuses on optimizing VOC's PI controller-based Vienna rectifier for EV battery chargers.
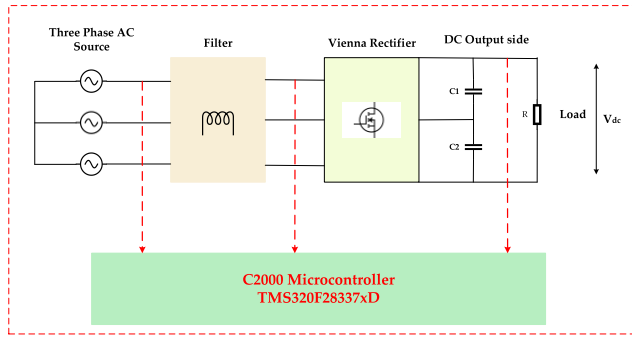
FIGURE 1. Block diagram of three-phase Vienna rectifier with a TMS 320F28337xD.
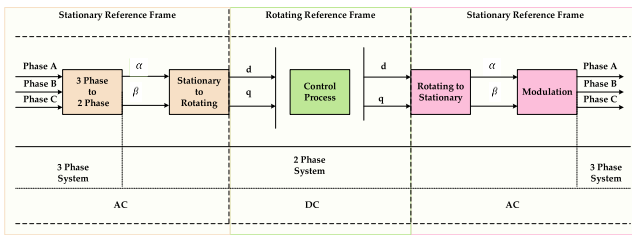

FIGURE 2. The Park's and Clark's transformation voltage-oriented controller.

The VOC's PI controller is optimized with the help of PSO technique using MATLAB software. The findings show a reduction in input current THD of 3.27% to satisfy the IEEE-519 standard. Furthermore, the proposed PSO-PI-based VOC with Vienna rectifier for the EV battery charger improves the output voltage and current stability. The system parameters such as rise time and settling time values are 0.16 seconds and 0.31 seconds, respectively, which is better than the trial-and-error method. Also, the peak overshoot value is 1.21% for the Vienna rectifier with VOC for the EV battery chargers. The system parameters such as rise time, settling time, and peak overshoot of output voltage and current are improved using PSO-PI technique for the Vienna rectifier with a VOC. Hence, the findings show that the proposed system outperforms the existing trial-and-error control method in terms of performance [39]. In addition to the previous research, this research focuses on experimental validation of PSO technique for VOC's PI controller to provide highly efficient and stabilized EV battery chargers. The prototype of the EV battery charger is designed and developed using a TMS 320F28337xD control card on the experimental test board. The Code Composer Studio (CCS) platform integrates the PSO technique for EV battery chargers into the experimental setup. In simulations and real-time experimental tests, it is clear that the proposed PSO-PI controller-based Vienna rectifier significantly improves the output voltage and current stability for EV battery chargers.

II. VIENNA RECTIFIER WITH VOLTAGE-ORIENTED CONTROLLER

The Vienna rectifier is an energy-efficient converter used in various advanced industrial applications such as electric vehicle charging stations, telecommunication applications,
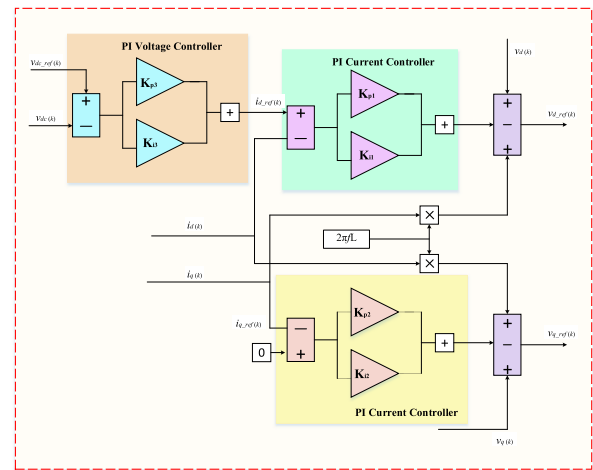

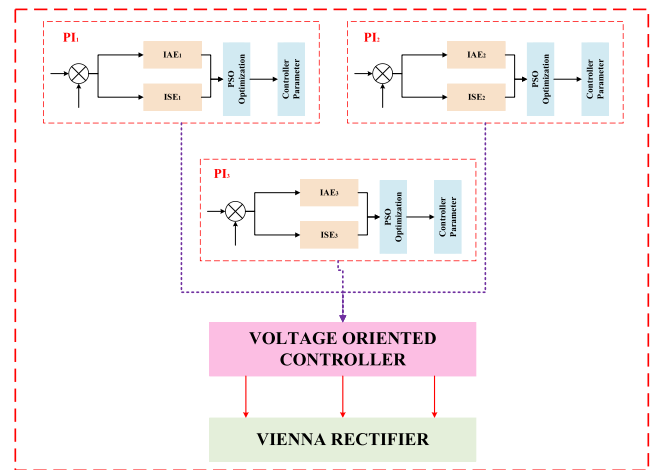**FIGURE 3.** PI controller structure in voltage-oriented controller.

FIGURE 4. The PSO optimized objective functions for VOC's PI controller.

