Chapter 1

INTRODUCTION

This chapter presents a brief overview of the importance of the problem associated with the increasing penetration of Electric Vehicles (EVs) in the power grid. It motivates the foundation for the research conducted and reported in this thesis. This chapter starts with the background and prevailing situation, further delineates the literature review, research gap, and motivation sets research objectives for this thesis and concludes with the thesis organization.

1.1 BACKGROUND OVERVIEW

In recent decades, environmental degradation and climate change have grown to be major worldwide concerns. Governments throughout the world aggressively search for alternative energy resources and promote the use of clean energies to create a green and sustainable society in order to lessen their reliance on conventional fossil fuels and the emissions of greenhouse gases. There are no difficulties with the grid being penetrated by Renewable Energy Sources (RESs) at the lower level. However, because of the sporadic nature and fluctuation of Renewable Energy (RE), the higher-level integration of RESs may provide additional grid operation issues. The large-scale integration of RES-based Distributed Energy Resources (DERs), as depicted in Fig. 1.1, is structurally changing the traditional power system, which presents the system operator with ongoing technological challenges in the context of system stability, protection, islanding, and power quality. This is due to the variety and unpredictability of RESs. Smart grid technology and the flexibility of Active Distribution Network (ADN) operation in a centralized and decentralized manner have facilitated this extensive integration of RESs.

In order to support the growth of renewable energy sources and solve climate change challenges, the transportation system must be electrified. Even though the government has implemented a number of incentives to encourage people to buy electric vehicles, the adoption rate of EVs is still low. One of the biggest barriers to EV marketing is the absence of accessible charging stations and the limited vehicle range. The aggregated charging demand of EVs may also result in a high peak load that has a detrimental impact on the power system if coordination is poor. EV integration brings both challenges and opportunities in the smart grid. As a result, it is crucial for EVs, charging stations, and the smart grid to construct a reliable charging scheduling mechanism to create a sustainable, intelligent, and efficient transportation system.

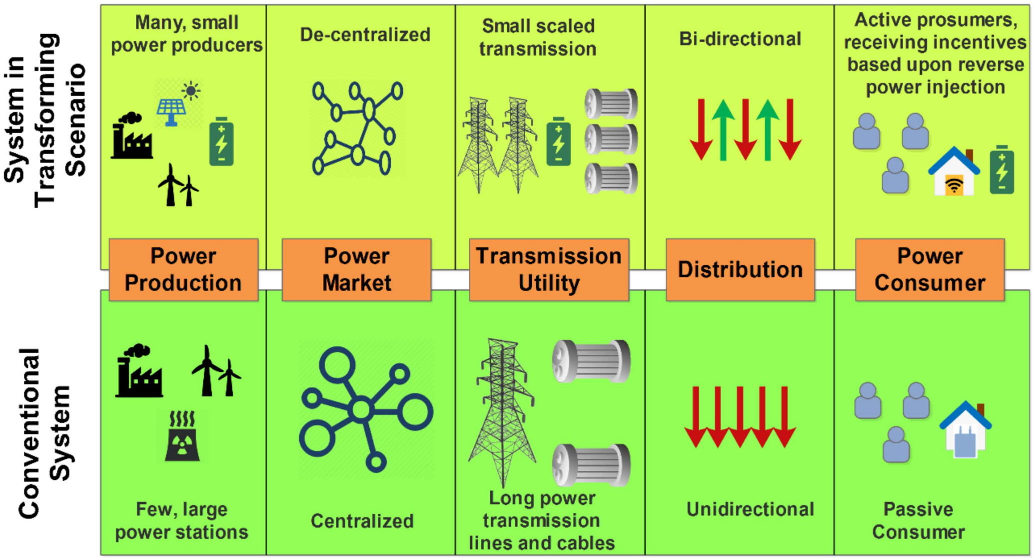

Fig. 1.1 Structural transformation of conventional power system into the smart grid.

