Chapter 1

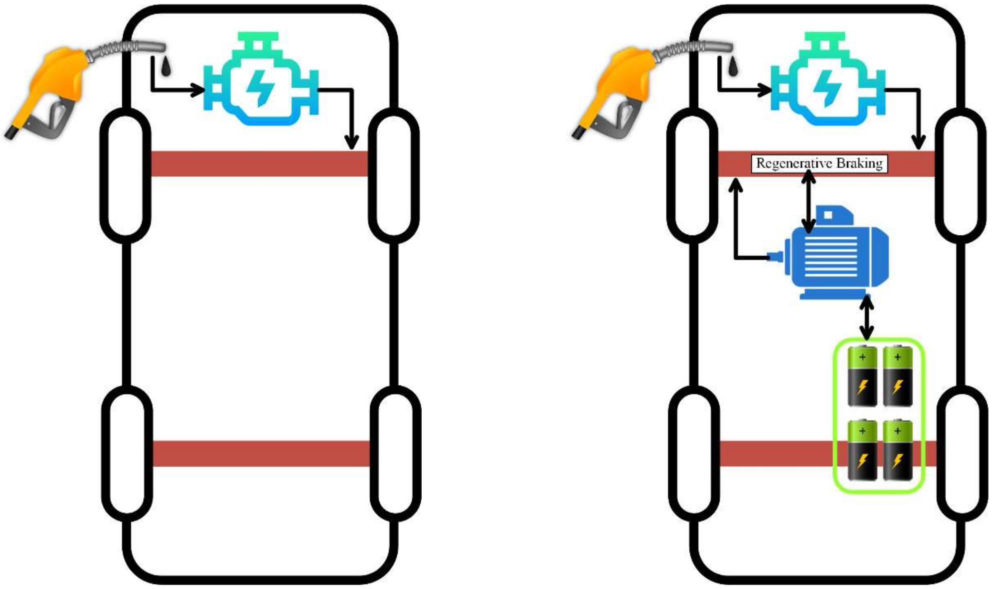
Introduction

1.1 Background

The rapid depletion of fossil fuel and the ever-increasing price of petrochemical products have led the way to search for other alternate sources of energy for transportation system. Conventionally, internal combustion engines (ICE) use petroleum products as the source of energy for the vehicles. The other alternatives of petroleum products to run the vehicles are bio-diesel, compressed natural gas (CNG), hydrogen fuel cell, gasoline and electrical sources of energy. The electric vehicle (EV) is the most promising and most shouted technology that can replace the conventional IC engine and have added advantages like cleaner environment, low running cost and reduced noise pollution [1], [2]. The EVs are broadly classified into three categories, which are as follows:

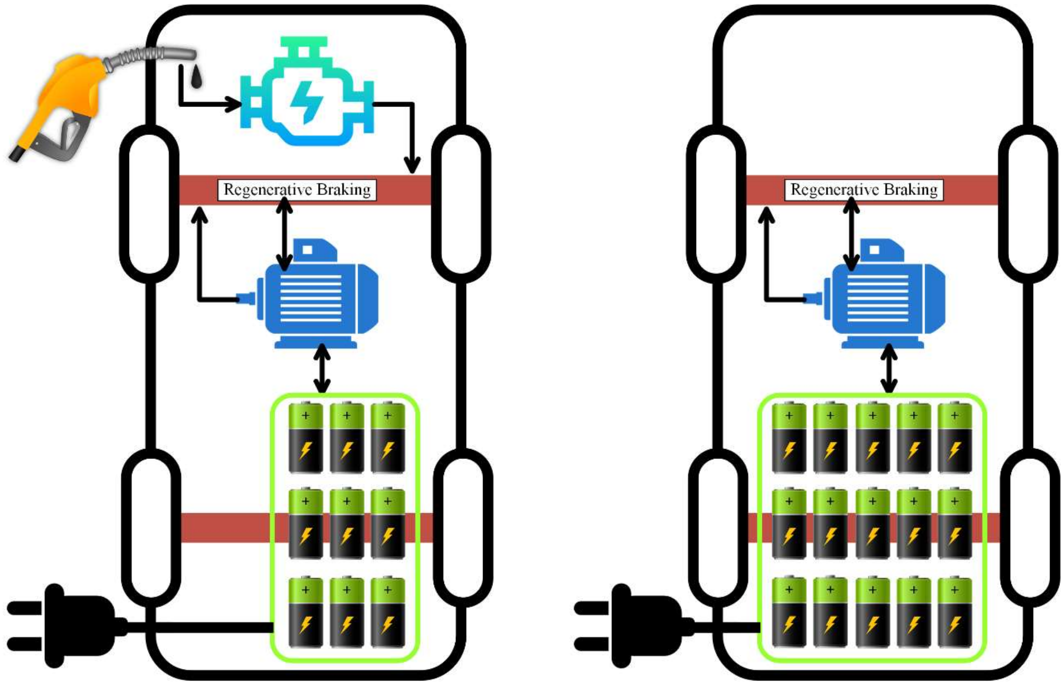
1) Hybrid electric vehicles (HEVs),
2) Plug-in hybrid electric vehicles (PHEVs) and
3) Battery powered electric vehicles (BEVs) or all electric vehicles.

The powertrain architectures of the above three types and the conventional ICE vehicle are shown in Fig. 1.1. A comparative study between these three types and the ICE vehicle is presented in Fig. 1.2. The hybrid electric vehicles are equipped with both IC engine and electric motor drive [3]. The only source for this vehicle is the petroleum products or natural gases. The battery pack of the HEV is charged through the regenerative braking, which provides extra energy to the driving wheels during acceleration through the electric motor-drive set [4], [5]. The conventional HEV does not have the option to charge the battery externally from an electrical energy source and thus cannot be plugged into the grid to recharge the battery pack [6] [7]. Though the PHEVs are equipped with both gas engine and electric motor drive, they have larger battery packs to support the electric drive in most of the time [8]–[10]. The PHEVs can be recharged from a grid supply by plugging into the grid, which is also clearly evident from its naming [11]–[13]. The BEVs are only equipped with the motor drive and do not have gas engines. The BEVs are fully electric in nature with a very large rechargeable battery pack and hence called as all electric vehicles [14], [15]. These vehicles are zero emission vehicles as they do not generate any tailpipe emissions and are free from air pollution. These vehicles are also highly efficient robust and reliable. In general, the BEVs are more frequently called as simply electric vehicles (EVs) and hence, here after EV designates battery electric vehicle in this thesis.



(a) Vehicle with IC engine

(b) Hybrid electric vehicle (HEV)



(c) Plugged-in electric vehicle (PHEV)

(d) Battery electric vehicle (BEV)

Fig. 1.1. Powertrain architecture of different types of vehicles.

