THD analysis and its mitigation using DSTATCOM integrated with EV charging station in the distribution network

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ABSTRACT

With the increase in carbon emissions, noise pollution and other environmental impacts caused by conventional vehicles, the demand for electric vehicles (EVs) is continuously increasing in the market. The transport sector has also been revolutionized with the use of EVs. The unique features such as reduction in noise pollution, carbon emissions and running costs and the capability of EVs to work in both grid-vehicle (G2V) and vehicle-grid (V2G) have made EVs popular nowadays. Still, it has several effects on the power distribution grid. There are several power issues due to the incorporation of electric vehicles (EVs) in the distribution network such as voltage instability, harmonics, and voltage fluctuations. This research paper focuses mainly on the harmonics caused in the system when EVs are connected to the distribution side. A distributed static compensator (DSTATCOM) based on the d-q theory is introduced to mitigate the harmonics along with the improvement in the voltage profile of the distribution side. By using MATLAB Simulink, the performance of DSTATCOM is validated and the comparison of the proposed approach is also done with that of similar work already existing in the literature.

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1. INTRODUCTION

With the increasing concern about environmental issues, the transportation sector is changing from conventional fossil fuel vehicles to electric vehicles which has increased the concern about power issues in the grid due to V2G and G2V capabilities [1]. Different scenarios are observed on grid stability, power quality and electricity markets with grid integration of EVs [2]. Great potential is offered by the battery-operated EVs to demand and charge flexibility over the standing time due to their built-in storage capability and to achieve a state of charge (SOC) of 80%. Issues such as high load peaks, transformer and line overloading are caused by purely market-oriented strategies while these issues are reduced by using a simple balanced charging strategy [3]. The current and bus voltage is affected during the charging as well as discharging of EV which affects the voltage profile of the network [4]. The two charging scenarios are presented i.e., controlled, and uncontrolled charging. It shows improvement in power quality with controlled charging of EVs [5], [6]. Based on the power flow, charging cost minimization and total cost minimization are the two types of charging strategies for EVs [7].

A real-time monitoring infrastructure is required by the distribution operators to make their grids work in a safe mode according to power quality standards by capturing the states of EV chargers [8]. Flexibility to electricity system, and value for different stakeholders such as system operators, end-customers, and aggregators, also help in the integration of renewable energy through the smart charging and V2G interfacing of EVs [9]. The electric vehicle along with its charging station induces current harmonics in the system which degrades the power quality of the supply network [10]. Rusan *et al.* show the possibility of deteriorating the power quality when electric vehicle charging stations (EVCS) and photovoltaics are connected to the network [11].

Particle swarm optimization (PSO) algorithm is used for finding optimal EVCS locations and thus reducing the computing time. It is also used for designing the hybrid active power filter to boost the quality of power and minimize the current source harmonics under ideal voltage conditions for DC-link control [12]-[15]. Zaidi *et al.* describe mechanisms to achieve voltage support and possible voltage level mitigation solutions through battery energy storage system (BESS)-STATCOM [16]. Kazemtarghi *et al.* [17] presented a unique harmonics elimination method in the EV charging station, which compensates the predominant third harmonic in the supply side. The effectiveness of harmonic filters for compensating disturbances is tested in different scenarios by comparing a single harmonic filter on the distribution line with individual filters on each charging station [18], [19]. By using the DSTATCOM in the grid, several benefits like reduction in the harmonics, switching losses and voltage stability analysis are done [20], [21]. For the power factor correction and harmonic reduction, a capacitor-less DSTATCOM based on the matrix converter (MC) is proposed and for active and reactive power control, the synchronous reference frame (SRF) method is accomplished because of the fast response and harmonic elimination and in voltage control mode (VCM) to provide fast voltage regulation [22]-[24]. Evaluation of voltage total harmonic distortion (THD) is performed with different current harmonic spectrum caused by EV charging in low voltage distribution systems [25].

A lot of research work has already been published on DSTATCOM to improve the power quality in the distribution network using different techniques. Considering the limitations of various studies presented in the literature, this paper presents DSTATCOM using the d-q algorithm to analyze and mitigate the THD, reducing the effect of power issues on the distribution network. MATLAB/Simulink has been used for the simulation of DSTATCOM to reduce the effect of harmonics in the distribution grid.