The power grid, aggregator, and clients are typically the three parties involved in EV charging operations. Thus, three essential perspectives have been used to study the EV charging issues: the smart grid perspective, the charging aggregator perspective, and the user perspective. The first category deals with concerns including load flattening, frequency regulation, voltage regulation, and other things relating to how EV charging operations affect the power system. The charging aggregator serves as a link between EV users and the electricity grid.

In particular, a charging aggregator is in charge of meeting the charging needs of EV customers while also ensuring a reliable system operation. The foremost motivation for an aggregator is to increase profits, while the primary issue for an EV charging client is service quality, such as how quickly the charging is done, how much it costs, how well the battery is being charged, etc. The First-Come-First-Serve (FCFS) technique is frequently used in existing works that address the EV charging scheduling problem without giving full regard to other important considerations, such as energy cost, battery State of Charge (SOC), etc. In such circumstances, it is advisable to arrange the charge flexibly and not always to follow the coming order, provided that it can be completed before the deadline. Some existing works merely take into account the interests of the aggregator or EV owner when scheduling the EV charging operations, for example, by increasing the profits of the aggregator or minimizing the cost incurred by the owner. While scheduling the charging requirements, it is appropriate and crucial to take all factors into account in order to protect both parties interests. Additionally, a variable factor affecting SOC is the battery charging rate. A consistent charging rate throughout the whole process would be inaccurate if this aspect is ignored, as would be the case in an actual EV charging scenario. Furthermore, it offers guidelines for efficient charging schedule design. The battery's performance is crucial to the functioning of any EV because it is the source of all of the vehicle's energy. During the charging process, it's crucial to ensure the battery's health and effective performance as well as to extend the battery's lifetime. All the problems mentioned above provide new difficulties and chances for improving the scheduling of EV charging. This dissertation has provided efficient and feasible solutions for tackling the aforementioned concerns, which will be examined in more detail in the following sections.

1.2 LITERATURE SURVEY

This section gives a literature review on the impact of large-scale EV penetration on the existing grid and various optimal EV charging schemes. The review contains the advantages, disadvantages, and limitations of the methods reported by researchers.

As discussed in the previous section, as a result of their arbitrary charging and discharging, the large-scale integration of Plug-in Electric Vehicles (PEVs) has a negative impact on the load profile. In a distribution system, this causes transformer overloading, increased line losses, and significant voltage variations [1]. Uncontrolled fast charging of PEVs puts additional strain on the power system's components and necessitates network re-configuration, capacity expansion, and peak load reduction [2].

Despite these challenges, PEVs with bi-directional power flow capabilities may also inject electricity into the grid while discharging, a mode of operation known as "Vehicle-to-Grid" (V2G). There are several other motivations for EV owners to support the system by providing ancillary services and generating revenue. This may be done by adjusting EV charging power in accordance with grid demand [3]. In [4], EV charging in the presence of renewable energy sources is discussed with the aim of minimizing the charging costs. While [5] implements the best scheduling of renewables to reduce the microgrid's operational costs. In [6], a variety of EV types and travel patterns were used to determine which Time of Use (TOU)-based pricing structure offered the PEV owner the most incentives for charging during off-peak hours.

1.2.1 Electric Vehicles for Ancillary Services

The deployment of EVs over V2G can successfully lower peak demand and offer ancillary services [7], [8]. Aspects, including system security and losses, are evaluated at various degrees of EV penetration in the various reported charging schemes, which enable EVs to operate in either V2G or Grid-to-Vehicle (G2V) modes. The performance of the distribution system can be enhanced to some extent by regulated EV charging. In order to create an EV charging system that flattens the load voltage profile more effectively and is more customer-centric as a consequence of lower charging costs, additional research is needed. In [9], the relationships between feeder loss, load factor, and load variation for coordinating EV charging is explored to reduce distribution system loss. In [10], a local and global optimum scheduling strategy with the aim of lowering EV charging costs is presented. In order to enhance system performance, a distributed optimum charging method that incorporates peak shaving and phase balancing is provided in [11]. Several studies have been conducted to examine the effects of EV charging on the distribution network. In order to manage the PEV peak load demand in the home distribution grid, a hybrid V2G approach is put forth in [12]. While [13] presents a statistical study of EV use with the aim of assessing the techno-economic effect. In order to coordinate EV charging for loss reduction and to enhance grid load factor, [14] uses two separate programming approaches, namely quadratic and dynamic programming. In [15], mixed-integer programming for V2G optimization to increase system dependability is proposed. Further, [16] presents the impact of EV adoption on system loads. In addition, an intelligent EV charging strategy is suggested to flatten the load curve. In order to optimize the degree of EV penetration within the current grid infrastructure, a real-time energy management plan is provided in [17], which quantifies the effects of increased EV penetration on the demand profile. Further in [18], a Monte

