Bidirectional AC-DC Converter Simulation For V2X Power Transmission

Hari Krishna Nelluru
Department of Electrical Engineering
National Institute of Technology Warangal
Hanumakonda, India
nh22eem3r11@student.nitw.ac.in

Ch. Venkaiah, SM, IEEE
Department of Electrical Engineering
National Institute of Technology Warangal
Hanumakonda, India
ch.venkaiah@ieee.org

Senthilnathan Thangavelu
Advanced Engineering
TATA Passenger Electric Mobility
Pune, India
stt770131@tatamotors.com

***Abstract*—This paper primarily focuses on the implementation of V2X technology in Electric Vehicles (EV). The pivotal role of power electronics and its control mechanisms is emphasized to enable this technology. We employ a bidirectional totem pole Power Factor Correction (PFC) to convert AC power into DC power, facilitating both the charging and discharging of the EV battery. A detailed exploration of V2X operation and the control intricacies of the AC-DC converter is presented. The converter exhibits a maximum efficiency of 98.5% across various operational modes, with a power factor of 0.995 during charging. Additionally, the paper provides a comparative analysis of different AC-DC converters. Bidirectional PFC plays a pivotal role in aligning with the regulatory mandates and fostering the development of an advancing smart grid ecosystem.**

***Index Terms*—V2X (X - load, house, building, grid), Totem-pole PFC, PFC (power factor correction), Electric Vehicle (EV), Electric Vehicle Supply Equipment (EVSE).**

I. Introduction

In recent times, the prominence of Electric Vehicles (EVs) in the automotive industry has escalated significantly. The shift towards EVs is driven by various factors such as environmental concerns, including the reduction of greenhouse gas emissions, energy independence and security through the diversification of energy resources, economical benefits with long-term cost savings, and technological advancements, specifically in battery technology and power converters [1]. Government incentives and supportive policies, coupled with considerations of urban planning and air quality, further contribute to the compelling case for EV adoption [2]. This transition to EVs represents a multifaceted response to the imperative for sustainable, energy-efficient, and environmentally friendly transportation solutions.

The term ”vehicle-to-everything” (V2X) collectively encompasses various modes like vehicle-to-home/building (V2H), vehicle-to-load (V2L) [3], vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G) [4]. These modes leverage the vehicle to provide power during a power outage or displace grid energy with energy sourced from vehicle energy storage [5].

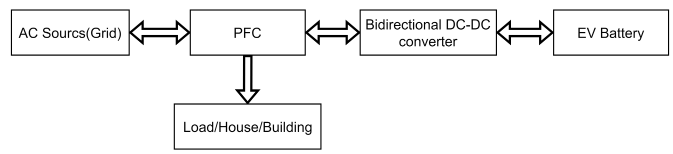

Fig. 1. General block diagram of Power flow in an EV

In EVs, power converters such as AC-DC (Power Factor Correction [PFC]) [6] and DC-DC (Buck-Boost) play pivotal roles in the charging and discharging processes of Battery Electric Vehicles (BEVs). The advancement in battery technology, encompassing increased storing capacity, discharging power, and overall lifespan, allows batteries to serve as a reliable energy source when needed. This concept leads to the transmission of power from the vehicle to various destinations, including loads, houses, buildings, and the grid [5].

The implementation of converters in EVs for these applications involves selecting the appropriate converter based on its merits and demerits, tailored to the specific requirements of the application. This paper conducts a comparative analysis of various converters suitable for a vehicle-level 400V, 12kW battery system. The simulation results of the finalized converters are also discussed [7].

Typically, within the context of an Electric Vehicle (EV), the power transmission process occurs in two distinct stages when transferring energy from the Electric Vehicle Supply Equipment (EVSE) to the EV battery or from the battery to various destinations such as loads, houses, buildings, and the grid. The initial stage involves AC-DC conversion, specifically PFC, while the subsequent stage employs DC-DC conversion,

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specifically utilizing a Buck-Boost converter, to ensure DC voltage leveling at the battery connection. This paper exclusively concentrates on the PFC block, specifically the AC-DC converter, within this two-stage power transmission framework.