2. INTERFACING OF EVs WITH DISTRIBUTION GRID

The circuit diagram representation of the model used in the paper showing the interfacing of EVs to the distribution grid is shown in Figure 1. The basic components used in the system are a utility grid with transformers forming a distribution grid which is connected through DSTATCOM to DC/AC converter with its voltage-oriented controller, a DC/DC converter with its constant current controller to step up and step down the DC link voltage respectively during charging and discharging state, and an EV battery of lithium-ion type. The main purpose of the work is to simulate the impact of EV charging stations on the distribution grid and analyze the filtering of resulting harmonics.

2.1. AC/DC converter

The converter used in the circuit is front end converter also known as the active filter. It maintains a constant voltage across the DC bus by converting the AC grid voltage to DC. It is used to regulate 800 V DC across the bus. To build this converter in the simulation, IGBT/ Diodes are used in the Simulink design.

2.2. Voltage oriented control (VOC)

The control strategy used for the AC/DC converter is the voltage-oriented controller. The primary objective of the controller is to improve the power factor. The first step to achieve this control method is to create a phase-locked loop (PLL) to obtain the angle (wt) from the three-phase voltage. It is done by using the transformation in (1).

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1\backslash 2 & -1\backslash 2 \\ 0 & \frac{\sqrt{3}}{2} & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{1}$$

The next step is to convert the voltage and current from the abc frame to dq frame. The transformation equations used are (2) and (3).

$$i_d = 2/3[i_a \cos(\theta) + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3)] \tag{2}$$

$$i_q = -2/3[i_a \cos(\theta) + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3)] \tag{3}$$

After the transformation, a decoupled controller can be used. For this control scheme, the impedance of the filters is multiplied by i_d and i_q and then compared to the controllers. After this step, again the dq frame is converted to abc frame. This can be done by the transformation in (4)-(6).

$$i_a = i_d \cos(\theta) - i_q \sin(\theta) \quad (4)$$

$$i_b = i_d \cos(\theta - 2\pi/3) - i_q \sin(\theta - 2\pi/3) \quad (5)$$

$$i_c = i_d \cos(\theta + 2\pi/3) - i_q \sin(\theta + 2\pi/3) \quad (6)$$

From this, the signals can be run through a pulse width modulation (PWM) to generate the control signals for the converter.

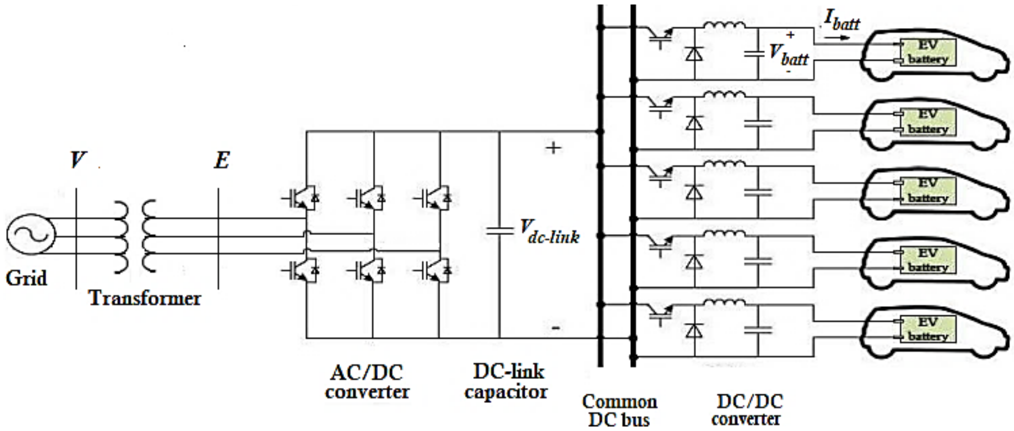

Figure 1. Circuit topology of the model

2.3. DC/DC converter

The DC/DC converter used in this work is a buck-boost converter. It is an important part of the system as it converts the voltage input to the battery and comes out of the battery for optimal use. It operates in the buck mode during charging and in the boost mode during discharging of the battery as shown in Figure 2. The device used in the converter is a MOSFET semiconductor.

