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Charging and Discharging Strategies of Electric Vehicles with V2g Operation Scenarios

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Abstract:
Adverse effects of fossil fuel burning internal combustion engine vehicles have alarmed nations worldwide. With recent technological advancements in Electric Vehicle (EV) industry, governments throughout the world are promoting wider adoption of electric vehicles to mitigate environmental issues. However, increasing popularity of electric vehicles will pose a great threat to existing electric grids due to added load of electric vehicles in power systems distribution network. The approach adopted in this study to develop smart charging schedule is based on optimization technique to minimize cost of charging for both, electric utilities (EU) and EV owners. This will essentially level utility load throughout the day by providing power to charge EV batteries during off-peak hours, and, on the other hand, utilities will take power from EV batteries for peak power shaving during peak power demand hours of the day. The optimization method adopted in this study is particularly quadratic programing to minimize cost of charging.

Keywords: *Electrical Vehicles, Electric Utilities, Smart Charging, V2G Operation, Quadratic Programming*

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I. INTRODUCTION

In recent years, electric vehicles (EV) have become very popular, and this trend seems to continue to grow in the near future until most of the transportation sector is composed of electric vehicles, according to new policies initiated by multiple governments around the world. The electrification of the transportation sector appears to be a viable solution for reducing greenhouse gas emissions from internal combustion engines and power companies that use electric vehicle batteries as distributed energy sources (DER) to improve power quality. With the rapid growth of electric vehicles on the road, it has brought new challenges to its development [1]. Also, with the increase in the number of electric vehicles worldwide, the realization of Vehicle-to-Grid (V2G) technology seems feasible. However, to effectively implement V2G technology, efficient two-way charging stations are required, because charging equipment plays a vital role in the development of V2G. In order to fully tap the full potential of V2G and avoid unnecessary adverse effects on the grid, utility companies must design smart charging and discharging strategies. The tasks related to the control and management of the electric vehicle (discharge) charging plan and the responsibility for coordinating the participation of electric vehicles in the electricity market in the distribution network are handled by this entity, called the Aggregator [2]. Finding a cost-effective charging solution in a given area is also expected to become one of the main functions of the aggregator, because V2G is meaningful in the aggregation scenario, which is to integrate large electric vehicle fleets into the power system network to increase energy storage. Some aspects of integrating electric vehicle intelligence into the grid include load balancing, peak shaving and valley filling and minimizing utility costs, while minimizing charging costs for electric vehicle users [3]. According to V2G phenomenon, the two-way flow of electricity is considered, that is, the electric vehicle battery can be charged from the grid during off-peak hours, and power can be supplied from the electric vehicle battery to the grid during peak hours to reduce the utility load [4]. In [5] proposed a coordinated bidding strategy using fuzzy logic for the auxiliary services provided by V2G operations and in [6] proposed an optimization model based on global optimal scheduling solutions and distributed scheduling solutions to minimize the total cost. In [7] compared three different (dis) charge scheduling techniques using secondary planning. They introduced two methods, one based on the classical optimization method using quadratic planning and the other based on market-based coordination, a multi-agent system, which uses bidding on the virtual market to achieve an equilibrium price that meets demand and supply. Relevant studies discovered based on the methods and strategies adopted in this study are introduced in [8] and [9]. These studies focus on achieving the target curve based on the secondary optimization technology. This concept is similar to the concept of problem definitions and mathematical models used to derive utility (discharge) plans to achieve peak shaving and load balancing [10]. In [11] described the impact of electric vehicle charging on the hourly load curve of the United States and [12] & [13] determine that EV charging has a slight impact on the load of the component and does not violate the voltage limit. In [14] & [15] the research on an optimal EV charging control scheme was proposed. This solution uses real-time data to efficiently use energy to meet customer needs in a scenario where only energy is the power grid. In [16], a scheme based on autonomous scheduling of charging was proposed. The model combines renewable energy and electric vehicles with the distribution network, both of which are considered distributed energy sources. The models [17]-[20] promise to balance the demand and supply of active power according to grid conditions. In addition, heuristic algorithms are used to study charging plans that use V2G technology to support active and reactive power.

