Overview of EV Charging Smart Control Architecture- Recent Developments

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Abstract— **Electric Vehicle Charging Infrastructure is an essential component in deployment of Electric Vehicles at large scale in the world. The Smart Control Architecture is the backbone for facilitating the EV charging/Battery swapping in real time environment. The massive usage of EV in transportation is only feasible once the charging infrastructure is structured/facilitated intelligently to provide seamless charging in the respective region with upcoming EV penetration. The massive integration of EVs charging point/bay in Distribution System may also result in an unacceptable performance at given point of time in case the power infeed to the charging infrastructure is not properly regulated depending on the vehicle penetration. The paper firstly reviews the concept for Smart Control Architecture for upcoming EV Charging points/bay in each distribution/sub-transmission system and also highlights the requirements of intelligent power control to the respective charging infrastructure for quality and quick charging in order to ensure regulated power control for distribution system sustainability and reliability.**

Keywords— Electric Vehicle (EV), Renewable Energy (RE), Energy Storage Units (ESU), Photovoltaic (PV) System, EV Charging Infrastructure (EVCI), Smart Control Architecture for EV (SCAEV), State of Charge (SoC), Energy Storage System (ESS)

I. Introduction

Globally, the transportation system is based on internal combustion-based engine driven by conventional fuels thus producing greenhouse gases (Carbon Dioxide, Nitrous Oxide, Methane and Fluorinated Gases) having adverse effect on health and environment. EV may be one of the acceptable options for reduced carbon footprint and least dependency on Diesel and Petrol. Electric Vehicle (EVs) may become future transportation system due to favorable regulations/incentives and technological advancements having Smart Control Architecture. EVs require huge electricity for battery charging/swapping industries. As indicated in [1], if EVs reach 30% of global vehicle market, the additional global electricity demand in 2030 will equal the electricity demand from 92 million U.S. homes (73% of U.S. homes). This is an indicator of higher power consumption. The unnoticeable pattern of EVs charging at given time frame may lead to major impacts on Grid, specially at distribution and sub-transmission systems which may be seen as unacceptable voltage and frequency at the point of connectivity, and also, harmonics injection in interface systems [2]. The varying pattern of charging may result as stress to transmission assets such as reduced life of transformers and the intermittent loading of distribution/sub-transmission network [3]. These impacts may be reduced to the minimum with adequate smart control architecture and a smart charging infrastructure that regulates the power injection pattern in respective stressed network as the EVs are coming to the charging points.

The Grid–to-Vehicle (G2V) and Vehicle–to-Grid (V2G) concept may be used for achieving acceptable EV charging infrastructure once the intelligent automation is incorporated with smart tracking of EVs on specific location along with SoC of battery. The EVs can be charged during the off-peak hours from Grid having cheapest intermittent renewable energy sources (like solar energy and wind energy), and in turn, may re-wheel electrical energy to Grid during peak hours in case of standstill condition of vehicle [4,5]. This may be only possible if the EV owner gets economic benefits by selling the electricity without purchasing any extra energy storage system. However, this concept requires a reliable communication corridor with IoT platform and associated smart distribution system architecture. Since this operation requires power re-wheeling corridor depending on the real time scenario, the Smart Control Architecture is only the option. An effective V2G infrastructure is required for feeding electricity to grid at point of common coupling through which power can be rerouted to loads in the network, else it be viewed as arbitrary power injection at interface bus of EV/cluster of EV, which in turn, may damage the EVs as well.

Vehicle to vehicle and vehicle to grid technology can be used for providing power to military-based system to reduce grid dependency in remote areas [6]. Due to lack of achieving real time data, day ahead scheduling based EV charging is reported in [7] for reducing the charging cost, battery degradation problem and providing voltage support to the grid. Demand side management (DSM) is also proposed for providing EV charging. By scheduling loads for minimizing peak demand of grid thus reducing voltage deviation and keep respective phase in balanced [8]. In literature, a modern technique such as wireless charging infrastructure has been reported to solve the problem of range and charging time of EV batteries in which real time EV batteries load demand and power supply is coordinated for reducing peak demand and grid overloading [9]. Other methods are also proposed for achieving grid stability, voltage, and frequency within IEGC limits [14,18,26]. Till now there is no unified methodology for EV charging infrastructure development depending on vehicle penetration rate without affecting grid parameters and provide seamless supply for EV batteries with minimum recharge time. For achieving this, a homogeneous coordination will be required between EV loading pattern in distribution network and sub-transmission system.

