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Power Quality Analysis for Electric Vehicle Charging and its Mitigation Strategies

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Abstract:
Abstract – Electric Vehicle charging from gird may lead to power quality issue in the grid due to AC- DC conversion required to charge Electric Vehicle battery. Thus, a proper power quality analysis is required to study the influence of these issues into the grid system. This paper deals with studying the harmonic distortion injected into the grid supply while charging and discharging an Electric Vehicle.An analysis is done with passive and active filters connected on grid side to find the best mitigation strategy applicable to reduce the influence of harmonic distortion on the grid. As a result of this study, it is found that the passive filter is more suitable for a pre-defined load, while D-Statcom is more suitable for dynamic load conditions

Keywords: *Electric Vehicle (EV), Charging, Discharging, Total Harmonic Distortion (THD)*

I. INTRODUCTION

Electric Vehicle have come as a promising technology to curb the air pollution caused due to transportation industry per year.The problem however lies with the infrastructure that is needed for large scale adoption of EVs, the main part of which is the charging infrastructure, which needs to be placed in such a manner to compete with the availability of petrol and diesel around the world. The main part of this includes deploying charging infrastructure in such a way that an EV wouldn't have to look long or travel larger distances to charge the battery.

It is only evident that with a stiff grid present in the country and being energy-sufficient in that regard with the grid, a basic charging infrastructure would include taking the power from the grid to charge the EVs. Electric Vehicles being an DC load, there is an obvious need to convert the AC power available at the grid side to a DC power, which can be then used to charge the EVs.

In order to enable a proper flow of power and enable V2G and G2V, all the converters used in the system must be bidirectional in nature so that a pool of Electric Vehicle can supply power back to grid if needed. Care must be taken however to make sure that the effect of EV charging on the grid is not very large inorder to prevent unwanted losses occurring in the system.

The problem with such a system is that while charging a single EV wouldn't be an issue, simultaneous charging a large pool of EVs from the grid can affect the overall profile of the AC parameters, such as voltage and current available at the grid.

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Another technology which can offer proper availability of charging for EV is the V2V charging technology where idle standing EVs can provide power to an EV which needs immediate charging. But such a system needs proper communication between the vehicles and the infrastructure.

The semiconductor devices used in the converters for AC to DC conversion affect the grid side supply in such a manner that the Harmonic injection into the grid increase many folds and affect the whole system. These THDs can shoot up to more than 30% which is not acceptable according to the THD standards set in the country [9 - 10] [13-14].In order to understand the impact, study is done on the residential grid side which means that the first point of study is the charging infrastructure for the residential charging, as the EV charging from residential supply is distributed over a large area and needs to be considered for power quality issues [11-12][17]. Multiple technologies are available for AC-DC conversion keeping DC link voltage constant, one of which is using a DC-DC boost converter with variable duty cycle control.

This paper deals with comparison of harmonic distortion in different condition while charging and discharging an Electric Vehicle, which include harmonic distortion comparison without using the filters and while using the filters. The comparative study between passive and active filters gives a good idea about how the filters can easily control the harmonic distortion in the AC side parameters.

One of the possible solutions to curb the impact of harmonics on the grid side parameters is to design a isolated DC microgrid system with renewable energy source to charge the electric vehicle battery. PV solar based DC microgrid is one possible solution [6].

II. ELECTRIC VEHICLE BATTERY OPERATION

The harmonic analysis in this paper is done considering two cases, where EV battery is charged and discharged with and without use of filters.

Figure 1 gives a general overview block diagram of the whole circuit used to study the harmonic distortion.

The circuit consist of a 3 phase 150kW, 25kV, 50 Hz source, which is connected to anAC-DC bidirectional converter and the output is constant DC link voltage during rectification. At the DC link, two components are connected, one being a DC load such as the DC motor, and other being the EV battery. The EV battery is connected to the DC link using a DC-DC Bidirectional converter.The details of the EV battery are listed in Table 1.

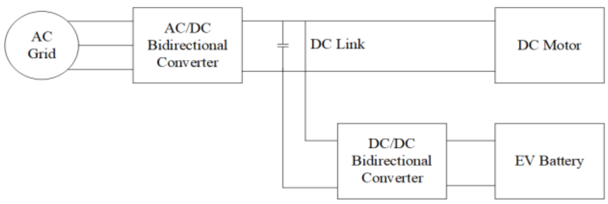

Fig. 1: Block Diagram of circuit used

Table 1: Battery Parameters

Parameters	Battery Rating	DC Motor Rating
Voltage	72V	240 V
Power	20kW	5 HP
Ampere hour	222Ah	16.2 A (current rating)
Speed	-	1200 rpm

III. CHARGING AND DISCHARGING OF ELECTRIC BATTERY

The upper switch Buck_SW works when the battery is charging and the lower switch Boost_SW works when the battery is discharging.

