Chapter 1

Introduction

1.1 Background

The traditional distribution system structure is designed to operate with unidirectional power flow due to lack of power sources except from generating unit. However, as expected load demand goes up in future, to meet such increased load demand, there is a need of upgrade/add the capacity of generation or integrate small generation units in distribution system near to the loads. High costs related to the upgrade/add the capacity of generation centers and to meet climate neutrality objective by reducing GHGs emission, are some of the main reasons that have driven the growth of small scale generation located near to actual load consumption. Smaller power generation sources near to the load demand refers as distributed Energy Resources (DERs). As the distribution system architecture continues to modernise, DERs such as storage and advanced renewable technologies can help facilitate the transition to a smart grid. DER units can be classified as small power unit sources such as Photo-Voltaic (PV) system, small wind generator, fuel cell and Battery Energy Storage System (BESS).

Greenhouse gas emissions are spread highly unevenly across the world's countries (as shown in Fig. 1.1 [1]), with the top ten GHG emitting countries generating $> 60\%$ of total emissions, and three countries, China (22.7%), the United States of America (15.6%) and India (5.7%) being the largest contributors. According to 2014 statistics in the U.S., electricity generation sector shares 30% of total GHG emission while 26% of GHG emitted from transportation sector [2]. India's 2014 GHG profile was dominated by emissions from the energy sector and transportation sector, which accounted for 51% and 17% of total emissions respectively [3].

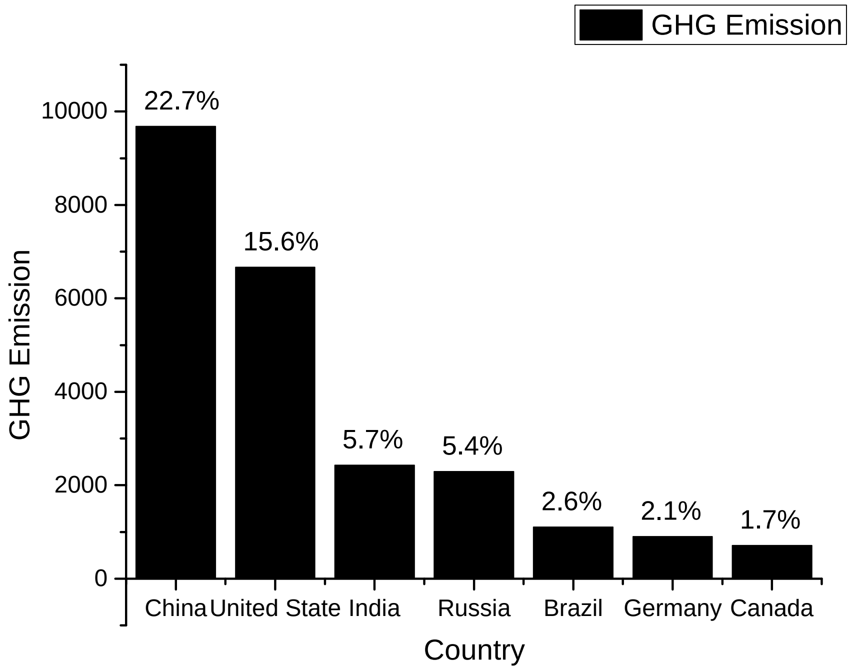

Figure 1.1: Major Producer GHG

In December 2015, the Paris Agreement [4], a new global agreement to maintain climate change was adopted under the United Nations Framework Convention on Climate Change (UNFCCC). In preparation of this agreement, countries submitted national plans of targets and actions for reducing greenhouse gas (GHG) emissions are core components. As a matter of fact, to reduce GHG emission, the center of interest are electricity generation and transportation sector. However, an alternative solution for conventional fossil fuel based electricity generation is use of renewable energy resources like solar, wind, fuel cell etc and to further dampen out the effect of GHGs, transportation sector is to be served by zero-emission vehicles i.e Electric Vehicles (EVs). In view of this fact, to encourage the use of renewable resources and zero-emission vehicle, many countries provide a subsidy on to use RES and zero emission vehicles. The EPRI forecasted, in the U.S by 2050, 50% of the vehicle on the road will be replaced by an electric vehicle which increases the electricity demands by 8% [5]. In [6] the impact of PEVs charging on the EPS in Sweden was investigated for different scenarios, with most severe scenario assuming that 80% of all vehicles in Sweden would be PEVs by 2030. This would result in increased electricity consumption of about 6%, that is about 9.5 TWh/year. A report by Europe-based Florence School of Regulation forecasted that energy consumption by EVs will be 3% of

India's total demand by 2030 after 30% market share of EV.

As of now, EVs are connected to a grid for charging the battery. As a technology matures, the EVs can be used as a distributed resource/storage (in V2G mode) and able to smoothen out the abrupt variation and uncertainties in distribution system load demand . To facilitate such advantageous operation of DERs, two way communication is needed for remotely connect and disconnect services, record waveforms, monitor voltage and current, and support time-of-use and real-time tariff.

1.1.1 Adoption of Electric Vehicles (EVs)

The current distribution system structure is capable of accommodating low penetration of the electric vehicle. As expected penetration level of the electric vehicle goes up in future. A large number of potential market penetration rates have been projected for the different region and plan to deploy EVs successfully as shown in Table 1.1.

Table 1.1: EV global penetration target (in Lakh)

Country	EV Uptake Target	Country	EV Uptake Target
Canada	5.0 by 2018	Switzerland	1.45 by 2020
Denmark	2.0 by 2020	India	30% Market share by 2030
France	2.0 by 2020	Germany	10.0 by 2020
Spain	25.0 by 2020	Netherland	2.0 by 2040
Sweden	6.0 by 2020	Japan	50% Market share by 2020
United kingdom	79.0 by 2030	China	50.0 by 2020
United State	37% by 2020; 54% by 2030; 62% by 2050	Australia	20% Market share by 2020; 65% Market share by 2050

The authors of [7] reported that distribution system could violate technical constraints even with the integration of lower penetration of EVs in distribution system. The uncoordinated and unpredictable penetration of EVs will generate significant stress on distribution network. This will lead to higher uncertainty in loading pattern on the distribution network. If this issue monitored and investigated properly, integration of EVs may have severe effects on distribution system.