In this paper, a smart control architecture for EV charging infrastructure is proposed as shown in Fig.1, in which power support is provided by smart power generation such as renewable energy sources, pumped water storage, gas-based turbine plant etc. for maintaining voltage well within limit, thus reducing overloading on grid assets and reducing peak demand on grid. With this concept, the proper coordination will be maintained between power delivered by distribution substation and load requirement of EV batteries and others loads using an intelligent control architecture based on Internet of Things (IOT) with fast communication. The information such as number of EVs connected, SoC of EV batteries cluster, total load on bus, total generation by solar energy and power supplied by grid etc. will be communicated in each sub-module such as EV aggregators, distribution grid, solar power system and control system for maintaining balance between power supply and demand for effective coordinated control.

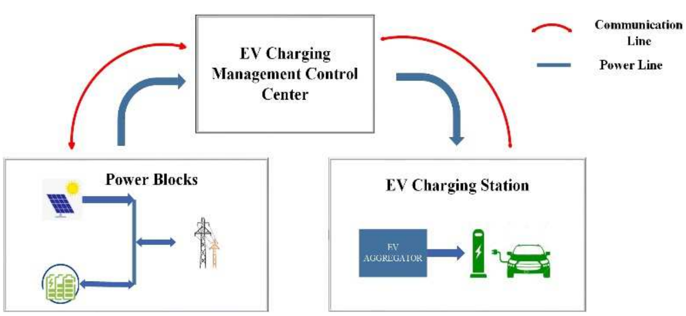

Fig. 1. The block diagram of smart control architecture for EV charging infrastructure

The block diagram shown in Fig. 1 consists of different parts as power block, EV charging management control center, EV charging infrastructure and communication technologies for providing proper coordination. This paper has been organized in seven sections. Section II presents the power block. The EV management control center is discussed in part III in which control methods and literature reviews of newly developed control techniques for smart EV charging is reported. Section IV presents the communication technologies for information flow among various power blocks, EV charging infrastructure and control center. The role of EV aggregator in EV charging infrastructure is discussed in section V. The part VI presents the concept of research work based on the review of literature and ground level requirements for achieving a smart EV charging infrastructure. The conclusion is discussed in last part VII.

II. Power Blocks

These blocks are used to provide electricity to battery charging of EV which consists of many power sources such as renewable energy sources (RES), energy storage units and grid depending on EV integration to grid. EVs can be supplied by local power sources and also by grid. The EV charging station is classified as grid connected and isolated EV charging station [10,11]. Based on the power flow, charging infrastructure has been classified as unidirectional and bidirectional [12]. The bidirectional EV charging infrastructure provides G2V and V2G modes. The renewable energy sources are used such as solar energy, wind energy and biomass etc. Most of time, solar energy is preferred due to modular installation feature. In [13,14] PV array has been operated in maximum power delivering condition whereas energy storage units (ESU) are charged in off peak time and also EVs are parked, and they used at peak time for reducing overloading of grid and maintain grid stability. Nowadays distributed energy resources are used for EV charging infrastructure to reduce grid dependency so that power grid operates in within limits.

III. Control infrastructure

The control and communication system are backbone for providing real time coordination between power blocks and EV charging infrastructure. When large number of EVs are connected at a given distribution system, it affects the voltage and frequency, which in turn impacts stability of nearest substation energizing the respective distribution system, and thus, grid is also affected to overcome these impacts. Hence, it is necessary to establish an EV charging infrastructure which is ready to charge battery at any point of time and maintain overall grid stability. For this purpose, a novel EV charging management center (EVCMC) is conceptualized which is based on different signaling/data processing along with control. The effective coordination can be achieved among distribution systems and cluster of EVs by updating/modifying the capacity of distribution substation based on data-analytics and real-time signal processing, thus initiating real time control action for quality volage regulation in given time frame of interest. The modification of capacity of distribution system such as: distribution lines, transformer and other equipment's is a static type of control which is possible by estimating the EV charging load demand. The real time signal processing is dynamic type of control which is taken at any instant of time for adequate control of grid voltage and frequency.