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A DC motor is used as a load with the battery, which helps in determining the bidirectional nature of the converters used.

Table 2: DC-DC Bidirectional converter switching

Parameters	Values	
	Charging	Discharging
Duty cycle	13.1%	86.9%

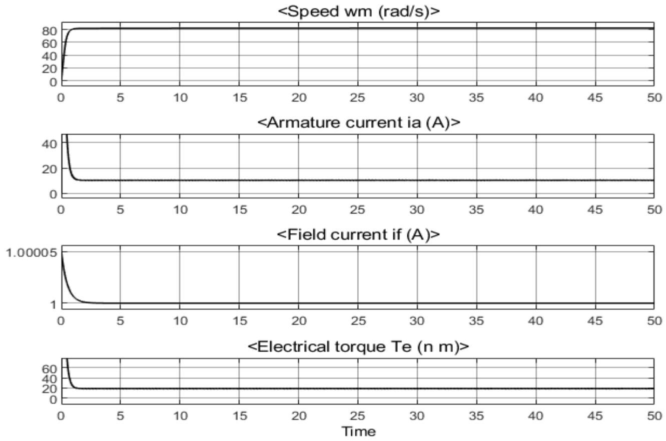


Fig. 2 Motor operation parameters

a. Without Filters

Case 1: Battery Charging

Consider Figure 3, the charging of EV battery is simulated in MATLAB. The voltage profile, Figure 4, remains constant in magnitude throughout the period after adding the Electric Vehicle as a load, but is distorted while the source current is constant and not distorted. The voltage THD however, as evident from Figure 5, is high at 9.81% while current THD is 1.46%. Voltage THD is considerably greater than the permissible limit (<5%) as specified by IEEE.

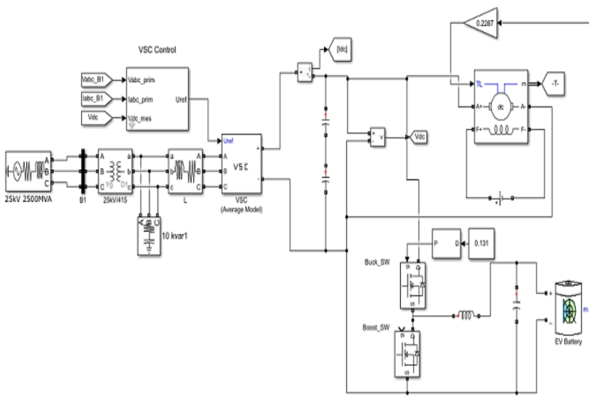


Fig. 3. Battery charging Matlab model

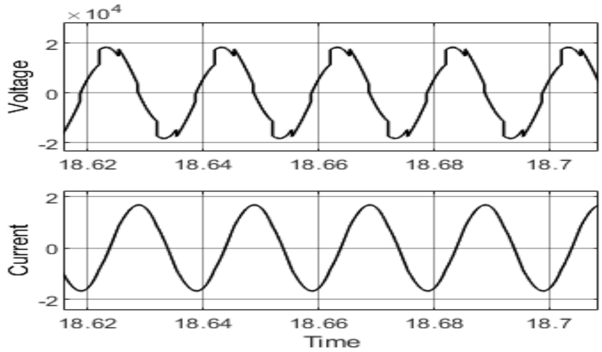
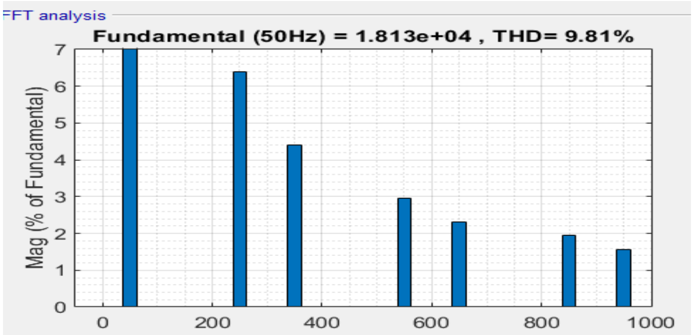


Fig. 4. Phase voltage and current profile



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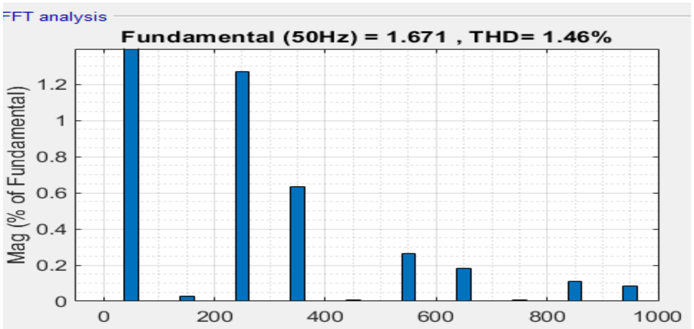

b.