II. DESIGN OF V2G INFRASTRUCTURE

In this study, it is assumed that all available EVs in an area participate in the charging and discharging of V2G, which is the best economic measure provided by the aggregator. The aggregator responsible for the interaction between electric vehicles and utilities is already in place as shown in the Fig.1. It can control and manage the charging and discharging of electric vehicles according to the requirements of consumers.

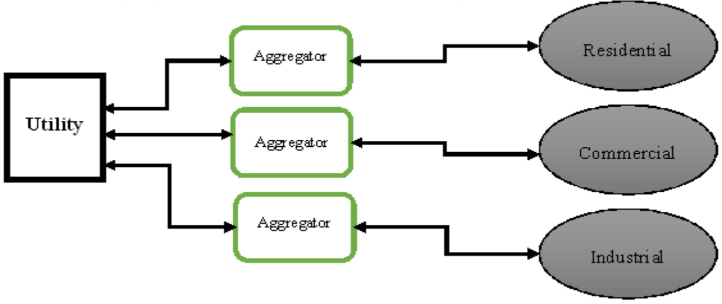

Figure 1: Role of Aggregator

In this paper successful V2G model is created which yields bidirectional power flow between EVs and electric grid/utility. The V2G model created here outlines that when the load demand is low, electric vehicle owners can take electricity from the grid to charge the electric vehicle battery. This is a beneficial technology for both consumers and power system operators. The proposed charging station strategy that uses DC fast charging technology to charge electric vehicles is shown in Fig.2. The DC fast charger can charge the EV battery in the shortest possible time interval, about 15 minutes at the shortest. The DC fast charging station includes an additional DC-DC converter for efficient energy conversion.

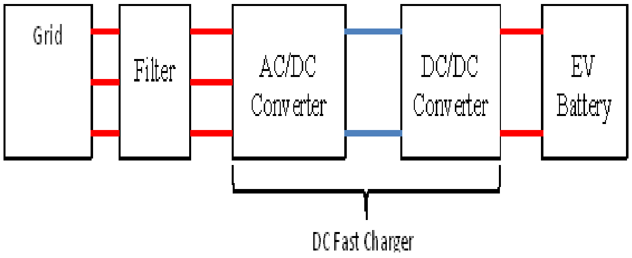

Figure 2: Block diagram of DC fast charging station

However, in addition to the charging station topology, the control mechanism of the converter used in the charging station is also very important for controlling the charging and discharging of electric vehicles. The two control mechanisms discussed and implemented in this study are the grid-side controller (GSC) and the local controller. The grid-side controller controls the operation of the AC-DC converter connected to the grid, and the local controller acts as an aggregator in the V2G scenario. The local controller controls the operation of the DC-DC converter based on the signals received from electric vehicle users and power companies. The local controller allows EV owners to charge the EV battery when needed. At the same time, it receives signals from the power company to adjust the charging schedule to balance the load and help the power company to run smoothly.

An overview of the V2G model created in this study is shown in Fig.3 below.