1. *Control Architecture*

The control center of smart EV charging infrastructure provides adequate control to power blocks, EV charging infrastructure. So proper control structure is required which can be categorized based on charging coordination and control structure as shown in Fig. 2 [12].

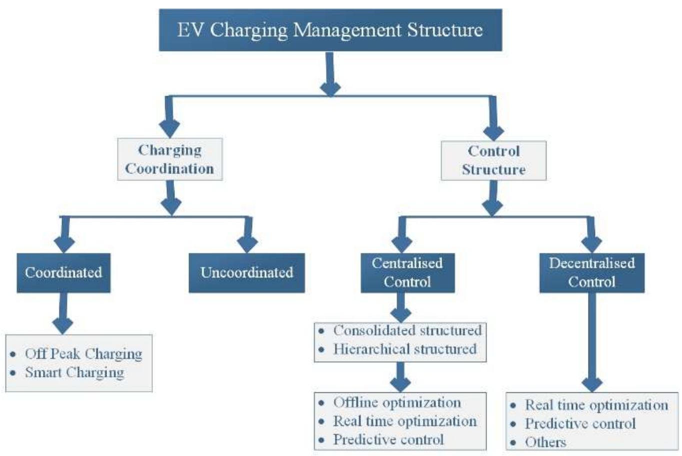

Fig. 2. Classification of control strategies used in EV charging infrastructure

A. Charging Coordination

The EV charging management can be done based on charging coordination. There are two types of charging as uncoordinated and coordinated charging. As name suggest, the uncoordinated charging charge EV batteries immediately after plugging in or taking some preset delay. It is conventional type of charging which charge EV batteries at any time without considering peak or off-peak period which in turn may increase load on grid [15]. Whereas in the coordinated charging a proper scheduling is done to charge EV batteries in off peak hours so does not affect grid parameters. A proper coordination between EVs loading pattern and power generation can be done in real time or day ahead scheduling [16].

B. Control structure strategies

To provide power to EV charging, the architecture of control system is categorized as centralized control and decentralized control. In centralized control structure, all the EV charging information is sent to central controller through EV aggregator which process the data and provide optimum solution for charging the batteries such as charging time, waiting time and allocation of EV bay etc. considering grid and EV user constraint. Normally hierarchical structure is preferred due to adequate control action in specific zone. The main limitation of this method is to find optimum solution of big size problem [17,18]. Decentralized control or distributed charging structure provides EV charging based on user convinces such as user decide own charging time with low-cost tariff. Using real time data, EV user can sell extra energy while EV is not used so this method benefits more user and also grid. This method also reduces the problem to solve big size optimization problem. But the main limitation of this method has been as there is no guarantee to achieve global optimum solution [12,18,19].

***2.** Literature review of control strategies for smart EV charging infrastructure*

To maintain equilibrium between power supply and load demand, different control strategies are proposed such as scheduling, clustering, and forecasting [20,21]. The scheduling strategy as name suggest, schedules the EV charging based on centralized and decentralized control structure for reducing the overall charging cost and burden on grid. Clustering is used to analyze the load profile of EV charging of a cluster. In this technique, groups are made of same pattern load which is known as clusters. The forecasting help to sustain equilibrium between power supply and demand by studying past usage and demand. In this way, this not only finds the load demand based on the data analytics for future charging pattern generation with cluster at different distribution/sub-transmission system but also helps to upgrade the entire eco-system for the grid stabilization and the least cost incurred with charging infrastructure for sustainable business model.

Some modern control methods have been developed for smart EV charging infrastructure to maintain grid parameters within limits. Haung, et al [22] proposed an energy sharing controller for the distributed battery energy storage system architecture in which a small power rating dc-dc converter was connected across each cell which maintains cell voltage and thus dc bus voltage has been maintained. The main advantage of this architecture has been in the form of no additional dc bus voltage controller. Thus, reducing the complexity of circuit and operation. In [23] a multi-layer algorithm is applied for optimal power flow management of microgrid which consists of PV power, energy storage system (ESS), grid and vehicle to grid technology. In this ESS is coordinated effectively with each power sources for optimum power flow which in turn reduces the cost and it's impacts on grid.