data centers, welding power sources, and electric aircraft applications. It is often used as a front-end power converter as it can provide input current with THD less than 5% and an improved power factor at the grid side to satisfy the IEEE-519 standards. The Vienna rectifier also has high-power density and high-power handling capability for conversion of AC/DC applications. The block diagram of a three-phase Vienna rectifier integrated with the C2000 microcontroller is shown in Fig. 1. In this study, the Vienna rectifier is used as a front-end converter with VOC for the EV battery charger. The VOC is a highly efficient controller for EV battery chargers compared to existing controllers with Vienna rectifier. The Park's and Clark's transformation of VOC is shown in Fig. 2, and the three PI controller in the voltage-oriented controller is shown in Fig. 3. Park's transformation helps to transform input three-phase quantities such as phase A, phase B, and phase C into two-phase stationary quantities (α and β). Also, Clark's transformation in the VOC helps to transform stationary two-phase quantities into two-phase rotating quantities or reference frames (d-axis and q-axis). Similarly, the inverse Park's transformation and Clark's transformation help to convert the rotating two-phase reference frame (d axis and q axis) into a stationary reference frame and the two-phase
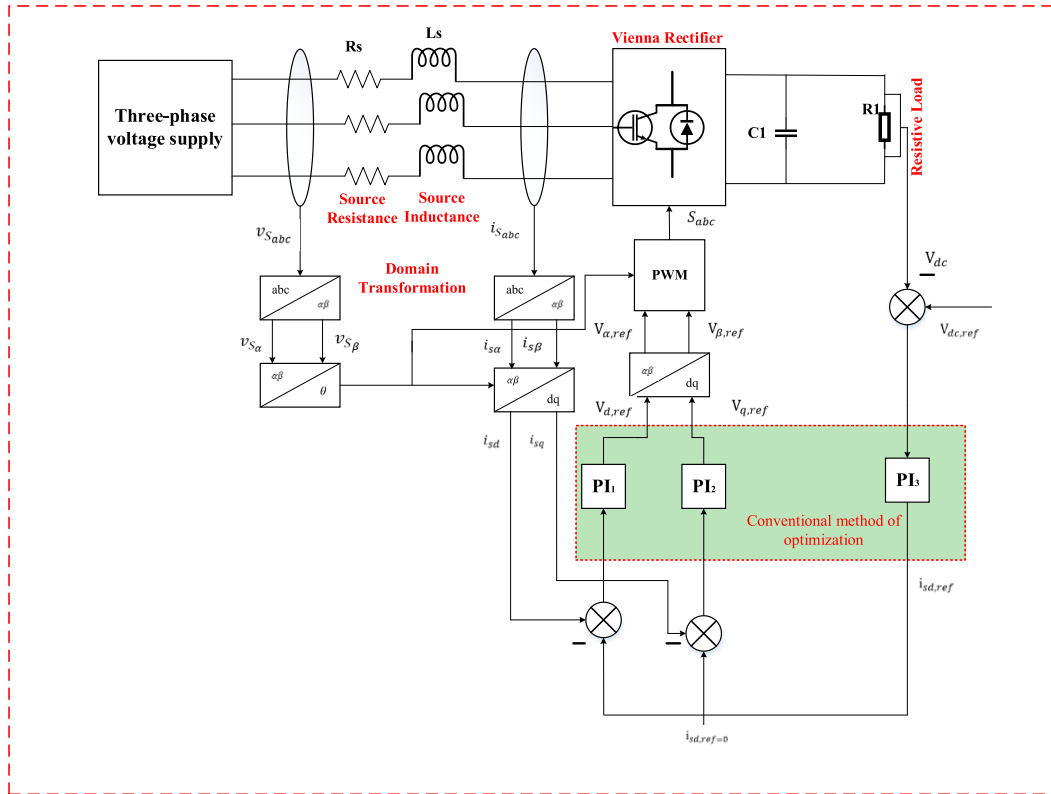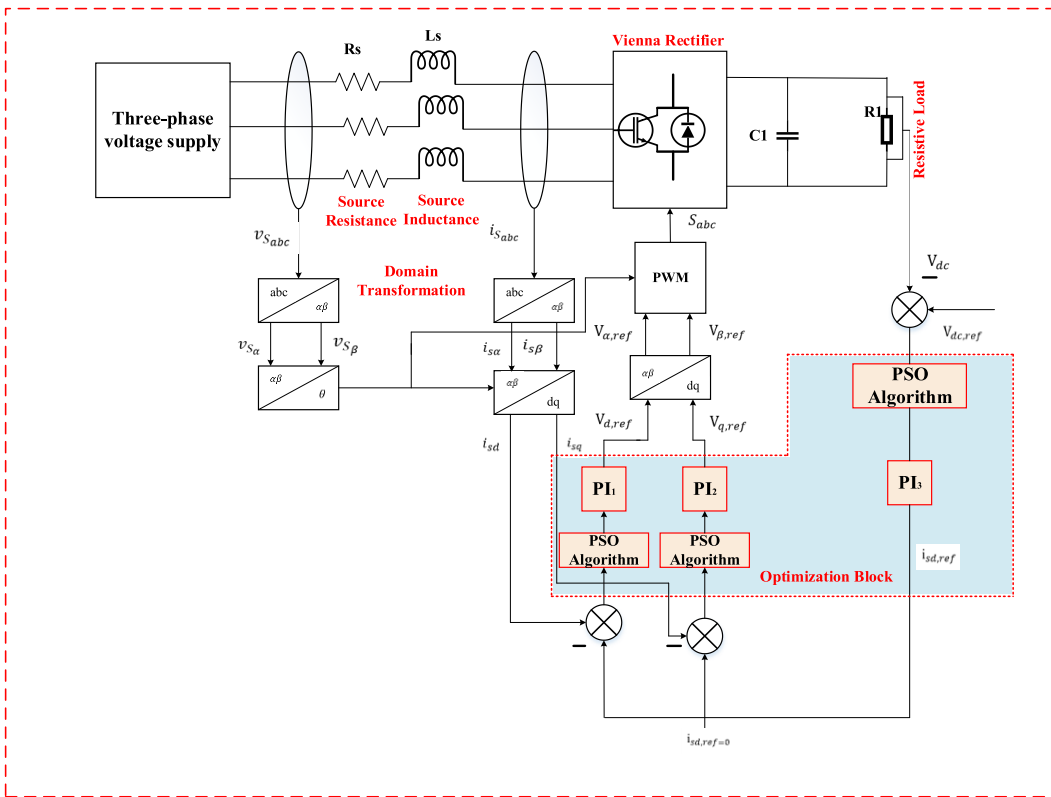
FIGURE 5. The Vienna rectifier with VOC's PI controller. (a). existing system with a trial-and-error method (Highlighted in green). (b). A proposed system with PSO optimization technique (Highlighted in blue).

TABLE 1. Various applications using PSO technique for PI controller optimization.

Ref.	Features	Applications	Remarks
[48]	The combination of PSO technique with PI controller and fuzzy with PI controller is proposed to improve the performance of the system.	Power system application	The input current harmonics are reduced to less than 5%, which satisfies IEEE-519 standards
[49]	The performance of the system has been improved with the help of a PSO optimized optimal fuzzy PI controller than a conventional PI controller.	Power system application	PSO-based PI controller with fuzzy controller provides better stable operation than the conventional PI controller for the power system control system.
[50]	A duplicate PSO (D-PSO) technique is proposed to track the maximum power at the wind energy system with zero reactive power.	Wind energy application	PSO-based PI controller optimization for DFIG parameter optimization provides good reference tracking performance with reduced overshoot and a faster settling time.
[51]	The power electronic system such as buck converter uses PSO technique for optimal K_p and K_i control parameters featured in PI controller in the system.	Power electronic application	PSO technique optimizes the PI controller that generates PWM for buck converters in DC/DC power converter applications.
[52]	The performance of the induction motor drive is attained using PSO technique for reducing the system performance parameters such as IAE and ISE values.	Induction motor drive for various applications	The response of the vector controller for induction motor drive is faster using the PSO technique for PI controller.
[53]	The tuning of PI controller featured in the Luo converter has been compared with the Zeigler Nicholas method and PSO technique for the application of SRM motor drive. The proposed PSO system performs better compared to the ZN tuning method.	Harmonics reduction for power electronic application	PSO technique optimizes the PI controller in the bridgeless Luo converter to reduce the input current harmonics in the utility grid side. The proposed system reduces the input current harmonics to 9% to satisfy IEEE-519 standards.
[54]	The gain constants (K_p and K_i) of PI controllers featured in the inverter for PV system has been tuning using PSO technique to give best results compared to the conventional tuning methods.	Solar Photo Voltaic system application	The power converter in the off-grid PV system is optimized to reduce input current THD by less than 5% to meet the IEEE-519 standards. As a result, the proposed system provides an input current THD of 3.94% for off-grid PV systems.
[55]	A novel hybrid PSO-pattern search technique for fuzzy-based PI controller tuning method surpasses many previously suggested strategies, making it a highly promising technique for handling more complex engineering optimization issues in the future.	Automatic Generation Control of multi-area power system application	PSO optimized fuzzy PI controller for automatic generation control of multi-area systems. The proposed system provides better performance for robustness analysis, sensitivity analysis, two area power systems with governor dead band nonlinearity, and three area power systems with generation rate constraints.
[56]	The capacitive voltage transformer's (CVT) error has been reduced using PSO technique. In this research, the double regression PSO technique has been proposed to perform better than the conventional controllers.	Power system operation and control application	PSO technique proposed in this study aims at the high-precision requirements of CVT measurement. The proposed system provides the lowest regression error based on amplitude or phase error calculation. Compared with different optimization algorithms, PSO can perform better to improve the accuracy of calculating the measurement error of the power transformer.
[57]	The Particle Swarm Optimisation technique provides the optimal scheduling for electric vehicles with a microgrid.	Electric vehicle charging schedule application	PSO optimization is used to optimize the placing of charging stations based on the location. Therefore, the proposed system can solve the scheduling problems, and adaption of the charging station is made according to the specific situation of the problem.

reference frame into three-phase ABC systems, respectively. The existing trial-and-error method-based Vienna rectifier with a voltage-oriented controller helps to reduce the input current THD to less than 5% and improve the power factor at the utility grid side. In addition, the PSO optimization of VOC's PI controller with Vienna rectifier for EV battery charger helps to optimize the gain constants of PI controller to improve the system's stability.