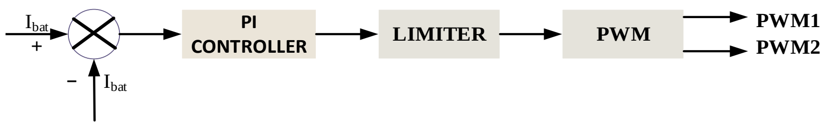

Figure 2. Block diagram for charging and discharging of battery

2.4. Constant current (CC) controller

It is used to supply a constant current to the battery during the charging process and serves to keep the balanced charging across the cells. It also keeps the battery in the normal operation mode. In addition to the DC link voltage and a current reference derived from the battery capacity, this technique makes use of the battery's current and voltage. To get the gate signals for the converters, the output signal is passed via a pulse width modulator. Trial and error are used in the PI controller design process to achieve nearly perfect accuracy between the reference current and the battery current.

2.5. DSTATCOM

The primary part of the system for mitigating the harmonics introduced into the distribution grid from the EV charging station is DSTATCOM. It is a shunt-connected custom power device used to inject current at the point of common coupling (PCC). Its components are a voltage source converter (VSC), a filter, a DC-link capacitor to store the energy with a coupling transformer as shown in Figure 3. It consists of controllers that enable the use of different algorithms along with semiconductor switches such as IGBT and GTO. The d-q theory is used in this study to implement the DSTATCOM controller design. Since DSTATCOM's creation or absorption of reactive power is dependent on the kind of load, it is crucial for EV loads, which are non-linear.

The VSC is a power electronic device that uses semiconductor switches to control the flow of power. A controller provides the gate pulses to these switches. The capacitor C_{dc} helps in maintaining a constant level of voltage for switching operation in VSC [21]. Due to reduced size and low switching losses, usually IGBT is preferred as the switching element in the distribution voltage level. The output voltage control can be executed through a pulse width modulation (PWM) switching pattern due to the low rating of converters employed in these devices.

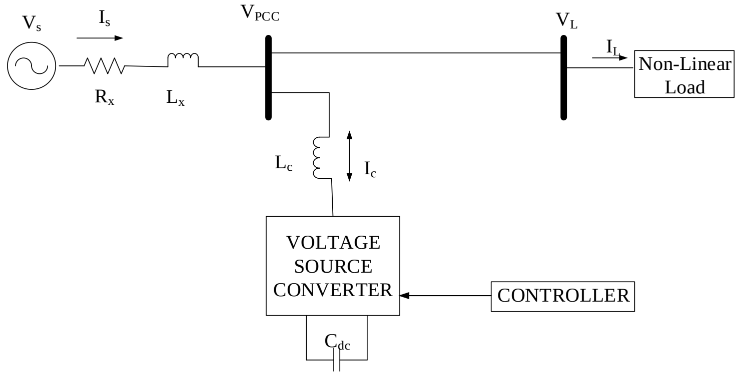

Figure 3. D-STATCOM schematic diagram

3. CONTROL ALGORITHM OF DSTATCOM

The inverter is the main part of the DSTATCOM system, and it can be supplied with a triggering pulse by several different algorithms. The PWM control technique is the one employed in this work to generate the triggering pulses for the IGBT-based inverter. Park and Clark's equations are used to convert the three-phase system to the reference frame system. The instantaneous voltage and current data are used in this method. The current is transformed from abc to dq0 by using PLL and then decoupled to i_d and i_q are regulated with PI regulators. Figure 4 shows the carrier-based PWM control method [21].