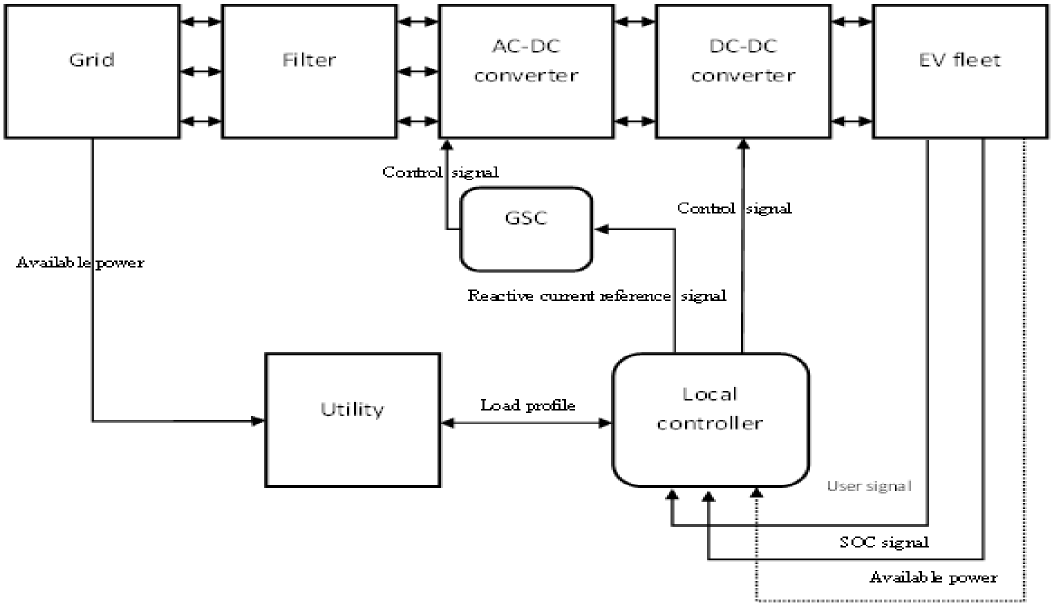

Figure 3: Schematic of Proposed V2G Model

2.1 Control Mechanism:

Two control strategies are used to implement V2G technology to regulate the power flow between the EV battery and the grid. A controller is dedicated to the switching control of the AC-DC converter, which provides active power for charging electric vehicles and reactive power for the grid. The second controller is a local controller that controls the power flow between the EV battery and the grid. The block diagram of Simulink GSC used in this study is shown in Fig.4. The GSC controller plays an important role in providing residual active power for charging electric vehicle batteries and providing reactive power to the grid to support utilities.

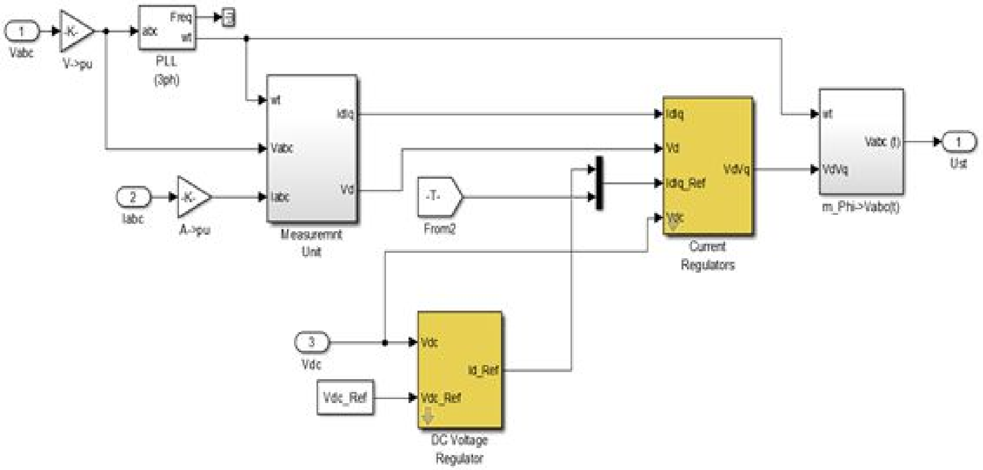

Figure 4: Simulink Block Diagram of Grid-Side Controller

The local controller in this V2G infrastructure model acts as an aggregator. It is directly connected to a controlled current source and interacts with utilities to determine the charging and discharging of electric vehicle batteries. In addition to active power support, the local controller also receives signals from utility companies to provide reactive power support. According to the utility request, the local controller calculates and sends a reference signal to the GSC in order to use the AC-DC converter DC-link to provide reactive power to the grid. The state of charge (SOC) is most important input for the G2V and V2G operating local controllers. The amount of charging current required to charge an EV battery is a function of its SOC as it determines how much charging current is required within the range of battery SOC.

The following flow chart shown in Fig.5 gives the information regarding the SOC of the EV battery operated by local controller.