II. AC-DC Converter

An indispensable element within Electric Vehicles (EVs), the bidirectional AC-DC converter facilitates efficient and versatile power transmission between the Alternating Current (AC) grid and the battery. It enables the transfer of stored energy from the battery back to various destinations such as loads, houses, buildings, and the grid, supporting Vehicle-to-X (V2X) applications. In charging scenarios, the AC-DC converter plays a crucial role in converting AC power to DC power and vice versa. However, the inherent inductive nature of the charging circuit and load conditions often result in a low power factor. To address this, a PFC block is employed, converting AC power to DC power with a power factor exceeding 0.95 [8].

Various topologies exist for power factor improvement, each with its own advantages and disadvantages depending on the application and rated power. The selection of an appropriate topology is influenced by the specific requirements of the application; for instance, some applications demand high-power supply with a high power factor, while others may suffice with a lower power factor. In the case of a 7.5kW power supply for single-phase charging/discharging, the Bridge-less Totem-pole [9] PFC proves sufficient for optimal system operation, offering maximum efficiency and a high power factor at minimal cost compared to alternatives with similar efficiency and power factor [10].

Various PFC converter topologies exist, and the subsequent discussion provides a comparative analysis of some converters in a table format [7] [11].

TABLE I
Comparative analysis of different topologies for PFC stage

Topology	Efficiency	Power Factor Range
Boost PFC	90-95%	0.95-0.99
Buck-Boost PFC	88-93%	0.92-0.98
Bridge less PFC	92-97%	0.96-0.99
Interleaved PFC	94-98%	0.97-0.99
Interleaved bridge less PFC	94-99%	0.97-0.99
Resonant PFC	95-99%	0.97-0.99
Totem-pole PFC	93-98%	0.95-0.99
Interleaved Totem-pole PFC	95-99%	0.97-0.99

A. Totem-pole PFC

The depicted Power Factor Correction topology is illustrated in Fig. 2. The power source for charging the batteries is derived from the 230V, 50Hz AC Grid. This grid power is directed to a bidirectional bridge-less converter. In the charging phase, the converter operates as a rectifier, while during discharge, it functions as an inverter by feeding power back to the grid. The primary aim of this bidirectional converter is to draw or supply grid current at unity power factor. The key functions of this grid-connected converter include:

1) Current drawn/supply to the grid at unity power factor.
2) To maintain constant DC voltage at DC link irrespective of disturbances in the grid.

Bridge less Totempole PFC has the following **advantages**:

1) Improved efficiency at higher power
2) Reduced conduction losses
3) Bidirectional Charging Capability
4) Improved Power Factor and Low Harmonics
5) Versatility and Adaptability
6) Moderate Complexity
7) High Power Rating
8) Advanced Control Techniques

The input inductance and output capacitor values are calculated based on the given formulae stated in equations (1), (2) and (3):

$$Li = Vg^2/(Iripple.P.Fsw).(1 - Vg, peak/Vdc) \quad (1)$$

$$Co1 > 2.P.Thold/(Vdc^2 - Vdc^2, min) \quad (2)$$

$$Co2 > p/(2.Vdc.\pi.f.delta(Vdc)) \quad (3)$$

$$Co = max(Co1,Co2)$$

Where *Li, Co, Vg, Iripple, P, Fsw, grid RMS voltage, Vg,peak, Vdc, Thold, f* are input inductance, output capacitance, percentage of ripple current, power rating of the system, switching frequency, grid peak voltage,output DC voltage (DC-link voltage), Hold up time and line (grid) frequency respectively.

The PFC block **system specifications** are specified as:

- Input voltage : 230 V (rms) 50 Hz
- Input current : 32 A (rms)
- Output voltage : 400 DC (desired)
- Switching frequency : 30 kHz
- Switching elements : N-mosfets
- Input side inductor : 1.7589 mH
- Input Side capacitor : 11.58 uF
- Out put capacitor : 6400 uF
- Power factor : greater than 0.95

B. Operation of Totempole PFC

The bidirectional PFC block functions predominantly in three distinct modes, each of which is elucidated in detail below.

