Implementation and Simulation of DC Battery Fast Charging Topologies

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***Abstract*—The demand for fast charging for DC batteries is increasing owing to the rapid expansion of the market of the electrical vehicle. In order to promote a clean and green environment and to reduce carbon emission, it is aspired to have 100 percent electrical vehicle mobility by the year 2030. For such a large number of the electric vehicle to be running on Indian roads, there is a critical need for fast charging stations and infrastructure. This paper presents different fast charging methods along with different charging topologies for fast charging of DC batteries. Implementation and simulation of these different topologies is performed using Simulink. Various characteristics of these topologies are also discussed.**

*Keywords— **DC Fast charging, Electric vehicle, Charging Methods, Charging Topologies, Control methods.***

I. INTRODUCTION

Increasing carbon emissions in the environment has become a major concern for the Government. The main factor leading to high CO2 emission is from the internal combustion engine vehicles (ICEVs). Electric vehicles (EVs) present a huge potential in becoming attractive alternatives to ICEVs because of their environmental benefits and the globally day to day increase of oil prices. Therefore, the development of fast-charging infrastructure for EVs has become a subject of core importance in emerging economies like India. Longer distance driving and lesser refueling time are the main problems of EV users which need to be addressed to make the electric vehicle popular among the masses [1], [2], [3].

The charging infrastructure is composed of an operating system, a customer information system, and a charging system [4]. Among these, the charging system is the most vital and integral component of the charging infrastructure. The charging system needs to be compatible with the EV battery system and is classified as either a slow charger or a fast charger depending on the power it handles [6-8]. The slow charger usually handles 3-4 KW of power and takes approximately 6–7 hours for full battery charging. For this reason, the slow charger is utilized for charging using a household grid power during the night time. However, the fast charger handles approximately 50 kW of power and quickly charges the EV in less than an hour. Most of the EVs are manufactured in view of optimum battery size for a given range are equipped with batteries that can take high charge current and thus necessitate a fast charging facility.

Although some studies claim that the slow insertion of EVs into the grid may not cause great harm considering the whole power grid others raise concerns on its impact on smaller circuits where the grid inertia and resilience is not large enough [9-11]. EV usage can prove to be a problem especially when it comes to fast charging, where the needed power of nearly 50kVA per car comes close to the size of transformers used to build the low voltage distribution system. Even the insertion of fast-charging stations with dedicated transformers in medium voltage lines may be harmful if we consider heavily loaded feeders, where faults may occur due to over current [12-16].

The fast chargers can be installed in public places or at petrol pumps. The chargers essentially create power quality issues because of non-linear devices in it and will be more prominent with the usage/popularity of EVs [1], [5], [8], [9]. The power quality issues arise in terms of voltage harmonics, current harmonics; poor power quality including low power factor may arise. The power factor correction technology can be considered in order to resolve the poor power factor problem [2-4].

Reliably recharge at home, enable long-distance travel, and to cope with range anxiety issues. Generally, public electric vehicle supply equipment is intended to provide electric vehicle drivers with mobility opportunities that are comparable to those offered by conventional gasoline vehicles. In particular, direct-current fast charging (DCFC), which typically supplies 50 kW of power or more, can quickly replenish the vehicle's battery by adding about 50 miles or more of range in 20 min [5], [8], [13]. To further reduce refueling time, extreme fast charging is currently being studied. Fast charging addresses the concern of charging the vehicle battery and is considered as one of the technological advancements in the electric vehicle domain [16]. The rest of the paper is organized as follows. Different charging methods are discussed in Section II. Different charging topologies are discussed in Section III. The implementation and simulation of these charging topologies is carried out in Section IV using Simulink. PID control block are also discussed in Section IV. The paper is concluded in Section V.

II. DC CHARGING METHODS

DC batteries require persistent charging. We first list out different charging Methods and then explain and work on different DC charging topologies which consists of two stages i.e. AC to DC converter stage (Rectifier) and DC to DC converter stage (Chopper).

I. Constant Voltage:

In this method, a constant voltage is maintained across the battery. Initially, it draws higher current but as the battery charges, the battery charging current tapers down. Such simple designs are often found in cheap car battery chargers. The lead-acid cells used for cars and backup power systems typically use constant voltage chargers [7].

II. Constant Current:

In this method, a constant current is maintained across the battery and the voltage is allowed to build up gradually. The charger is switched off as soon as the full charge [7] voltage is reached.

III. Pulse charging:

In the charging mode, the charging current in the form of pulses is applied to the battery [10], [11]. The charging rate (based on the average current) can be precisely controlled by varying the width of the pulses. During the charging process, the charging pulses are followed by short rest periods which allow the chemical actions in the battery to stabilize by equalizing the reaction throughout the bulk of the electrodes. This enables the chemical reaction to keep pace with the rate of inputting electrical energy. This method can reduce unwanted chemical reactions at the electrode surface such as gas formation, crystal growth, and passivation [13].