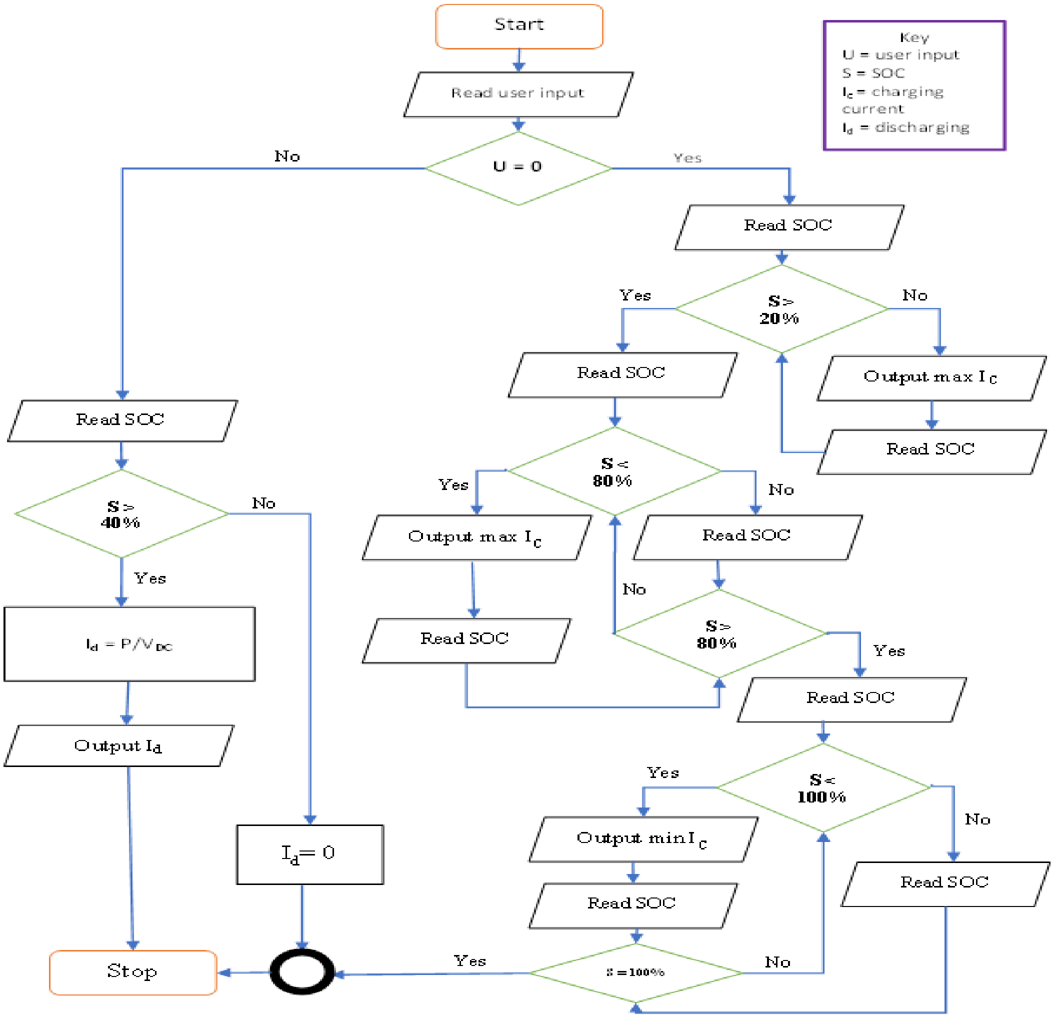

Figure 5: SOC Algorithm done by local controller

The required power is calculated inside the local controller and coordinated with conditional statements to satisfy algorithm criteria as given by the equations below.

$$P_{demand} = P_{load} - P_{threshold} \quad - \quad (1)$$

$$Q_{required} = Q_{reference} - Q_{demand} \quad - \quad (2)$$

Where,

P_{demand} = active power demanded by utilities;
P_{load} = load profile of utilities;
$P_{threshold}$ = threshold power set by local controller to meet demand
$Q_{required}$ = reactive power to be supplied to utilities;
$Q_{reference}$ = reference reactive power to determine $Q_{required}$
Q_{demand} = reactive power demanded by utilities