1. Grid to Vehicle (G2V): The Totem-pole PFC engages in both the positive and negative cycles of the AC main supply, regulating the current flow based on the switching of the MOSFETs. The high-frequency MOSFETs, in conjunction with the inductor, establish a synchronous mode boost converter. In the positive half cycle, S1 is consistently ON, and S2 is

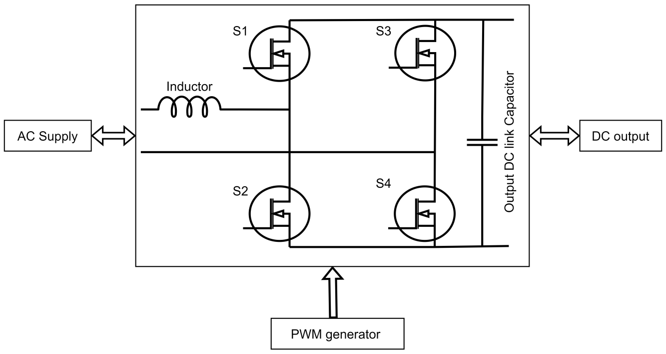

Fig. 2. Totem-pole PFC

consistently OFF. S3 and S4 are operated with duty cycle D and 1-D, respectively. Conversely, during the negative half cycle, the pulses are reversed, with S1 OFF, S2 ON, and S3 and S4 operated with 1-D and D, respectively. The control logic for this entire operation is depicted in Fig. 3, and the pulse sequence is illustrated in Fig. 4. Input power adheres to specified standards and is regulated through the current controller.

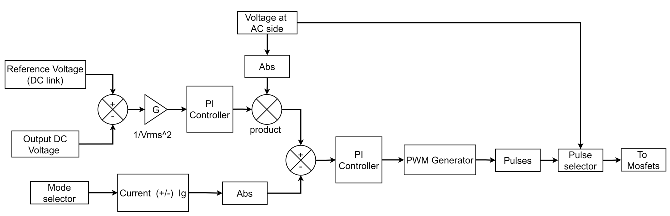

Fig. 3. Block diagram for control of Totempole PFC

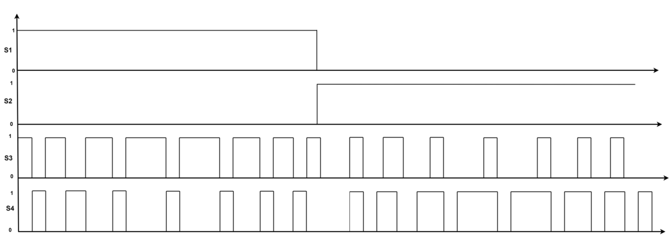

Fig. 4. Gating Pulses for Totempole PFC during G2V mode

2. Vehicle to Grid (V2G): This functionality enables vehicles to contribute electricity to the grid, with the utility or distribution system operator purchasing energy from participating customers. The power sourced from Electric Vehicles (EVs) presents a potentially more cost-effective alternative. Moreover, EV power can serve ancillary purposes, such as balancing supply and demand and contributing to frequency control, encompassing primary frequency regulation and secondary reserve. However, V2G implementation involves specialized hardware, specifically bidirectional inverters, which incur notable losses and exhibit limited round-trip efficiency. Additionally, the charge/discharge cycling in V2G mode may have implications for battery life.

The injected power into the grid is regulated through the current controller, with a maximum power injection of 7.5kW. Notably, in V2G mode, the current is out of phase with the grid voltage, given the power flow from the vehicle to the grid. The Phase Locked Loop (PLL) block identifies the grid phase, with the detected phase serving as input to the current controller, which constrains the maximum current flow in the circuit. The controller block diagram is depicted in Fig. 5, and the gating pulses for the PFC block in V2G mode are illustrated in Fig. 6.