IV. Negative Pulse charging:

This method is to be used along with the pulse charging method. During the charging rest period, very short duration discharge pulses (2 to 3 times of the charging current magnitude) are applied to depolarize the cell [13]. These discharge pulses remove gas bubbles developed on the electrodes during the charging, which enhances the stabilization process and the whole charging process. The release and diffusion of the gas bubbles are known as "burping".

III. CHARGING TOPOLOGIES

DC fast charger consists of two stages i.e. AC to DC converter stage (Rectifier) and DC to DC converter stage (Chopper). Here we discussed mainly four topologies, implement using Simulink software and discuss the model setting. The four common charging topologies are [13].

- SCR-based Full-Bridge Controlled Rectifier (Topology-I).
- Twelve pulse diode bridge rectifier followed by full-bridge DC – DC converter (Topology-II).
- Six pulse Thyristor bridge rectifier followed by full-bridge DC – DC converter (Topology-III).
- Twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter (Topology-IV).

These topologies are implemented here in different ways as mentioned in [13] and compared. The difference in implementation is with respect to the PID module setting.
Every topology is explained with the schematic, Simulink model and the waveform generated.

A. *SCR based full-bridge controlled rectifier (Topology-I)*

A three-phase, 6 pulses SCR based rectifier topology is used to charge the battery. A three-phase transformer is used to isolate the three-phase source from the power converter. A PID loop has been utilized to strictly follow the current in CC and voltage in CV profiles which will directly affect the Thyristor firing angle. This topology design is robust and does not require a DC-DC converter stage. Thyristors are capable of handling large amounts of voltage and currents and offer reduced complexity in the firing of Thyristors. Fig. 1 shows the schematic diagram of this topology [13].

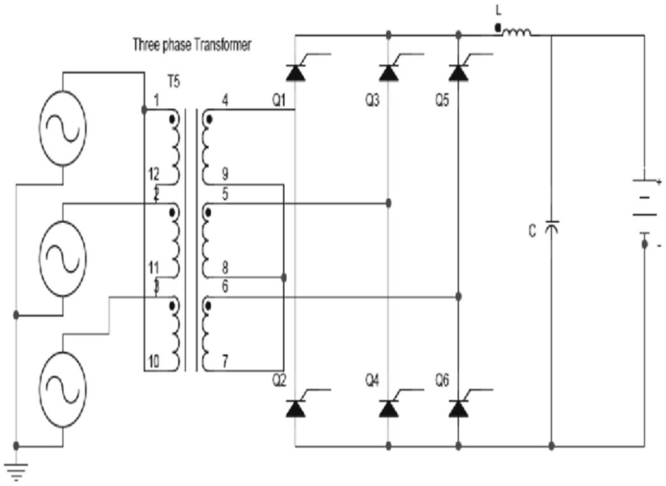

Fig. 1. SCR based full-bridge controlled rectifier [13]

B. *Twelve pulse diode bridge rectifier followed by full-bridge DC – DC converter (Topology-II)*

Three-phase ac is rectified by using a 12 pulse diode bridge rectifier. Three-phase isolation transformer with two secondary windings (one in delta and other in star connection) is used to generate twelve pulses. The two diode bridges are connected in series in order to reduce the current stress. The rectified DC voltage is processed by the inverter bridge, high-frequency transformer, high-speed diode stack, and filter to obtain the charging voltage as required [13].

The IGBTs are switched in pairs diagonally Q1 and Q4 forms one pair and Q2 and Q3 forms the other pair. The transformer's primary to secondary ratio considered in this case is 1:1. So the output voltage only depends on the duty cycle. Closed-loop operation is achieved using a discrete PID loop which stabilizes the required battery current and battery voltages. The duty cycle required to fire the IGBT will decide the output voltage needed to charge the battery at its charging voltage and current. The figure for this topology is shown in

Fig. 2 [13].

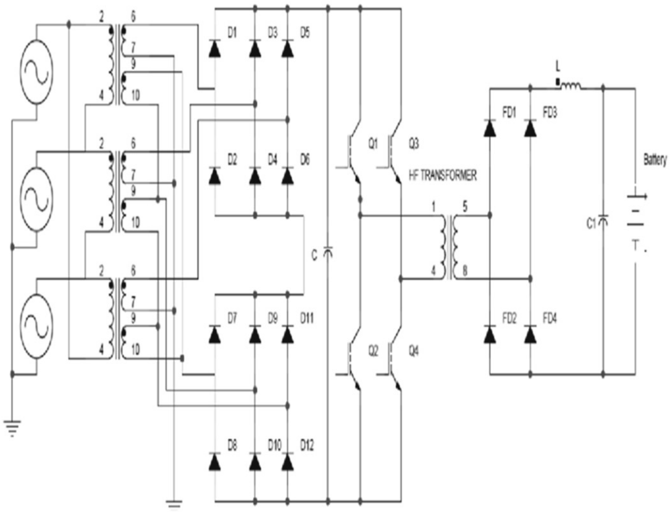

Fig. 2. Twelve pulse diode bridge rectifier followed by a full-bridge DC-DC converter [13]