The objective function can be written in the form

$$\min \sum_{t=1}^{T}\sum_{i=1}^{U}\left(P_t + C_{i,t}\right)^2 - \quad (3)$$

Further, substituting equations (1 & 2) in (3) yields complete objective function for optimization model used in this study. The objective function is:

$$\min \sum_{t=1}^{T}\sum_{i=1}^{U}\left(\left(P_t^{residential} + P_t^{industrial} + P_t^{commerical}\right) + C_{i,t}\right)^2 \quad - \quad (4)$$

The Objective function is subjected to set of constraints is given by the equation (5) below.

$$\left\{\begin{array}{c} I_{i,t}^{c} \geq I_{i}^{c,min} \\ I_{i,t}^{c} \leq I_{i}^{c,max} \\ S_{i,t} = S_{i,t-1} + b_i I_{i,t-1}^{c} \\ S_{i,t} \geq S_{i}^{min} \\ S_{i,t} \leq S_{i}^{max} \\ S_{i}^{min} \leq S_{i,t}^{desired} \quad \forall i, t = t^{desired} \\ C_{i,t} = I_{i,t}^{c} V_{DC} \\ C_{i,t} \geq C_{i}^{min} \\ C_{i,t} \leq C_{i}^{max} \\ P_t = P_t^{residential} + P_t^{industrial} + P_t^{commercial} \\ P_t \geq 0 \\ P_t \leq P_t + P_t + \sum_{i} C_{i}^{max} \end{array}\right. \qquad \forall t, i \quad - \quad (5)$$

III. RESULTS & DISCUSSIONS

The case study formulated in this section address working model of V2G fast charging infrastructure connected with utilities and local controller (Aggregator). The working model of charging infrastructure designed is implemented in MATLAB/ Simulink software.Table-1 and Table-2 gives parameters used for simulation of V2G charging infrastructure in MATLAB/Simulink.

Table 1: Battery Parameters and Specifications

Parameters	Specifications
Nominal voltage	360V
Capacity	210Ah
Initial SOC	57%
Battery response time	0.2s
Cut-off voltage	270V
Fully charged voltage	419.0354
Internal resistance	0.017143 ohms

Table 2: Simulation Parameters

Parameters	Values
Simulation time	60 sec
Charging currents	180A [20%-60% SOC] 105A [60%-80% SOC] 10A [80%-100% SOC]
SOC threshold	40%

The Fig. 6 shows EV battery status after simulation of V2G system developed. The battery is taking power from grid to charge during user specified time intervals; between 0 - 10 seconds, 20 - 40 seconds and 50 - 60 seconds.

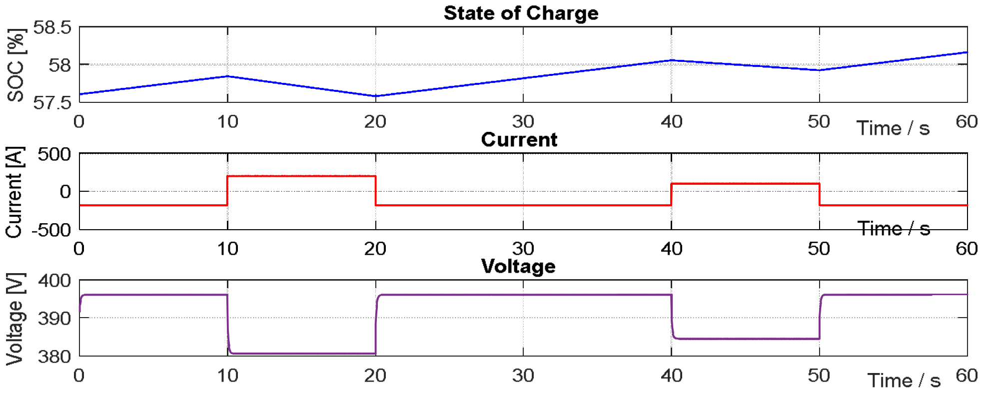

Figure 6: EV Battery Status after Simulation

The Fig. 7 shows active and reactive power provided by EV battery and AC-DC converter's DC-link, respectively, according to user defined signals of local controller.