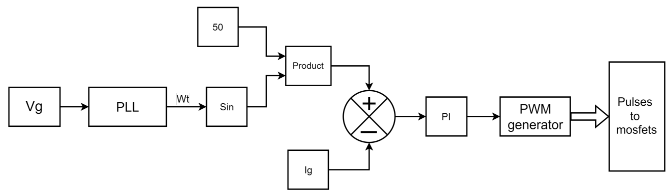

Fig. 5. Block diagram of control logic for PFC block during V2G mode

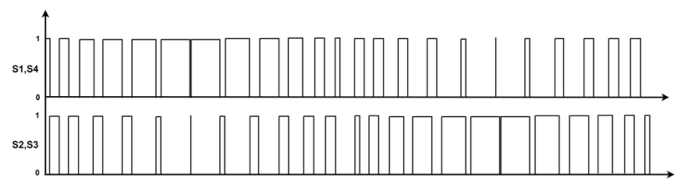

Fig. 6. Gating pulses of PFC block in V2G mode

3. Vehicle to Load (V2L/V2V): V2L facilitates bidirectional charging, allowing an electric vehicle's battery to power up the external devices. This versatile capability enables various applications, including charging other EVs, powering appliances during activities like camping or traveling, and serving as a backup electricity source during outages. Considerations for this mode encompass power limits, compatible adapters, and professional installation for V2H connections. It is important to note that V2L distinguishes itself from V2G, where larger power is fed back to the electrical grid. V2L caters to localized use cases, and its adoption is on the rise in new EV models. Additionally, V2L can be used to charge other devices such as smartphones or other electric cars, as well as power appliances like televisions or coffee machines.

The AC-DC converter's operation in V2L mode closely parallels that of V2G mode, the key distinction being the utilization of current in phase with the voltage. In this mode, S1 and S4 are operated with duty cycle D, while S2 and S3 are operated with duty cycle 1-D. The control logic for the totem pole PFC in V2L mode is illustrated in Fig. 7. The necessary pulses waveform are shown in figure 8.

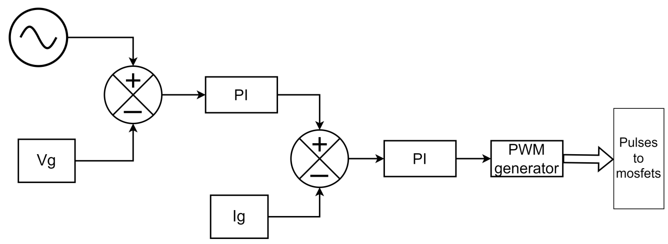

Fig. 7. Block diagram of PFC block controller during V2L mode

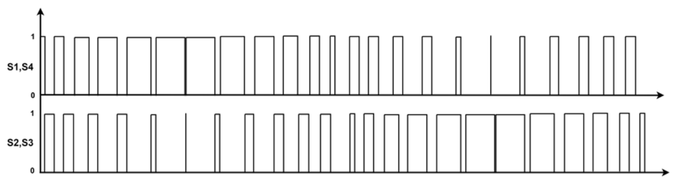

Fig. 8. Gating Pulses of Controller for PFC block in V2L mode

C. PI controller tuning

Determining PI controller parameters for each scenario: The transfer function remains consistent for both V2G and V2L modes and is represented as G(S). In this context, G(S) denotes the open-loop transfer function of the system, where Gv(S) stands for the open-loop voltage controller, and Gi(S) represents the open-loop transfer function of the current controller. The closed-loop feedback, denoted as H(S), is characterized by unity.

The Kp,Ki values for the both Outer voltage and inner current controller is determined through the given block diagram as shown in Fig. 9 and those values are as specified in the table II.

Where Kp_V, Ki_V are the outer Voltage controller proportional and integral constants values respectively. Kp_I, Ki_I are the Inner current controller proportional and integral constant values respectively.