The synthesis of the PI controllers is mathematically described by,

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \qquad (1)$$

where K_p is the proportional gain constant, K_i is the integral gain constant, and $e(t)$ is the difference between the set point and the plant output.
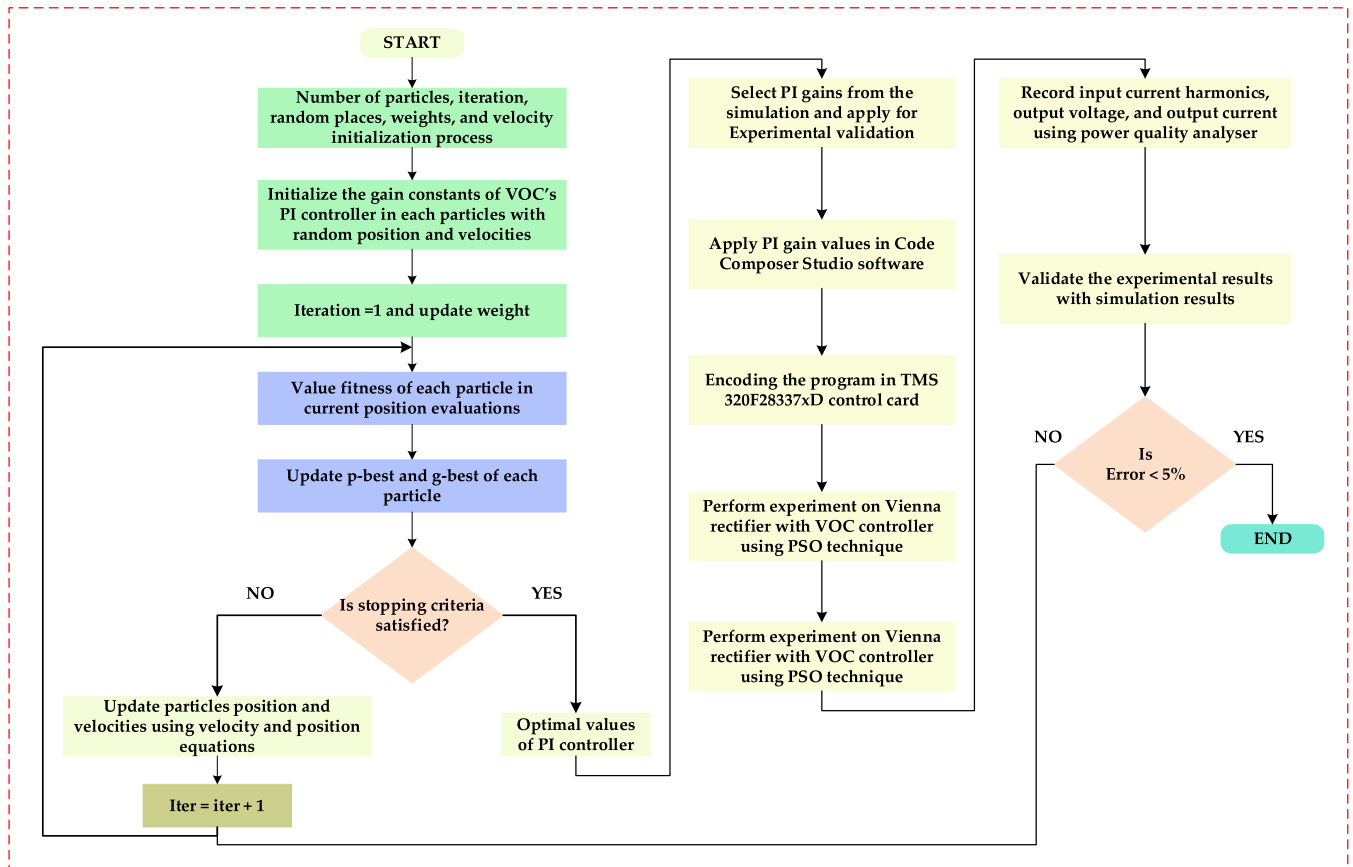
FIGURE 6. Flowchart of PSO technique for PI Controllers.

TABLE 2. Control parameters of PI controller with PSO algorithm [37].

W	Best Values	Iteration Number	K_p	K_i	M_P	$t_r(s)$	$t_s(s)$	ISE	IAE
0.25	1	50	0.5832	0.5352	0	3.4	3.2	6.527	2.845
	2	100	0.5682	0.5830	0	3.2	3.6	5.428	2.928
	3	150	0.5483	0.5416	0.002	4.2	3.1	6.467	2.586
0.5	1	50	0.6243	0.6924	0	4.4	4.5	7.934	2.674
	2	100	0.6300	0.6378	0	5.6	5.2	7.856	2.652
	3	150	0.6482	0.5518	0.006	2.9	7.5	6.54	2.451
0.75	1	50	0.6218	0.6457	0	3.3	5.4	7.456	2.670
	2	100	0.7346	0.6295	0.0046	6.4	7.1	5.98	2.954
	3	150	0.5873	0.5967	0	3.2	8.3	8.652	3.018
1.0	1	50	0.3865	0.7357	0.1524	1.5	7.9	4.672	1.976
	2	100	0.5760	0.8351	0.1211	1.6	8.8	3.651	1.789
	3	150	0.9582	0.5882	0	5.3	5.3	6.492	2.354

The K_p and K_i gain constant values of the VOC's PI controller are traditionally optimized with the help of the trial-and-error method. By using the trial-and-error method, the system's stability has been reduced and it takes a long time to process the overall system operation in the numerical analysis and the experimental test. In order to overcome the problems mentioned above in the VOC's PI controller, the PSO technique has been introduced. The PSO optimization technique helps to optimize the gain constant values of the PI controller with a reduction in the overall operation time. Consequently, the stability of the system has been improved.

III. PSO CONTROLLER DESIGN AND TUNING

The PSO approach is an evolutionary optimization method inspired by flocks of birds and schools of fish. It is often
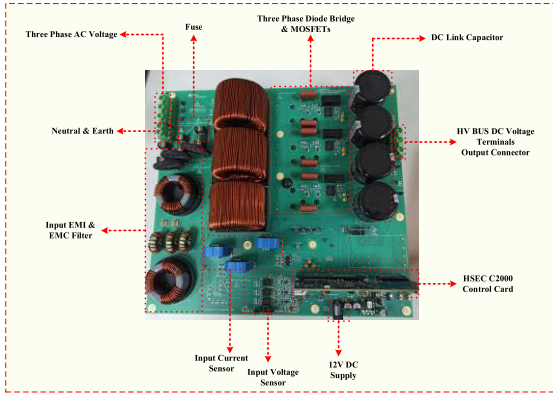
FIGURE 7. Cross-sectional Board view of Vienna Rectifier with VOC.

FIGURE 8. Experimental implementation of Vienna rectifier with VOC using PSO technique.

FIGURE 9. DC output voltage for Vienna rectifier with VOC for the transient condition during the load variations.

FIGURE 10. Three-phase input current with PSO technique, 650V DC output, and 1131W.

FIGURE 11. Three-phase input voltage with PSO technique, 650V DC output, and 1131W.

implemented in various engineering applications due to its superior computational efficiency [40], [41], [42]. The PSO approach converges faster and more consistently than other population-based stochastic optimization approaches, such as the genetic algorithm (GA) and ant colony optimization (ACO) [30], [31], [33], [43], [44], [45]. The PSO technique is a time-efficient technique that identifies the system parameters and configures PI controllers in process control applications for various scenarios [46]. The PSO technique used in various industries is presented in Table 1. In addition, the output performances of EV battery charger are simulated using MATLAB, and the results are presented in Table 2. The three main stages of PSO algorithm can be explained as follow:

- Evaluating the fitness value of each particle.
- Updating local and global best fitness and positions.
- Updating the velocity and the position of each particle.