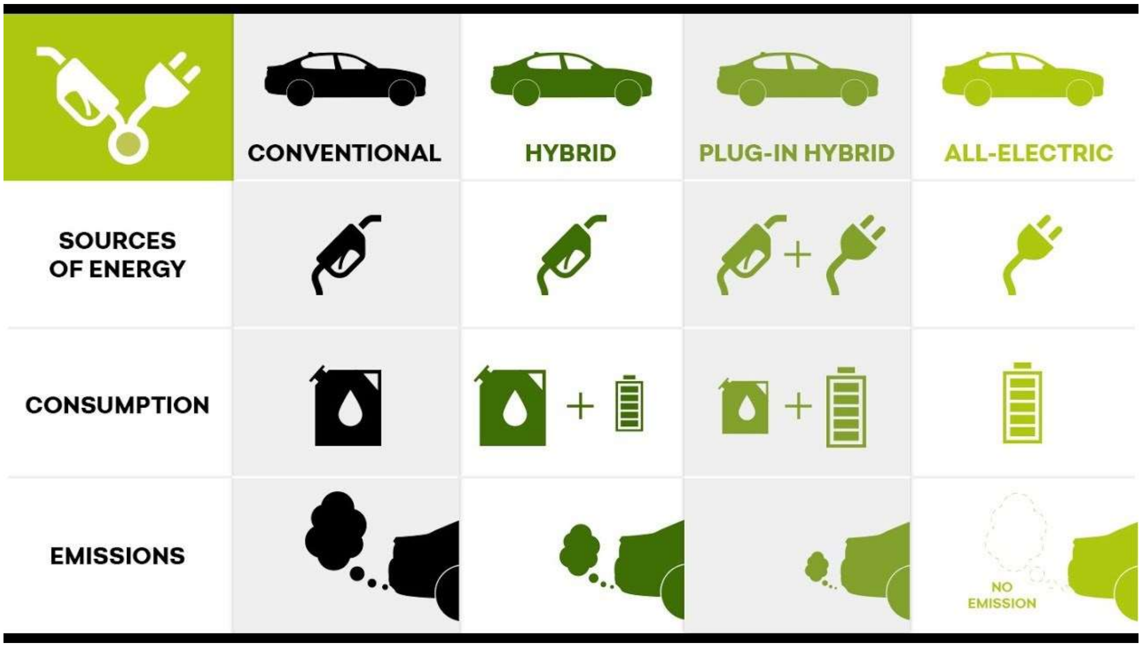


Fig. 1.2. A comparison study of different types of electric vehicles with ICE vehicle.

(*Image source:* https://driveelectricgeorgia.org/ev-101/)

1.2 Motivation

The major parts of an EV are battery packs, propulsion motor, motor control unit and a battery charger. The main source of energy in an EV is a rechargeable battery pack. So, a battery charger is an inevitable part of the EV system [16], [17]. Based on the placement of the charger, this can be broadly divided into two categories, on-board charger and off-board charger [18]. The on-board chargers are part of the vehicle itself, whereas the off-board chargers are usually found in charging stations with fast charging capabilities. The on-board chargers are lightweight and have lower power processing capabilities compared to the off-board chargers, as the on-board chargers are carried with the vehicle all the time. Most of the passenger cars use an on-board charger, as they can be charged from a home outlet [19], [20]. As the on-board charger is fitted inside the vehicle, its cost contributes to the overall cost of the vehicle. Therefore, reducing its cost while having all the standard features of an EV charger is necessary from economic point of view [21]–[23]. The cost of the charger can be reduced drastically by reducing its switch count and number of passive elements. Additionally, control scheme for an on-board charger can be made simpler with less number of controlled signals to reduce the cost.

The propulsion unit is the prime requirement in an EV that keeps the vehicle moving. This unit includes a propulsion motor and a power electronic interface that draws power from the battery pack and converts DC into three phase AC, and subsequently supply power to the driving motor. This power electronic interface is often called as motor control unit or the propulsion power processor or simply propulsion module. Thus, in a conventional EV, two major power electronic modules are present, which are propulsion module and charging module.

In case of an on-board EV charger, the vehicle is charged from a grid supply when it is stationary and the propulsion unit remains idle during charging process. Thus, the motoring and charging are two mutually exclusive operations in an EV. To take advantage of these mutually exclusive operations, the components from one power module can be reutilized to form the other one. This reutilization of components from one mode to another leads to amalgamation of two power processors into a single power processor and thus effectively reduces the number of components including the switch count. This approach saves cost, weight and volume of the power processors used in an EV and thus improves the power density of the on-board system.

Recently, wireless charging technique has gained wide popularity in the domain of EV charging that provides a convenient and hassle free charging experience to the EV users without using any physical wired connection between the power supply and the vehicle. In wireless EV charging system, the most important aspect is to generate a sinusoidal AC voltage or current waveform at very high frequency so that the power can be transferred wirelessly. The conventionally used inverters for producing high frequency AC face some of the following issues.

a) Require more number of switches,
b) Higher switching losses due to hard switching operation,
c) Do not support variable loading conditions like battery charging operation and
d) Do not support both constant current (CC) and constant voltage (CV) modes of operations.

Additionally, EV with wireless charging feature requires an additional receiving-end power processor to be included with the no-board system of the vehicle. Thus, an EV with wireless charging feature requires three different power processors for three different operations, which are propulsion, wired charging and wireless charging.

In order to address the above-discussed issues, this thesis investigates various power converter topologies to optimize the number of components and to reduce the number of power processors in an EV to reduce cost, weight and volume of the on-board power processors.

1.3 Literature Survey

This section discusses various power converter topologies already reported in the literature for optimizing the number of components and amalgamating the different power converters used in an EV. Additionally, recent literature regarding wireless charging technology for EV application is also discussed in this section.

1.3.1 Standard On-Board Charger with Minimum Number of Switch Count

A standard on-board EV charger should have following salient features [24]. These are listed below.

1) Power factor correction (PFC)
2) Galvanic isolation
3) Constant current–constant voltage (CC-CV) charging

Further, the on-board EV chargers are categorized into three types based on the number of stages present in it. These are single stage, two-stage and three-stage chargers. The single stage chargers are usually non-isolated in nature [25] and is hard to scale up the power level beyond a certain limit [26]. Most of the two-stage chargers are having galvanic isolation with higher power processing capability and are reviewed in detail in this sub-section. The three-stage EV chargers are mostly used either in renewable energy systems, high power traction systems or in wireless EV charging applications [27]–[30]. The various power converters based on dual active bridge (DAB) are also reported for EV. An isolated AC-DC topology based on DAB is reported in [31] that can be used as an EV charger. The several bidirectional power converter topologies including DAB are reported in [32]–[34] for battery charging applications. However, these topologies are aimed for bidirectional power flow and use more number of semiconductor devices.