The derivation of these values involves solving the transfer function in accordance with the provided block diagram, both in open loop and closed loop configurations. The gain for the inner current controller loop is assumed to be unity.

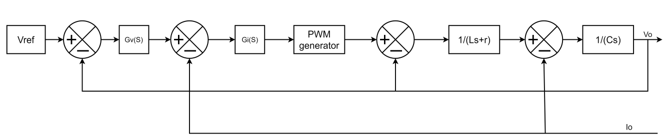

Fig. 9. Block diagram for tuning PI controller for V2X Modes

TABLE II
OUTER AND INNER CONTROLLER PARAMETERS FOR CHARGER CONTROLLER CIRCUIT

Parameter	G2V Mode Value	V2G Mode Value	V2L Mode Value
Kp_V	50	-	1
Ki_V	43.75	-	4.114
Kp_I	48.33	0.1	7.11
Ki_I	42.75	10	18.85

III. SIMULATION RESULTS AND DISCUSSION

In this section, we will delve into the simulation results pertaining to the previously discussed operational modes, all conducted on the MATLAB Simulink platform.

1. G2V mode: The operational procedures and control mechanisms have been previously addressed, and the corresponding plots are presented herein Fig.10 and Fig.11. During the charging phase, the power factor attains an exceptionally high value, reaching 0.999 for a maximum load of 7.5 kW. The Total Harmonic Distortion (THD) is initially less than 1%, diminishing to 0.8% as the simulation progresses. Notably, the Power Factor in this model closely approximates unity. The topology exhibits an efficiency of 99%, signifying remarkable performance. The DC voltage stabilizes at 400 V DC after 0.3 seconds of simulation, with minimal voltage variation of approximately +/- 5V. The output DC voltage spans between 389V and 404V, encompassing the minimum and maximum values, respectively.

TABLE III
RESULTS FOR G2V MODE OPERATION

Parameter	Value
Output DC Voltage	400 V
Power factor	0.99
Grid Current(RMS)	32 A
Maximum Power	7.5 kW
Total Harmonic Distortion(THD)	0.89%
maximum efficiency	99%

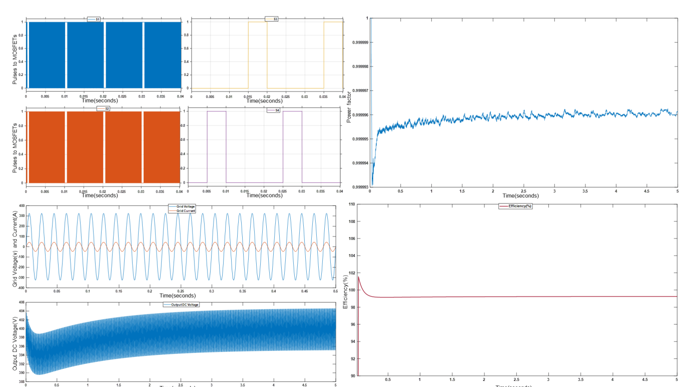

Fig. 10. AC voltage ,current, efficiency and power factor wave forms in G2V mode of PFC block