1.1.2 Distributed Energy Resources (DERs) integration development

The IEEE definition of Distributed Energy Resources (DERs) is *Distributed energy resources (DER) are smaller power sources that can be aggregated to provide the power necessary to meet regular demand. As the electricity grid continues to modernise, DER such as storage and advanced renewable technologies can help facilitate the transition to a smarter grid.* DER units can be classified as small power unit sources such as Photo-Voltaic (PV) system, small wind generator, fuel cell and Battery Energy Storage System (BESS). As a technology developed towards the management and control of DERs, the ability to regulate the power to mitigate undesirable peak demand due to unpredictable charging pattern of EVs would be a challenge faced by the distribution systems.

The wide adoption of DERs in distribution system is based on aggregator concept, which is responsible for DERs owners satisfaction and collects DER characteristics. To monitor and control the uncoordinated and unpredictable cluster of charging/discharging phenomena of EV on Electric Vehicle Charging Station (EVCS) in the presence of DERs, a new concept of Virtual Power Plants (VPPs) is developed in [8]. An optimal decentralized power scheduling task based on forecasted data by control operational characteristics of DER is performed by VPPs as an aggregator. The components of VPPs is shown in Fig. 1.2. VPP is an efficient way to couple small DG units with demand response (DR) and distributed energy storage into one large aggregation which can participate on real-time power balancing. VPP is a power plant with dynamic and limited power and energy capacity constraints. VPP's operating bounds are based on several factors in the VPP including customers' preferences and distribution network constraints.

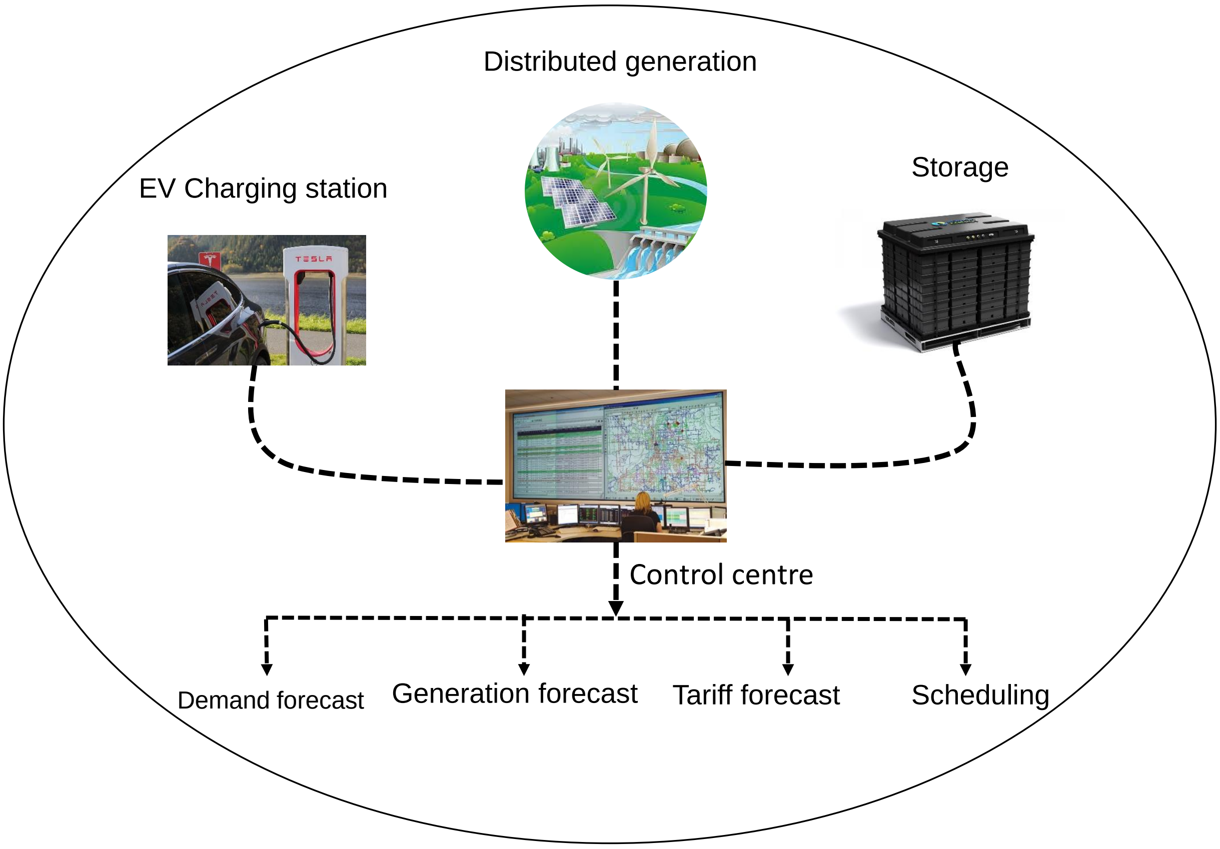

Figure 1.2: Components of virtual power plants (VPPs)

1.2 EVs and DERs Planning in Distribution System

Recently, some research work on the integration of EVs with DERs on distribution network is presented. Impacts of EVs and DERs on distribution system is classified in four categories as shown in Fig. 1.3. It is well reported in literature that unpredictable charging pattern of vehicle increase the distribution system peak load demand [9, 10]. Authors of [11] presented a report on German power grid, by 2030, 1 million EVs will increase power demand by 1.5%. Similarly, once the EVs proprietorship approaches 42 million, it will consequently enhance the power demand by 92% of the total electricity supply. In order to meet the climate-neutrality objective in the field of electrical energy, the integration of low-emission EVs and DERs in the distribution system have increased in last few decades. In ref. [12], it is reported that Nordic grid foresee that the inclusion of EVs during the duration of 2025-2030 would bring down the carbon dioxide emissions by 1-6% and 3-28% correspondingly. The existing distribution system planning architecture is based on two units, one unit is a prediction unit and another unit is an optimization