C. Six pulse Thyristor bridge rectifier followed by full-bridge DC – DC converter (Topology-III)

In this power scheme instead of a diode bridge which is an uncontrolled rectifier, a six pulse SCR based (controlled rectifier) is used for the rectification stage. The DC to DC full-bridge converter part remains the same as above topology.

Here as per the battery voltage requirement the DC voltage can be changed (which was fixed in the previous topology) by varying the firing angle of the SCR. Thus it gives a two-way control. But the input current has more harmonics and the input power factor is low compared to the previous topology. Fig. 3 shows the six pulse Thyristor bridge rectifier followed by a full-bridge DC-DC converter [13].

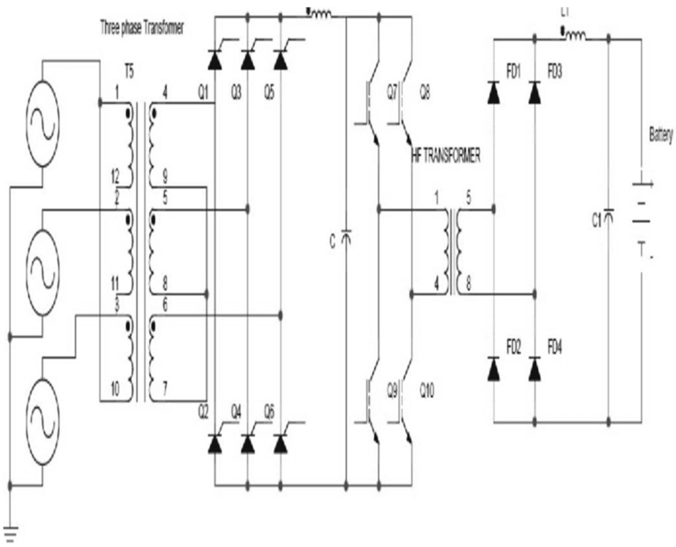

Fig. 3. Six pulse thyristor bridge rectifier followed by a full-bridge DC-DC converter [13]

D. Twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter (Topology-IV)

In this power scheme, a 12 pulse diode bridge rectifier is utilized to generate the rectified DC voltage. The next stage here comprises of a three-level buck converter. This three-level buck converter with the help of two capacitors reduces the voltage stress on each switch by half. Moreover, this topology can operate with both the switches on, only one switch on and both switches in off condition as well, the operation of which has already been explained above. This topology used less number of switches with higher power factor due to 12 pulse rectifier. Reduced current stress on the rectifier diodes as two rectifiers stages are connected in series. The reduced voltage stress on buck converter IGBTs as a voltage across them is halved by the use of midpoint clamped capacitors. The control part is simplified as only two IGBTs are to be controlled. Fig. 4 the circuit diagram of this topology [13].

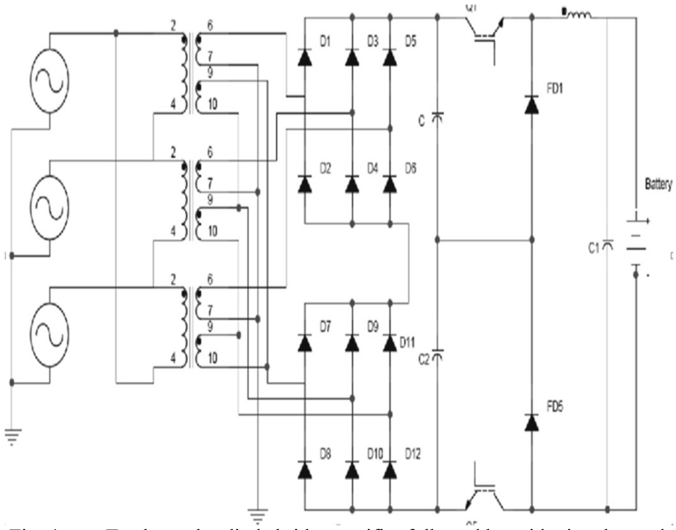

Fig. 4. Twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter [13]

IV. EXPERIMENTAL RESULTS

The Simulink models for all these discussed topologies have been implemented using Simulink modeling. Following sub-sections describes the implementation and corresponding results from the Simulink Models.

