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TOPICAL REVIEW

Smart Charging: A Comprehensive Review

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ABSTRACT Large scale adoption and public acceptance of Electric Vehicles (EVs) require availability of charging stations. Electrification of transport has been identified as the one of the significant factors that would increase the power demand. Management of charger load has become a matter of concern for the power system engineers. Uncoordinated charging can be detrimental to the smooth operation of the power grid. On the contrary, smart charging gives certain amount of control over the charging process with respect to the power grid. Hence, adaptivity of the charging process of EVs in smart charging assists to meet the needs of power system as well as EV users. A smart charger can adjust the charging power according to the power available from the grid, EV user needs, and also support the grid during emergency. Smart charging enables EVs to act as flexible grid resources thereby providing ancillary services to the grid in case of emergency. Further, EV users can gain significant financial benefits through smart timing of their charging against spot market prices. This work presents a comprehensive overview of smart charging thereby explaining its perception, impact, user acceptance, global status and pilot projects. Also, case studies highlighting the benefits of smart charging are presented. This detailed elucidation of smart charging will assist the researchers, and experts of power industry as well as transport to find research initiatives on smart charging at one platform thereby promoting adoption of smart charging.

INDEX TERMS Charging, electric vehicle, prediction, review, smart charging.

ABBREVIATIONS

AI-	Artificial Intelligence.
AENS-	Average Energy Not Served.
ANFIS-	Adaptive Neuro Fuzzy Inference System.
BEV-	Battery Electric Vehicle.
CAIDI-	Customer Average Interruption Duration Index.
CCS-	Combined Charging System.
CPO-	Charging Point Operator.
DAM-	Day Ahead Market.
DAC-	Dual Active Bridge.
DSO-	Distribution System Operator.
EB-	Electric Bus.
EPBC-EV-to-EV	Portable Battery Charger.
EPRI-	Electric Power Research Institute.
EMSP-E	mobility service provider.
EV-	Electric Vehicle.
EVCS-	Electric Vehicle Charging Station.
ERDF-	European Regional Development Fund.
HMM-	Hidden Markov Model.
IoT-	Internet of Things.
LOLE-	Loss of Load Expectation.
MITM-	Man-In-The- Middle Attacks.
NHTS-	National Household Travel Survey.
MSE-	Mean Square Error.
OCPP-	Open Charge Point Protocol.
PHEV-	Plugged In Hybrid Electric Vehicle.
RMSE-	Root Mean Square Error.

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SAIDI- System Average Interruption Duration Index.
SAIFI- System Average Interruption Frequency Index.
SoC- State of Charge.
SVM- Support Vector Machine.
TLBO- Teaching Learning Based Optimization.
VGI- Vehicle Grid Integration.
VRP- Voltage Stability, Reliability, Power loss.
V2B- Vehicle to Building.
V2G- Vehicle to Grid.
V2X- Vehicle to Everything.
V2H- Vehicle to Home.
WPA- Wolf Pack Algorithm.