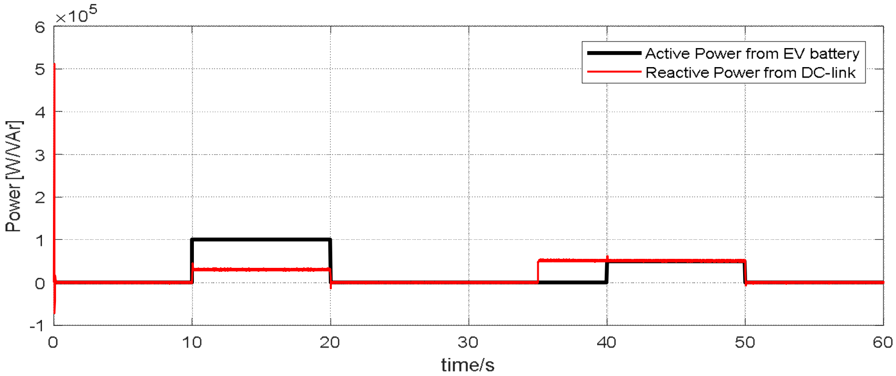

Figure 7: Power provided to Utilities

In this case, Utility load profile of region is used as load profile which is a sum of residential, industrial and commercial loads over a period of 24 hours and optimization is performed on overall utility load profile as shown in Fig. 8 below.

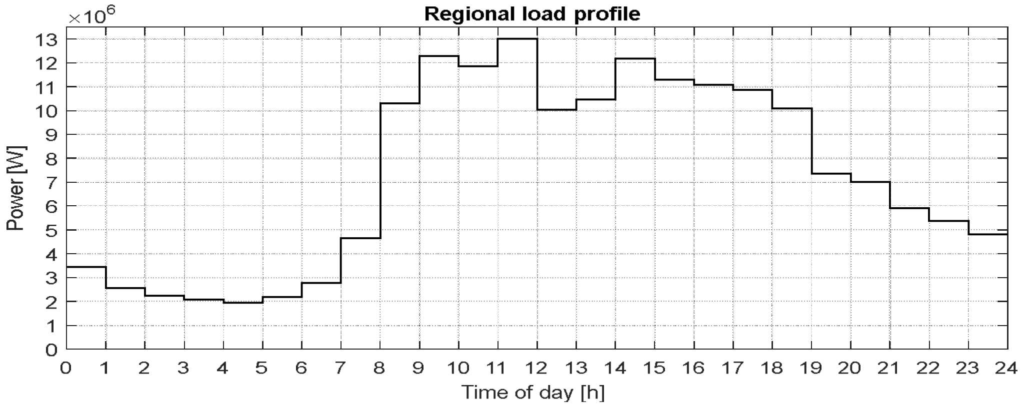

Figure 8: Regional load profile

A Quadratic Programing is used to implement optimization problem for regional load control and it is assumed that all EVs available in a region are participating in V2G scenario and that EVs are plugged in.

Table 3: Parameters and Values used in Optimization

Parameters	Values
Max. discharging current: $\boldsymbol{I_i^{c,min}}$	-125A
Max. Charging current: $\boldsymbol{I_i^{c,max}}$	125A
State of charge: $\boldsymbol{S_i^{min}}$	0.2 (20%)
State of charge: $\boldsymbol{S_i^{max}}$	0.9 (90%)
State of charge threshold: $\boldsymbol{S_{desired}}$	0.55 (55% for residential EVs), 0.60 (60% for industrial and commercial EVs), 0.80 (80% for all EVs)
Desired time for $\boldsymbol{S_{desired}}$: $\boldsymbol{t_{desired}}$	16:00 for residential, 17:00 for industrial and 18:00 for commercial EVs, 00:00 for all EVs
Max. discharging power: $\boldsymbol{C^{min}}$	- 1500 kW for residential area - 51.8 kW for commercial area - 600 kW for industrial area
Max. Charging power: $\boldsymbol{C^{max}}$	1500 kW for residential area 51.8 kW for commercial area 600 kW for industrial area
Total number of time steps	24

Utility base power	13 MW

The results obtained from regional load control optimization for optimal charging schedule are presented in Fig.9 to Fig.12 below. It can be seen that from Fig. 9, desired SOC for each region at a desired time (user defined), is maintained keeping SOC always within limits. Moreover, it can also be observed that EVs are charging to maximum point when utility power is available in off-peak load hours.