Fig. 5.THD analysis of- (a).Source Voltage and (b).current profile

Case 2: Battery Discharging

Figure 7 shows us the source voltage and current profile while the battery discharge is simulated in MATLAB(fig.6). Figure 4 & 7 shows that the power rating during both the cases is around 25kW, which is used to charge the battery and run the motor. Figure 8 shows the THD analysis of the source voltage and current during discharging. The THDs are considerably high as the voltage THD is 15.11% and current THD is 12.37%.

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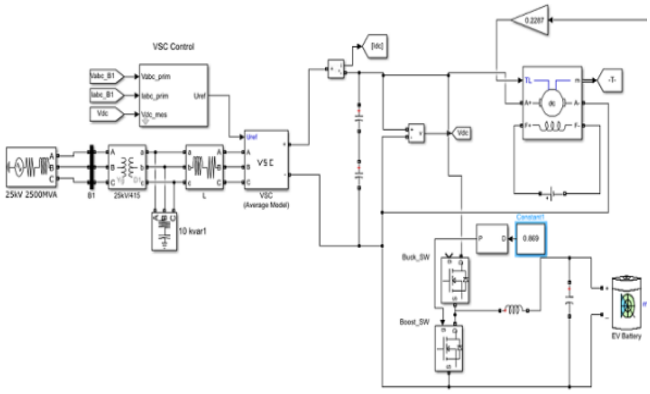


Fig. 6 Battery discharging Matlab model

Figure 9 shows motor armature and DC link current while the battery is charging (SoC increasing from 30%). The battery is getting charged with respect to its rated current as shown in Table 1, which is around 222A, armature current to the motor is at its rated current (16.2A) as shown in Table 2. The increasing battery SOC shows that the battery is getting charged as the SOC increases from 30% to 32% in 50 seconds.

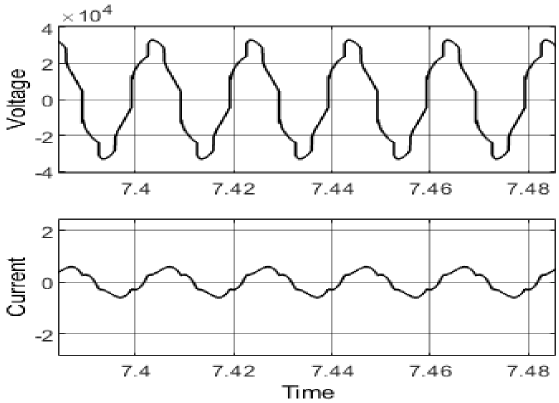
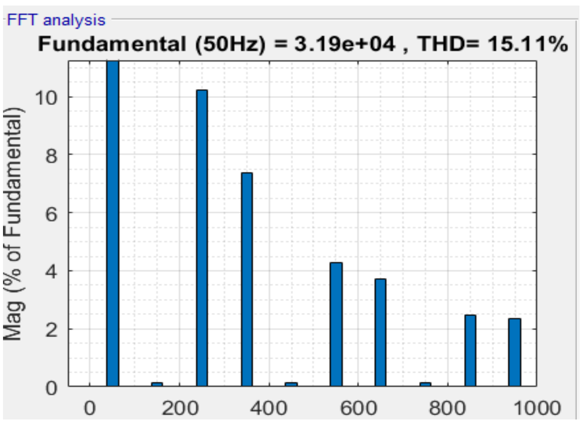


Fig. 7. Steady State Phase voltage and current profile



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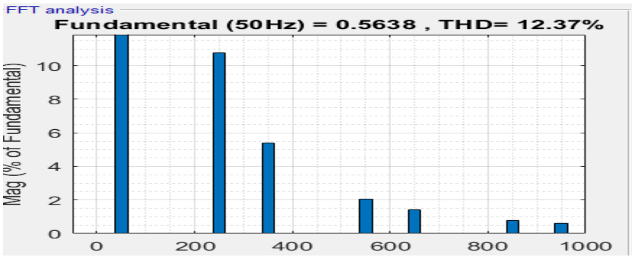

b.

Fig. 8. Steady State THD analysis of- (a). Phase voltage, (b). Phase current

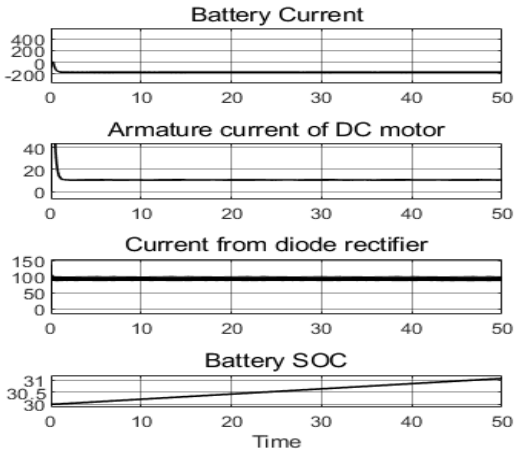

Fig.9. Current parameter during battery charging

Figure 10 on the other hand shows the power in the system while the battery is charging. The battery power is at its rated power (16kW) as shown in Table 1, and while the motor is not operating at full power (3.73 kW) which is due to low terminal voltage available at motor terminal than the rated voltage. Its is further observed , the total DC link power, which is around 20kW, is equal to the power supplied to the EV Battery plus the power given to motor.