I. INTRODUCTION

Transportation electrification is a viable alternative to deal with ever growing energy demand, air pollution, and global warming. Electrification of road transport has been identified as the one of the significant factors leading to increase in power demand. Uncoordinated charging is detrimental to power grid resulting in voltage instability, harmonic distortions, power losses, overloading, and degradation of grid reliability indices. For example, in ref [1] authors investigated how introducing EV charging load affects voltage stability, power losses, and reliability of the grid and found that fast chargers are detrimental to the smooth operation of 33 bus distribution network. In ref [2], the impact of fast EV chargers on the grid of a Latin American city is investigated. In ref [3], authors comprehensively reported how EV charging impacts grid operating parameters such as voltage stability, harmonics, power losses, reliability. In ref [4], the impact of EV charging induced harmonics on a real time demonstration of Los Angeles is reported. In ref [5], the impact of EV charging on distribution network reliability indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI) etc is investigated quantitatively. In ref [6], authors solved the distribution network planning problem in presence of EV charging load thereby considering the security of the power grid. In ref [7], authors comprehensively reviewed the charging standards and the impact of EV charging on different power distribution networks. In ref [8], authors presented a pre-normative charging technology roadmap for heavy-duty vehicles with a focus on Europe. In ref [9], authors meticulously reviewed EV charging infrastructures and their impacts on power-quality of the utility grid. In ref [10], authors presented long-term electric vehicles outlook and their potential impact on electric grid. In ref [11], authors reported data for heuristic optimization of EV charging based on loading parameters. Smart charging is an effective means to manage grid loads from charging of EVs. Smart charger can adjust and manage the charging power according to the power available from the grid, EV user needs, and also support the grid during emergency [12]. Smart charging enables sufficient degree of control over the charging process. Adaptivity and control over the charging process of EVs in smart charging helps to meet the needs of power system as well as EV users. Further, smart charging assists EVs to become flexible grid resources and provide ancillary services to the grid in case of emergency. Also, the penetration of renewable energy is increasing and the electricity generation, transmission, distribution sector is experiencing a paradigm shift. The flexibility needs of the grid are increasing with increasing penetration of variable renewable energy. From the EV users perspective, smart charging can offer significant financial benefits through smart timing of their charging against spot market prices. This detailed review of smart charging will help the researchers, and experts of power industry as well as transport to find research efforts on smart charging at one platform and in turn will help in adoption of smart charging. The contributions of this work as compared to the review works reported in Table 1 are:

- Detailed elucidation of smart charging thereby explaining different strategies for smart charging and their comparison
- Review of perception, user acceptance, global status of smart charging
- Review of use of AI and blockchain for smart charging
- Review of globally executed pilot projects on smart charging
- Case studies illustrating the effectiveness and benefits of smart charging

The remainder of the paper is organized as follows. Section II gives a detailed overview of smart charging thereby providing a comparison of different smart charging strategies. Section III presents the impact of smart charging through elaborating some of the benefits of smart charging. Section IV presents an overview of charging demand prediction. Section V presents the smart charging pilot projects. Section VI presents smart pricing strategies. Section VII reports perceptions regarding smart charging whereas Section VIII discusses the role of artificial intelligence and blockchain in smart charging. Section IX deals with charging solutions for emergencies. Section X reports the case studies. Finally, Section XI concludes the work.

II. OVERVIEW OF SMART CHARGING

Uncoordinated charging can be detrimental to the smooth operation of the power grid as shown in Table 2. Smart charging gives certain amount of control over the charging process. Adaptivity of the charging process of EVs in smart charging assists to meet the needs of power system as well as EV users. Different types of smart charging strategies are elaborated in Table 3. As depicted in Table 3, there are a variety of smart charging strategies such as ON/OFF control, V1G, V2G, V2B etc. It has been observed that the maturity and acceptance of ON/OFF control, V1G is high and V2G, and V2B is medium.

III. IMPACT OF SMART CHARGING

The impact of smart charging on power grid is elaborated in this section. As depicted in Table 3, smart charging

TABLE 1. Existing reviews on smart charging.

Ref	Year	Diligence
[12]	2014	Review of smart charging architectures such as centralized and decentralized control
[13]	2015	Review of the impact of different smart charging strategies on power distribution network
[14]	2013	Optimization and control method for smart charging of EVs
[15]	2020	Review of smart charging strategies in presence of photovoltaic power
[16]	2020	Review of carbon efficient smart charging using forecasts of marginal emission factors
[17]	2019	Review and expert survey on technical potentials and user acceptance of smart charging
[18]	2017	Review of modelling and implications for smart charging services.
[19]	2019	Review of global smart charging practices
[20]	2020	Review of consumer perception on smart charging
[21]	2017	Review of smart charging practices in Netherland
[22]	2020	Review of smart charging and discharging strategies
[23]	2021	Review of cybersecurity of electric vehicle smart charging management systems
[24]	2021	Review of smart electric vehicle charging strategies for sectoral coupling in a city energy system
[25]	2021	Review of intelligent charging and discharging control and application of EVs
[26]	2022	Review and quantification of the benefits of EV managed charging

TABLE 2. EV usage scenarios in different countries and possible impact of uncoordinated charging and coordinated smart charging [1], [2], [3], [4].