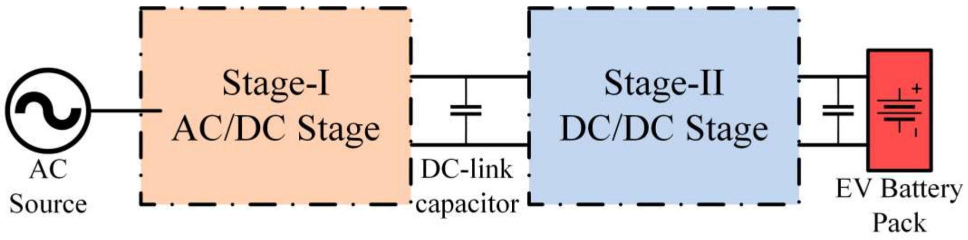


Fig. 1.3. Generalized block diagram of standard two-stage EV charger.

Considering the number of power semiconductor devices and properties like galvanic isolation, two stage chargers are considered as standard EV chargers and are more popular. A generalized block diagram of standard two-stage EV charger is depicted in Fig. 1.3. The first stage consists of an AC-DC conversion unit, which includes an AC-DC rectifier and a DC-DC boost converter with PFC operation [35]–[42]. The second stage shows a DC-DC conversion unit with or without galvanic isolation. The one with galvanic isolation, converts DC to high frequency AC and again back to DC, which allows a transformer to be included in the system for providing isolation [43].

A three-phase, two-stage EV charger with high power capability is reported in [44] and used as an off-board charger. A single-phase, two-stage bidirectional on-board battery charger using only six switches is reported in [45]. However, the chargers discussed in [44], [45] do not have galvanic isolation. A 3.3-kW on-board battery charger is reported in [46] with galvanic isolation as shown in Fig. 1.4. The reported EV charger topology consists of a full-bridge rectifier and a conventional DC-DC boost converter, which form the stage-I of the charger. The DC-DC stage consists of a full-bridge LLC resonant converter that provides galvanic isolation with four switches, four diodes and an isolation transformer. The first stage maintains a regulated DC-link and additionally performs PFC operation at the input grid side. The second stage provides galvanic isolation with soft switching operation. Though this topology is a standard two-stage battery charger having all the standard features as mentioned earlier, it requires a total number of five switches and five diodes. The reported topology herein contains a total of ten silicon devices, which can be further reduced to save the size of heat sink and the cost. Many such chargers with and without galvanic isolation are reviewed in [47]. Literature [47] also provides current status of battery chargers and charging power levels for plug-in EV and plug-in hybrid EV. For fast charging operation using on-board charger, these chargers can be connected in parallel modules to fulfil higher load demand as reviewed in [48], as the power-processing requirement is very high.

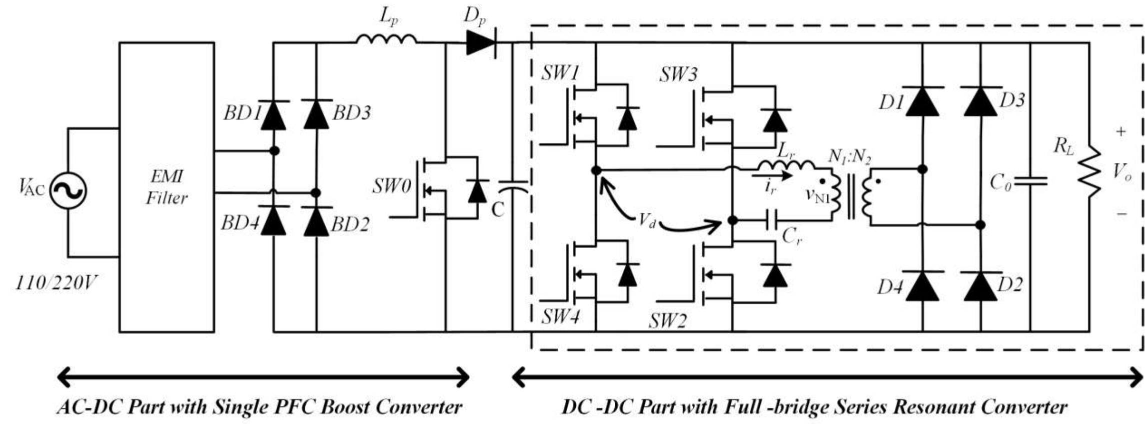


Fig. 1.4. A 3.3-kW on-board battery charger topology as reported in [46].

It can be observed from the above literature survey, though the component count in two-stage chargers is more than single stage chargers, they have many advantages like isolation and high-power delivery capability.

A modified bridgeless landsman converter fed EV battery charger is reported in [49], which is also a standard two-stage battery EV charger as shown in Fig. 1.5. The first stage is a bridge-less modified Landsman converter that replaces the diode converter at the source side. This stage is also responsible for PFC operation. The first stage of the charger is cascaded to a fly-back converter that charges the EV battery pack first in CC mode and then in CV mode. The complete charger consists of three switches and five diodes, which can be further reduced without losing any standard features of an on-board EV charger.

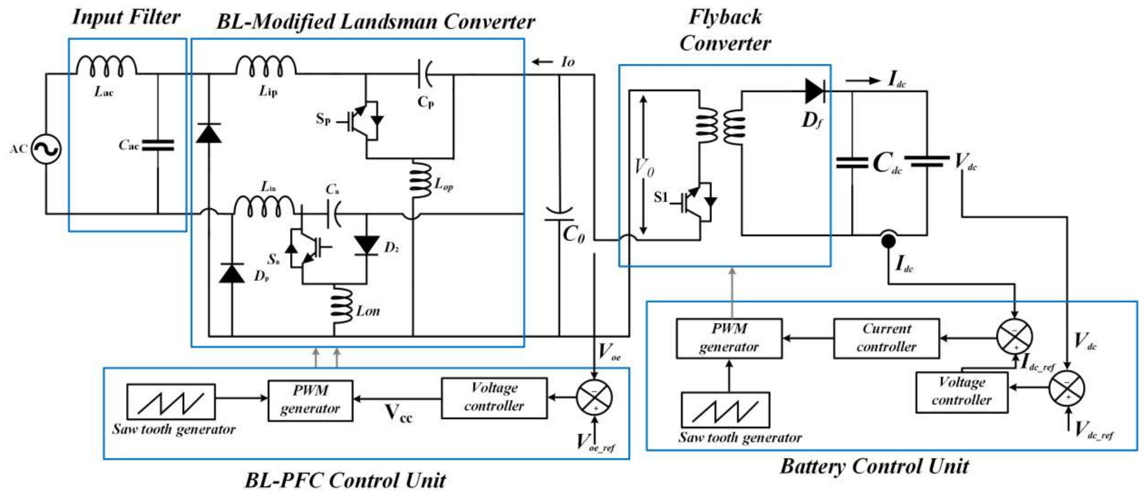


Fig. 1.5. A modified bridgeless landsman converter fed EV battery charger as reported in [49].