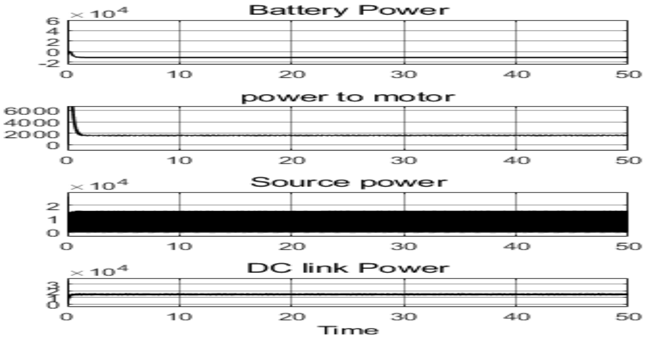

Fig.10. Power parameter during battery charging

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In both charging and discharge cases considered its obvious that voltage THD is higher than the IEEE permissible standards for both cases while current THD during discharge is higher. Its evident that EV charging and discharging has great impact on the power quality of the grid. The next section discusses the methods to mitigate this power quality issues.

IV. PASSIVE AND ACTIVE FILTER

To mitigate the power quality issue there are two filters (1) Passive (2) Active filter.

a. Passive filter

The type of passive filter which could be used for the above circuit is the double tuned Band Pass filter. In this filter, there is a parallel resonance of band pass filter, combined with series resonance of inductor and capacitor, which gives two resonant frequencies, as shown in Figure 11. The cost of this filter is less compared to two independent series filter.

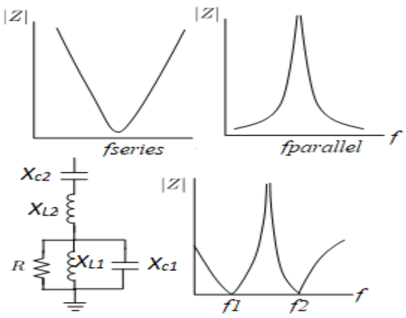

Fig. 11 Impedance characteristics of double tuned filter

The parameters of the filters are designed with the following equations (1) – (4)

$$L_1 = L_2 = \frac{V^2}{2\pi f Q_c (h_o^2 - 1)} \qquad (1)$$

$$C_1 = \frac{(h^2-1)Q_c}{2\pi f h^2 V^2} \qquad (2)$$

$$C_2 = \frac{(h^2-1)Q_c}{2\pi f h V^2} \qquad (3)$$

$$R = \frac{QV^2}{hQ_c} \qquad (4)$$

Where:h = tuning point of filter, Q_c = Reactive power of filter, Q = Quality factor, f = system frequency [Hz], V = System Voltage [V]

From the observations made from figure 5 and 8, the harmonic to be curbed are 5^{th} and 7^{th} harmonics, thus there are two cutoff frequencies possible:

$$f_1 = 5*50 = 250\text{Hz}, \qquad f_2 = 7*50 = 350\text{Hz}$$

Considering h = 5, f = 50Hz, Q_c = 200kVAr, Q = 20 and V = 25kV, the parameters obtained for filter components are $X_{L1} = X_{L2} = 130.06\Omega$, $X_{C1} = 81.38\ k\Omega$, $X_{C2} = 3.255\ k\Omega$, $R = 2.6\ k\Omega$

The total equivalent impedance connected is:Z_{eq} of filter = 6.49 – j2996.01 Ω

b. Active Filter

D-Statcom is used as an active filter for harmonic reduction in the model. D-Statcom(Fig.12) works on the principle of synchronous reference frame control of the AC phase voltage and current. D-Statcom consist of three main parts, a voltage source converter (VSC) and a set of coupling reactors and a controller. The DC capacitor connected to inverter (VSI) generated controllable AC voltage. Controller performs feedback control by comparing all the voltage and current which are measured and fed back.

The algorithm makes use of park transformation to convert three phase current or voltages into synchronously rotating d-q reference frame as follows:

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 120) & \cos(\theta + 120) \\ \sin\theta & \sin(\theta - 120) & \sin(\theta + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

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$$\begin{bmatrix} i_a \\ i_b \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta-120) & -\sin(\theta-120) & 1 \\ \cos(\theta+120) & -\sin(\theta+120) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

c. Simulation results With Passive and Active Filter

The MATLAB model for battery charging and discharging has passive band pass filter and a D-Statcom connected via a circuit breaker switch, which helps connect only one filter at a time is shown in Figure 13.