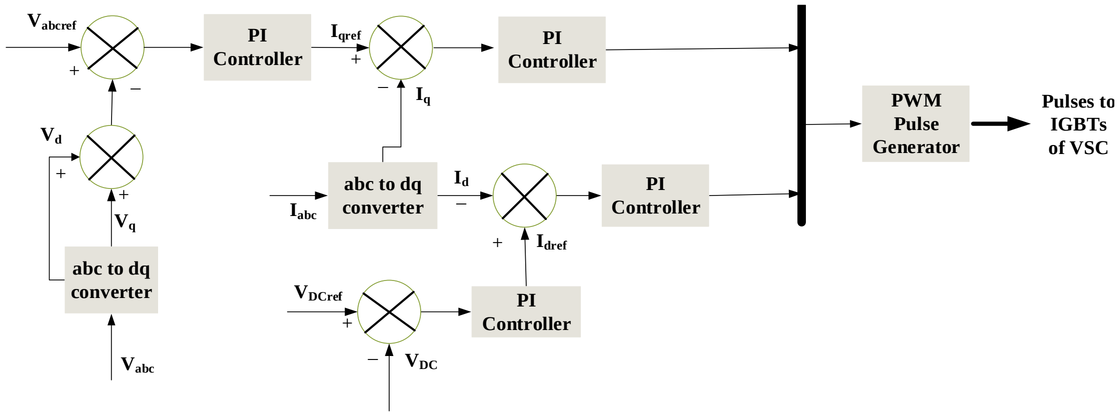

Figure 4. Block diagram of DSTATCOM controller

4. SIMULATION RESULTS AND ANALYSIS

Due to the non-linear loading conditions, the harmonics are induced in the distribution network which results in the variations of voltage and current. Harmonic distortion causes several disturbances and damages like overheating and power loss. THD for any system should be kept low which helps in improving the power factor and efficiency and also reduces the peak currents.

The simulation model of the system is shown in Figure 5. A three-phase source is connected to the transformer and a parallel RLC load. The V-I measurement block is used for the measurement of rated current and voltage, connected to the other transformer. DSTATCOM is used to compensate for the harmonics in the distribution grid due to the integration of EVs. The current measurement block is used to measure the three-phase current of the grid. The current and voltage is passed to an active rectifier to change the AC to DC required for the charging of electric vehicles in the stations. The pulse width modulation technique is used to provide signals to the rectifier. A subsystem is created of different charging stations. In this simulation model, five charging stations are used that consist of Lithium-ion batteries for charging.