Carlo technique is used to assess the effect of EV charging on system voltage imbalance and under/over voltage. Due to its comparably longer scheduling window, PEV charging is a time-flexible load and complies with Demand-Side Management (DSM) [19]. For PEVs to deliver auxiliary services at the grid level, several research investigations have been carried out. Reactive power support was suggested in [20], and [21] utilizes it as a means of reducing the adverse effects of PEVs on the distribution system voltage. However, neither study has taken into account active power assistance via PEVs, i.e., the V2G mode of operation. In [22],[23], the fast active power flow capabilities of PEVs in V2G mode is utilized for grid frequency control.

1.2.2 Controlling Charging/Discharging Power of EVs for Frequency Regulation

The important finding of these researches is the controllability over the EV charging loads to enable further EV integration without impairing the optimal performance of the power system. In [24], frequency control by EVs in microgrid networks is studied. In order to adapt the charging power of EVs to changes in system frequency, droop control is developed. EV load estimating tool is created in [25] based on EV type, battery type and capacity, travel patterns, and battery SOC in order to predict the charging load. While supplying electricity to the grid, EVs in V2G mode can be made to offer auxiliary services like frequency control [26]. An autonomous distributed self-terminal frequency droop-based V2G control is proposed in [27], whereby EV owner preferences are also taken into consideration. In [28], a hierarchical control algorithm for PEVs is presented to mitigate the intermittencies arising out of wind power fluctuations. A dynamic PEV model with feedback control for frequency regulation is proposed in

[29]. A decentralized V2G control to achieve scheduled charging and provide frequency regulation is presented in [30].

In these V2G schemes, the Independent System Operator (ISO) broadcasts the Automatic Generation Control (AGC) signal to all EVs, and each EV then adjusts its charging power in response to the AGC signal for the duration of the contract. In accordance with the agreement, EVs, if available at Charging Stations (CS), can also inject electricity into the grid. The agreement on price and power exchange is carried out for a certain period of time after the network operator transmits the AGC signal to the CS operator. The CS operator also takes into account the choice of EV owners since some of them may prefer to store enough battery capacity for a long trip planned ahead or do not want to discharge if incentives are insufficient.

The advantages of EVs cooperating in frequency regulation were examined in [31], and [32] analyzed the available EV power for Load Frequency Control (LFC). In [33] and [34], a demand-based predictive control approach for LFC is discussed. In [35], a new LFC method for conventional power plants utilizing RES and EVs is proposed. A fuzzy logic-based frequency control algorithm for the power system integrated with RES, EVs, and Energy Storage Systems (ESS) is presented in [36]. However, the creation of fuzzy sets resulted in a significant increase in processing time. In [37], LFC with model predictive control for EVs is introduced. For frequency control, [38] used a fuzzy Proportional-Integral (PI) controller and an adaptive droop control scheme. For electric vehicles (EVs) and renewable energy sources (RES), a coordinated control strategy has been devised [39]. While [40] presents a simplified control strategy for V2G operation for frequency control, taking day-ahead scheduling into account. For microgrid frequency management, a centralized model predictive control for EVs, Photovoltaics (PVs), and ESS is provided in [41]. The authors in [42] have researched the impact of EV charging load on the industrial microgrid. In [43], a V2G frequency regulating mechanism using ISO is suggested. However, because of the unavailability of a sufficient number of EVs, the strategy is unable to remove frequency variations in certain intervals completely.