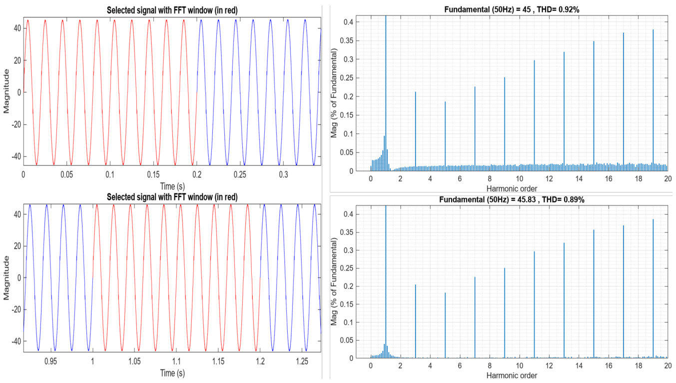

Fig. 11. Total Harmonic Distortion of input grid side current in G2V mode

2. V2G mode: In addition to the presented simulation results, it is worth noting that the 180-degree phase shift between the current and the grid voltage, optimizes the power transfer from the Electric Vehicle to the grid. The utilization of the Phase Locked Loop (PLL) block ensures accurate determination of the grid voltage phase. The demonstrated simulation outcomes, depicted in the accompanying figures Fig.12 and Fig.13, highlight not only the remarkable maximum efficiency of 98.5% but also the consistent performance of the system under varying conditions. Furthermore, the observed THD values, commencing at 0.78%, exhibit a gradual reduction to 0.2% throughout the simulation, showcasing the effectiveness of the bidirectional PFC block in mitigating harmonic distortions. The specified maximum power limit of 7.5 kW for feeding into the grid further underscores the practical applicability and adherence to standards within the V2G operational mode.

TABLE IV
RESULTS OF PFC BLOCK FOR V2G MODE

Parameter	Value
Output AC current	32 A
Power factor	0.99
Maximum Power	7.5 kW
Total Harmonic Distortion(THD)	0.65%
maximum efficiency	98.5%

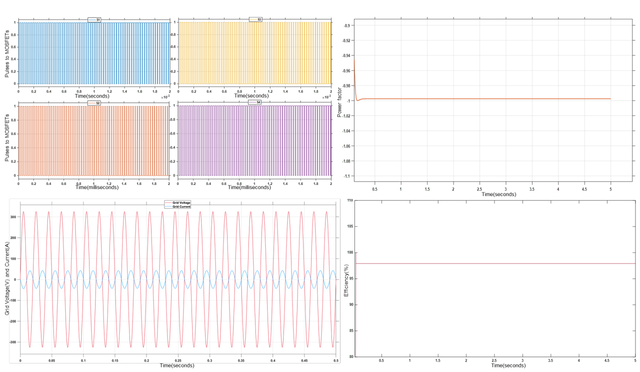

Fig. 12. Grid Side AC Voltage, Current, efficiency and power factor wave forms in V2G mode

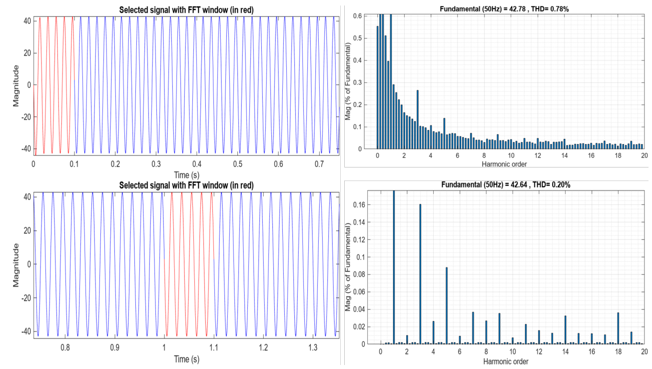

Fig. 13. THD values of Output AC current at the grid side from PFC block in V2G mode

3. V2L mode: Additionally, it is pertinent to highlight that in V2L mode, the operational characteristics closely align with those observed in V2G mode. The ensuing output parameters, encompassing AC voltage, current, and THD, demonstrate variations within the range of 0.01% to 0.1%. These fluctuations are intricately linked to the applied load, a relationship effectively depicted in the accompanying figures Fig.14,Fig.15 and Fig.16. Specifically, the load is systematically adjusted in 2 kW increment/decrement, spanning from 1 kW to 5 kW, with the maximum allowed load remaining at 7.5 kW. This systematic load variation provides valuable insights into the adaptability and robustness of the bidirectional PFC block in V2L mode across a spectrum of practical load scenarios.