The following equations give the particle position and velocity update for optimizing the PSO algorithm [47].

$$V_i^{k+1} = w.V_i^k + C_1.r_1\left[X_{pbest}^k - X_i^k\right] + C_2.r_2\left[X_{gbest}^k - X_i^k\right] \tag{2}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{3}$$

where i = index of the particle

V_i^k and X_i^k = velocity and position of particle

w = inertia constant and C_1 and C_2 = coefficients

r_1 and r_2 = random values and X_{pbest}^k and X_{gbest}^k = local and global best positions of each particle.

This study's novel or original contribution is optimizing VOC's PI controller for electric vehicle charging stations. In this study, the VOC's PI controller has been optimized by using the particle swarm optimization technique to improve the stability of the EV charging stations. Also, the PSO technique helps to reduce the input current THD to less than 5% to meet the IEEE-519 standards and to improve the power factor near unity at the utility grid.

One of the critical performance criteria in the design of PI controller is the error between plant output and the set point signal value. Using these criteria as the fitness function of the optimization method leads to a minimum overshoot and
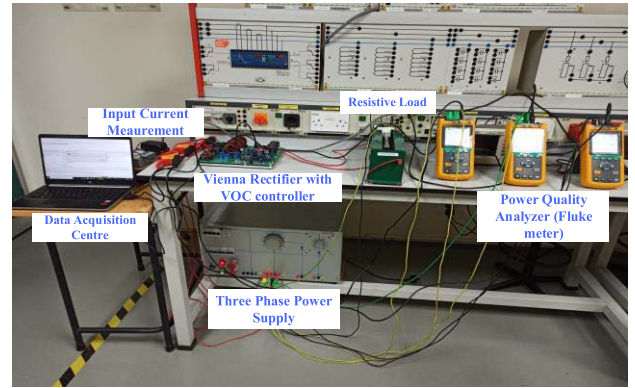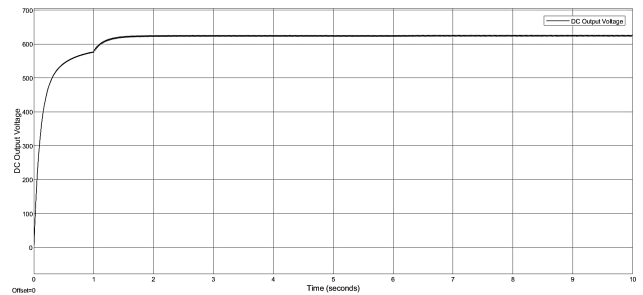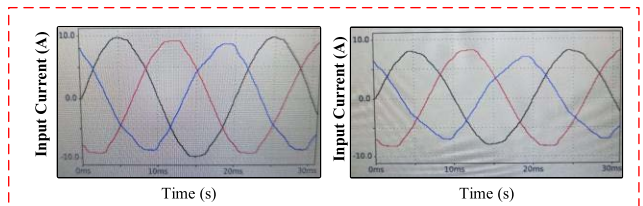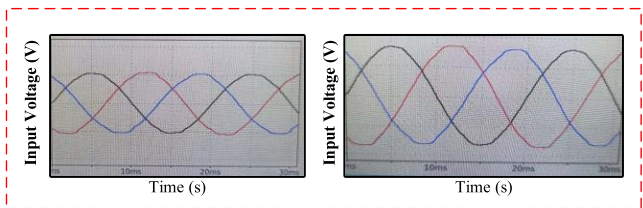
a considerable settling period. Typically, fitness functions are derived from error equations. The fitness functions used in this research work are integral square error (ISE) and integral absolute error (IAE), and the equations are as follows:

$$ISE_{PI_1} = \int_0^t \left[(v_{dref} - v_{feedback})(t)\right]^2 .dt \tag{4}$$

$$IAE_{PI_1} = \int_0^t \left|((v_{dref} - v_{feedback})(t))\right| .dt \tag{5}$$

$$ISE_{PI_2} = \int_0^t \left[(i_{ref} - i_{feedback})(t)\right]^2 .dt \tag{6}$$
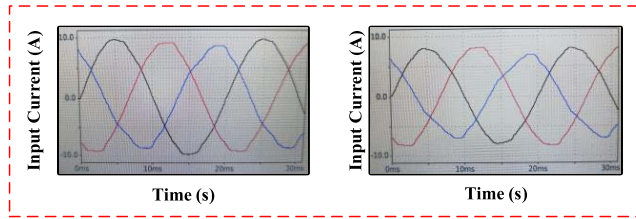
FIGURE 12. Three-phase input current with PSO technique, 650V DC output, and 1176.5W.
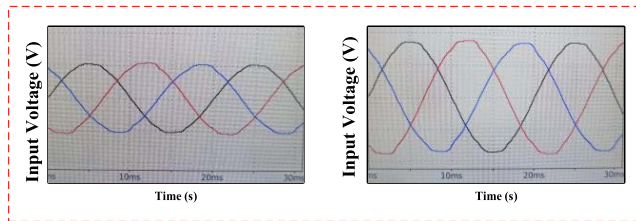

FIGURE 13. Three-phase input voltage with PSO technique, 650V DC output, and 1176.5W.

$$IAE_{PI_2} = \int_0^t \left| ((i_{ref} - i_{feedback})(t)) \right| .dt \qquad (7)$$

$$ISE_{PI_3} = \int_0^t [(i_{ref} - i_{feedback})(t)]^2 .dt \qquad (8)$$

$$IAE_{PI_3} = \int_0^t \left| ((i_{ref} - i_{feedback})(t)) \right| .dt \qquad (9)$$

The cumulative objective function for the proposed PSO optimized VOC's PI controller is

$$\begin{aligned}
\text{Obj. function} = &\int_0^t [(v_{dref} - v_{feedback})(t)]^2 .dt \\
&+ \int_0^t \left| ((v_{dref} - v_{feedback})(t)) \right| .dt \\
&+ \int_0^t [(i_{ref} - i_{feedback})(t)]^2 .dt \\
&+ \int_0^t \left| ((i_{ref} - i_{feedback})(t)) \right| .dt \\
&+ \int_0^t [(i_{ref} - i_{feedback})(t)]^2 .dt \\
&+ \int_0^t \left| ((i_{ref} - i_{feedback})(t)) \right| .dt \qquad (10)
\end{aligned}$$

where, equations (4) and (5) represent the integral square error and integral absolute error for voltage controller, and equations (6), (7), (8), and (9) represent the integral square error and integral absolute error for current controllers in the VOC. The proposed objective function for the VOC's PI controller is represented by equation 10. Based on the design and control system, engineers are able to develop fitness-specific functionalities. The fitness function used to monitor the optimization search affects evolutionary algorithms' overall performance (convergence speed and optimization precision). To determine the optimal fitness function i.e., the objective function of the PSO technique, the optimization process has been conducted for the standard

FIGURE 14. Input current THD for PSO-based Vienna rectifier with 1131W output power.