A. SCR based Full-Bridge Controlled Rectifier (Topology-I)

A Simulink model for this topology is developed as shown in Fig. 5. A PID control is implemented in the simulation to have the closed loop operation as shown in Fig. 6. A battery charging voltage of 56 V and current loop maintains a maximum of 80 A. Depending on the current requirement the duty cycle for the two IGBT's is adjusted. If the battery voltage is less than 56 V then it will allow the maximum charging current of 80 A. If the battery voltage reaches 56 V the current will taper down with the decrease in the duty cycle.

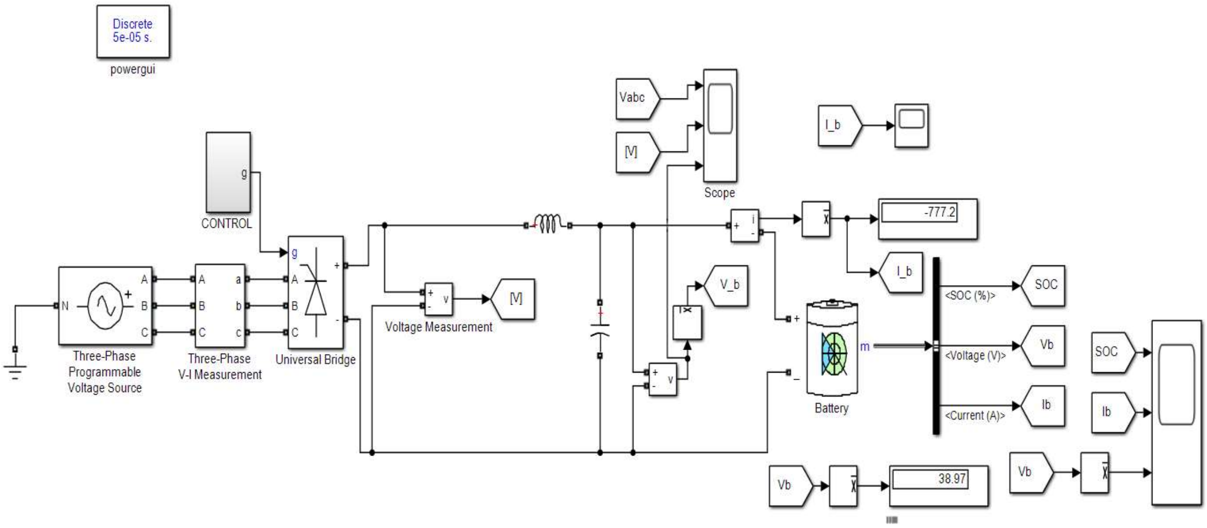

Fig. 5. Simulink model for SCR based full-bridge controlled rectifier

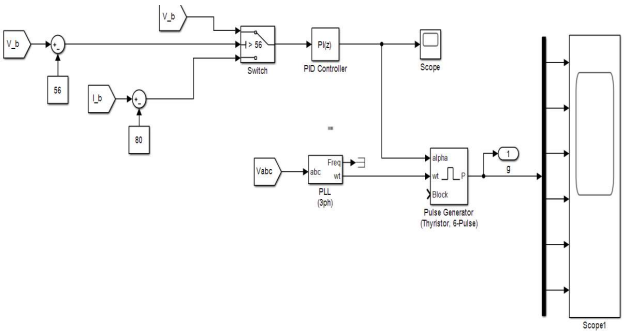

Fig. 6. Simulink PID controlling model

The Pulse generator is used to provide Thyristor 6 pulses and act input to the universal bridge as shown in Fig. 7.

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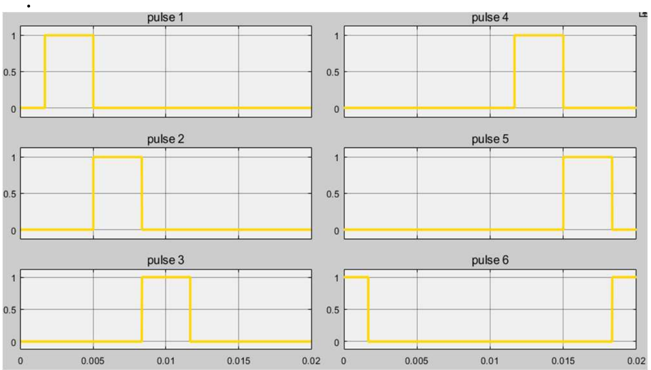

Fig. 7. Thyristor Six Pulses

The generated corresponding input voltages and rectified output are shown in Fig. 8.

The Simulink results as shown in Fig. 9 that the battery current ripple was more than 3% and also the input power factor is low. Also, the pulse charging scheme cannot be adopted in this topology as SCR remains conducting until zero crossings of the input ac signal.