Scenario	Parameter	Impact	
		Uncoordinated charging	Smart charging
10 million EVs in UK by 2035	Peak load	Increase in evening peak load by 3 GW	Increase in evening peak load by 0.5 GW
25% share of EVs in New England	Peak load	Increase in peak demand by 19%	Increase in peak demand by 0 to 6% by delaying the charging activities to evening
5% EV market penetration in USA	Transformer overloading	4% of distribution transformers overloaded	No transformer overloading
10 million EVs by 2035 in Germany	Grid upgradation cost	50% increase in low voltage grid and transformer costs	No grid upgradation cost
5 charging stations placed at 33 bus distribution network	Reliability indices	Increase in SAIDI by 44%	Negligible increase in SAIDI

strategies have several benefits such as peak shaving, congestion management, frequency regulation, voltage profile improvement etc. The research initiatives quantifying the impact of smart charging are reported in Table 4. In [28], a fuzzy logic controller was proposed to control smart

TABLE 3. Types of smart charging [27].

Type	Control Strategy	Uses
Uncontrolled with TOU tariff	None	Peak shaving with implicit demand response; long-term grid capacity management
Basis Control	ON/OFF	Congestion management of grid
Unidirectional V1G	Increase and decrease of real time charging rate	Ancillary services and frequency regulation
Bidirectional V2G	Instant reaction to grid conditions with the provision of returning power back to the grid; requires hardware adjustments to most vehicles and EVSE	Ancillary services, frequency regulation, voltage regulation, load following, reliability improvement, short term integration of renewable energy
Bidirectional V2X (V2H, V2B)	Integration between V2G and home/building management systems	Microgrid optimization

charging and it was observed that by smart charging, maximum power and transformer overloading was reduced by 20% as compared to uncontrolled charging. Also, by applying a smart charging strategy, reduction of cable maximum loading by more than 10% as compared to uncontrolled charging was achieved. In [29], a convex optimization model for smart charging was proposed that reduced networks requiring intervention from 28% to 9 %. In [30], a water filling based smart charging strategy was proposed that reduced the monthly demand charges by 20 to 35% for 30% EV penetration. In [31], an optimal charging strategy integrated with utility demand response program was proposed that reduced the transformer ageing by 80%. In [32], centralized and decentralized smart charging strategies were compared. It was found that decentralized approaches provide the same CO_2 emissions benefits and within 2% of the NO_x emissions benefits achieved with centralized approaches, but only if the frequency of communication between vehicles and the electric grid is sufficiently high (less than 60 min). In [33], it was reported that with 100 % EV penetration scenario in Norway, Denmark, Germany and Sweden and V2G, 7% reduction in peak load can be achieved. In [34], it was reported that with 1 million EVs in Guangzhou, China and smart charging 43% to 50% reduction in peak load can be achieved. In [35], it was observed that with smart charging strategies, reliability indices such as LOLE and AENS improved considerably.

IV. CHARGING DEMAND PREDICTION

The shift towards EVs will increase the load demand of the power grid as the EVs need to be charged after travelling certain distance depending on their driving range. Thus, accurate prediction of the charging load is essential in order to save the power grid from becoming overloaded. This section puts forward a systematic review of charging demand prediction of EVs. In recent years, accurate prediction and forecasting

TABLE 4. Impact of smart charging.