Hariri, et al [24] reported a decentralized multi agent system (MAS) which consist of three layers: EV agent, EV park agent and Higher-level agent. The layers relate to internet of things (IoT) for transferring information at each level and a suitable park for charging was allocated by using fuzzy logic controller. In [25], a modern fuzzy logic controller has proposed for EV charging by varying the base load pattern timing for distributed, fast and battery swapping infrastructure. MAS architecture has been proposed to assist in decision making for EV owners with charging or discharging information is gathered from EV aggregator. An optimization model has been proposed for EV coordination and V2G resources which reduce the cost of electricity for EV owner [26].

Cheng, Qifu, et al [27] reported a smart charging algorithm (SCA) to maximize the output power of PV system and high utilization of grid interlinked converter (GICs) in dc fast charging station without use of energy storage system. SCA contains two algorithms: one is self-regulated algorithm for EVs and another grid-regulated algorithm (GRA) for highly used GICs. In [28], the optimal position of charging infrastructure and scheduling of EV charging has been done using branch and bound algorithm in mobile EV charging infrastructure.

Savari, George F., et al [29] presented an IOT based smart EV charging infrastructure. The charging of EV is controlled by real-time online scheduling scheme for reducing the waiting time and quick charging. All the charging station is interlinked and provides the real-time status for users. The charging station location and reserve for charging is provided based on SoC of the battery with the aim provide fast charging, reduce the charging cost and secure infrastructure. In [30] a Multitask Learning (MTL) method is proposed to forecast EV charging load demand in IOT enabled EV charging station.

Shiyuan Xu, et al [31] propose a blockchain based EV charging infrastructure for connected EVs and also designed a secure system for EVs and EV service providers (EVSP). Blockchain is a new technology that provide distributed, secure and decentralized environment to perform transactions by which it is best suited for smart EV charging infrastructure [32]. The blockchain based system works in three phases as registration, scheduling and charge payment. In first phase, EV and EVSP submit a registration application to distributed public key infrastructure using hash value of their identity and provide a digital certificate. In charge scheduling phase, sends the scheduling request to EVSP and verify smart contracts, then receive three tokens separately for scheduling, charging and payments respectively and protect the actual EV user information. Zero-knowledge proof and ring-signature superposition methods are used to verify smart contracts. In last payment phase, EV user receives payment token and pay using the virtual currency and signed that.

Yu WU et al. [33] proposed a real time energy management scheme for DC EV charging infrastructure which considered renewable energy, local grid, and ESS. In this paper, the consumption of renewable energy is maximized in large extent for EV charging using convex optimization problem so that local grid doesn't affect. The ESS is charged with surplus renewable energy and low-price electricity from local grid which benefits more in peak time. In last, we can say that hierarchical method and real time controlling methods like as MAS, IoT and blockchain based methods are best suitable to achieve smart EV Charging infrastructure.

IV. COMMUNICATION SYSTEM

The mobile EVs can reach at any EV charging station for charging, so proper communication infrastructure is essential for management of EV charging process to achieve grid sustainability. In literature different communication technologies are proposed to enable communication between EV and charging station to exchange the information's such as SoC status of battery, location of EV, scheduling of battery, waiting time and finds optimal routes. Nowadays, dedicated short range communication (DSRC) and cellular network have been developed for providing vehicle to everything (V2X) communication which is used by Honda, Nissan and Toyota [34]. Some communication technologies are listed below which may be used according to requirements [35].

The IEC 61850 and ISO/IEC 15118 standards are used for providing direct wired communication between EV and EV charging station [36,37].

TABLE I. COMMUNICATION TECHNOLOGIES USED IN EV CHARGING INFRASTRUCTURE

Types	Frequency Range	Reach	Data Rate	Applications
Satellite Network	1-40 GHz	Extreme Large	Up to 1000 Gbps	Aggregator (AG) rural – Smart Grid (SG)/Inter- AG
Broadband PLC	1.8-100 MHz	Up to 150km	Up to 200 Mbps	Intra-AG/ Home
Narrowband PLC	3-500 kHz	Up to 150km	Up to 500 kbps	Inter- AG
Ultra-Narrowband PLC	≤ 3 kHz	Up to 150km	100 bps	AG (urban)- SG
DSRC	5.850-5.925 GHz	10-100 m	3-27 Mbps	Inter EV/AG-EV
5G (Cellular)	24-100 GHz	500 m/cell	Up to 50 Gbps	AG-SG/ Inter-AG/ AG-EVs
WIFI	2.4 GHz, 5 GHz	46 m (indoor) - 92 m (outdoor)	54 Gbps	Intra- AG/ home communication
ZigBee	865 MHz, 915 MHz, 2.4 GHz	10-100 m	20-250 kbps	In AG and home communication

V. EV CHARGING STATION

A charging station consists of the right of way (ROW) for EV charging and EV aggregator. The EV aggregator contains all the information of EV as number of EV plug in for charging, power required by EV loads, time of charging, SoC of charging, electricity price and information of charging system locations etc. It provides interface between EVs and grid [38]. All information is transferred to control system for initiating control action well within time by respective power blocks so that voltage violation of grid, overloading of grid assets doesn't occur.