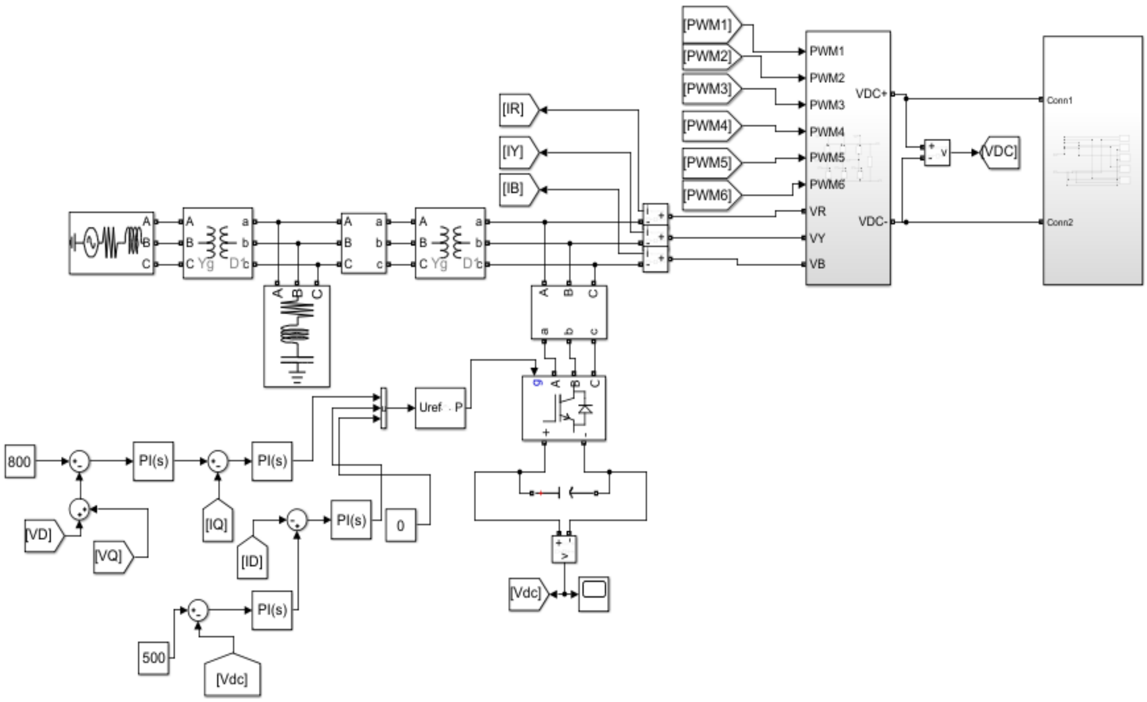

Figure 5. Simulation model of the system

The parameters of each component used in the Simulink are shown in Table 1. It can be seen from Figure 6 that when EV charging stations are connected to the distribution network in both V2G and G2V modes, the THD percentage is 18.61% which is not suitable according to IEEE Standard-519, which creates a negative impact on the grid. However, by connecting DSTATCOM at the distribution grid in both modes as represented in Figure 7, the value of THD percentage has improved significantly and reduced to 0.31%, which is now feasible and according to the IEEE standards. Figure 8 shows the voltage waveform without using DSTATCOM with harmonics. In Figure 9, the harmonics in the voltage waveform have been reduced using DSTATCOM and Figure 10 shows the DC output waveform of the system. The results obtained are compared with the reference paper [21], a summary of which is shown in Table 2. The comparison results clearly show the improvement in THD content as well as the effectiveness of the proposed technique.

Table 1. Simulink parameters

S.No	System parameters	Specifications
1.	Grid source voltage (V_g)	120 kV
2.	Grid load voltage (V_L)	25 kV
3.	Low side AC voltage (V_{AC})	260 V
4.	DC link voltage (V_{DC})	800 V
5.	DC battery voltage (V_{BATT})	360 V
6.	DC link capacitor ($V_{dc\text{-}link}$)	5600 uF
7.	DC bus capacitor (V_{dc})	7000 uF

Table 2. Comparison of THD improvement results

S.No	Methodology	Before (%)	After (%)
1.	Proposed by DSTATCOM	18.61	0.31
2.	Projected earlier by DSTATCOM [21]	17.29	2.68