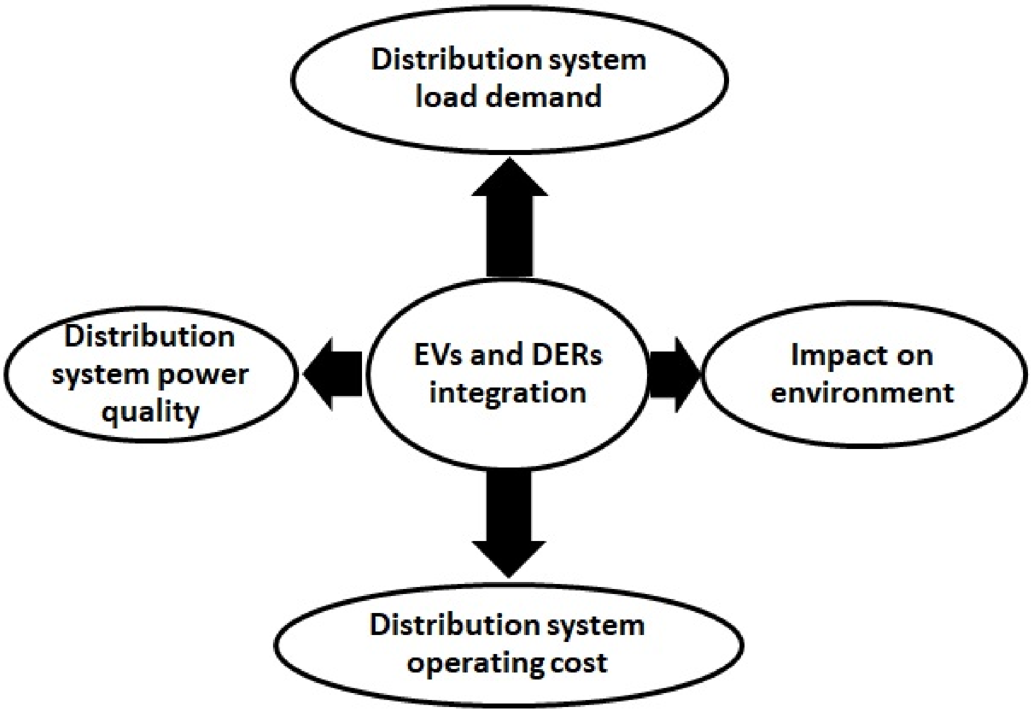

Figure 1.3: Impacts of EVs and DERs

unit. The prediction unit provides an accurate scheduling of future EVs load demand, and the optimization unit generates optimal coordinated charging/discharging decisions that maximize service reliability, minimize operating costs, and satisfy system constraints keeping consumer load intact. Distribution System Operator (DSO) have to provide quality power on the distribution network. Then, distribution system voltage profile, phase unbalance and energy losses must be monitored and maintained within acceptable limits. Authors of [13–15] concluded that the incremental energy losses and investment can be reduced if one controls the charging strategies.

With the integration of EVs in distribution system, mainly two charging/discharging scenarios are likely viz. uncoordinated charging and coordinated charging. In uncoordinated charging scheme, EVs will start charging/discharging immediately as soon as they are connected to the grid. To get along with uncoordinated charging scheme needs of planning of distribution system to manage extra unpredictable loading of EVs and development of stochastic load model of EVs. Despite the unpredictable loading scenario, the Local Distribution Companies (LDC) are responsible for operating the system with acceptable technical constraints with a low-operating cost. Therefore, several studies incorporating these uncertainties need to be carried out for investigating the possible voltage violation, phase imbalance, peak demand increases and power quality with a major increase in operating cost. As the technology matures, the coordinated charging scheme can be developed as a smart grid architecture. In the coordinated charging scheme, EV chargers must have on board power electronics, real-time measurements and proper two-way smart grid communication infrastructure to facilitate the control and management of the bidirectional flow of power between EVs and grid. The main objective of such a charging scheme is to boost the consumer benefits by possible shifting of charging loads without hampering the on board equipment. Taking above mention concerns into consideration, the coordinated or controlled charging scheme studies have been carried out at different penetration levels of EVs in [10]. It is found that the controlled charging method can be employed to reduce energy losses with reduced operating cost.

The charging and discharging of vehicles can be coordinated as per requirement through electricity tariff. Demand response basically reflects changes the pattern of electricity usages in response to change in the price of electricity. For example, if a price is dropped by certain units, how many consumer (in terms of load) would respond. Demand response can be achieved by the consumer by considering the following three general action.

- Consumer can reduce his electricity usage during peak hours when the tariff is high without changing consumption pattern.

- Consumer may respond to the high tariff by shifting some of their peak demand hours to valley hours.

- Consumer response is by using on-site own distributed generation.

The price-based programs (i.e. time of uses, critical Peak pricing, extreme day pricing, real-time pricing) are used for demand response analysis. The price-based programs are based on dynamic pricing. Demand response programme aims to flatten the load curve during peak hour and valley hours.

The charging scenario presented in [16,17] shows that unpredictable charging pattern of EVs increases the peak load demand.

EVs chargers could provide active and reactive power simultaneously without degrading State-of-Charge (SOC) of batteries [18]. The proposal of using PEV for the supply of reactive power to the grid has been investigated in [19]. A decentralized voltage- dependent charging strategy, which requires only local voltage measurements, can be used for mitigating the low EV-induced voltages [20, 21].

In the beginning, electric vehicles were connected to a grid for charging the battery. As the technology matures, the electric vehicle can be used as a distributed resource/storage. Now-a-days different driving range of vehicles with different battery capacities are introduced in the market, in this situation charging/discharging of electric vehicles is to be properly coordinated with the grid. As the number of electric vehicles increase, the energy storage capacity will also increase. This will help to meet load demand in the peak hour without adding further generation making distribution system becomes more reliable.

The charging load demand and load characteristics of EVs are correlated to the charging scenario, and hence, it influences the load modelling.

In modern era of the smart grid, the usage of BESS also plays an important role in the electrical power system. BESS can be installed by either distribution system operator (DSO) or individual customer. BESS owned by DSO is a centralised battery installed on the secondary side of distribution transformer for the off-peak shaving. BESS ensures reliable services to customers during power congestion. It also supports the grid during peak demand and stores energy at low tariff period during the off-peak hours. In recent years, BESS and V2G operation mode of EVs manages the residential loads at larger scale.