Ref	Year	Diligence	Impact
[28]	2019	Fuzzy logic controller for smart charging	Reduction of maximum power demand by 20% as compared to uncontrolled charging Reduction of transformer overloading during the day by 20% as compared to uncontrolled charging Reduction of cable maximum loading by more than 10% as compared to uncontrolled charging
[29]	2020	Convex optimization-based model for smart charging	Reduction of networks requiring intervention from 28% to 9 %
[30]	2017	Water filling based smart charging strategy	Reduction in monthly demand charges by 25 % to 30 % for 30% EV penetration
[31]	2016	Optimal charging strategy integrated with utility demand response program	Reduction of transformer ageing by 80%
[32]	2018	Comparison of centralized and decentralized grid interactive smart charging strategy	Better emission reduction is achieved by centralized smart charging strategy
[33]	2017	Modelling of EVs as flexible load	With 100 % EV penetration scenario in Norway, Denmark, Germany and Sweden and V2G 7% reduction in peak load can be achieved
[34]	2018	Modelling of charging aggregator for smart charging	With 1 million EVs in Guangzhou, China and smart charging 43% to 50% reduction in peak load can be achieved
[35]	2019	Reliability improvement of power distribution network by using EVs as demand response resources	Improvement in Loss of Load Expectation (LOLE) by 22.15% to 27. 42% Improvement in Expected Energy Not Served (EENS) by 18.07% to 18. 20%

TABLE 5. Review of research works on charging demand prediction.

Ref	Year	Vehicle Category	Methodology	Test network
[36]	2017	Private EV	Wavelet decomposition	Urban area of Sri Lanka
[37]	2017	Private EV	Markov Chain and graph theory	Seoul, South Korea
[38]	2021	Private EV	Gradient Boosting, SVM	Nebraska, USA
[39]	2019	Private EV	Probabilistic approach based on normal distribution	Copenhagen, Denmark
[40]	2021	Private EV	Data driven two-layer approach and neural network	Guangzhou, China
[41]	2020	Taxi, e bus, official EVs	Monte Carlo	Shenzhen, China
[42]	2017	Private EVs	Monte Carlo and HMM	IEEE 53 bus system
[43]	2017	Private EVs	Queuing theory and Monte Carlo	33 node road network
[44]	2018	Private EVs	TLBO and ANFIS	Experimental data from the Prognostics Center of Excellence at NASA
[45]	2018	E bus	SVM and WPA	Baoding, China
[46]	2019	Private EVs	Fuzzy logic and Monte Carlo	NHTS dataset
[47]	2020	Private EVs	Reinforcement Learning	Generated dataset considering different EV penetration rate
[48]	2018	E bus	Markov Model	Schenzen, China
[49]	2017	E taxi	Monte Carlo	Ideal city with E taxi

of EV charging load has received a lot of research focus. Table 5 presents a systematic review of research works on this arena. In [36], a wavelet decomposition-based approach was used charging demand prediction of central road that is an urban area of Sri Lanka. In [37], a Markov chain and graph theory-based approach was used for predicting the charging demand of private EVs operating in Seoul, South Korea. In [38], authors have used different machine learning techniques such as Gradient Boosting, Support Vector Machine (SVM) for charging demand prediction of Nebraska, USA. Further, the performance of Gradient Boosting and SVM on charging demand prediction was compared based on Mean square error (MSE) and Root Mean square error (RMSE). In [39], a probabilistic approach based on normal distribution was used for charging demand prediction of Copenhagen, Denmark. In [40], a two-layer data driven approach and neural network was used for predicting the charging demand of Guangzhou, China. In [41], the authors have used Monte

TABLE 6. Globally executed pilot projects on smart charging [21], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59].