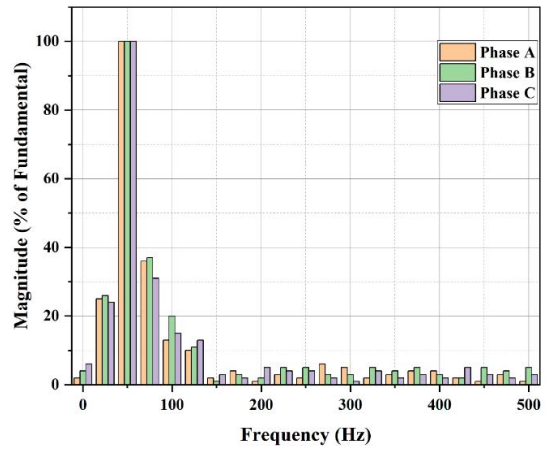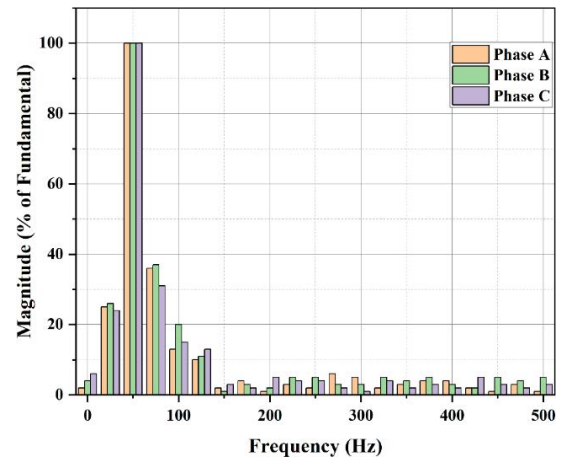**FIGURE 15.** Input current THD for PSO-based Vienna rectifier with 1176.5W output power.
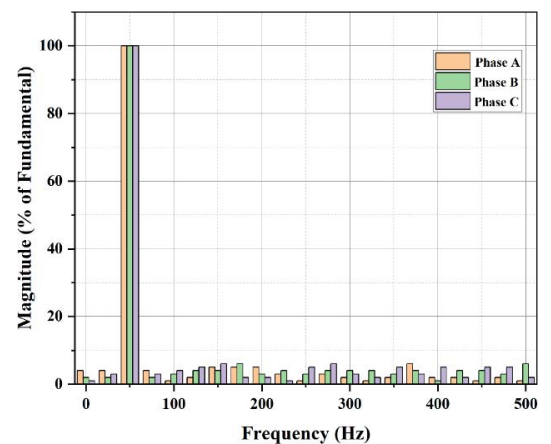

FIGURE 16. Input current THD for PSO-based Vienna rectifier with 1215.5W output power.

two error equations (ISE and IAE) for different iterations such as 100, 200, 500, and 1000 cycles. Table 2 provides a detailed performance of Objective functions for PSO optimized VOC's PI controller. The integral absolute error (IAE)

TABLE 3. Output performance of vienna rectifier for EV charging stations with and without PSO algorithm for different load conditions.

Conventional VOC					VOC with PSO algorithm				
Input Current THD (%)	Input Voltage THD (%)	DC Output Voltage (V)	DC Output Current (A)	Output Power (W)	Input Current THD (%)	Input Voltage THD (%)	DC Output Voltage (V)	DC Output Current (A)	Output Power (W)
3.48	1.47	650V	0.56	364	2.62	1.41	650V	0.49	318.5
3.37	1.39	650V	0.61	396.5	2.46	1.36	650V	0.65	422.5
3.27	1.38	650V	0.68	442	2.47	1.36	650V	0.69	448.5
3.25	1.39	650V	0.78	507	2.46	1.39	650V	0.85	552.5
3.27	1.42	650V	0.90	585	2.42	1.38	650V	0.95	617.5
3.27	1.39	650V	1.10	715	2.47	1.37	650V	1.16	754
3.28	1.38	650V	1.45	942.5	2.46	1.36	650V	1.35	877.5
3.27	1.39	650V	1.62	1053	2.47	1.39	650V	1.74	1131
3.35	1.58	650V	0.66	429	2.72	1.52	650V	0.54	351
3.36	1.49	650V	0.71	461.5	2.56	1.66	650V	0.61	396.5
3.29	1.48	650V	0.78	507	2.21	1.86	650V	0.65	422.5
3.28	1.39	650V	0.88	572	2.34	1.81	650V	0.77	500.5
3.21	1.62	650V	1.2	780	2.37	1.84	650V	0.93	604.5
3.23	1.49	650V	1.36	884	2.31	1.74	650V	1.30	845
3.25	1.48	650V	1.55	1007.5	2.34	1.87	650V	1.56	1014
3.27	1.49	650V	1.65	1072.5	2.37	1.69	650V	1.81	1176.5
3.44	1.43	650V	0.54	351	2.65	1.45	650V	0.51	331.5
3.47	1.46	650V	0.61	396.5	2.45	1.32	650V	0.63	409.5
3.17	1.29	650V	0.66	429	2.47	1.38	650V	0.68	442
3.35	1.48	650V	0.75	487.5	2.46	1.57	650V	0.88	572
3.46	1.37	650V	0.94	611	2.47	1.86	650V	1.06	689
3.27	1.58	650V	1.13	734.5	2.47	1.79	650V	1.25	812.5
3.52	1.64	650V	1.47	955.5	2.46	1.93	650V	1.58	1027
3.35	1.85	650V	1.63	1059.5	2.47	2.16	650V	1.87	1215.5

provides the minimum settling time, peak overshoot, and rise time among the two conventional objective functions. As stated before, any objective function could be used to optimize the PI parameters. However, the challenging part is reducing the rise time without increasing the peak overshoot value. By decreasing the rise time, the system will attempt to track the set point faster, resulting in higher inertia and

a higher risk of peak overshoot value. With the help of the best convergence values of integral absolute error, the optimal time response (rise time, settling time, and peak overshoot) has been obtained in all cases.

The PSO optimized objective functions such as integrated square error and integrated absolute error of voltage and current controller in the VOC's PI controller for EV charging
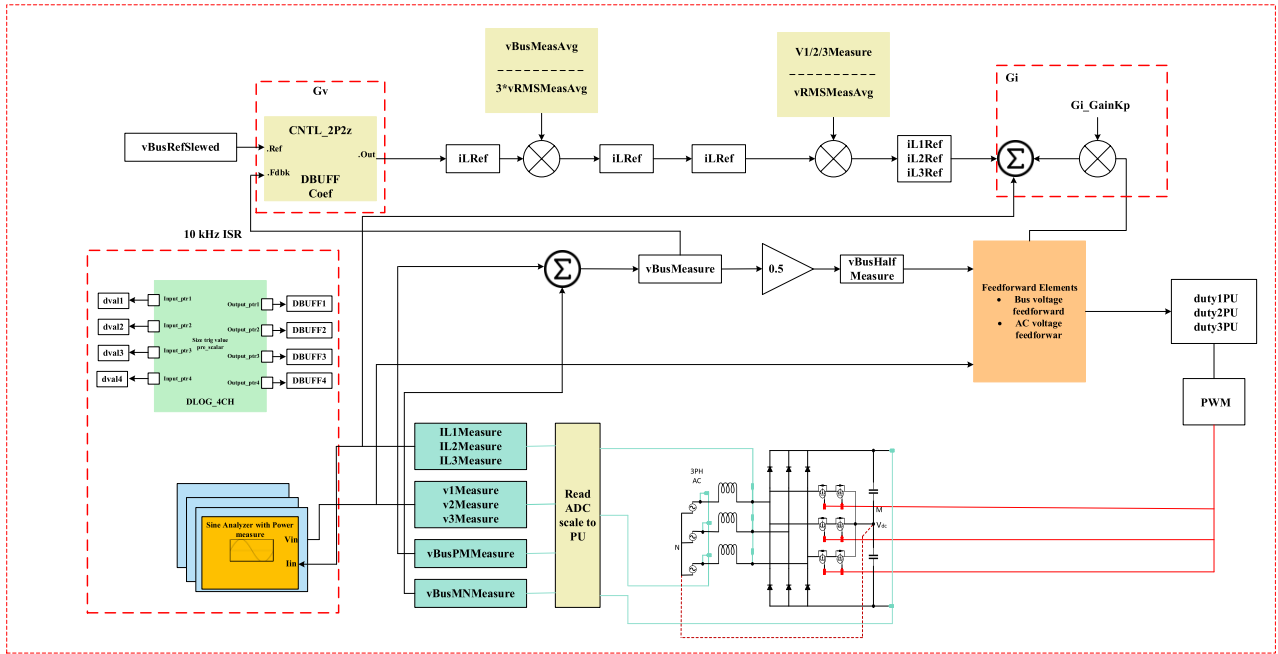
FIGURE 17. Overall control circuit: output voltage control with inner current loop.

application are shown in Fig. 4. The objective functions are optimized with the help of PSO technique in order to provide stable operation of an EV charging station. Consequently, PSO optimized VOC's PI controllers provide regulated DC output voltage, maintaining input current THD less than 5% to meet IEEE-519 standards, and power factor nearly unity at the utility grid side. The existing system consists of a Vienna rectifier with a trial-and-error method of VOC's PI controller, which is represented by Fig. 5(a) in contrast with the proposed Vienna rectifier with VOC's PI controller optimization using the PSO technique shown in Fig. 5(b). and the flowchart of PSO technique for PI controller optimization is shown in Fig. 6.