For effective utilisation of EVs as a distributed resource, integration of EVs with DERs is to be properly coordinated into the distribution system. As expected increase integration of DER and EVs, needs to upgrade the existing distribution system with co-ordinated planning and operation. The effective utilization of DERs and EVs as an ancillary service, it supports distribution grid in terms of reducing energy losses, reduced peak demand, improve voltage profile and phase balancing among the phase with low operating cost [22, 23].

1.3 Literature Review

The present thesis deals with compressive view of the assessment and impact of the PHEVs on distribution system in presence of Distributed Energy Resources (DERs). The works presented in this thesis can be viewed in four sequential stages. In first stage, the diversity of vehicles driving habit and EV manufacturing perspective are considered for generation of stochastic load profile on distribution system is presented. The charging/disharging load demand and load characteristics of EVs are correlated to charging scenario, hence it influences the EV load modelling. Thus, assessment of the effects of EV load model taking into account the effect of grid voltage and state of charge (SOC) of EVs by reliable and robust power flow method for the planning and operation of the existing distribution system are presented in second stage. In third stage, techno-economic power scheduling of PHEVs in presence of DER modules is presented while considering the demand responsiveness of EV charging/discharging. Furthermore, optimal scheduling of PHEVs is also obtained utilizing the models developed. In addition to this, coordinated scheduling of DGs and EVCS with reactive power support to distribution grids is also performed in this thesis.

This section provides a discussion on previous research work related to work presented in this thesis.

1.3.1 Modelling of PHEVs load profile

The load profile of a PHEV can be seen as sum of total of the charging loads that is reflected as load demand on the distribution system buses. The reflection of PHEV load demand can depend upon various factors of PHEV's, systems and assumptions. Following are the major PHEV characteristics which determine the load behaviour of PHEVs on the distribution system.

- The driving and charging patterns to PHEV through out the day.
- Methods of aggregating the driving and charging pattern to reflect as load in time perspective (hourly load on system) and the location perspective (locating the load on the buses).
- The design perspective such as charger types (fast, slow etc.), battery capacity and

AER.

- The system perspective such as demand response programm for coordinating charging times of vehicles for maintaining distribution system performance.

Several papers ave been published where the modelling of PHEV load has been addressed. In the following paragraph the features of load modelling addressed by each of the papers are indicate.

In ref. [24], a specific daily mileage is assigned to all vehicles, and a single charge per day is assumed. The reality is that vehicle mileage varies from one vehicle to another, and some vehicles may charge more than once per day or not at all. The work presented in ref. [11, 25] involves a rigid recharging schedule, based on which vehicles are plugged in at a specific time and left until fully charged. Energy consumption is assumed to be constant for charging of EVs, whereas in the real world, charging could occur at any time during the day, with different amounts of energy consumption, depending on the available charge in the battery. The PEV charging model presented in ref. [26] assumes one charging event per day after the last trip of vehicle. In ref. [27], all PEVs are assumed to have the same charging duration as well as a rigid starting time. The work conducted in [28] is based on different battery capacities, but all vehicles are assumed to consume and charge all their batteries each day, which does not account for variable usage. The authors of ref. [29] have attempted to combine transport related modelling from EV travel data based on agent based modelling. In agent based modelling, after each trip of vehicle, the aggregated data of EVs location as well as their battery SOC have been calculated by agents and further EVs load profiles are generated for optimal power flow model. A probabilistic model of EVs charging pattern associated with residential load profile is developed in [30]. A stochastic approach was applied with consideration of various realistic factors such as EV battery capacity, state of charge (SOC), driving pattern, i.e., purpose of trip, plug-in time, mileage, recharging frequency per day, charging power rate and dynamic EV charging price under controlled and uncontrolled charging schemes. The EVs load profile proposed in [31] assumed that all battery chargers start charging at the same time, and batteries were charged from the fully discharged state.

In ref. [32], it is assumed that a specific percentage of PHEVs will be operated in electric mode. However, this percentage is entirely dependent on travel patterns and can change from day to day. Authors of ref. [33] have assumed same AER for all PHEVs, which does not reflect the diversity available in the market. A study is reported in ref. [34] with respect to quantifying the benefits of smart metering and demand side management in a distribution system. The work includes consideration of the control of PEV charging, however, drivers' travel patterns are not taken into account, and all trips shorter than 100 miles are assumed to be powered by the batteries. In ref. [35], a typical value of total distance travelled by vehicle (80 miles) was considered for EVs load profile simulation and authors also assume that all private EVs are recharged once every two days, while company vehicles are recharged once per day and that recharge is carried out to full capacity of battery. The authors of ref. [36], examined the impacts of the PHEV charging load through a comparison of the utility load duration curve with and without the charging load. However, the model was based on the assumption that the overall PHEV fleet derives 40% of its miles from electricity, neglecting the uncertainties related to driving pattern of vehicle. The PEV energy consumption model presented in ref. [37] excludes the uncertainties related to driving patterns. An investigation of the impact of PEV charging on power system and gas emissions is described in ref. [38] with respect to three different charging schemes, uncontrolled at home, uncontrolled at any location, and coordinated. In ref. [39], the EVs load profile was generated based on the Flemish Mobility Study, where it was considered that the EVs would mostly start charging in the morning hours for the business areas and in the evening hours for the residential areas. The authors of [40] also used similar observations based on the US National Household Travel Survey regarding the arrival and departure times for EVs load profile simulation. In ref. [41], proposed a model for assessing the impacts of PHEVs on system demand peaks. it was assumed that all PHEVs are driven 33 miles/day, which is the U.S. average.

The authors of ref. [42] studied the impacts of PHEVs on distribution transformers for a variety of charging scenarios. However, they assumed that all PHEVs start charging at 6 P.M., with an initial SOC of 30%, which was contrary to the considerable number of vehicles begin charging at other times of the day. The authors of ref. [43] attempted to determine the percentage of conventional vehicles that could be replaced by PHEVs without violating the system's technical constraints in terms of voltage profiles and imbalances between phases. However, the model was based on the assumption that all PHEVs are charged for 4 hour daily irrespective of the daily distance travelled by each vehicle.