Project Name	Location	Start year	Type	Project Summary
Avista Utilities	Washington state	2016	V1G	Project focused on determination of how much PEV load can be shifted from peak load times to off-peak times without using TOU rates.
BMW icharge Forward	San Francisco Bay Area	2015	V1G	Project tested the value proposition of residential V1G business models to the utility, the aggregator, and the PEV owner.
V2G Pilot Project	Hong Kong	2011	V2G	Small scale proof of concept trial in Hong Kong
Jeju Smart grid project	South Korea	2009	V1G	First smart grid test-beds globally to test commercialization of smart grid technology incorporating V1G scheme
Toyota Tsuho Pilot Project	Japan	2018	V2G	First government funded V2G trial of Japan
Yokohama City Pilot Project	Japan	2010	V1G	Provided 2000 EVs and their charging infrastructure. Also focussed on smart charging
Ella V2G	Belgium	2018	V1G/V2G	Belgium project to evaluate the potential of V2G and V1G to provide frequency response services to TSO Ella
Parker Project	Denmark	2016	V2G	Danish demonstration project to validate that series-produced electric vehicle as part of an operational vehicle fleet can support the power grid by becoming a vertically integrated resource, providing seamless support to the power grid.
ACES Project	Denmark	2017	V2G	Danish project to evaluate the techno-economic benefits of V2G
Suvilahti Project	Finland	2017	V2G	Finland's first two-way public charger in connection with a solar plant and electrical storage facility
Grid Motion	France	2017	V1G/V2G	Privately funded demonstration of France to analyze V1G and V2G targeting frequency response
Redispatch V2G	Germany	2018	V2G	German trial with 10 EVs having both uni- and bi-directional capability. Project investigated dispatchability of EVs to manage network constraints, reduce curtailment, and reduce upgrades.
INEES	Germany	2012	V2G	German lighthouse project that demonstrated the real world technical feasibility of V2G through the use of 20 SMA bi-directional inverters and modified Volkswagen UP vehicles.
Genoa Project	Italy	2017	V1G/V2G	Two car trial testing V1G and awaiting definition of regulatory framework for V2G in Italy
SEEV4City	Netherlands, Norway, UK, Belgium	2016	V2G	North European trial delivering 5 projects in 4 countries namely Netherland, Norway, UK, and Belgium. The 5 pilots include: • Loughborough Living Lab • Amsterdam Arena with upto 200 unidirectional and bidirectional connected EVs as a part of the smart energy system • City depot of Kortrijk with single Nissan LEAF van providing V2B with onsite solar • Leicester City Hall investigating Vehicle to business trial with four vehicle • Vulkan Real Estate Building Oslo investigating innovative EV parking garage seeking to deploy V2G in next phase
Smart Solar Charging	Netherland	2015	V2G	V2G project with 22 chargers installed as part of city-car share scheme and solar in Lombok. Now seeking to scale up to 1000 chargers across region of Utrecht.
New Motion V2G	Netherland	2016	V2G	First V2G project in Netherland to provide frequency response services to TSO TenneT with chargers installed at homes, offices, and public locations.
Hitachi, Mitsubishi and Engie Project	Netherland	2018	V2G	One V2G charger installed at Engie office in order to increase self consumption of on-site generation from solar PV
Amsterdam V2G Project	Netherland	2017	V2G	Solar and V2G combination to store and supply electricity. Energy buffer solutions and societal issues are explored in this project
Grow Smarter	Spain	2015	V2G	6 V2G chargers installed at Endesa facility and used for Time shift, Power balancing and Power quality support
Zem2All	Spain	2012	V2G	Largest real world V2G trial in world, forming part of wider e-mobility trial in Malaga
Nissan Enel UK Project	UK	2016	V2G	Large-scale trial proposed in UK by Enel and Nissan seeking to connect one hundred V2G units

TABLE 6. ***(Continued.)*** **Globally executed pilot projects on smart charging [21], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59].**