TABLE V
RESULTS OF PFC BLOCK IN V2L MODE

Parameter	Value
Output AC Voltage(RMS)	230 +/-10 V
Power factor	0.99
Grid Current(RMS)	32 A
Maximum Power Capacity	7.5 kW
Total Harmonic Distortion(THD)	0.01-0.1%
maximum efficiency	98.5%

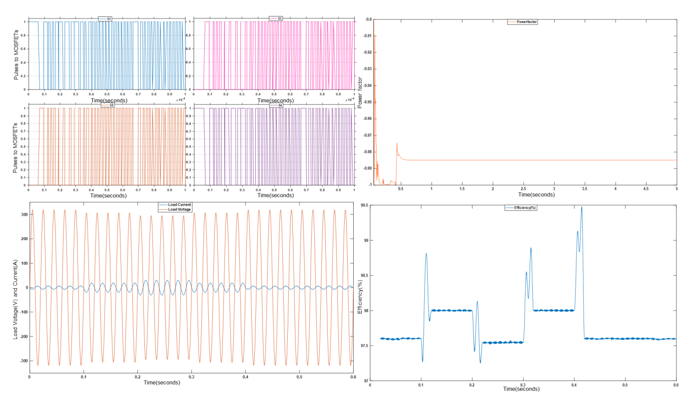

Fig. 14. Voltage , Current, Power factor and efficiency wave forms in V2L mode respectively

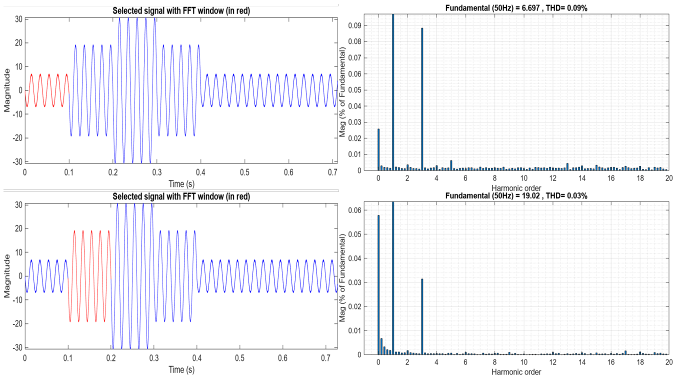

Fig. 15. THD of Current wave forms at different loading conditions in V2L mode

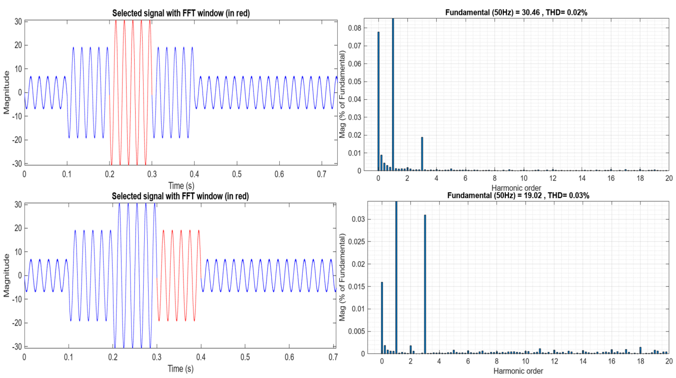

Fig. 16. THD of Current wave forms at different loading conditions in V2L mode

IV. Conclusion

The Bidirectional PFC block, as expounded in this paper, achieves a notable maximum efficiency of 98.5% with a MOSFET switching frequency of 30 kHz. Across all V2X operation modes discussed herein, the topology adheres to the standards set by IEEE. The incorporation of Silicon Carbide (SiC) and Gallium Nitride (GaN) could potentially enhance its efficiency, given their superior characteristics. These materials can operate at higher switching frequencies, leading to a substantial decrease in THD, and can handle increased power ratings due to their elevated electron mobility compared to MOSFETs. The system's response can be significantly improved by leveraging their fast-switching capabilities.

The extension of this same topology to a three-phase system caters to rapid and high power charging capacity. Additionally, integration with the bidirectional Dual Active Bridge converter (DAB) for power transmission within the vehicle and as well as for the V2X technology represents a promising avenue for future research. The forthcoming scope of this paper entails modeling both converters and seamlessly integrating them into a cohesive system.

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