1.2.3 Optimizing the EV Charging/Discharging for Economic Benefits

In order to provide controlled charging and discharging that provides socioeconomic advantages, Electric Vehicle Aggregator (EVA) acts as a control interface between distinct customers and ISO. According to the available information regarding the driving patterns of EV users and time constraints, EVA generates the charging schedule for EVs. The research work in [44] takes into account the economic viewpoint with the aim of minimizing EV charging costs. In comparison to dumb charging, a logical control-based V2G algorithm is described in [45], which results in a 47.9% decrease in average charging costs. The scheme, however, does not account for the cost of battery degradation or its effects on the network of the power system, such as voltage limit violations. The work carried out in [46] suggested fuzzy logic-based EV scheduling to increase the revenue of the EV. To further observe the effects of EV routing and scheduling adjustments, EV driver responses are effective indicators. The cost of charging PEVs is affected by the desired and available battery SOC, the vehicle's arrival and departure timings, the tariff structure, and the system parameters. Dumb charging of PEVs results in more significant charging costs for the EV owner and more strain on the system infrastructure. With TOU-based pricing, scheduling may take into account the behaviour of price-responsive EV owners. Since the price of power is cheaper during the off-peak period compared to the peak period, charging an EV in off-peak price hours in a TOU-based environment increases the incentives for potential EV owners.

By modifying the charging rate and time slot in the TOU-based power market, the cost of charging EVs may be minimized. The authors of [47] describe an online EV charging method that lowers the cost of charging in real-time pricing while adhering to customer satisfaction standards. A quadratic programming approach is implemented in [48] to reduce EV charging costs concurrently and increase profit from EV discharge. Similar research in [49] creates two distinct EV charging coordination frameworks with the goals of enhancing energy management and reducing charging costs. Additionally, [50] uses a multi-level V2G approach to regulate EV charging in order to save operating expenses in the TOU pricing structure.

The authors in [51] present a spot-priced battery swapping method for EV charging. However, the approach's usefulness is constrained by the need for enormous storage areas and the high upfront expenses needed. The objective developed in [52] takes into account the technical and financial elements of PEV charging. Later, in [53], a cutting-edge hybrid planning methodology included PEVs with the potential of bi-directional power flow. For Vehicle-to-Vehicle (V2V) energy transmission, [54] suggested charging cost optimization using a mixed-integer programming technique. However, these methods ignore grid-level restrictions and are constrained by the inconvenience of the EV owner.

1.2.4 Network Re-configuration Techniques with Different Objective Functions

The PEV connected to a heavily loaded bus cannot change the charging power. By moving the load from severely loaded to lighter loaded buses, network re-configuration aids in load balancing. As a result, the PEV has more freedom to charge in the periods when electricity prices are lower, which lowers the PEV's cost of charging.

In order to increase system performance, a method for network re-configuration with the optimal dispatch of DERs is provided in [55]. To increase the utility's profit in a re-configurable environment, an evolutionary algorithm is used to simultaneously reduce power loss and voltage imbalance [56]. A heuristic Branch Exchange (BE) technique for network re-configuration is developed in [57] with the goal of minimizing the system loss. In order to expedite the multi-hour stochastic network re-configuration procedure, a three-step switch opening and exchange mechanism is devised [58]. With the aims of loss reduction, load balancing, and limiting the voltage deviation, a multiobjective game re-configuration approach of the distribution network and an enhanced social learning-based beetle swarm algorithm is presented [59]. To find the optimum Distributed Generation (DG) location and network re-configuration, the discretized network re-configuration using dataset technique and water cycle algorithm is utilized [60]. Another study used an effective mathematical model for distribution network loss minimization while taking the system voltage profile into account [61].