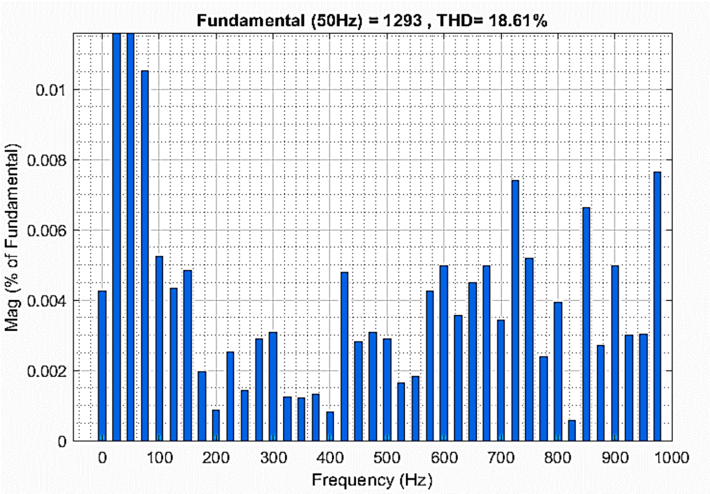

Figure 6. Total harmonic distortion without DSTATCOM

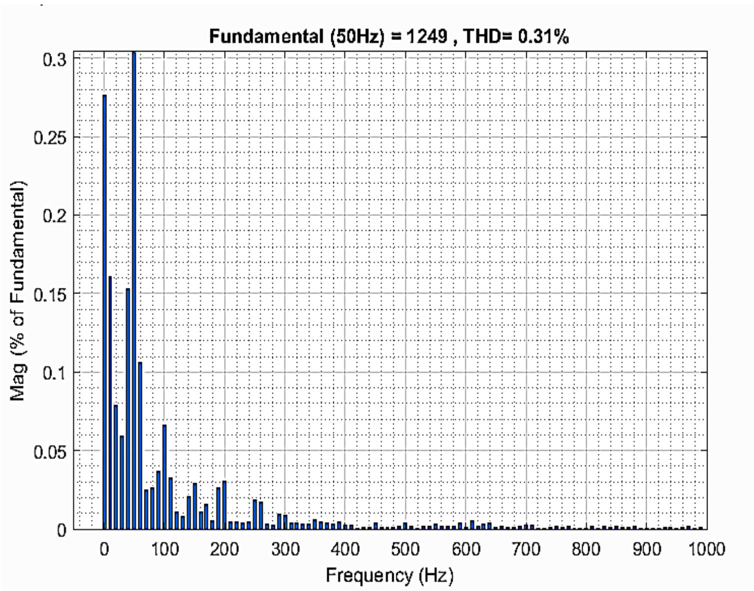

Figure 7. Total harmonic distortion using DSTATCOM

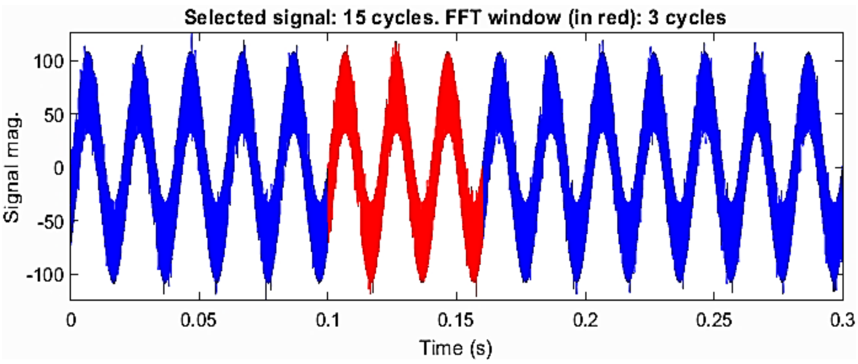

Figure 8. Voltage waveform without using DSTATCOM

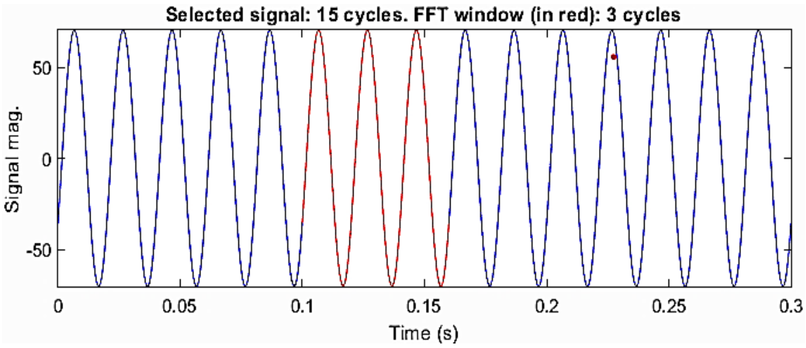

Figure 9. Voltage waveform using DSTATCOM

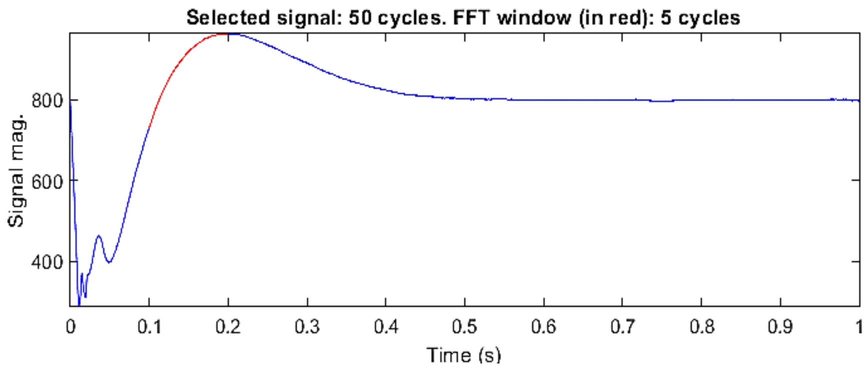

Figure 10. DC output waveform

5. CONCLUSION

In this research paper, a study of V2G and G2V with five EV charging stations connected to a distribution grid has been developed and its effect has been analyzed using MATLAB Simulink platform. To overcome the issues arising after connecting different EVs, a DSTATCOM model has been presented which is connected at the point of common coupling to the distribution network. The performance of DSTATCOM is tested using the d-q control algorithm under different loading conditions which shows remarkable improvement in the THD content from 18.61% to 0.31% as per the IEEE-519 limits. The main finding of the work is to minimize the THD within limits while integrating EVs into the grid. For this, DSTATCOM is utilized and satisfactory results are presented. A comparative study is also done to validate the proposed work.

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