The aggregated impacts of DGs unit and PHEVs on distribution networks were evaluated in [44]. However, the authors based their analysis on the generation of a random charging duration for each vehicle owner irrespective of the specific distances travelled by each vehicle. The authors also assumed that the uncontrolled charging of PHEVs occurs at the time when residential peak load occurs. The authors of ref. [45] used a large-scale distribution planning model to study the impacts of PHEVs on investment cost and incremental energy losses in the distribution network. However, the model again did not include consideration of the dissimilarities in individual driving habits, instead, the assumption was that 85% of the vehicles are charged during valley hours and the remaining 15% are charged during peak hours, irrespective of the arrival times.

Authors of ref. [46] proposed a probabilistic approach based on Monte Carlo (MC) simulations as a means of investigating the impacts of the uncontrolled charging of PHEVs on distribution networks. However, the authors simplified the problem by assuming that each vehicle starts charging with a battery SOC that is uniformly distributed between empty and half of its capacity. The impacts of PHEVs on the distribution grid in terms of power losses and voltage deviations were studied in [47, 48]. The model developed in these papers assumed that the batteries would begin charging from a fully discharged state irrespective of the individual distance travelled and that all PHEVs are equipped with 11 kWh batteries charged by 4 kW chargers.

From the above background and existing research work, it is observed that the variability and uncertainty in vehicle usage are ignored and there is a requirement of comprehensive modelling strategy for PHEVs. the load demand generated through the proposed stochastic modelling was used in impact studies on PHEVs on distribution system. Thus, the generation of stochastic load modelling of PHEVs in this thesis was motivated by the above shortcomings.

1.3.2 Load modelling

The load parameters are input data for power system analysis and the accuracy of the desired studies are directly dependent on load parameters. True representation of power system loads may result in remarkable savings in system operational cost and increase the reliability of power system. Most of the power system loads are dependent of voltage and frequency, hence its accurate modelling is needed power system operational analysis.

The load model is a set of equations representing the mathematical relationship between a bus voltage magnitude and frequency at a given buses for the active and reactive power flowing into the load on the same bus. Usage of different type of battery chargers to charge EVs can produce negative effects on distribution systems. The fast charger power rating can even exceed 200 kW and charging duration falls into a scale of minutes.

A large number of load models have been developed depending on load composition and the purpose of load modelling was according to the desired accuracy. A discussion on previous work related to conventional load modelling and EV load modelling is presented in following subsections.

Conventional load model

A study performed in ref. [49] addressed composite loads and load parameters and included the effects of feeders and distribution transformers. The voltage and frequency dependency of these composite loads were also investigated. In ref. [50], authors have summarized the current status on power system load modeling. Definitions of basic load modeling concepts were explained and the importance of further developments in load modeling was discussed. In refs. [51–53], compares the performance of available load models. A mathematical expression relating load characteristics dependent on voltage magnitude by the sum of constant impedance (CZ), constant current (CC), and constant power (CP) components, was introduced in [54]. However, the use of such a linear combination was first introduced in [55]. The ZIP coefficients model has been widely used to represent the relation between voltage and power characteristics of loads [56, 57]. In general with the conventional load, system with constant power load model exhibits high voltage drop along the feeder compared to other static loads. This voltage variation may become a serious problem for distribution network which can damage or reduce the life of the equipments connected to it [58]. Distribution system customers are generally grouped into three major classes viz. residential, commercial and industrial. In each class, the load consists of the sum of several different load components, each of which contributes some fraction to the total load [59]. A series of survey were performed to evaluate ZIP parameters for typical residential, commercial, and industrial customers in [60].

EV load model

Evaluation of effect of EV load modeling for distribution system planning studies requires a detailed characteristics of battery and charging technology. The charging load demand and load characteristics of EVs are correlated to the charging scenario, and hence, it influences the load modelling. Different kinds of load models have been used in the existing literature to represent EV load behavior in power systems.

In ref. [61] modeled EV as a constant current (CC) load, considering its power electronic grid interface. In ref. [62], EV load was modelled as constant power (CP) load and as constant impedance (CI) load . To examine the different charging methods viz. constant voltage (CV), constant power (CP) and constant current (CC) of fast charger with the proper management of cell chemical reactions inside batteries are given in ref. [63] and multistage CC-CV, CC-CV were discussed in [64,65]. However, these references have been used to model fast charger based on given charging methods.

The process for the adaptation of the proposed EV ZIP load model in the load-flow program is demonstrated and used for the analysis of power flows in [66]. It has been observed that the distribution loading margin is influenced by the EV load model. The results show that the EV ZIP model can provide true values of the power losses, bus voltages, and real and reactive power demands, which are lower compared with the values obtained using the constant power load model. The research work presented in [67] considers constant power load model to represent the EV charging load in the power flow analysis. It concludes that the charging power of EV is independent of variation in system voltage. The CPL model might not be able to represent the actual behaviour of the EVs. V2G mode operation effects on short-term voltage stability of the grid was assessed in [68], by representing the EV load as a constant current load (I). In ref. [68], it was observed that the existing studies have been done with an uncertainty of the EV load behavior, by representing the EV load with different load models (CP, CC, CI). In order to facilitate fast charging technology in distribution system, it is important to assess their impact on power systems as it draws considerable amount of power from grid in short time. In order to examine the effect of fast charging technology on voltage stability analysis, a voltage-dependent load model was presented in [69]. Voltage-dependent EV load model has the ability to regulate both active and reactive power with fast EV charging scenario in a modern distribution system. It is observed that loading margin with the voltage-dependent EV load model is the lowest when compared with the other load models (P, I and Z). To accommodate high penetration of EV in distribution system, a optimal load management strategy is proposed with the constant current EV load model in [70]. Constant current EV load model is based on only active power injection approach. It is observed that the proposed optimal load management formulation with consideration of constant current load model reduces computational burden and improve accuracy of results.

Incorporation of EV load models in load flow routines

As a matter of fact, the effects of load modeling are particularly important in load flow analysis due to its dependency on voltage and frequency of the loads. In addition to this, load modeling can significantly change the convergence performance of the load flow algorithm. In intermediate stage of distribution system planning and operation, an efficient and robust power flow algorithm is needed to perform load flow analysis with inclusion of appropriate load model. The research in [71] addresses the overall differences in load-flow results with the inclusion of different mathematical load modelling of conventional loads in load-flow algorithm. Thus, it is essential to examine the effect of EV load models taking into account the effect of grid voltage and state of charge (SOC) of EVs by reliable and robust power flow method for the planning and operation of the existing distribution system.