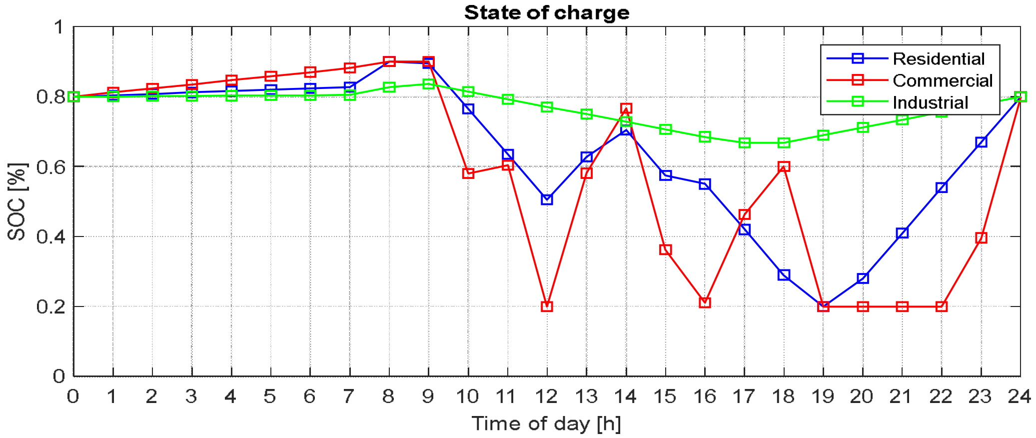

Figure 9: Collective State of Charge of EVs in Different Areas of Region

The Fig.10 and Fig.11 shows that EVs in each region are charging with maximum charging current and charging power when power is available (off-peak time) during the day, staying within their defined limits achieving accurate results.