Case 1: Battery Charging

Figure 14 shows the effect of adding Band pass filter on the source voltage and current. THD analysis of the band pass filter added to the system to tune out 5^{th} and 7^{th} harmonic is shown in Figure 15. The addition of filter to the circuit results in making the voltage and current profile more uniform over the operation range. According to the FFT analysis done in Figure 15, the source voltage THD have come down to 1.64% and the source current THD has come down to 0.02%.

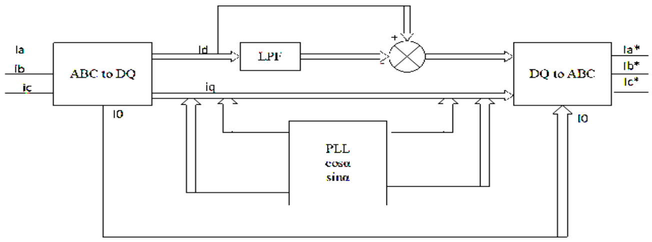


Fig. 12 Block diagram of D-Statcom working

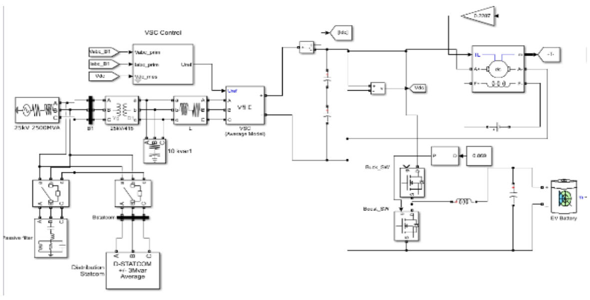


Fig. 13: MATALB model with filters

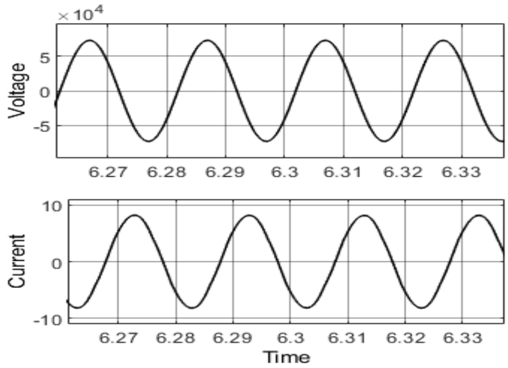
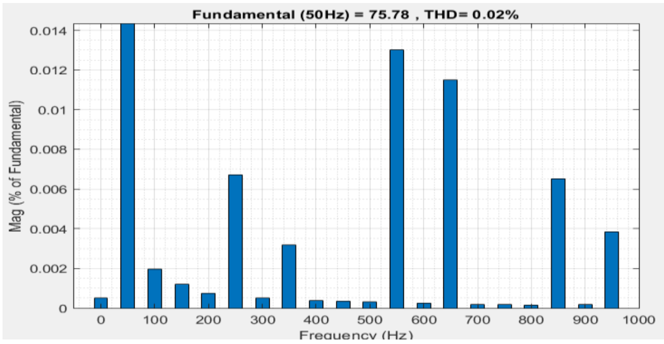


Fig. 14: Phase voltage and Current with Band-pass filter.

I_d and I_q are the control currents generated after the abc to dq transformation which is used to generate the control voltages V_d and V_q, which in turn control the switching of the converter switches used inside the D-Statcom.The THD analysis done in Figure 18 reveals that the harmonic distortion done to the AC side parameters reduces drastically, as the source voltage and current THD has fallen to 0.15%.



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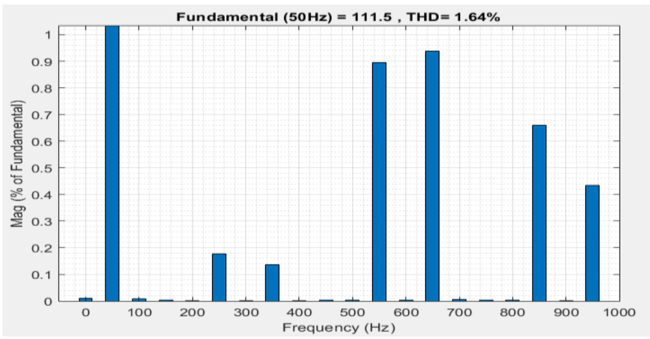


b.