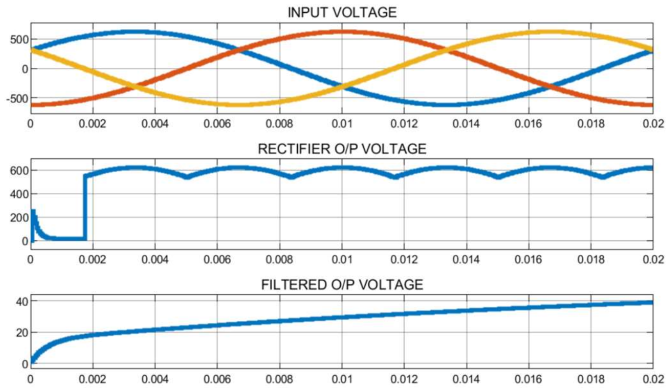

Fig. 8. Simulink model input voltage and rectified output voltages

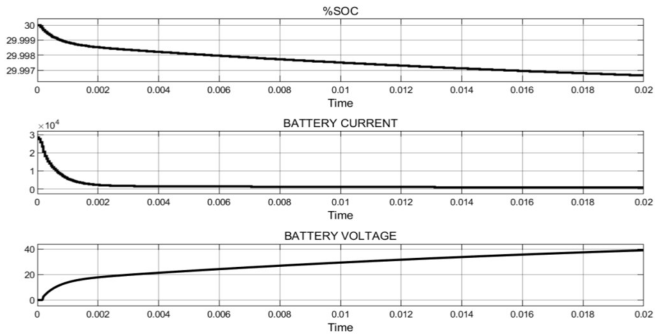

Fig. 9. Simulink results for SCR based full-bridge controlled rectifier

B. Twelve pulse diode bridge rectifier followed by full-bridge DC – DC converter (Topology-II)

Simulink model for this topology is shown in shown in Fig. 10.

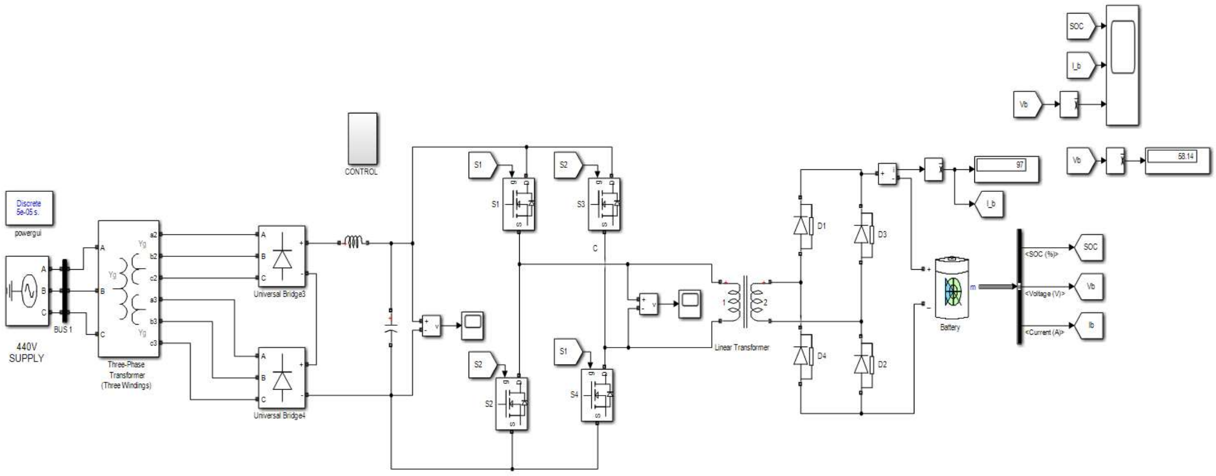

Fig. 10. Simulink model for twelve pulse diode bridge rectifier followed by a full-bridge DC-DC converter

A PID control is implemented in the simulation to have the closed loop operation. A battery charging voltage of 56 V and current loop maintains a maximum of 80 A. Depending on the current requirement the duty cycle for the two IGBT's is adjusted. If the battery voltage is less than 56 V then it will allow the maximum charging current of 80 A. If the battery voltage reaches 56 V the current will taper down with the decrease in the duty cycle.

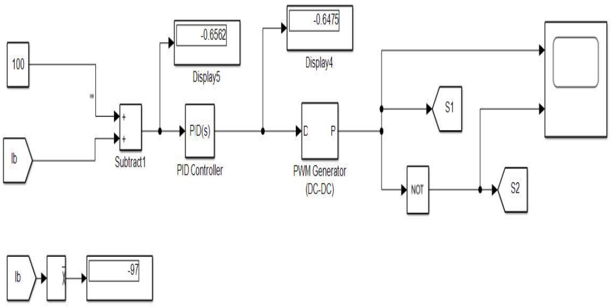

Fig. 11. Simulink model H-bridge pulse controlling model

The Fig. 12 depicts the figure where a the pulse generator is used to have Thyristor 4 pulses and act input to the switches (pulse1 for s1and s1' pulse2 for the s2 and s2').