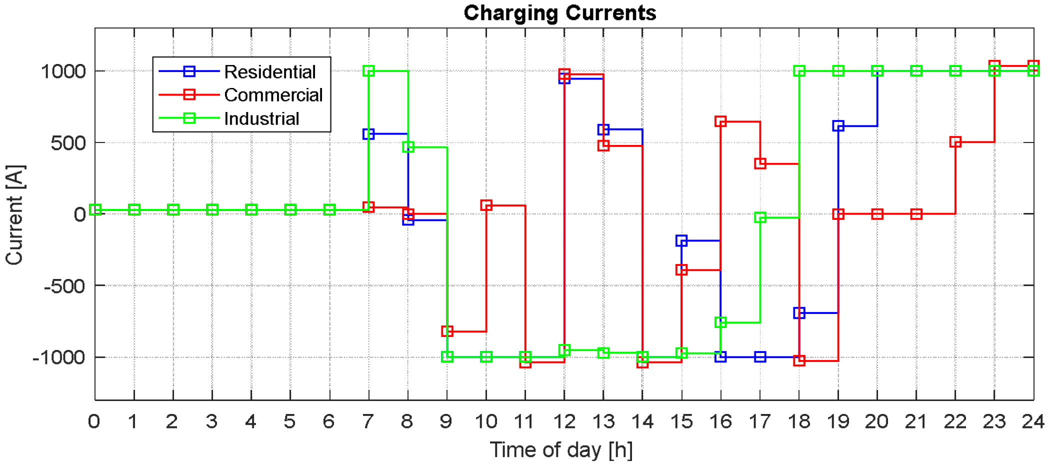

Figure 10: Collective Charging Currents in Different Areas of Region

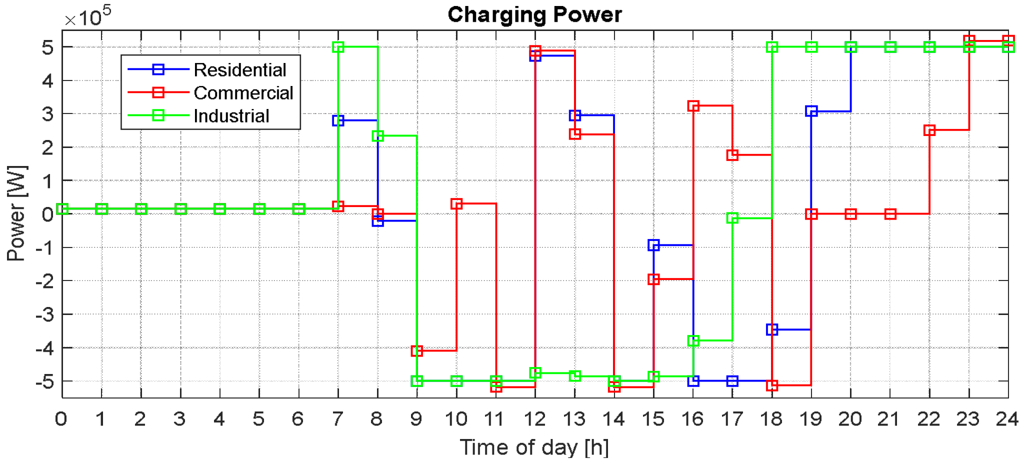

Figure 11: Collective Charging Powers of Different Areas in Region

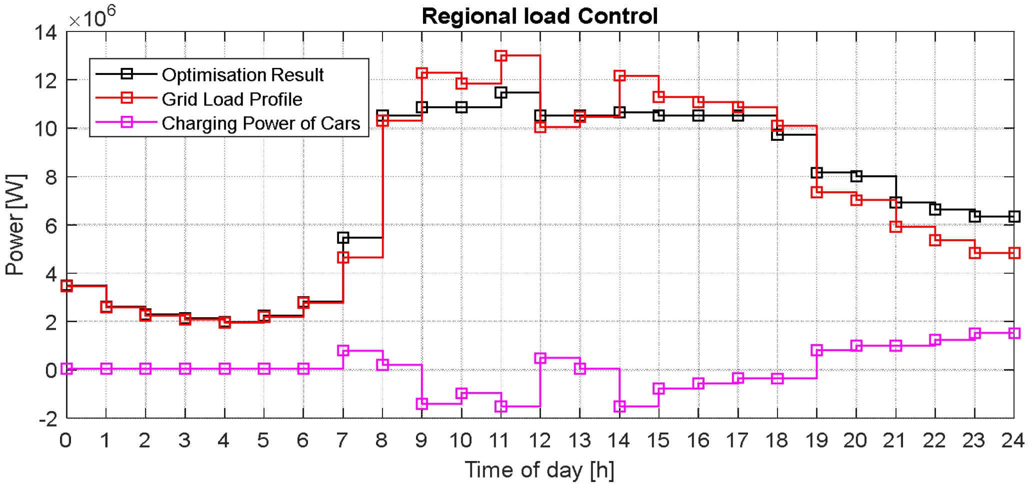

Figure 12: Optimization Results ofRegional Load Control

The above Fig.12 verifies results expected of regional load control optimization model formulated. EVs are charging during off-peak power demand hours of the day, between 19:00 – 07:00. Similarly, EV batteries are providing utilities with active power support for peak power shaving during high power demand hours, that is, between 09:00 - 19:00 hours. The results obtained from quadratic optimization achieve significant power reduction during peak times. It can be seen that peak power from 13 MW is reduced to approximately 11.5 MW with a reduction of almost 1.5 MW. The average power is approximately 7.33 MW after optimization and standard deviation of approximately 3.56 MW, as compared to standard deviation of 3.973 MW before optimization.

IV. CONCLUSION

In this article an approach to develop smart charging schedule based on optimization technique to minimize cost of charging for both, electric utilities and EV owners is developed. This will essentially level utility load throughout the day by providing power to charge EV batteries during off-peak hours, and, on the other hand, utilities will take power from EV batteries for peak power shaving during peak power demand hours of the day. The Quadratic Programing Optimization method adopted in this study is particularly to minimize cost of charging of EVs and also regional load control optimization w.r.t load profile is validated and presented through simulation results.

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