Fig. 15: THD analysis of- (a). Phase current and (b). voltage profile after adding Band-pass filter

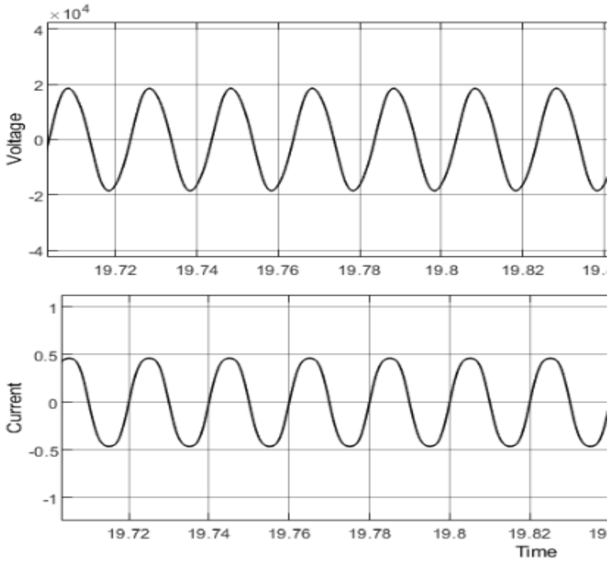


Fig. 16: Phase voltage and Current profile after adding D-Statcom

Case 2: Battery Discharging

During the battery discharging, the battery is sufficiently large enough to provide power to the DC motor connected, so the AC to DC conversion doesn’t play much more. According to the Figure 19, it is evident that adding the Band pass filter in the circuit has reduced the harmonic content drastically. The THD analysis done in Figure 20 shows that the source voltage THD has come down to 0.33% and source current THD to 0.0%.

It can be seen from Figure 21 that the battery is providing a positive current to the DC load (DC motor) connected. The discharging of battery is also evident from the decreasing SOC of the battery where the SOC decreases from 100% to around 97% in about 50 seconds.The battery is discharging with a current of 200A, while the DC motor is demanding a low amount of current (around 8A), due to the low terminal voltage available at the DC motor terminal. This is also due to the inversion from DC-AC where most part of power is being given back to the grid.

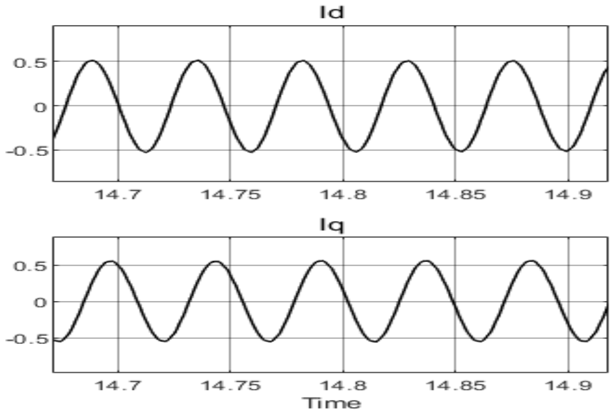
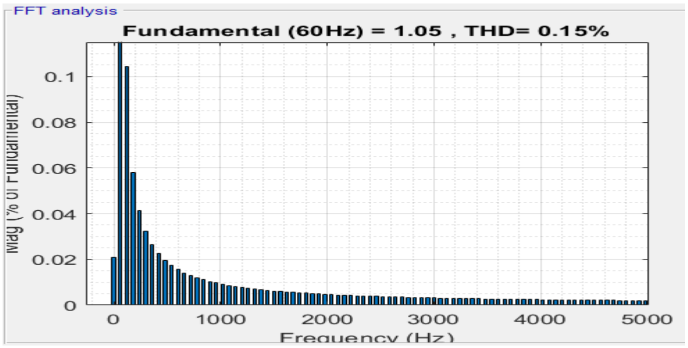


Fig. 17: Id-Iq current



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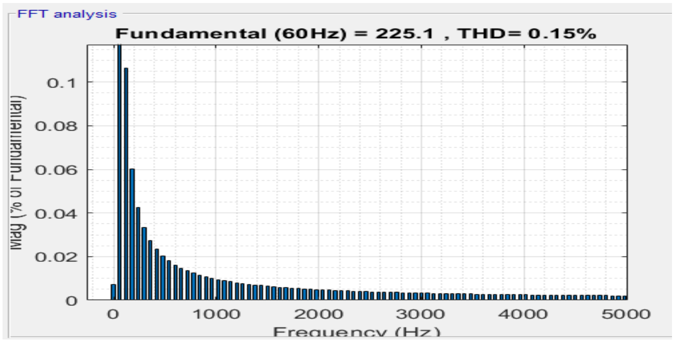

b.

Fig. 18: THD analysis of- (a). Phase voltage and (b). Current profile after adding D-Statcom

Figure 22 shows variation of battery power while its discharging with respect to the power supplied to the DC motor and the variation in source power.Carefully observing Figure 22 shows that the Battery power reveals that it is decreasing over the period as the battery is discharging.