Conventionally, the control scheme for two-stage EV charging topology uses two separate control schemes for two different power stages. In addition, multiple switches in each stage require multiple controlled PWM signals. A multifunctional on-board EV charger is reported in [50]. In this topology, the front-end full bridge converter (FBC) with four switches acts as AC-DC converter with PFC stage and the back-end FBC having eight switches acts as isolated DC-DC converter. The control scheme of this paper uses eight different controlled PWM signals for its eight switches (Q1 to Q8).

Additionally, for the topology discussed in [49], two separate control blocks are used for the two power stages. The two control stages have separate controller with their corresponding PWM generators. The bridgeless PFC control unit is implemented for the first stage and a separate battery control unit is used for the second stage, which is independent of the first one. Such multi-controller based topologies are also discussed in [51]–[53], where multiple proportional-integral (PI) controllers are used. A non-isolated EV charger uses such two-loop control technique reported in [54]. It may be observed that all the conventional control strategies suggest different controllers and different switching pattern for different switches. This makes the overall system cumbersome.

1.3.2 Integrated Chargers for Both Motoring and Charging

In conventional EVs, there are two different power processors for two separate modes of operations. During the propulsion mode, usually an inverter is employed to drive the traction motor that draws DC power from the battery and supplies AC power to the motor [55]. During the charging mode, a separate on-board charger is required to charge the battery pack that draws AC power from the grid and converts it to DC power. As the charging and the driving operations are mutually exclusive in nature, the same power electronics hardware can be utilized for both the operations and the total number of components including switch count can be reduced. This approach saves costs and improves the power density of the on-board system. This idea of utilizing components from the motoring operation in deriving the charging module is presented in literature study as integrated charger. Many such efforts of integrating the traction inverter with battery charger for EVs have been studied widely in recent publications [47], [56]–[62].

In [63], an integrated charger topology is presented, which uses the drive system of an EV to charge the battery from a single-phase or a three-phase AC source. This topology also uses motor windings as boost inductors and hence do not require extra inductors. The inverter that produces three-phase AC to drive the motor during propulsion mode is used as an AC-DC converter in charging mode by reutilizing the power semiconductor switches. During the charging mode, only lower side switches are activated. The antiparallel body diodes of the upper side switches are reused as power diodes as shown in Fig. 1.6. However, the major disadvantage of this topology is that it requires an additional rectifier stage at the motor terminals that converts the single-phase or three-phase AC to DC. In addition, the reported topology does not have galvanic isolation during charging mode, which is generally not preferred. For validation, the researchers have implemented the reported topology using an e-scooter with the on-board bidirectional DC-DC converter and a high voltage battery pack (260 V). The charger in this topology is integrated with the propulsion system. The motor windings act as boost inductor and the power semiconductor switches are reutilized during the charging mode. However, it requires three-phase power supply and it is meant for high power applications.

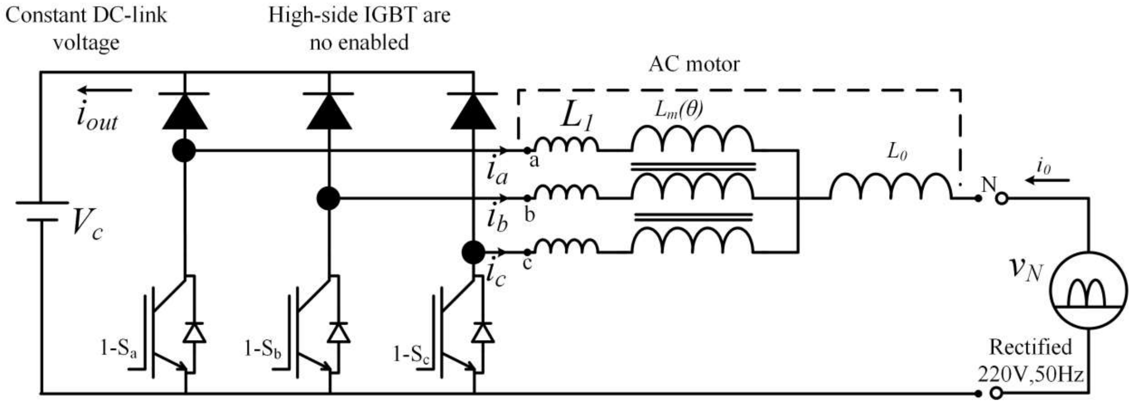


Fig. 1.6. An integral battery charger with power factor correction as reported in [63].

Three-phase integrated battery chargers are presented in [64], [65]. In [65], an interior permanent magnet (IPM) motor with access to the neutral connection of the star connected winding is used as the propulsion unit. In this work, the authors have used an add-on three-phase power electronic interface to the propulsion system and the motor windings are utilized as coupled DC inductors during the charging mode as shown in Fig. 1.7. At the DC side of the interface, the positive terminal (*p* point) is connected to one of the propulsion motor's phase terminals (phase-A terminal used in Fig. 1.7), while the negative terminal (*n* point) is connected to the negative terminal of the inverter's DC -link. This idea is applicable to EV system with a

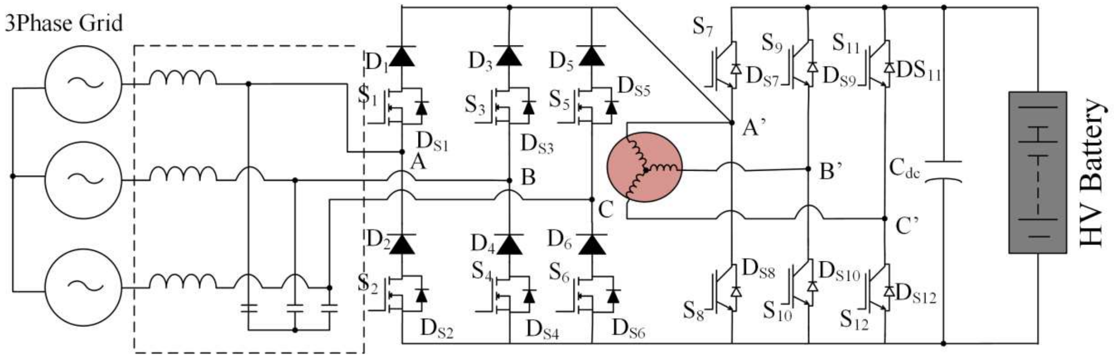


Fig. 1.7. A three-phase integrated onboard charger for plug-in electric vehicles as reported in [65].

three-phase propulsion motor with feasible access to the phase terminals (*a*, *b*, *c*). Though the two switches in leg S_7/S_8 are disabled during charging, the body diode D_{S8} in leg S_7/S_8 conducts motor winding currents when all switches S_1-S_6 in the interface are turned OFF. Due to the body diode D_{S8}, the interface needs no freewheeling diode at the DC side. Thus, the leg S_7/S_8 is necessary in the charging mode. An additional transformer is required at the AC supply side to provide galvanic isolation, which is the main part of the electric vehicle supply equipment (EVSE). Thus, this transformer is a bulky one as operated at line frequency. Therefore, this work is also classified under non-isolated class EV charger.