Role of EV aggregator in smart EV charging

EV aggregators are a mediator between the grid and EVs which coordinates distributed generation and responsive loads for improving grid flexibility. It benefits both the power system operators and EV owners by purchasing low-cost electricity from grid in off-peak hours and store power in EV battery and earn money by selling electricity at peak time once price is high [39,40]. It works like as central coordinator to maintain battery SoC level of EVs in a particular area. The main challenges of EV aggregator are to maintain SoC level of EVs, variation in electricity price, reserve requirements etc. with satisfying the grid stability and EV load requirements [41]. The role of EV aggregators is described in Fig. 3 [42].

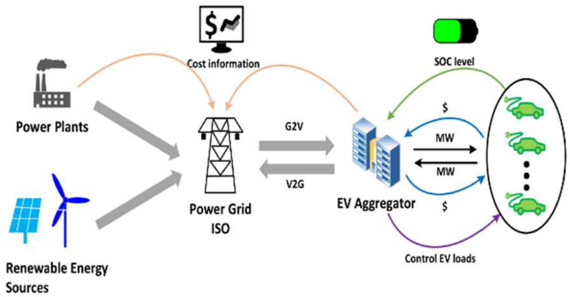

Fig. 3. The role of EV aggregator in EV charging infrastructure

EV aggregator will not only open new gateway of cheap electricity but also encourage the battery swapping industries and EV battery charging time minimization and least cost usage of renewable power at large and making the entire world free from GHG emission and reduced carbon footprint.

VI. FUTURE TRENDS

Due to limitation of high charging time, a far installed EV charging station, negative impacts of grid, high charging cost, EVs are not being used at larger scale. To overcome these drawbacks, digital advancement technology usage such as IoT, data analytics and multi-agent architecture for decision making in EV charging infrastructure can become an open area of research and associated industrial development. Also, for EV business model and more investment in EV sector some of the points are brought on record for researchers and industries:

- The optimal locations and size of charging station, fast and ultra-fast charging station increase interest of consumers to use EV in future such as petrol pumps are installed at appropriate location so there is no difficulty of fuelling vehicles.
- For reducing harmonics injection into grid many modern converters may be used in EV charging infrastructure such as multiport DC-DC converter which reduces requirement of extra DC-DC converter and thus improves overall efficiency of converter in comparison of more than one DC-DC converter.
- The adaptation of renewable energy sources like solar energy, wind energy and biomass energy etc. in charging infrastructure will have the reduced burden on grid assets, reduced emission, reduced cost of charging and may maintain parameters of grid effectively due to IoT platform in decentralised nature.
- By deployment of smart control techniques having intelligent control based on IoT and optimization algorithm, the coordination between EV load demand and power supply may be acceptable which may result in the effective grid operation.
- For economic benefits of the EV consumers, EVs are used as energy storage device at parking and standing time and using grid to vehicle (G2V) technology, the electricity may be transferred to grid at peak time. Thus, G2V technology helps not only EV consumers but also grid by maintaining voltage and frequency in unified way.
- For reducing the grid dependency for EV, a new technology of special Solar Electric Vehicle is upcoming in which high-capacity new technology driven solar panel is installed on rooftop/body of EV itself, so that EV is charged by solar energy when they are parked or in drive.

VII. CONCLUSION

With the advancement in EV charging infrastructure, the EVs may be popular in next decade for reducing carbon emission and ready to ensure clean and green environment. This paper reviews in depth the evolving EV charging station concept, smart control architecture for EV charging infrastructure with advance control techniques and suggests some of the future research directions for the deployment of EV charging infrastructure for policy decision makers. The concept proposed helps to decide an intelligent control architecture for effective quality power supply and low-cost smart charging architecture development along with sustainable Grid.

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