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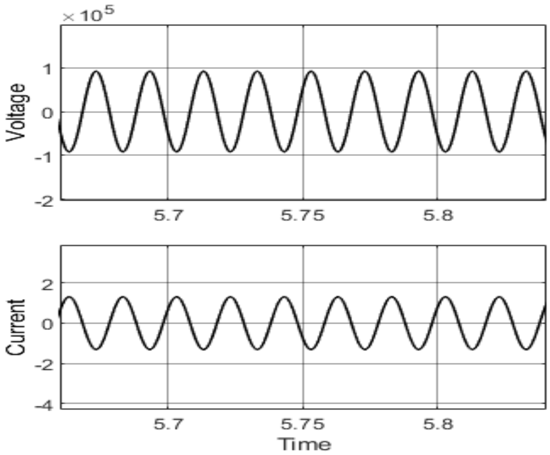
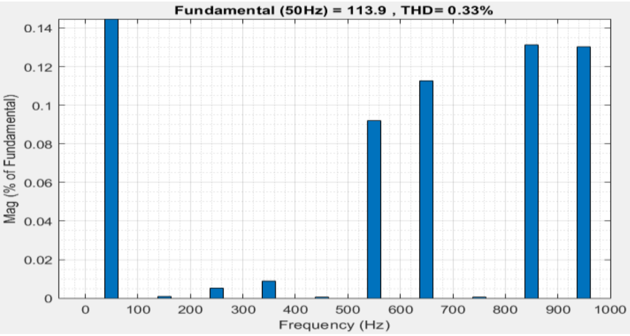
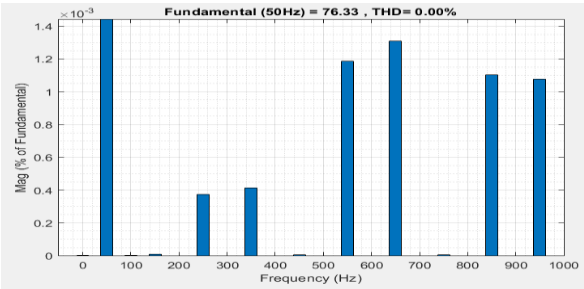


Fig.19: Phase voltage and Current profile after adding Band-pass filter



a.



b.

Fig. 20: THD analysis of- (a). phase voltage and (b). phase current

The battery is also providing power back to the source which is evident from Figure 22 as the Source power is in negative axis, showing flow of power from DC link to Source side. It can be seen from Figure 22 that the total power given to motor plus(around 3kW) the power given back to the grid(around 2 kW) is equal to the total power of EV Battery.

Figure 23 shows the voltage and current profile when D-Statcom is added to the system while the battery is discharging and providing power to grid and the motor. The voltage and current are much more uniform. Figure 24 shows the THD analysis of phase voltage and current.

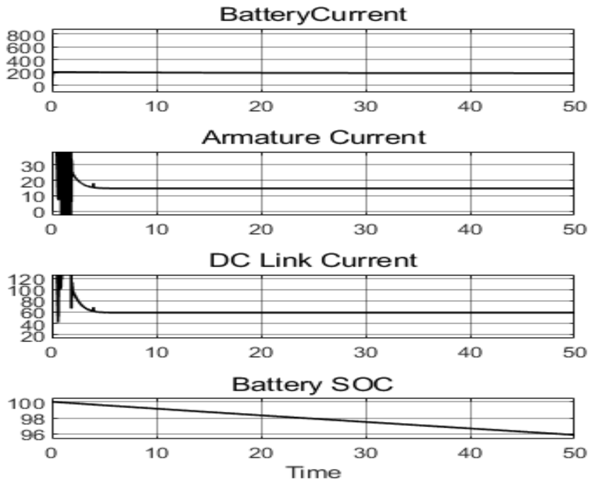


Fig. 21: Battery Discharging characteristics

Table 3: THD comparison without filter

Parameter	Without Filter	
	Charging battery	Discharging battery
Voltage	9.87%	15.11
Current	1.41%	12.37%

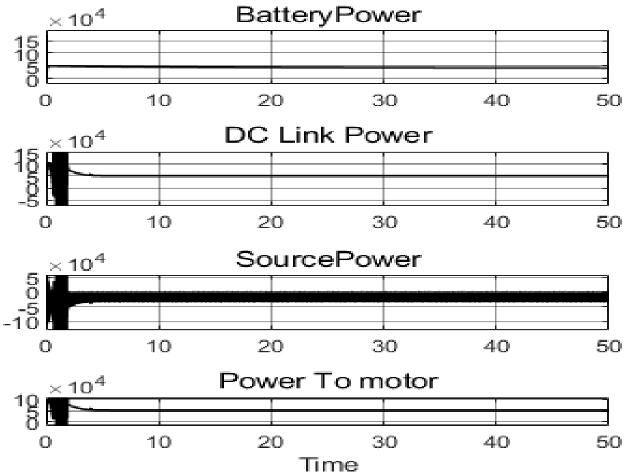


Fig. 22: Battery power, Dc motor power and Source power while battery discharging.