In most of the above mentioned literature, inclusion of EV load model in load flow routines were done by conventional Newton-Raphson method. Conventional Newton-Raphson (CNR) power flow analysis has limitation of the convergence when applied to the distribution system with large number of voltage-controlled buses [72]. The development of backward/forward sweep method mitigated this problem of convergence. However, forward/backward methods have limitations as far as the handling of voltage-controlled buses are concerned [73].

The Current Injection-based Newton-Raphson (CINR) load flow algorithm [74] has the ability to circumvent the problem of convergence and handling of voltage-controlled buses in radial distribution system. Current injection-based formulation of the power flow problem with a mixed polar and rectangular form of state variables are proposed in [75–77], where each load bus is defined by two current mismatch equations expressed in terms of the active and reactive bus voltage, and it can be presented by a single equation in terms of active power mismatch and the angle deviation. In ref. [78], a current injection load flow algorithm based on the constant nodal admittance matrix is presented. Due to the absence of the proper modeling of voltage-controlled buses, this current injection-based algorithm [78] cannot be applied to general power flow applications. Even with the available voltage-controlled bus modeling, the convergence property of this methods are not satisfactory. In ref. [74, 79] the proposed method has used $2n$ current injection mismatch equations expressed in rectangular coordinate for both the PQ and PV buses. In case of PV bus, an extra dependent variable ΔQ is considered. Consequently, three additional equations for each voltage-controlled bus are introduced in the problem formulation. The authors of ref. [80] extended the work of [79] to improve the convergence characteristics with large number of PV buses present in distribution system. In ref. [80] the proposed method represents PQ bus as current mismatch equation and PV bus as power mismatch equation. It is observed that representation of PV buses itself introduces a new equation related to the voltage-controlled bus in the load flow formulation. This modification in PV bus representation improves its convergence but also increase computational time and storage due to inclusion of new equation related to voltage-controlled bus. In ref. [81] proposed a simplified current injection power flow formulation in which $2n$ current equation and m active power injection equations are written in polar coordinates, where n and m are the total numbers of load buses and voltage-controlled buses respectively.

Current injection power flow formulations, written in the polar coordinate [81–83], have also been developed in which $2n$ current equations and m active power injection equations are written in polar co-ordinate. The storage and computational time between consecutive iterations is improved due to the less number of floating-point operations (flops) as compared to conventional Newton-Raphson (CNR) method [79]. Table 1.2 provides a summary of existing methods to solve load flow problems.

In view of the above, inclusion of ZIP load model, voltage-dependent load model, and constant current load model of EVs in modified current injection Newton-Raphson based load flow algorithm have been used in this thesis to study their effects on planning and distribution of existing distribution system.

Table 1.2: A summary of existing load flow algorithm for solving load flow problem.

Ref. Number	Power flow		Eq. form			Bus Type		Line Type		Structure Type		LM	DG
	S	I	R	P	C	PQ	PV	B	U	Rad	$Mesh$		
[74]	×	✓	✓	×	×	✓	✓	×	✓	✓	✓	✓	×
[76]	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	×
[77]	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	×
[79]	×	✓	✓	×	×	✓	✓	✓	×	✓	✓	✓	×
[81]	×	✓	×	×	✓	✓	✓	×	✓	✓	×	×	×
[82]	×	✓	×	✓	×	✓	✓	✓	×	✓	✓	✓	×
[84]	×	✓	✓	×	×	✓	×	×	✓	✓	✓	✓	×
[85]	×	✓	✓	×	×	✓	✓	×	✓	✓	✓	✓	×
[86]	×	✓	✓	×	×	✓	✓	×	✓	✓	✓	✓	×
[87]	×	✓	✓	×	×	✓	×	×	✓	✓	✓	×	×
[88]	×	✓	✓	×	×	✓	✓	×	✓	✓	✓	✓	×
[89]	×	✓	✓	×	×	✓	✓	×	✓	✓	✓	✓	×
[90]	×	✓	✓	×	×	✓	✓	×	✓	✓	✓	✓	×
[91]	×	✓	×	×	✓	✓	✓	✓	×	✓	✓	✓	✓
[92]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×
[93]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×
[94]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×
[95]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×
[96]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×
[97]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×
[98]	✓	×	×	✓	×	✓	✓	✓	×	×	✓	×	×

S	:	Power Injection	I	:	Current Injection
R	:	Rectangular	P	:	Polar
C	:	Complex	PQ	:	Load Bus
PV	:	Generation Bus	B	:	Balanced
U	:	Unbalanced	Rad	:	Radial
Mesh	:	Meshed	LM	:	Load Model
DG	:	Distributed Generation			

1.3.3 Integration of EVs in presence of RERs in distribution System

The study of EVs integration and its impact on the distribution system began in 1980s. The current distribution system structure is capable of accommodating low penetration of electric vehicle. As expected penetration level of the electric vehicle goes up in future, Local Distribution Companies (LDC) will have no control over the unpredictable penetration, location, and schedule of charging of an electric vehicle. This will lead to higher uncertainty in loading pattern on the distribution network. LDC have to provide quality power on the distribution network. Then, distribution system peak load, voltage profile, and energy losses must be monitored and maintained within acceptable limits. Several studies have been carried out to assess the upgradation of distribution system architecture to meet desired generation capacity and infrastructure to accept large penetrations of EVs. The charging impacts of PHEVs on the distribution systems can be categorized into, effects on distribution system equipment, which include effects on transformers, cables, circuit breakers, and fuses, and general effects on distribution system characteristics, which include harmonics, power quality, load profile, and power loss. In the current scenario, renewable energy sources (RES) become an important part of the power system structure. In the near future, integration of RES and BESS into the distribution system will be utilized to support the grid when the distribution system will experience the electric vehicles as a significant load to the system.

A discussion on previous work related to impact of EVs in presence of RERs on existing distribution system is presented in following paragraphs.