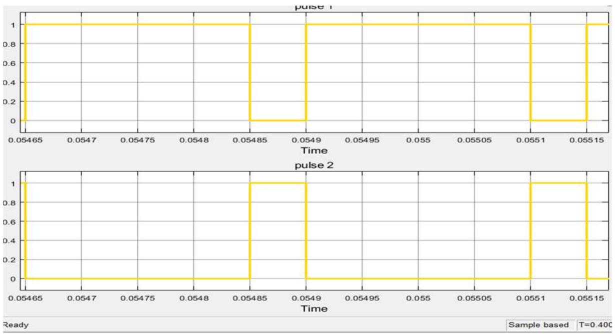

Fig. 12. Pulse generator is used to have thyristor 4 pulses

In this topology, the current ripple is reduced to less than 0.5% as it has better control derived by high switching frequency of full-bridge DC-DC converter. Input current harmonics are also low due to the inclusion of 12 pulse diode bridge rectifier. But the design requires a high-frequency transformer and high-frequency diodes to operate. Also, there are two transformers which makes it costlier. The Fig. 13 shows the Simulink results for twelve pulse diode bridge rectifier followed by the full-bridge DC-DC converter.

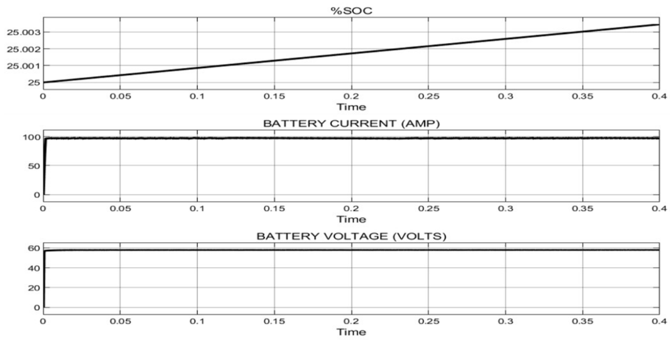

Fig. 13. Simulink results for twelve pulse diode bridge rectifier followed by the full-bridge DC-DC converter

C. Six pulse Thyristor bridge rectifier followed by full-bridge DC – DC converter (Topology-III)

In this power scheme instead of a diode bridge which is an uncontrolled rectifier, a six pulse SCR based (controlled rectifier) is used for the rectification stage. The DC to DC full-bridge converter part remains the same as above topology.

Here as per the battery voltage requirement the DC voltage can be changed (which was fixed in the previous topology) by varying the firing angle of the SCR. Thus it gives a two-way control. But the input current has more harmonics and the input power factor is low compared to the previous topology. The Simulink model for six pulse thyristor bridge rectifier followed by a full-bridge DC-DC converter is shown in Fig. 14.

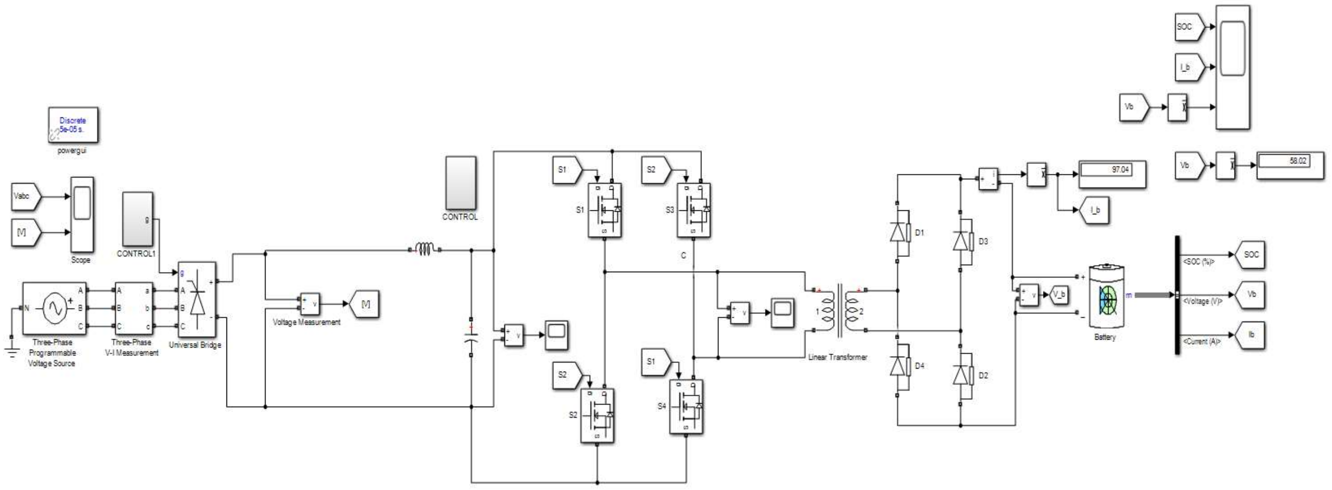

Fig. 14. Simulink model for six pulse thyristor bridge rectifier followed by a full-bridge DC-DC converter

The PID model used in earlier topologies and mentioned in Fig. 11 can be adopted for this topology as well with the same settings and parameters.