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The voltage profile had advantage over Band pass filter results, while the current is very minutely distorted. But there are several advantages of D-Statcom over Band pass filter that make it a better option than band pass filter which are listed in conclusion.Table 3 and 4 show us advantage of using filters in curbing the harmonics, and Table 4 shows us the difference in harmonics by using two different filters.

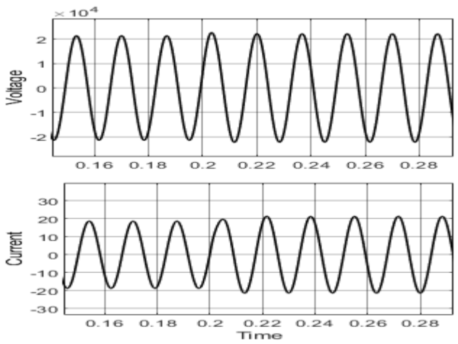
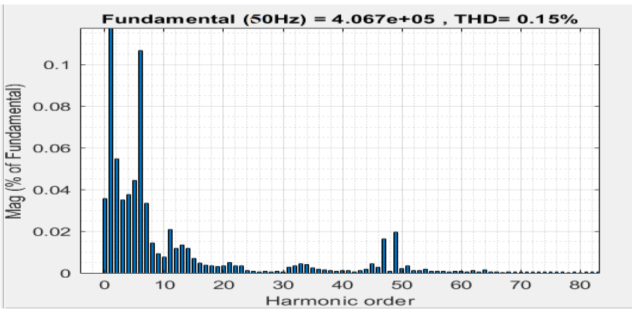


Fig. 23: Phase voltage and current after adding D-Statcom



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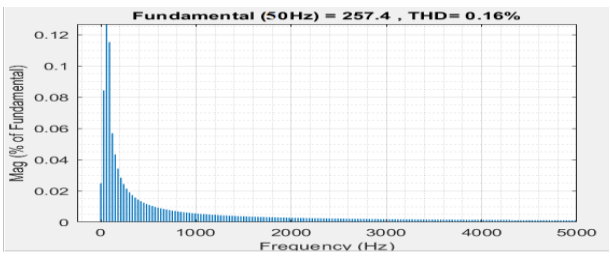

b.

Fig. 24: THD analysis of (a). Phase Voltage and (b). Phase Current after adding D-Statcom

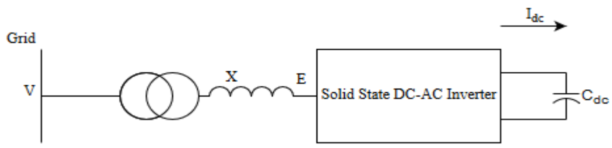

Fig. 25: D-Statcom block diagram

Table 4: THD comparison with filter

Parameter	Charging battery		Discharging battery	
	Band Pass	D-Statcom	Band pass	D-Statcom
Voltage	1.64%	0.15%	0.33%	0.15%
Current	0.02%	0.15%	0.00%	0.16%

As the calculation of inductor and capacitor of Band pass filter value is dependent on the system specification, a filter designed for one system can't be efficiently used for another system. This filter can only work then for a defined load.D-Statcom reactive power generation is dependent on the difference in the grid side voltage V and converter voltage E, as shown in Figure 25. The reactive power drawn is:

$$Q = \frac{1 - \frac{E}{V}}{X} V^2$$

By controlling the magnitude of E, the reactive output power is controlled, thus the operation of control of harmonics in the system is much better in D-Statcom as the firing angle or PWM control allows us to control the voltage E to a greater extent than the passive filter.

V. CONCLUSION

A very simple method to curb EV charging induced harmonics is to use filters to remove specific frequency of harmonics. A double tuned band pass filter is used which provides option of two resonant frequencies and are less costly to make than two parallel independent series filters.Using a D-STATCOM is another option which can work with a wide range of power ratings unlike passive filters which are designed for a specific system.D- STATCOM are much preferred as there is not active power exchange between the STATCOM and the grid and hence no active power losses which can affect the working of the D- STATCOM.

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Comparing the performance of Band pass filter (passive) and D- STATCOM (active filter), from Table 4, one can conclude that the performance of both the filter is almost same, but the D-STATCOM has advantage over Passive filter. The THDs in case of D- STATCOM are very less. Being an active filter, D- STATCOM can be designed for a wide variety of power ratings, unlike passive filter which requires changing the filter with change in power rating of the system. D-Statcom doesn't have any active power loss, asactive power exchange between D-Statcom and the systemdoes not exist, thus operating efficiency is not affected of the system. EV charging is not predictable and hence mitigation of power quality issues for this dynamic load variation is effective only with active filter.

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