Multiphase machine based on-board battery chargers are also discussed [66]–[71]. Such machines are not generally used in applications like e-scooters, electric motorcycles or light motor vehicles, etc. due to the machine size and large switch count required for the motor drive inverters. In [72], an on-board DC-DC converter targeted at plug-in hybrid electric vehicles is presented. The battery charging feature is integrated with the bidirectional DC-DC converter. The application of the topology with respect to pure electric vehicles is limited to the context of vehicles with powertrain consisting of a DC-DC stage.

1.3.3 Wireless Battery Charger

The wireless EV charging system reduces the weight burden on the vehicle, since it only contains a receiving coil and a rectifier unit as most of the power electronics interfaces are transferred from the vehicle to the transmitting side. A comprehensive topological analysis between conductive and inductive charging solutions is presented in [73]. A pictorial representation of a typical wireless EV charging system that draws power from a single-phase or three-phase grid is represented in Fig. 1.8. It can be observed from Fig. 1.8 that wireless EV charging offers contactless power transfer and lighter on-board charging system

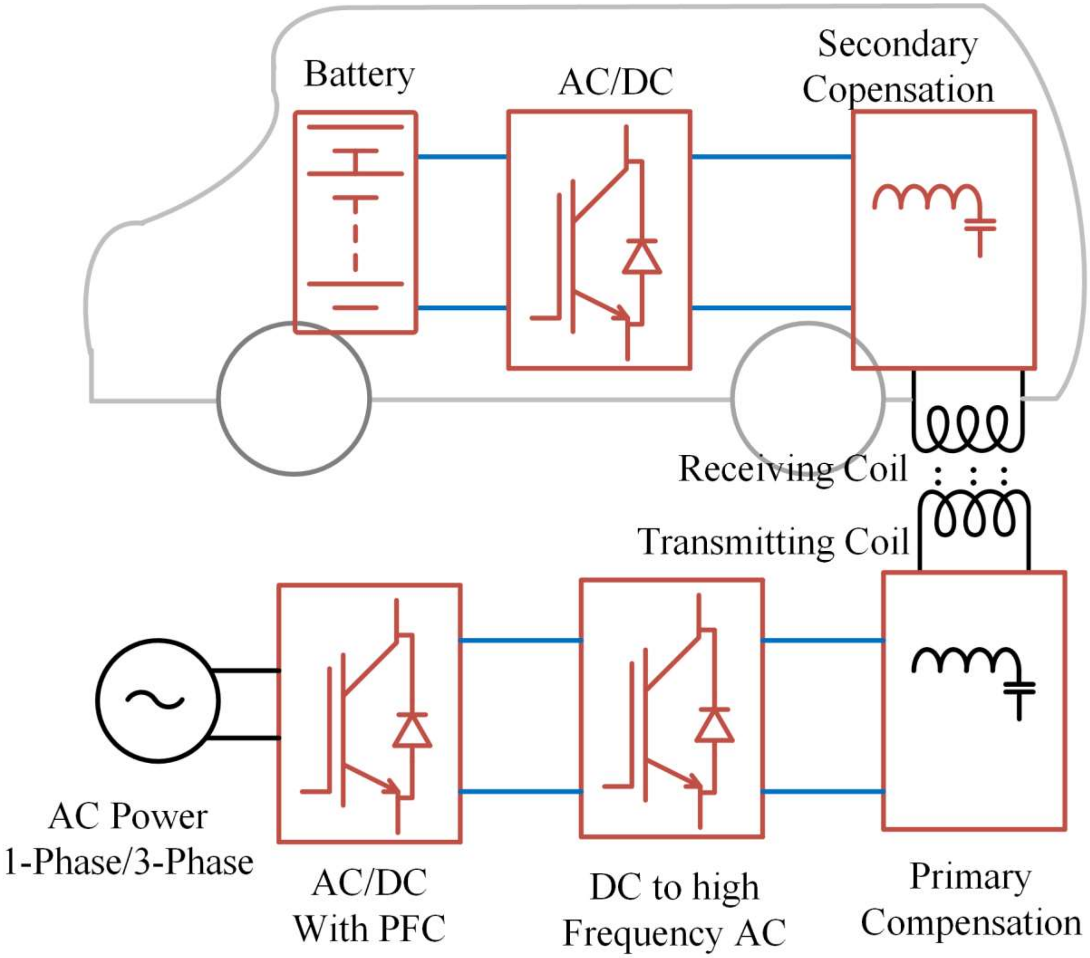


Fig. 1.8. A pictorial representation of a typical wireless EV charging system.

[27], [74], [75]. An overview of wireless power transfer (WPT) technology for EV charging is reported in [76].

The basic concept of WPT lies in transmitting a high frequency sinusoidal AC wave from the transmitting side to the receiving side without any wired connection [77], [78]. Instead of using a conventional step-up cycloconverter for producing high frequency AC (HFAC) from the grid supply, an inverter is preferred to generate HFAC by operating this inverter at high switching frequency. So, a high frequency inverter (HF inverter) is considered as the heart of the WPT system, which requires a DC source at its input to produce HFAC. The conventional WPT system uses an H-bridge inverter with filtering elements, operated at high frequency to generate HFAC [79]–[83]. The higher number of switches and hard switching of MOSFETs in case of H-bridge inverter are the two major concerns. This led to the introduction of resonant inverters for WPT applications.

Many resonant inverters using resonance network with H-bridge inverter are discussed in [84]. The Class D inverter is one of the resonant inverters that finds applications in WPT system as is shown in Fig. 1.9. The steady-state analysis and design procedure of Class D inverter at any duty ratio is reported in [85]. The fundamental-frequency-component-approximation approach is used to derive the design equations and the relationships between the circuit parameters. Similarly, the steady-state analysis and design of Class DE inverter at any duty ratio is reported in [86]. It is observed from [85], [86] that using only two switches, sinusoidal output waves are obtained in both Class D and Class DE configurations.