Several studies have been performed to estimate EVs growth in market and its impact on distribution system [99–102]. A common finding of these studies was the uncoordinated charging scenario of EVs can be coincide with the peak load timing on distribution system. According to [103–105], due to unpredictable location and timing of integration of EVs in distribution system, EV charging could require additional power generation or increase the utilization of existing capacity and possibly reduce the reserve margins. A methodology is presented in [47] for the modeling and optimal coordination of PEV charging so that energy losses and voltage deviations on a radial distribution feeder are minimized. The results reveal the effectiveness of the methodology with respect to reducing system energy losses, but the study is based on assumed fixed battery capacities and identical charger ratings for all vehicles. Coordinated charging techniques to improve losses and voltage deviations have been investigated in [47].

A number of studies have found that the integration of RERs in coordination with EVs load can reduce the negative impacts on distribution system [106–108]. A two-step procedure to determine the sizing and siting of RESs and the sizing of EVs by minimizing the overall system cost meeting the relevant technical constraints is presented in [109]. Simultaneous allocations of EVs and RESs into the distribution system are addressed in [110]. Scheduling of EVs and RES for microgrid perspective is presented in [111]. The possible solutions to mitigate the effect of PEVs on the distribution system are suggested in literature [112, 113]. It includes the time variant pricing scheme, the demand response management, V2G discharging, renewable energy resource integration and utilization of battery storage system into the grid. From a distribution grid point of view, a photovoltaic charging station for EVs is presented in [114]. The results show that the large percentage of energy transfer from the photovoltaic (PV) system to the EVs range from to 56% to 72%. In ref. [115], the real-time price based demand response for a EV charging station was proposed. In ref. [116], an optimum location technique and a charging management method are introduced for the EVs that support the distribution grid voltage and frequency profile while considering the EV charging and discharging. In ref. [117], the optimal location of EV parking lots in a distribution network is investigated along with the distribution reliability constraints. In ref. [118], a method for optimal allocation and sizing problem of RES and EV charging stations simultaneously and managing vehicle charging process is presented as a multi-objective optimization problem, which can reduce power loss, voltage fluctuation, charging and demand cost, and EV battery cost. In [119], reduction in greenhouse gas emission due to EVs was studied. In ref. [120], the optimal scheduling of a local distribution system containing RESs and EVs is investigated, where wind turbines (WTs) and PVs are included, and the EVs are also considered in V2G mode. Effect of EVs in presence of DGs on distribution system is studied in [121, 122]. The study proposes an optimal coordination of PEV charging schedule, penetration level of PEV, sizing and siting of DG units, to mitigate the effect of PEVs on the distribution system. A method to minimize the domestic peak load using an EV, BESS and renewable sources is proposed in [123, 124]. Optimal utilization of renewable energy resources, EV and BESS to manage operating cost of utility is proposed in [125–127]. Potential of BESS to accommodate high penetration of PVs is investigated in [128]. For the peak shaving and valley filling, PAR minimization problem considers the optimal use of RESs, BESS and integration of electric vehicle in G2V and V2G mode in distribution system.

In recent years, BESS and V2G operation mode of electric vehicle manages the residential loads at higher scale. Utilization of EV with PV units to support the residential load demand is presented in [102, 129]. A dynamic adjustment of EVs charging/discharging is proposed by controlling the charging rate to support the load demand by effective use of available battery capacity [130]. In the literature, studies have been carried out by considering the coordinated effect of PHEVs with DGs or PHEVs with BESS on distribution network. A summary literature survey related to this thesis is presented in Table 1.3.

Table 1.3: Taxonomy of the reviewed papers based on the objective functions

Ref.	DG	PHEV	V2G	BESS	COST	CO_2	Load flattening	Loss
[108]	✓	✓	✓	✓	✓	×	×	×
[109]	✓	✓	×	×	×	×	×	✓
[113]	✓	✓	×	✓	×	×	✓	×
[121, 122]	✓	✓	✓	✓	✓	×	×	✓
[123]	✓	✓	✓	✓	×	×	✓	×
[126]	✓	✓	×	✓	✓	×	×	×
[128]	×	×	×	✓	✓	×	✓	×
[131]	✓	✓	×	✓	✓	×	×	✓
[132]	✓	✓	×	✓	✓	✓	×	×
[133]	×	✓	×	×	✓	×	✓	×

1.3.4 Integration of EVs and DERs with reactive power support

Every single EVs consumes some amount of reactive power during charging. Reactive power flow affects voltages throughout the distribution system, and if it is regulated properly in distribution system it improves voltage profile and phase balancing. Traditionally, reactive power is generated by synchronous generators, synchronous condensers, capacitors, static VAR compensators and distributed generation. The generation of reactive power is limited and it needs to be transmitted from a fixed place to the loads [134, 135]. In most of literature EV load is considered as active power load or source (V2G) to solve the distribution system planning problem. The EVs could generate/consume reactive power at any SOC level without impacting life cycle of the batteries [136, 137]. With this control flexibility, EVs can support reactive power and voltage control applications in the power grid [138]. Hence, EVs provide an efficient way to support power grids with reactive power.

Specifically, to solve phase balancing and voltage support problem, the authors of [139–142] examines the aggregator based simulation for phase balancing and voltage support using renewable source with PEVs (in Grid-to-Vehicle (G2V) & Vehicle-to-Grid (V2G) mode), but it is assumed that PEV charger and renewable source does not inject or absorb reactive power. Optimal active and reactive power scheduling of EVs and DGs for maximizing the benefit consider single phase system for their investigation in [143, 144]. The authors used decision making algorithm for scheduling of EVs and DGs. In order to minimize daily energy cost based on charging strategy of all storage system in three phase balance microgrid have been studied in [145]. An optimal short-term active and reactive power scheduling of EV and DGs for peak procurement and voltage control on single phase basis is performed in [146]. The authors of [147,148] also proposed an optimal resource scheduling in smart grid considering minimization of cost and voltage deviation in single phase system.

1.4 Motivation and Objectives of the Thesis

Based on the background and the research survey presented in the previous section, it is observed that a detailed investigations are required to thoroughly address the techo-economic scheduling of Plug-in-Hybrid Electric Vehicles (PHEVs) in presence of DER modules in a way that would not be counterproductive on distribution system. The motivation and the objectives of the thesis are detailed below.

- Modelling of detailed characteristics of PHEVs such as battery capacity, All Electric Range (AER), State-of-charge (SOC), Total Energy Required (TER) for charging, and V2G connection analysis and their performances on the distribution network need investigated in detail. EVs charging/discharging load profile plays crucial role to determine its impact of distribution system. A stochastic load model of EVs is needed to facilitate unpredictable EVs charging/discharging which reflects realistic behaviour of EVs on distribution system.