IV. EXPERIMENTAL IMPLEMENTATION

The cross-sectional board view of Vienna rectifier with VOC and experimental implementation of the PSO algorithm-based voltage-oriented controller for the Vienna rectifier is developed using the TMS320F28837xD digital signal controller. In this study, the switching frequency is 50 kHz, which helps to design the input filter (inductor) and output filter (split capacitor) in the Vienna rectifier topology (refer to Fig. 4). The board view of the Vienna rectifier setup is shown in Fig. 7 and Fig. 8. The MATLAB code generated in MATLAB software has been encoded with the digital signal controller (TMS320F28337xD). The PI controller featured in the VOC is optimized using the PSO technique and the constant values (K_P and K_I) are encoded in the code composer studio software for the experimental implementation. The transient conditions of Vienna rectifier with VOC for various load conditions has been analyzed using MATLAB/Simulink software. The DC output voltage of the Vienna rectifier with

VOC for a transient condition is shown in Fig. 9. The test board has experimented with various load conditions and different periods for electric vehicle charging stations. The load used in this study is a resistive load (R_L) for the experimental validation. The output performance parameters are recorded using a power quality analyzer. The input current and voltage for the Vienna rectifier with PSO technique for the 650V DC with 1131W and output power are illustrated in Fig. 10 and Fig. 11, respectively. Also, the input current and input voltage for the Vienna rectifier with the PSO technique for the 650V DC output voltage with 1176.5W output power is illustrated in Fig. 12 and Fig. 13, respectively. According to the experimental test analysis, it has been shown that the input current THD is 2.47% which is less than 5% to meet the IEEE-519 standards. The input current THD for different load conditions is illustrated in Fig. 14, Fig. 15, and Fig. 16, respectively. The experimental test with the PSO technique is conducted for 1.5 kW output power for the EV charging stations. The DC voltage at the output side using Vienna rectifier with PSO technique is 650V which meets the basic requirement for EV charging stations. The output performance of the Vienna rectifier with the PSO algorithm for three different periods of time in experimental test is presented in Table 3. In addition, the overall control circuit with Vienna rectifier with VOC controller for EV battery charger in order to reduce the input current THD less than 5% and to improve the power factor at the utility grid side is shown in Fig. 17.

V. CONCLUSION

In this research work, the Vienna rectifier with VOC is designed and developed as an experimental setup for the

electric vehicle battery charger. The PSO technique is used in this research work to optimize the gain values (K_p and K_i) of the VOC's PI controller. The PSO technique optimizes the system parameters such as rise time and settling time is 1.6 seconds and 3.1 seconds, respectively, which is better than the conventional controller (trial-and-error method). Also, the peak overshoot value is 1.21% for the Vienna rectifier with a VOC. The findings show that the voltage and current stability are improved by 12% compared to the existing trial-and-error method. The experimental test uses a digital signal controller (TMS 320F28337xD) with the Code Composer Studio (CCS) platform. The input current THD measured during the experimental validation is 2.47%, less than 5% to meet the IEEE-519 standards. In addition to the input current THD, the power factor at the utility grid is maintained at near unity. Thus, by utilizing the PSO technique for PI controllers featured in the VOC, the Vienna rectifier provides the DC output voltage of 650V and output current of 85A with a unity power factor at mains and an input current THD less than 5% to meet the basic requirements for DC fast-charging stations and IEEE-519 standards.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

REFERENCES

[1] G. Lou, H. Ma, T. Fan, and H. K. Chan, "Impact of the dual-credit policy on improvements in fuel economy and the production of internal combustion engine vehicles," *Resour., Conservation Recycling*, vol. 156, May 2020, Art. no. 104712.

[2] Y. Qin, X. Tang, T. Jia, Z. Duan, J. Zhang, Y. Li, and L. Zheng, "Noise and vibration suppression in hybrid electric vehicles: State of the art and challenges," *Renew. Sustain. Energy Rev.*, vol. 124, May 2020, Art. no. 109782.

[3] T. Liu, X. Tang, H. Wang, H. Yu, and X. Hu, "Adaptive hierarchical energy management design for a plug-in hybrid electric vehicle," *IEEE Trans. Veh. Technol.*, vol. 68, no. 12, pp. 11513–11522, Jul. 2019.

[4] H. Zhang, X. Li, X. Liu, and J. Yan, "Enhancing fuel cell durability for fuel cell plug-in hybrid electric vehicles through strategic power management," *Appl. Energy*, vol. 241, pp. 483–490, May 2019.

[5] M. S. Sulaiman, B. Singh, and W. A. N. W. Mohamed, "Experimental and theoretical study of thermoelectric generator waste heat recovery model for an ultra-low temperature PEM fuel cell powered vehicle," *Energy*, vol. 179, pp. 628–646, Jul. 2019.

[6] S. Verma, G. Dwivedi, and P. Verma, "Life cycle assessment of electric vehicles in comparison to combustion engine vehicles: A review," *Mater. Today, Proc.*, vol. 49, pp. 217–222, Feb. 2021.

[7] S. Verma, S. Mohapatra, S. Chowdhury, and G. Dwivedi, "Cooling techniques of the PV module: A review," *Mater. Today, Proc.*, vol. 38, pp. 253–258, Jan. 2021.

[8] A. Perujo and B. Ciuffo, "The introduction of electric vehicles in the private fleet: Potential impact on the electric supply system and on the environment. A case study for the province of Milan, Italy," *Energy Policy*, vol. 38, no. 8, pp. 4549–4561, Aug. 2010.

[9] V. Nian, M. P. Hari, and J. Yuan, "A new business model for encouraging the adoption of electric vehicles in the absence of policy support," *Appl. Energy*, vol. 235, pp. 1106–1117, Feb. 2019.

[10] L. Wang, J. Liang, G. Xu, K. Xu, and Z. Song, "A novel battery charger for plug-in hybrid electric vehicles," in *Proc. IEEE Int. Conf. Inf. Autom.*, Jun. 2012, pp. 168–173.

[11] G. Rajendran, C. A. Vaithilingam, N. Misron, K. Naidu, and M. R. Ahmed, "A comprehensive review on system architecture and international standards for electric vehicle charging stations," *J. Energy Storage*, vol. 42, Oct. 2021, Art. no. 103099, doi: 10.1016/j.est.2021.103099.

[12] G. Rajendran, C. A. Vaithilingam, K. Naidu, and K. S. P. Oruganti, "Energy-efficient converters for electric vehicle charging stations," *Social Netw. Appl. Sci.*, vol. 2, no. 4, p. 583, Apr. 2020, doi: 10.1007/s42452-020-2369-0.

[13] G. Rajendran, C. A. Vaithilingam, N. Misron, K. Naidu, and M. R. Ahmed, "Voltage oriented controller based Vienna rectifier for electric vehicle charging stations," *IEEE Access*, vol. 9, pp. 50798–50809, 2021.

[14] J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers," *Trans. ASME*, vol. 64, no. 11, pp. 1–7, Nov. 1942.

[15] S. M. G. Kumar, R. Sivasankar, T. K. Radhakrishnan, V. Dharmalingam, and N. Anantharaman, "Particle swarm optimization technique based design of PI controller for a real-time non-linear process," *Instrum. Sci. Technol.*, vol. 36, no. 5, pp. 525–542, Jul. 2008.