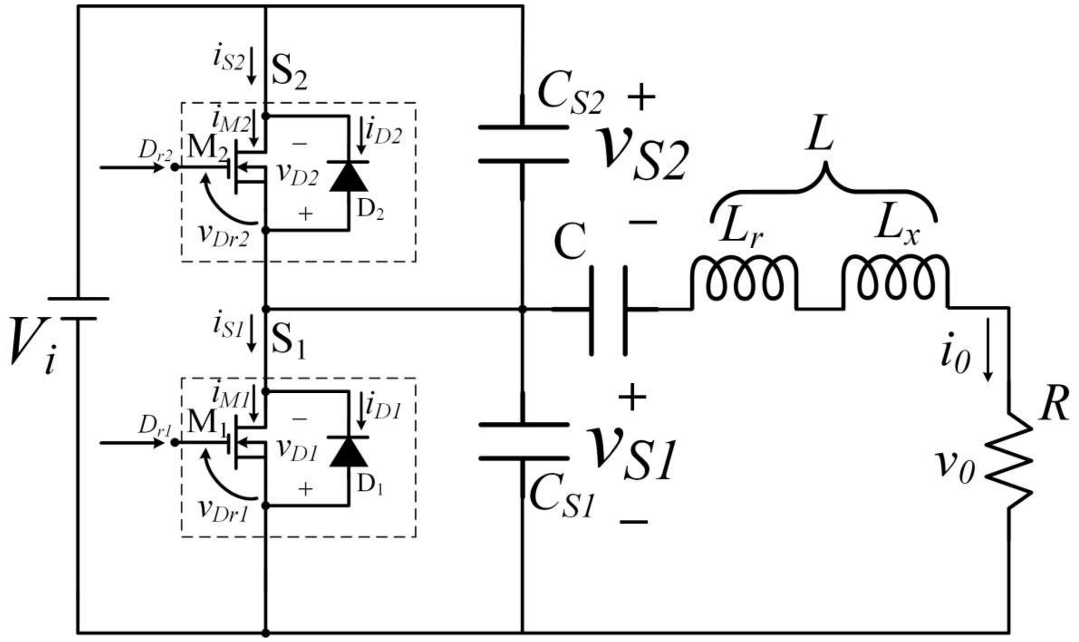


Fig. 1.9. Circuit schematics of a class-D ZVS Inverter.

A Class E inverter as shown in Fig. 1.10, reported in [87], achieves zero-voltage switching (ZVS) with a loosely coupled transformer. At a selected maximum coupling coefficient, the inverter satisfies both ZVS and zero-derivative switching (ZDS) conditions to achieve a high efficiency. As the coupling coefficient is decreased from its maximum value to zero, the inverter satisfies the ZVS condition over a wide range of load resistances. Therefore, the Class E inverters are widely used in WPT application as they use only a single switch to produce HFAC. The soft switching properties like ZVS and ZDS in Class E inverter reduces the switching losses. The major concern in case of a Class E inverter is the higher voltage stress during the off period across the switch caused by the resonating elements that produces sinusoidal current at the output. This extra voltage stress on the switch reduces the power processing capability of the inverter.

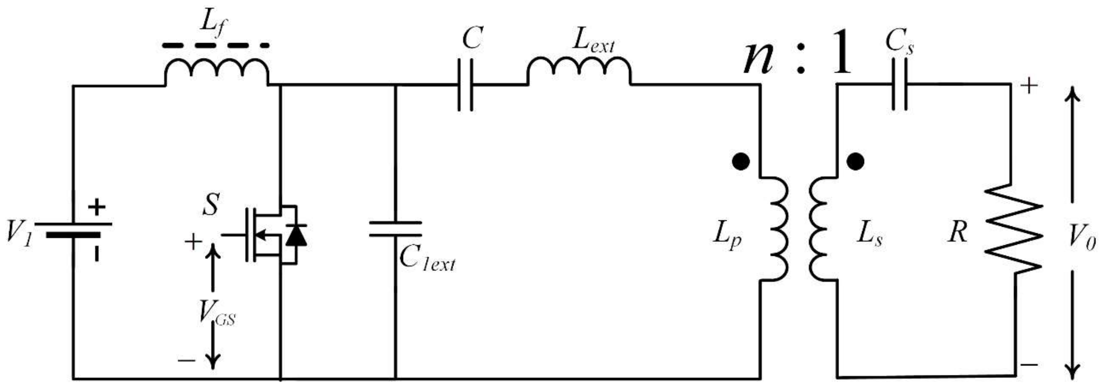


Fig. 1.10. Circuit diagram of a Class E inverter.

To overcome the above described issues, another class of resonant inverters called EF_n inverter is obtained by adding few components to the already existing Class E inverter. It has been reported in [88]–[91] that the efficiency of the Class E inverter can be improved and its voltage or current stresses can be reduced by adding a resonant network, either in parallel or in series to its load network. The method of adding resonant networks to the load network is used in class F and class F^{-1} inverters. The idea of incorporating an additional resonant network with Class E inverter results in a hybrid inverter, which has been referred to as Class EF_n or Class E/F_n inverter. The subscript n refers to the ratio of the resonant frequency of the added resonant network to the switching frequency of the inverter and is an integer number greater than or equal to two. The EF_n term is used, if n is an even integer and the E/F_n term is used if n is an odd integer.

Thus, a Class EF_n inverter additionally uses a series LC network in parallel with the switch to reduce the voltage stress. The EF_n inverter is capable to achieve ZVS as well as ZDS. The Class EF_n inverters are hybrid inverters that combine the improved switch voltage and current waveforms of class F inverters with the efficient switching of Class E inverters. As a result, their efficiency, output power and power output capability can be higher in some cases in comparison to Class E inverter. Considering $n = 2$, a series L-C network is tuned to twice the switching frequency and added in parallel with the switch, termed as class EF_2 inverter. The circuit schematic of Class EF_2 inverter is shown in Fig. 1.11.

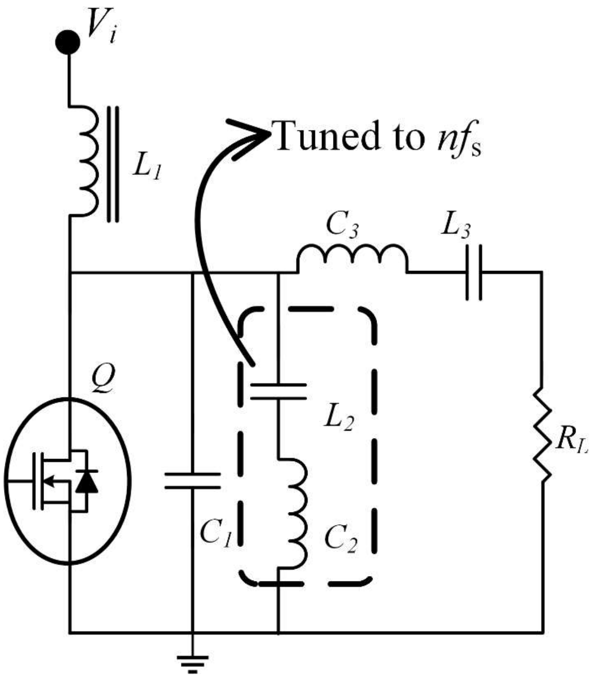


Fig. 1.11. Circuit schematic of Class EF_2 inverter.