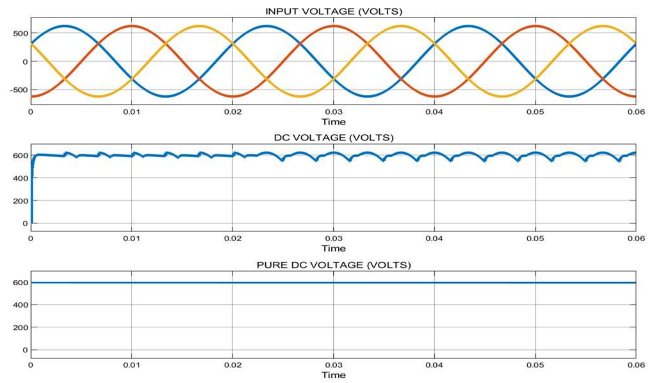

Fig. 15. Simulink model input voltage and Rectified voltages

In this topology in order to have control over DC link voltage, the SCR bridge is used at the primary stage. Due to this 6 pulse Thyristor bridge, the input power factor is low. The Simulink results for six pulse Thyristor bridge rectifier followed by full-bridge DC-DC converter: Battery parameters with respect to time are shown in Fig. 16.

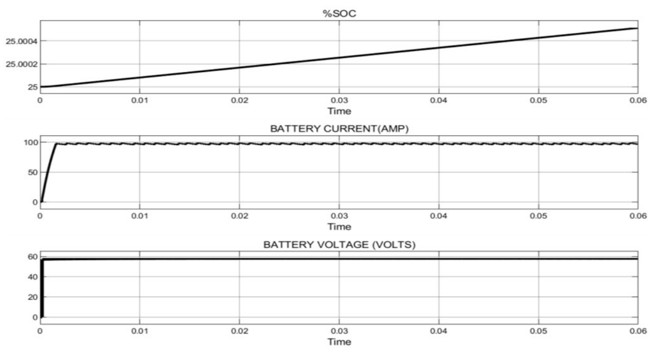

Fig. 16. Simulink results for six pulse thyristor bridge rectifier followed by a full-bridge DC-DC converter

D. Twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter (Topology-IV)

In this power scheme, a 12 pulse diode bridge rectifier is utilized to generate the rectified DC voltage. The next stage here comprises of a three-level buck converter. This three-level buck converter with the help of two capacitors reduces the voltage stress on each switch by half. Moreover, this topology can operate with both the switches on, only one switch on and both switches in off condition as well, the operation of which has already been explained above. A dual PID loop is implemented in the simulation as shown in Fig.17. The outer PID loop maintains the battery charging voltage of 57.6 V and the inner current loop maintains a maximum of 100 A. Depending on the current requirement the duty cycle for the two IGBT's is adjusted. If the battery voltage is less than 57.6 V then it will allow the maximum charging current of 100 A. If the battery voltage reaches 57.6 V the current will taper down with the decrease in the duty cycle. The Simulink model for twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter is shown in Fig.18.

A PID control is implemented in the simulation to have the closed loop operation. A battery charging voltage of 56 V and current loop maintains a maximum of 80 A. Depending on the current requirement the duty cycle for the two IGBT's is adjusted. If the battery voltage is less than 56 V then it will allow the maximum charging current of 80 A. If the battery voltage reaches 56 V the current will taper down with the decrease in the duty cycle.