The present thesis aims towards development of a stochastic simulation of PHEVs load considering the uncertainties related to driving pattern, based on the demand responsiveness and conventional approach.

- It is essential for distribution system planner/operator to examine the effect of different EV load models on assessing the energy losses, voltage deviation and line flow capacity violation incurred due to charging of EVs specifically when there is high penetration of EVs in distribution system. In most of studies, the adoption of EV load modelling for load flow routines, aiming several perspective of distribution system planning and operation, is done with conventional N-R methods.

  As one of the aims the present thesis develops a modified current injection newton-raphson ($MCINR$) based load flow method for modern distribution system is proposed by revisiting the process of deriving the power flow equations and reformulation of their derivatives. The quantification the effect of EV load models are also investigated in terms of impact indices viz. ILP, ILQ, IVD, and IC are evaluated for each load model.

- Investigation of EVs will lead to higher uncertainty in loading pattern on the distribution network. LDC have to provide quality power on the distribution network. Then, distribution system peak load, voltage profile, and energy losses must be monitored and maintained within acceptable limits by taking care of consumer satisfaction.

  The present works aims to develop a method for a 24-hour optimal scheduling of DGs in conjunction with PHEVs charging/discharging considering the different types and different penetration of vehicles and also to investigate its performance on a sample systems .

- In near future, integration of RES and BESS into the distribution system will be utilized to support the grid when the distribution system will experience the EVs as significant load to the system. The scheduling of PHEVs (between start trip time and last trip arrival time), D-BESS and DGs are required to mitigate significant consequences on the distribution system in distribution system.

A further development of a 24-hour day-ahead scheduling of PHEVs, DGs and D-BESSs to optimization of four contradictory objectives simultaneously (i.e. cost minimization, CO_2 emission minimization, real power losses minimization and load flattening). Furthermore, to perform case studies to segregate the effects of PHEVs, D-BESS and DGs scheduling on distribution system.

- The uncoordinated and unpredictable cluster of charging/discharging phenomena of EV cause increased phase currents in distribution system resulting in phase unbalance and may lead to tripping of the distribution system. Maintaining the techno-economical constraints and phase balance of distribution networks throughout the day is a challenging problem. The works aims to formulate a multi-objective function including cost, phase balancing and load flattening as components. From other perspective, formulation could be to use cost as main objective and unbalancing and PAR (load flattening) as constraints.

  The objective is to develop a 24-hour optimal active and reactive power scheduling of DGs and PHEVs under current and voltage unbalance constraint are proposed for three phase unbalance distribution system.

1.5 Thesis Outline

The outline of the thesis and preface of all seven chapters are as follows.

- ***Chapter 2***: In this chapter, modelling of detailed characteristics of PHEVs such as battery capacity, All Electric Range (AER), State of Charge (SOC), Total Energy Required (TER) for charging and V2G connection analysis for PHEVs performances on the distribution network is discussed. In addition to this, a stochastic modelling of PHEVs is also developed. A stochastic modelling of PHEV is classified in two categories. The first categories deal with vehicle design perspective such as battery capacity, All Electric Range (AER), State of Charge (SOC), Total Energy Required (TER) for charging and V2G connection analysis. Whereas, the second categories dealt with dynamic nature of vehicle's driving pattern such as *daily-distance-travelled*, *start-trip-time* and *last-trip-arrival-time.*

- ***Chapter 3***: In this chapter, the modified current injection based power flow analysis of the modern distribution network with inclusion of three different type of EV load models is proposed. In proposed formulation, a modified representation of PQ buses according to the considered EV load model is presented. Moreover, the proposed power flow analysis is implemented to evaluate the system performance indices for examining the effects of different EV load modelling in modern distribution system. Three impact indices have been considered in this work, for characterizing the effect of different EV load models for modern distribution system planning and operation. The indices including viz. real power loss index (ILP), reactive power loss index (ILQ), voltage profile index (IVD) and MVA capacity index (IC) are obtained using numerical simulation carried out on 38 bus distribution system in presence of DGs.

- ***Chapter 4***: In this chapter, a base case of distribution system without PHEVs and DGs has been studied to evaluate system performance characteristics. Further, the effect of the introduction of PHEVs has been investigated in terms of system operating cost, losses, voltage profile, and load flattening. The 24-hour DGs scheduling is carried out to optimize the system cost, which is a function of charging/discharging cost, losses, and cost of DGs power. Differential evolution (DE) search algorithm is used to optimize a single objective weighted fitness function.A 38-bus test system is considered for demonstration of the investigations.

- ***Chapter 5***: In this chapter, a 24-hour day ahead power scheduling of PHEVs (in between arrival and departure time), D-BESS and DGs are proposed to mitigate its effect on the distribution system. The proposed strategy of power scheduling is tested on standard IEEE 38-bus distribution system. Four objective functions, including system operating cost, CO2 emission, energy losses and load flattening, are considered to examine the effect of distributed sources on the IEEE 38-bus distribution system. These four objective functions are converted into a single objective fitness function with the help of the weighted sum approach. An Effective Butterfly Optimizer (EBO) is implemented to minimise the fitness (single-objective) function. To understand the individual, as well as the combined effect of unscheduled PHEVs charging, scheduled charging/discharging of PHEVs, D-BESS and DGs various case studies, are performed. Moreover, a studies based on setting of weights is presented which reflects relative importance of the individual objective function on distribution system planning and operation problem.

- ***Chapter 6***: In this chapter,a 24-hour day ahead optimal active and reactive power scheduling of DGs and EVCS which aims the minimize VPPs operational cost considering current and voltage unbalance and PAR constraints is performed. The work also investigates the inter dependencies of cost on load flattening and unbalance factor in a distribution system. This dependencies of cost and losses are investigated with helps of pay-off tables. The pay-off tables relates unbalance factor and PAR to cost and losses. To simulate the model of proposed idea, a IEEE-25 bus three phase unbalanced system is adopted and for these investigation all the analytical simulation are performed in GAMS/MATLAB environment.
- ***Chapter 7***: In this chapter, the main conclusion of thesis are summarised and suggestion for the future work on this subject are given.