The modelling and analysis of Class EF and Class E/F inverters with series tuned resonant networks is given in [92]. The design and development of the Class EF_2 inverter and rectifier for high frequency operation is reported in [93]. This demonstrates wireless power transfer using a Class EF_2 inverter at the transmitting side and a Class EF_2 rectifier at the receiving side. The disadvantage of Class EF_2 inverter is that it cannot be used in battery charging application as it supports constant load resistance at its output since a battery behaves as a variable resistance during the charging process. When the load resistance of the Class EF_2 inverter is changed to a value other than the designed value, the soft switching operation (e.g., ZVS and ZDS) is lost.

During the charging process of a battery, as the internal resistances of the battery continuously increases with the increase in the state of charge (SoC), the inverter used in the wireless charger should be capable to handle variable load resistances. To accommodate variable load resistances, a Class EF_2 inverter with load independent criteria is discussed in [94]. The reported Class EF_2 inverter behaves as a constant AC current source for variable load resistance at the output. However, to verify the load independent criteria, researchers have used a fixed load resistance of 50 Ω at the secondary side of the WPT and the distance between the transmitting coil and receiving coil was varied to demonstrate the variable load resistance reflected across the output of EF_2 inverter as an outcome of change in distance.

To implement CC-CV charging technique, the charger should behave as a source of constant current during CC mode and a source of constant voltage during CV mode. The earlier reported Class EF_2 inverter can be implemented for CC mode but it fails to deliver power to the battery during CV mode. Additionally, the EF_2 inverter uses a DC source as its input to provide AC power at high frequency. Drawing power from the AC grid is more convenient as the grid is more reliable and easily available as compared to any DC power source.

1.3.4 Reconfigurable Power Processor with Wired and Wireless Charging

Conventionally, propulsion and charging modules are the two major power electronic modules in an EV with on-board charger. Vehicles that offer wireless charging facility require an additional power electronic module to be included on-board with the system. This converts high frequency AC power from the receiving side coil to DC power for charging the EV battery. Thus, conventionally, an EV with on-board charger and wireless charging feature contains three separate power electronic modules for three different modes of operation, which are: 1) propulsion, 2) wired charging and 3) wireless charging as depicted in Fig. 1.12.

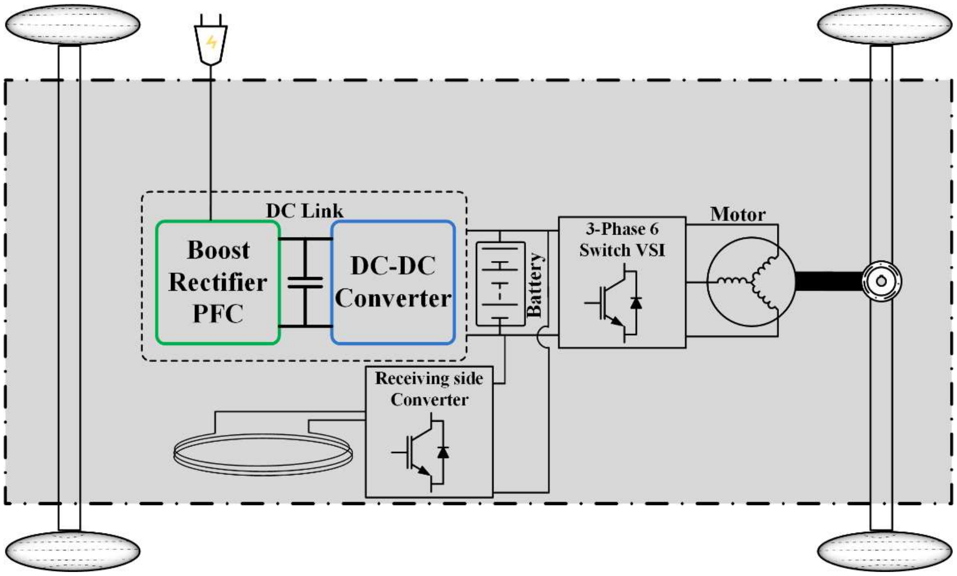


Fig. 1.12. Conventional powertrain architecture in a conventional EV with wireless charging feature.

In case of stationary charging, the above three modes of operations are mutually exclusive in nature, as the vehicle remains stand still for the entire charging duration. The power electronic module that supplies power to the motor unit and the motor itself are unutilized and remains idle for the entire charging duration. To take advantage of this situation, recently researchers have developed integrated battery chargers, where components of the power module including motor windings are reutilized during charging mode [47], [66], [67], [95]. A single phase two-stage on-board integrated battery charger using a five-phase hybrid-excitation flux-switching machine is presented in [96], where the armature windings are utilized as boost inductors in AC-DC boost stage (stage-I) and the field winding is used as an inductor in the DC-DC stage (stage-II). A three-phase EV charger integrated with dual drive motor is reported in [97], where the use of dual inverter reduces the current ripple and the size of grid side LC filter. An integrated on-board EV charger with a three-phase interior permanent magnet (IPM) motor is studied in [98], where a synchronous buck converter is derived using the motor windings as inductors. However, this forms a non-isolated charging circuit and requires an AC-DC rectifier to charge the battery from the AC grid. Three-phase based Ćuk-derived PFC convertors with reduced number of components and high efficiency are presented in [99], [100], but these too are non-isolated topologies. A discontinuous current mode (DCM) based PFC converter for EV charging application is presented in [101], but this needs an additional DC-DC converter as second stage.

The motor windings of a three-phase induction motor are reused as filter inductors during charging mode as reported in [52] but has no galvanic isolation. The reutilization of circuit components to form different topologies using contactors is well documented in [63] and also widely used in industry [61]. The reutilization of power modules as well as the motor windings is well studied in [102]. Though this work proposes vehicle-to-vehicle (V-V) power transfer, the motor windings of both the vehicles are reutilized as filter inductors to reduce the current ripple and the VSIs of both vehicles are connected to form a bidirectional DC-DC converter. An on-board charger is combined with low voltage DC-DC converter to improve the power density as reported in [103], but this does not involve the motor windings. In [104], a WPT system is interfaced to an on-board DC-DC conductive charger, where a common rectifier is reutilized in both the charging modes, but one additional power processor is required for propulsion mode. However, this topology cannot tap power from an AC grid supply, as the reported one is a DC-DC converter.

The existing integrated power processors as discussed above are compared with the proposed reconfigurable power processor (RPP) from various aspects and presented in Table 1. 1, where X is the number of controlled switches, Y is the number of uncontrolled switches and Z is the total number of Switches (Z = X+Y). In this table M0, M1 and M2 represents propulsion, wired charging and wireless charging modes respectively.