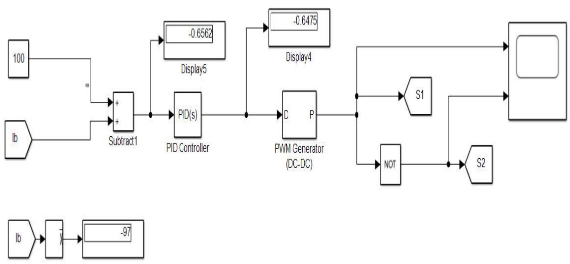

Fig. 17. Simulink model H-bridge pulse controlling model

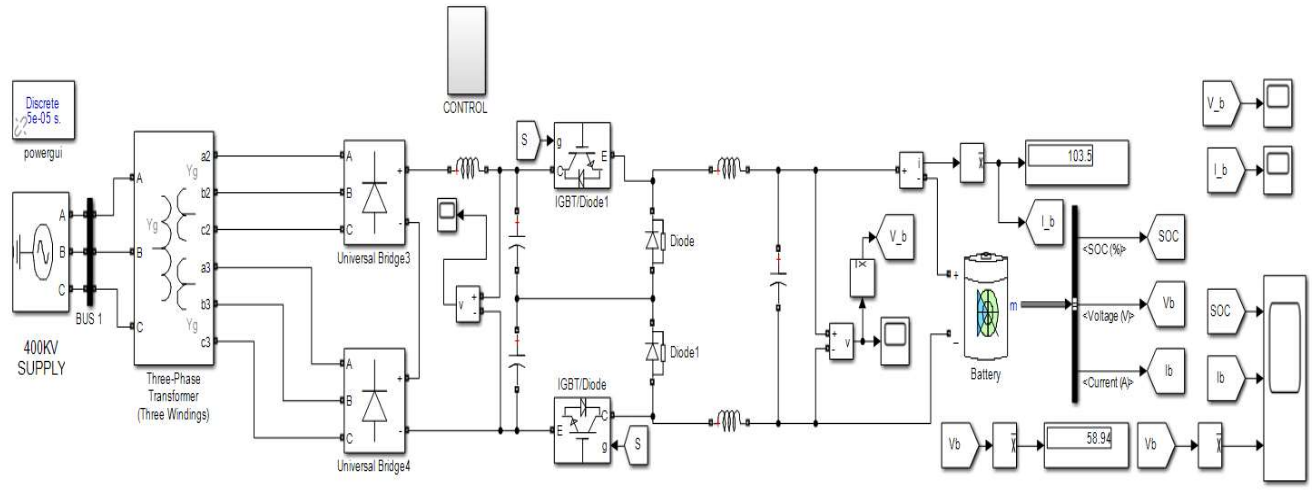

Fig. 18. Simulink model for twelve pulse diode bridge rectifier

The Fig.19 describes the Simulink model input line and phase voltage and input current.

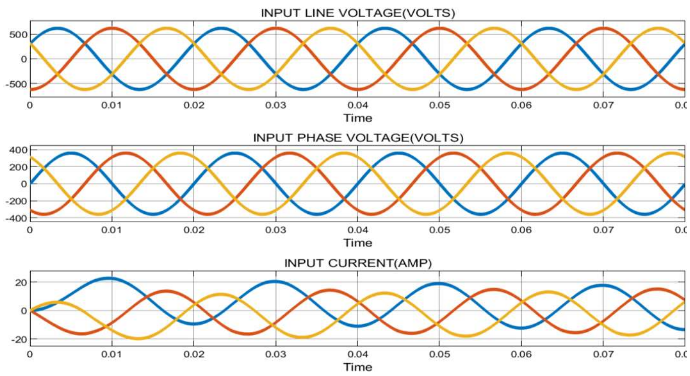

Fig. 19. Simulink model input line and phase voltage and input current

In this topology due to the use of 12 pulse diode bridge rectifier input power factor is high. Also due to the use of midpoint clamped three-level buck converter the current and voltage stress is reduced by half as each power switch is exposed to half the voltage which leads to more economical design. Simulink results for twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter with battery parameters with respect to time are depicted in Fig. 20

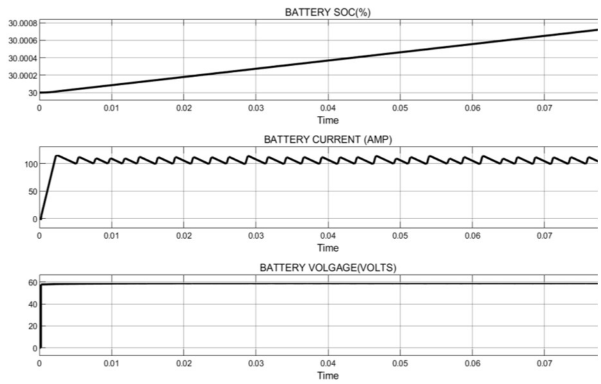

Fig. 20. Simulink results for twelve pulse diode bridge rectifier

V. CONCLUSION

In this paper, four different topologies are discussed and compared based on their MATLAB simulations. Topology-I is the easiest in implementation and also the most robust topology but the battery current ripple is more and also the power factor is low. In topology –II, better control is achieved and the power factor is also high but it is costlier due to the high power rating components like high-frequency transformers and diodes. In topology III, twelve pulse diode bridge is replaced by six pulse SCR bridge and full-bridge DC-DC converter remains the same. The input power factor is low and also the cost implication is the same as Topology-II. Based on the comparison of all the topologies, Topology-IV comprising of twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter is the most suited for EV charging application due to reduced voltage and current stress, thermal stress, reduced complexity and above all better control over battery parameters.

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