1.2.5 Volt/Var Optimization (VVO) and Conservation Voltage Reduction (CVR) for Higher Cost Benefits

The significant penetration of renewable energy presents difficulties for the grid's functioning, making it more probable that distribution system voltage limitations would be violated. A well-known strategy called Volt/Var Optimization (VVO) makes use of capacitor banks and on-load tap changing transformers (OLTCs) as voltage management mechanisms. VVO and Conservation Voltage Reduction (CVR) present a strategy for energy conservation by lowering system voltage within acceptable bounds. In [62], a multi-mode VVO-based CVR method to reduce voltage fluctuations and energy saving is presented. For the trade-off analysis between energy savings and line losses in

Medium/Low Voltage (MV/LV) networks, a Pareto Particle Swarm Optimization (PPSO) based active voltage control technique is proposed in [63]. According to [64], CVR in an imbalanced distribution network is accomplished by controlling DER inverters. Further in [65], a multi-layered hybrid VVO approach for loss mitigation and effective DG utilization is proposed.

1.2.6 The challenge of Fast and Non-spurious Islanding Detection Scheme

As discussed earlier, the uncertain power output of RES raises issues in operation and control of the RES penetrated power system. Along with having an impact on the power quality, intermittency-related fluctuations also have an impact on the system dynamics and provide challenges for integrating DERs into the grid. One of the key aspects to be looked into is the islanding detection of the microgrid from the main grid. In the cases of intentional islanding, the system reliability is not compromised as the control mechanisms for such a situation are already established. Unintentional islanding, however, endangers the system since the main grid can no longer control voltage and frequency. As per the IEEE Std. 1547-2018, an islanding event must be detected within 2 s from its time of inception. This necessitates the requirement of a fast and non-spurious Islanding Detection Scheme (IDS) for DG protection. Various IDSs available in the literature are classified into three foremost sets as: communication-based IDSs, active IDSs and passive IDSs.

In large-scale power distribution systems with numerous DGs and feeders, communication-based IDSs necessitate additional communication infrastructures, such as Phasor Measurement Units (PMUs), Supervisory Control and Data Acquisition (SCADA), and Power Line Carrier Communication (PLCC) [66]. In [67], Pearson's correlation coefficient is utilized in the micro-PMU (μPMU) based approach for islanding detection. In [68], phasors of voltages, frequency, and rate of change of frequency from several locations in grid-connected Micro-Grid (MG) operation were processed using principal component analysis and an extended mathematical morphological filter. Due to the large costs and complexity involved in the infrastructural transformation for communication-based IDSs, active and passive IDS are favoured for islanding detection.

Active IDSs rely on the local measurements obtained from the DG interconnection point. For inverter-type DGs, Active Frequency Shift (AFS) [69], Slip-Mode frequency Shift (SMS) [70], Sandia Voltage Shift (SVS) [71], and Sandia Frequency Shift (SFS) [72] approaches have been widely employed. Additionally, several combinations with variants of the aforementioned IDSs have also been used for DERs of the inverter type. The small Non-Detection Zone (NDZ) in active IDSs, however, affects the Power Quality (PQ) of the system because it continually injects the disturbance signal at the Point of Common Coupling (PCC) and injects harmonics in the voltage signal. Additionally, it makes fine-tuning the control loop in the functioning of DERs of the inverter type more difficult.

For islanding protection methods, passive IDSs based on Under Voltage/Frequency (UV/UF) and Over Voltage/Frequency (OV/OF) relays [73]–[82], or Rate of Change of Frequency (ROCOF) protection method [83] are frequently utilized. The Voltage Unbalance and Total Harmonic Distortion (VU/THD) technique [84], voltage Phase Jump Detection (PJD) method [85], Rate of Change of Active Power (ROCOAP) method [86], and under/overvoltage protection and under/over frequency protection methods are a few examples of frequently used passive methods. When there is a power imbalance between load and generation, passive IDSs performance is remarkable, but if the power mismatch is small, they are unable to identify islanding events.

The combination of active and passive IDSs to extract the advantages of both methods resulted in a new category of IDSs called hybrid islanding detection methods. The following are a few hybrid islanding detection methods available in the literature: In [87], a reliable hybrid islanding detection approach is presented that combines the current injection method as the active method with the frequency relay, voltage relay, and THD method as the passive method. In order to provide an effective approach for synchronously spinning DGs, [88] integrates the ideas of the voltage imbalance and THD (passive) techniques with the positive feedback (active) technique.