Table 1. 1 Comparison of the proposed RPP with existing integrated power processors available in the Literatures

Lit	Available Modes			X	Y	Z	Features for wired charging mode	
	M 0	M 1	M 2				Nature of AC supply	Galvanic Isolation
[61]	YES	YES	NO	14	0	14	3-Ph	NO
[65]	YES	YES	NO	6	4	10	1-Ph	NO
[66]	YES	YES	NO	10	0	10	3-Ph	NO
[96]	YES	YES	NO	12	0	12	3-Ph	NO
[104]	NO	YES	YES	8	0	8	NO AC	YES
Proposed MMP	YES	YES	YES	6	2	8	1-Ph	YES

1.4 Challenges with the Existing System

The prime motive behind popularizing the EV is to reduce the carbon emission in the atmosphere to reduce the air pollution. At the same time, a potential buyer looks forward for a vehicle with an alternate source of energy (other than fossil fuel) that is reliable, robust and safe enough with a competitive price as compared to the conventional vehicle with IC engine. Therefore, the aim is to design the EV with safe and reliable power modules at a reduced cost. The optimal design of power processors plays an important role while designing the powertrain architecture of an EV.

For this, many researchers have proposed various power electronic converters for charging and motoring operation with optimal number of components. However, the following issues are observed in the already reported topologies.

- ❖ For on-board wired charging:
    - Higher number of components leading to costlier EV charger that adds to the cost of the EV.
    - No PFC operation at the grid side that distorts the other loads connected to the grid.

  - No galvanic isolation within the charger to limit the supply side fault from the EV battery pack.
  - Though the already reported work uses optimal battery charging technique like CC-CV, but require additional switch for changing from CC mode to CV mode.

- ❖ For integrated chargers:
  - Conventionally, two separate power processors are used for charging and motoring operations.
  - Most of the integrated chargers do not offer galvanic isolation during the charging mode.
  - Many of the reported topologies require additional rectifier stage to make it compatible with single-phase or three-phase AC grid during charging mode.
  - Many integrated chargers reutilize only motor windings as inductors for deriving the charger topology and not the power electronic components.
  - For deriving charger topology from the propulsion module, most of the power processors require additional power electronic devices (MOSFETs or IGBTs) that leads to increased cost, weight and volume.
- ❖ For wireless charging:
  - The required high frequency inverter uses more number of switches as the conventional powertrain in a WPT system uses H-bridge inverter for this purpose.
  - Hard switching of power electronic switches used in high frequency inverter leads to higher switching losses.
  - Resonant inverters are introduced to reduce the number of switches, but these are subjected to high voltage stress across the switches.
  - Many of the topologies reported in the literature are unable to deliver power at a constant voltage or constant current to a load with variable resistances.
  - Does not support both CC and CV mode of charging.
- ❖ For a single power processor with both wired and wireless charging:
  - EVs with increased charger topology requires an additional power converter on-board with the vehicle that adds to the cost, weight and volume of the EV.
  - The reported works supporting both wired and wireless charging require additional power processor for motoring operation.

- Most of the reported works require DC power at its input, which is not universal as AC source.
- Many topologies require additional rectifier unit at the input side during wired charging mode.

1.5 Objective of the Thesis

It is evident from the literature survey that there is no topology reported, where a single power processor can have all three modes of operations of an EV: propulsion, wired charging and wireless charging. Additionally, the already reported topologies supporting any of the two modes also have the disadvantages, such as (a) they require an additional power module for propulsion mode, (b) they do not provide isolation in wired charging mode and (c) they do not support CC-CV charging during wireless charging mode. Some common disadvantages in both the charging modes are also observed, which are: requirement of additional rectifier stage at the input side to enable the system to draw power from the AC grid, hard switching operations of MOSFETs/IGBTs, etc.

In order to address the above issues, this thesis aims to develop a single reconfigurable power processor with minimum switch count that acts as three different topologies to cater three different requirements during three modes of operations: propulsion, wired charging and wireless charging.

During the wired charging mode, the aim is to develop a two-stage charger with all standard features that require minimum number of switching elements using a simple control algorithm that reduces number of sensors and controllers. For wireless EV charging system, the present work aims to develop a novel powertrain architecture for transmitting side power module that draws power from a single-phase supply to increase the adaptability as single-phase AC supply is universally available.

During both the charging modes, this work aims to achieve soft switching operations like ZVS by using resonant converters. In wired charging mode, a half-bridge LLC resonant converter is used as the second stage (DC-DC stage) of the charger that offers galvanic isolation by using a high frequency transformer. Similarly, in wireless charging mode, the transmitting side power module uses a high frequency resonant inverter that generate high frequency AC waves at constant voltage or constant current, as required by the CC-CV charging algorithm.

During both the charging modes as the proposed work draws power from a single-phase AC supply, the proposed charger maintains near unity power factor at the grid side by employing power-factor correction operation.

1.6 Organization of the Thesis

The present thesis contains six chapters. The background, motivation and literature survey with research gap and the objective of the thesis are described in chapter 1.

The chapter 2 presents a standard two-stage on-board EV charger with minimum switch count. This chapter also proposes a new control scheme called “single controlled PWM technique (SCPT)” that uses only one controlled PWM signal for the operation of EV charger. The proposed EV charger is capable to maintain CC-CV at the battery terminal and near unity power factor at the input AC side. A comparison of switch count used in the earlier reported topologies is also presented with the proposed one in this chapter. The proposed charger is verified with the laboratory developed prototype and the experimental results are presented.

In chapter 3, a reconfigurable on-board power converter for EV application is presented that replaces two separate power converters used in a conventional EV. This amalgamates the propulsion module and the charging module as required by an EV during its two operating modes. Derivation of the proposed topology, its mathematical analysis and design criteria in two different modes are presented in this chapter. The detailed operation and the control schemes implemented in both the propulsion and charging modes are presented in this chapter. The proposed concept of reconfiguration is verified experimentally and the results during both the modes are presented in this chapter.

The chapter 4 presents a novel powertrain architecture for wireless EV charging application that taps power from a single-phase AC grid. The transmitting side power module contains an EF_2 inverter that supports both CC and CV modes of operation, while delivering power to load with variable resistances. The wireless coils are first simulated using Ansys Maxwell package and using the obtained values of self and mutual inductances, the complete wireless EV charger is simulated using PSIM simulation software. A prototype of the proposed wireless EV charger is fabricated and tested experimentally.

Combining all the works, a reconfigurable power processor (RPP) with wired and wireless charging for EVs is presented in chapter 5. The proposed power processor replaces three different power processors required for three different operations: propulsion, wired and wireless charging. The detailed mathematical analysis with its design details and control techniques implemented during three different modes are explained in this chapter. The implementation of the proposed RPP leads to save in cost, size and weight, which makes the EV more efficient. All the three modes are experimentally validated and the corresponding results are discussed. The efficiency and power loss distributions in both the charging modes are presented in this chapter. Finally, the proposed power processor is compared with the already reported topologies in terms of different aspects, such as component utilization factor (CUF), total switch count, nature of AC supply required and galvanic isolation properties. Additionally, a cost comparison table showing percentage saving in cost by the proposed RPP is presented in this chapter.

Chapter 6 contains conclusion of this research work carried out in this thesis and the scope of future work in this area.