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, 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.
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 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, 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 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).
The combination of PSO technique with PI controller and fuzzy with PI controller is proposed to improve the performance of the system.

The performance of the system has been improved with the help of a PSO optimized optimal fuzzy PI controller than a conventional PI controller.

A duplicate PSO (D-PSO) technique is proposed to track the maximum power at the wind energy system with zero reactive power.

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.

The performance of the induction motor drive is attained using PSO technique for reducing the system performance parameters such as IAE and ISE values.

The tuning of PI controller featured in the Luo converter has been compared with the Zeigler Nichols method and PSO technique for the application of SRM motor drive. The proposed PSO system performs better compared to the ZN tuning method.

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.

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.

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.

The Particle Swarm Optimisation technique provides the optimal scheduling for electric vehicles with a microgrid.

The synthesis of the PI controllers is mathematically described by,

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt$$  \hspace{1cm} (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.

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 input current harmonics are reduced to less than 5%, which satisfies IEEE-519 standards.

PSO-based PI controller with fuzzy controller provides better stable operation than the conventional PI controller for the power system control system.

PSO-based PI controller optimization for DFIG parameter optimization provides good reference tracking performance with reduced overshoot and a faster settling time.

PSO technique optimizes the PI controller that generates PWM for buck converters in DC/DC power converter applications.

The response of the vector controller for induction motor drive is faster using the PSO technique for PI controller.

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.

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.

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.

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.

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.
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

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**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) | $t_z$(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  |
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].

\[ V_{i}^{k+1} = w.V_{i}^{k} + C_1.r_1 . [X_{pbest}^{k} - X_{i}^{k}] + C_2.r_2 . [X_{gbest}^{k} - X_{i}^{k}] \]

\[ X_{i}^{k+1} = X_{i}^{k} + V_{i}^{k+1} \]  

(2)

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:

\[ ISE_{PI1} = \int_{0}^{T} [(v_{dref} - v_{feedback}(t))^2].dt \]  

(4)

\[ IAE_{PI1} = \int_{0}^{T} |(v_{dref} - v_{feedback}(t))|.dt \]  

(5)

\[ ISE_{PI2} = \int_{0}^{T} [(i_{ref} - i_{feedback}(t))^2].dt \]  

(6)
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 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.

| Input Current THD (%) | Input Voltage THD (%) | DC Output Voltage (V) | DC Output Current (A) | Output Power (W) |
|-----------------------|-----------------------|-----------------------|-----------------------|------------------|
| Conventional VOC      |                        |                        |                        |                  |
| 3.48                  | 1.47                  | 650V                  | 0.56                  | 364              |
| 3.37                  | 1.39                  | 650V                  | 0.61                  | 396.5            |
| 3.27                  | 1.38                  | 650V                  | 0.68                  | 442              |
| 3.25                  | 1.39                  | 650V                  | 0.78                  | 507              |
| 3.27                  | 1.42                  | 650V                  | 0.90                  | 585              |
| 3.27                  | 1.39                  | 650V                  | 1.10                  | 715              |
| 3.28                  | 1.38                  | 650V                  | 1.45                  | 942.5            |
| 3.27                  | 1.39                  | 650V                  | 1.62                  | 1053             |
| 3.35                  | 1.58                  | 650V                  | 0.66                  | 429              |
| 3.36                  | 1.49                  | 650V                  | 0.71                  | 461.5            |
| 3.29                  | 1.48                  | 650V                  | 0.78                  | 507              |
| 3.28                  | 1.39                  | 650V                  | 0.88                  | 572              |
| 3.21                  | 1.62                  | 650V                  | 1.2                   | 780              |
| 3.23                  | 1.49                  | 650V                  | 1.36                  | 884              |
| 3.25                  | 1.48                  | 650V                  | 1.55                  | 1007.5           |
| 3.27                  | 1.49                  | 650V                  | 1.65                  | 1072.5           |
| 3.44                  | 1.43                  | 650V                  | 0.54                  | 351              |
| 3.47                  | 1.46                  | 650V                  | 0.61                  | 396.5            |
| 3.17                  | 1.29                  | 650V                  | 0.66                  | 429              |
| 3.35                  | 1.48                  | 650V                  | 0.75                  | 487.5            |
| 3.46                  | 1.37                  | 650V                  | 0.94                  | 611              |
| 3.27                  | 1.58                  | 650V                  | 1.13                  | 734.5            |
| 3.52                  | 1.64                  | 650V                  | 1.47                  | 955.5            |
| 3.35                  | 1.85                  | 650V                  | 1.63                  | 1059.5           |

| VOC with PSO algorithm | Input Current THD (%) | Input Voltage THD (%) | DC Output Voltage (V) | DC Output Current (A) | Output Power (W) |
|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------|
| 2.62                  | 1.41                  | 650V                  | 0.49                  | 318.5                |
| 2.46                  | 1.36                  | 650V                  | 0.65                  | 422.5                |
| 2.47                  | 1.36                  | 650V                  | 0.69                  | 448.5                |
| 2.46                  | 1.39                  | 650V                  | 0.85                  | 552.5                |
| 2.42                  | 1.38                  | 650V                  | 0.95                  | 617.5                |
| 2.47                  | 1.37                  | 650V                  | 1.16                  | 754                  |
| 2.46                  | 1.36                  | 650V                  | 1.35                  | 877.5                |
| 2.47                  | 1.39                  | 650V                  | 1.74                  | 1131                 |
| 2.72                  | 1.52                  | 650V                  | 0.54                  | 351                  |
| 2.56                  | 1.66                  | 650V                  | 0.61                  | 396.5                |
| 2.21                  | 1.86                  | 650V                  | 0.65                  | 422.5                |
| 2.34                  | 1.81                  | 650V                  | 0.77                  | 500.5                |
| 2.37                  | 1.84                  | 650V                  | 0.93                  | 604.5                |
| 2.31                  | 1.74                  | 650V                  | 1.30                  | 845                  |
| 2.34                  | 1.87                  | 650V                  | 1.56                  | 1014                 |
| 2.37                  | 1.69                  | 650V                  | 1.81                  | 1176.5               |
| 2.65                  | 1.45                  | 650V                  | 0.51                  | 331.5                |
| 2.45                  | 1.32                  | 650V                  | 0.63                  | 409.5                |
| 2.47                  | 1.38                  | 650V                  | 0.68                  | 442                  |
| 2.46                  | 1.57                  | 650V                  | 0.88                  | 572                  |
| 2.47                  | 1.86                  | 650V                  | 1.06                  | 689                  |
| 2.47                  | 1.79                  | 650V                  | 1.25                  | 812.5                |
| 2.46                  | 1.93                  | 650V                  | 1.58                  | 1027                 |
| 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
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 TMS320F28337xD 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 have 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 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 VOCS 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 VOCS. 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 320F28337D) 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 VOCS, 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.

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