1.3 RESEARCH GAP AND MOTIVATION

In the context of large-scale integration of EVs in the existing grid infrastructure, optimal scheduling schemes are required. This work makes a contribution to the complex technical and economic interdependencies by offering a techno-economic evaluation of various goals for EV charging coordination. The Research Questions (RQs) are answered in light of TOU-based pricing, the modelling of driving behaviours, and price-responsive EV owners:

RQ:1 How network re-configuration may help in providing optimal charging to PEVs, thereby reducing the overall charging cost?

The literature makes it clear that the influence of network re-configuration has been researched in order to enhance the performance of the distribution system, including loss reduction and voltage profile enhancement. It appears that little attempt is being made to achieve optimal PEV charging when the distribution network is re-configured.

The investigation carried out in Chapter 2 delineates the performance of the scheme under network re-configuration to achieve a reduction in charging costs.

RQ:2 What can be the potential of CVR deployment to lower operating costs and improve the performance of distribution networks in the presence of EVs?

A further study carried out in Chapter 2 aims at reducing the operational cost of the EV-integrated distribution network in the presence of CVR.

RQ:3 Taking the advantages of both utility-benefitting schemes and customer-centric schemes, what scheme can be proposed to simultaneously minimize the charging cost of the PEVs and provide ancillary service to the grid?

The optimal charging scheme researched in Chapter 3 aims at minimizing the overall charging cost of the PEVs together with reducing the system voltage variability. The proposed scheme is also tested for real-time feasibility in a Real-Time Digital Simulator (RTDS), and Real-Time Automation Controller (RTAC) based co-simulation platform.

RQ:4 How a large EV fleet having bi-directional flow capability can be utilized to provide frequency regulation to the grid?

This study focussed in Chapter 4 on regulating grid frequency based on the SOC of the EV batteries and frequency deviation. With the proposed controller, frequency deviations and power exchange in the tie-line between interconnected systems may be efficiently reduced.

RQ:5 How can an IDS for Electric Vehicle Charging Station (EVCS) as an inverter-based DG wherein EVs are in V2G mode be utilized for un-intentional islanding detection?

The research work in Chapter 5 employs a hybrid IDS utilizing Modified-Sandia Frequency Shift (M-SFS) as the active method and Fast Rate of Change of Frequency (FROCOF) as the passive method for un-intentional islanding detection for EVCS type DG.

1.4 RESEARCH OBJECTIVES

The research objectives of this thesis are outlined as follows:

- To obtain an optimal charging schedule for EVs for maximizing customer benefits through network re-configuration and Conservation Voltage Reduction (CVR) in a TOU-based pricing structure.
- To develop an EV charging schedule that maximizes EV owner’s benefits with simultaneously providing ancillary support through voltage variability minimization.
- To investigate frequency regulation under contingencies though V2G operation of Electric Vehicles.
- To develop a new Islanding Detection Scheme (IDS) that overcomes limitations of active and passive methods of islanding detection for fast disconnection of EV charging stations under the un-intentional islanding of microgrid.

1.5 THESIS ORGANIZATION

The thesis has been organized in the following six chapters:

- **Chapter 1:** This chapter presents a brief introduction of the subject, literature review, and research gap, along with problem formulation.
- **Chapter 2:** Optimal scheduling of PEVs for charging cost minimization in the re-configurable network considering CVR has been proposed.

- **Chapter 3:** An intelligent scheduling of PEVs has been suggested that considers customer benefits together with providing voltage support to the micro-grid.
- **Chapter 4:** The application of electric vehicles for frequency regulation using SOC-based V2G controller has been suggested.
- **Chapter 5:** A hybrid IDS combining a proposed Modified-Sandia Frequency Shift (M-SFS) and Fast Rate of Change of Frequency (FROCOF) is proposed for un-intentional islanding detection in V2G environment for protection of Electric Vehicle Charging Station (EVCS).
- **Chapter 6:** Concludes with summarizing the main findings in this thesis and sets future research directions to be explored.