[16] T. M. Shami, A. A. El-Saleh, M. Alswaitti, Q. Al-Tashi, M. A. Summakieh, and S. Mirjalili, "Particle swarm optimization: A comprehensive survey," *IEEE Access*, vol. 10, pp. 10031–10061, 2022, doi: 10.1109/ACCESS.2022.3142859.

[17] P. B. de Moura Oliveira, J. D. Hedengren, and E. J. S. Pires, "Swarm-based design of proportional integral and derivative controllers using a compromise cost function: An Arduino temperature laboratory case study," *Algorithms*, vol. 13, no. 12, p. 315, Nov. 2020.

[18] Y. Peng, D. Vrančić, and R. Hanus, "Anti-windup, bumpless, and conditioned transfer techniques for PID controllers," *IEEE Control Syst.*, vol. 16, no. 4, pp. 48–57, Aug. 1996.

[19] K. J. Åström, T. Hägglund, and K. J. Astrom, "ISA-the instrumentation, systems, and automation society research triangle~···," *Adv. PID Control*, vol. 461, 2006.

[20] D. E. Seborg, D. A. Mellichamp, T. F. Edgar, and F. J. Doyle, III, *Process Dynamics and Control*. Hoboken, NJ, USA: Wiley, 2010.

[21] R. Vilanova and A. Visioli, *PID Control in the Third Millennium*. Cham, Switzerland: Springer, 2012.

[22] R. Sandip, N. Karthik, and T. G. A. Mani, "PSO based PI controller for BLDC motor," in *Proc. 8th Int. Conf. Smart Struct. Syst. (ICSSS)*, Apr. 2022, pp. 1–5, doi: 10.1109/ICSSS54381.2022.9782223.

[23] T. Yucelen, O. Kaymakci, and S. Kurtulan, "Self-tuning PID controller using ziegler-nichols method for programmable logic controllers," *IFAC Proc. Volumes*, vol. 39, no. 14, pp. 11–16, Jan. 2006.

[24] J. C. Basilio and S. R. Matos, "Design of PI and PID controllers with transient performance specification," *IEEE Trans. Educ.*, vol. 45, no. 4, pp. 364–370, Nov. 2002.

[25] S. W. Sung, I.-B. Lee, and J. Lee, "Modified proportional-integral derivative (PID) controller and a new tuning method for the PID controller," *Ind. Eng. Chem. Res.*, vol. 34, no. 11, pp. 4127–4132, Nov. 1995.

[26] W. Anjum, A. R. Husain, J. A. Aziz, M. A. Abbasi, and H. Alqaraghuli, "Continuous dynamic sliding mode control strategy of PWM based voltage source inverter under load variations," *PLoS ONE*, vol. 15, no. 2, Feb. 2020, Art. no. e0228636.

[27] K. E. Parsopoulos and M. N. Vrahatis, "Particle swarm optimizer in noisy and continuously changing environments," *Methods*, vol. 5, no. 6, p. 23, 2001.

[28] Z.-L. Gaing, "A particle swarm optimization approach for optimum design of PID controller in AVR system," *IEEE Trans. Energy Convers.*, vol. 19, no. 2, pp. 384–391, Jun. 2004.

[29] K. E. Parsopoulos and M. N. Vrahatis, "Recent approaches to global optimization problems through particle swarm optimization," *Natural Comput.*, vol. 1, nos. 2–3, pp. 235–306, 2002.

[30] U. S. Banu and G. Uma, "Fuzzy gain scheduled continuous stirred tank reactor with particle swarm optimization based PID control minimizing integral square error," *Instrum. Sci. Technol.*, vol. 36, no. 4, pp. 394–409, Jun. 2008.

[31] M. S. Arumugam and M. V. C. Rao, "On the performance of the particle swarm optimization algorithm with various inertia weight variants for computing optimal control of a class of hybrid systems," *Discrete Dyn. Nature Soc.*, vol. 2006, pp. 1–17, Jun. 2006.

[32] R.-M. Chen and C.-M. Wang, "Project scheduling heuristics-based standard PSO for task-resource assignment in heterogeneous grid," *Abstract Appl. Anal.*, vol. 2011, Feb. 2011, Art. no. 589862.

[33] R. F. Abdel-Kader, "Particle swarm optimization for constrained instruction scheduling," *VLSI Des.*, vol. 2008, pp. 1–7, Mar. 2008.

[34] M. Zamani, M. Karimi-Ghartemani, N. Sadati, and M. Parniani, "Design of a fractional order PID controller for an AVR using particle swarm optimization," *Control Eng. Pract.*, vol. 17, no. 12, pp. 1380–1387, 2009.

[35] E. E. El-Araby and N. Yorino, "A hybrid PSO technique for procuring VAR ancillary service in the deregulated electricity markets," *Int. J. Electr. Power Energy Syst.*, vol. 32, no. 6, pp. 664–670, Jul. 2010, doi: 10.1016/j.ijepes.2009.11.025.

[36] S. Panda, N. K. Yegireddy, and S. K. Mohapatra, "Hybrid BFOA–PSO approach for coordinated design of PSS and SSSC-based controller considering time delays," *Int. J. Electr. Power Energy Syst.*, vol. 49, pp. 221–233, Jul. 2013, doi: 10.1016/j.ijepes.2013.01.006.

[37] P. M. Oliveira, E. S. Pires, J. Boaventura-Cunha, and T. M. Pinho, "Review of nature and biologically inspired metaheuristics for greenhouse environment control," *Trans. Inst. Meas. Control*, vol. 42, no. 12, pp. 2338–2358, Aug. 2020.

[38] S.-K.-S. Fan and C.-H. Jen, "An enhanced partial search to particle swarm optimization for unconstrained optimization," *Mathematics*, vol. 7, no. 4, p. 357, Apr. 2019.

[39] G. Rajendran, C. A. Vaithilingam, K. Naidu, A. A. Alsakati, and H. Ahmad, "PSO-based PI controller for voltage-oriented controller based Vienna rectifier for electric vehicle charging stations," in *Proc. IEEE 19th Student Conf. Res. Develop. (SCOReD)*, Nov. 2021, pp. 356–361, doi: 10.1109/SCOReD53546.2021.9652686.

[40] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. Int. Conf. Neural Netw.*, vol. 4, Jun. 1995, pp. 1942–1948.

[41] H. Qabouche, A. Sahel, A. Badri, and I. E. Mourabit, "Energy efficient PSO-based routing protocol for large WSN," in *Proc. 2nd Int. Conf. Innov. Res. Appl. Sci., Eng. Technol. (IRASET)*, Mar. 2022, pp. 1–7, doi: 10.1109/IRASET52964.2022.9738078.

[42] G. Sebastian, M. A. Hannan, A. Q. Al-Shetwi, P. J. Ker, M. S. A. Rahman, M. Mansur, and K. M. Muttaqi, "A novel PSO based fuzzy controller for robust operation of solid-state transfer switch and fast load transfer in power systems," *IEEE Access*, vol. 10, pp. 37369–37381, 2022, doi: 10.1109/ACCESS.2022.3165021.

[43] M. S. Arumugam and M. V. C. Rao, "On the optimal control of single-stage hybrid manufacturing systems via novel and different variants of particle swarm optimization algorithm," *Discrete Dyn. Nature Soc.*, vol. 2005, no. 3, pp. 257–279, 2005.

[44] C.-H. Lin, J.-L. Chen, and Z.-L. Gaing, "Combining biometric fractal pattern and particle swarm optimization-based classifier for fingerprint recognition," *Math. Problems Eng.*, vol. 2010, pp. 1–14, Jan. 2010.

[45] J. Zhang and K. W. Chau, "Multilayer ensemble pruning via novel multi-sub-swarm particle swarm optimization," *J. UCS*, vol. 15, no. 4, pp. 840–858, 2009.

[46] A. Alfi and H. Modares, "System identification and control using adaptive particle swarm optimization," *Appl. Math. Model.*, vol. 35, no. 3, pp. 1210–1221, 2011.

[47] Y. Valle, G. K. Venayagamoorthy, S. Mohagheghi, J. C. Hernandez, and R. G. Harley, "Particle swarm optimization: Basic concepts, variants and applications in power systems," *IEEE Trans. Evol. Comput.*, vol. 12, no. 2, pp. 171–195, Apr. 2008, doi: 10.1109/TEVC.2007.896686.

[48] R. R. Nasyrov and R. I. Aljendy, "Comprehensive comparison between hybrid fuzzy-PI and PSO-PI controllers based active power filter for compensation of harmonics and reactive power under different load conditions," in *Proc. IEEE Conf. Russian Young Researchers Electr. Electron. Eng. (EIConRus)*, Jan. 2018, pp. 725–730, doi: 10.1109/EIConRus.2018.8317195.

[49] H. Kaur, P. Kumar, S. K. Sinha, and V. K. Tayal, "Automatic generation control using PSO optimized PI and optimal fuzzy controller," in *Proc. Annu. IEEE India Conf. (INDICON)*, Dec. 2015, pp. 1–6, doi: 10.1109/INDICON.2015.7443490.

[50] S. Labdai, B. Hemici, L. Nezli, N. Bounar, A. Boulkroune, and L. Chrifi-Alaoui, "Control of a DFIG based WECS with optimized PI controllers via a duplicate PSO algorithm," in *Proc. Int. Conf. Control, Autom. Diagnosis (ICCAD)*, Jul. 2019, pp. 1–6, doi: 10.1109/ICCAD46983.2019.9037879.

[51] G. Muhurcu, E. Kose, A. Muhurcu, and A. Kuyumcu, "Parameter optimization of PI controller by PSO for optimal controlling of a buck converter's output," in *Proc. Int. Artif. Intell. Data Process. Symp. (IDAP)*, Sep. 2017, pp. 1–6, doi: 10.1109/IDAP.2017.8090234.

[52] T. Banerjee, S. Choudhuri, J. Bera, and A. Maity, "Off-line optimization of PI and PID controller for a vector controlled induction motor drive using PSO," in *Proc. Int. Conf. Electr. Comput. Eng. (ICECE)*, Dec. 2010, pp. 74–77, doi: 10.1109/ICELCE.2010.5700556.

[53] R. K. Selvi and R. S. M. Malar, "A bridgeless LUO converter based speed control of switched reluctance motor using particle swarm optimization (Pso) tuned proportional integral (Pi) controller," *Microprocessors Microsyst.*, vol. 75, Jun. 2020, Art. no. 103039, doi: 10.1016/j.micpro.2020.103039.

[54] M. G. M. Abdolrasol, M. A. Hannan, S. M. S. Hussain, and T. S. Ustun, "Optimal PI controller based PSO optimization for PV inverter using SPWM techniques," *Energy Rep.*, vol. 8, pp. 1003–1011, Apr. 2022, doi: 10.1016/j.egyr.2021.11.180.

[55] R. K. Sahu, S. Panda, and G. T. Chandra Sekhar, "A novel hybrid PSO-PS optimized fuzzy PI controller for AGC in multi area interconnected power systems," *Int. J. Electr. Power Energy Syst.*, vol. 64, pp. 880–893, Jan. 2015, doi: 10.1016/j.ijepes.2014.08.021.

[56] F. Zhou, J. Yu, P. Zhao, C. Yue, S. Liang, and H. Li, "CVT measurement error correction by double regression-based particle swarm optimization compensation algorithm," *Energy Rep.*, vol. 7, pp. 191–200, Nov. 2021, doi: 10.1016/j.egyr.2021.08.056.

[57] Z. Zheng and S. Yang, "Particle swarm optimisation for scheduling electric vehicles with microgrids," in *Proc. IEEE Congr. Evol. Comput. (CEC)*, Jul. 2020, pp. 1–7, doi: 10.1109/CEC48606.2020.9185853.

GOWTHAMRAJ RAJENDRAN (Graduate Student Member, IEEE) received the Bachelor of Engineering degree from the Government College of Engineering, Salem, India, in 2014, and the Master of Engineering degree (Hons.) from the PSG College of Technology, Coimbatore, India. He is currently pursuing the Ph.D. degree in electrical engineering with Taylor's University, Malaysia. His current research is focused on the ac–dc power converters for electric vehicle charging stations. His research interest includes high-frequency semiconductor devices (silicon carbide and gallium nitride) for power converters in electric vehicle charging stations. He is working under the Research Cluster VERTICALS, aligned with SDG goals on sustainable energy and mobility (SDG 7, 11). He is a member of IET U.K. He is also a Professional Engineer (Electrical) by the Board of Engineers Malaysia (BEM).

CHOCKALINGAM ARAVIND VAITHILINGAM (Senior Member, IEEE) received the B.Eng. and M.Eng. degrees from Bharathiyar University, India, in 1998 and 2001, respectively, and the Ph.D. degree in electrical power engineering from the Universiti Putra Malaysia, in 2013. He is currently heading the Electrical and Electronic Engineering Program, Faculty of Innovation and Technology, Taylor's University, Malaysia, and heading the Research Cluster VERTICALS aligned with SDG goals on sustainable energy and mobility (SDG 7, 11). He is a very frequent speaker at various international and national platforms. He is a member of IET, U.K., and a Registered Chartered Engineer registered professional with the Engineering Council, U.K. He is also a Professional Technologists with the Malaysian Board of Technologists. He is a member of the Society of Engineering Education Malaysia.

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KANENDRA NAIDU received the master's and Ph.D. degrees in electrical engineering from the University of Malaya, in 2011 and 2015, respectively. He is currently a Senior Lecturer with the Universiti Teknologi MARA (UiTM), Shah Alam. He has a strong research interest in the field of electrical engineering specializing in the implementation of artificial intelligence in power systems. He also has strong working experience in a variety of evolutionary and swarm-based optimization techniques, graph theory, wavelet transform, and artificial neural networks.

KAMESWARA SATYA PRAKASH ORUGANTI (Graduate Student Member, IEEE) is currently pursuing the Ph.D. degree in electrical engineering with Taylor's University. He is working under the Research Cluster VERTICALS, aligned with SDG goals on sustainable energy and mobility (SDG 7, 11). His main interest involves sustainable energy solutions for the betterment of people. His current research is focused on renewable energy-based dc–dc power converters for electric vehicle charging stations. His research interests include renewable energy sizing, control of power electronics, and systems engineering.

AHMAD ADEL ALSAKATI (Graduate Student Member, IEEE) received the B.Eng. degree in electrical engineering and the master's degree in electrical power systems engineering from Damascus University, Syria, in 2007 and 2012, respectively. He is currently pursuing the Ph.D. degree with the School of Computer Science and Engineering, Taylor's University, Malaysia. His research interests include electrical power system operating, planning, and optimization. He also focuses on renewable energy integration power systems and the impact of distributed generation on power system stability.

MOHD FAIZAL FAUZAN received the Ph.D. degree in engineering from the Universiti Malaya, Malaysia, in 2015. He currently holds the position of a Senior Lecturer and a Research Fellow at the Universiti Kebangsaan Malaysia (UKM). He is an Award-Winning Academics at the Solar Energy Research Institute (SERI), UKM. His research works focus specifically on sustainable development and green technology. Prior to joining UKM, in 2021, he has served various private institutions in Malaysia, including UNISEL, INTI International University, and Taylor's University, for more than 12 years. He has received several important recognitions to his career, including "Vice Chancellor's Award, Taylor's Most Cited Academic," "Anugerah Khas YB Menteri Pendidikan Malaysia: Rekabentuk Kurikulum & Penyampaian Inovatif (AKRI)," and also several awards from Elsevier for "Outstanding Contribution in Reviewing." He is also recognized as a Professional Technologists (Green Technology) by the Malaysia Board of Technologists (MBOT) and a Professional Engineer (Mechanical) by the Board of Engineers Malaysia (BEM).

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