The Network Impact of Grid-Integrated Vehicles Project	UK	2018	V2G	Distribution Network Operator run project to understand the negative and positive impacts of V2G-enabled EVs on the distribution network
ITHECA	UK	2015	V2G	Micro-grid demonstration project at Aston University which installed UK's first ever V2G charger
EFES	UK	2013	V2G	Cenex led project developing V2G technology and software for residential and commercial applications
Integrated Transport and Smart Energy Solutions (ITSES)	UK	2015	V2G	Projects sets out to find new technical solutions and business models for integrating V2G with two urban systems: energy and transport
IREO	Canada	2012	V2G	Technology demonstration of bi-directional power flow for an assembled electric test vehicle and charging station
Powerstream Pilot	Canada	2013	V2G	Small scale, microgrid proof-of-concept trial incorporating V2G in phase 2
NYSERDA	USA	2016	V2G	6 Nissan LEAF vehicles used to provide V2G services on the CUNY Queens College campus
BlueBird School Bus V2G Project	USA	2017	V2G	8 Bluebird electric school buses deployed at the Rialto Unified School District providing ancillary services and energy management services
US Air Force Project	USA	2012	V2G	Small-scale V2G pilot completed by the US Department of Defense
KIA Motors, Hyundai Technical Center Project	USA	2016	V2G	UC Irvine partnered with KIA/Hyundai to demonstrate V2G control software, understand charging behaviour and assess impact on the grid
US DoD – Fort Carson	USA	2013	V2G	V2G grid services demonstration was performed at Fort Carson. This was part of the three-phase SPIDERS programme that sought to demonstrate the practicality and benefits of creating secure microgrid architecture
Grid on Wheels	USA	2012	V2G	First, real world field test of V2G technology with 15 vehicles providing frequency response services over two year period and variety of driving patterns
Fiat-Chrysler V2G	USA	2009	V2G	Large scale demonstration having 140 PHEVs, a portion of which were fitted with bi-directional charging capability, to test V2H and V2G capability
Clinton Global Initiative School Bus Demo	USA	2014	V2G	Project seeking to improve economic viability of electric school buses through V2G and V2B trials in two school districts
Distribution System V2G for Grid Stability as well as Reliability Project	USA	2015	V2G	Project initiated by EPRI seeking to assess the value of, and barriers to, V2G at the distribution level, including whether these benefits can be monetized and quantified
UCLA Win Smart EV project	USA		V2G	Research project to achieve maximum power flow from EVs, simultaneously addressing response time and control, for applications such as reactive power, voltage regulation, and distributed storage
Massachusetts Electric School Bus Pilot	USA	2015	V2G	Pilot project to test deployment of three electric school buses in cold weather environments in US for V2G technology
INVENT Pilot Project	USA	2017	V2G	Nuvve seeking to deploy V2G technology on 50 UC San Diego electric vehicles in collaboration with California Energy Commission
Torrance V2G School Bus	USA	2014	V2G	Department of Energy funded project that retrofitted 2 school buses for V2G technology

Carlo method for predicting the charging demand of taxis, buses and official EVs of Shenzhen, China. In [42], authors have used Monte Carlo technique for simulating the EV arrival rate and Hidden Markov Model (HMM) for predicting the charging demand of standard IEEE 53 bus network considering dumb as well smart charging scenario. In [43], the authors proposed a queuing theory and Monte Carlo based model for charging demand prediction. The model was validated on 33 node road network. In [44], authors have proposed an Adaptive Neuro Fuzzy Inference System (ANFIS) and Teaching Learning Based Optimization (TLBO) model for predicting State of Charge (SoC) of private EVs. The proposed model was validated on experimental datasets from the Prognostics Center of Excellence at NASA. In [45], a Support Vector Machine (SVM) and Wolf Pack Algorithm (WPA) based approach is used for short term load forecasting of e bus charging stations. In [46], the authors proposed a hybrid fuzzy inference and Monte Carlo based approach for charging demand prediction of private EVs. In [47], the authors have proposed a Q learning based model for charging demand prediction of EVs considering different scenarios such as uncoordinated charging, coordinated charging, and

TABLE 7. Smart pricing strategies [66], [67], [68], [69].

Type	Country	Feature	Prerequisite
Two period Time of Use	Spain	80 % discount for EV drivers who are charging during the pre-defined night time	Binary meter
Octopus Agile	UK	Integration with half hourly day ahead market, supports use of renewable energy and flexibility	Smart meter, mobile app, customer participation
Radius	Denmark	Time of use network tariff with additional surcharge during winter peak hours	None

TABLE 8. Charging behavior.

Ref	Year	Type	Inference
[67]	2015	BEV	Most charging events take place at home during early evening
[68]	2013	BEV	With mean mileage 38 km drivers charged their vehicles 3 times a day
[67]	2015	PHEV	PHEV drivers charge more frequently as compared to BEV
[69]	2020	BEV	Charging load prediction considering probabilistic travel patterns
[70]	2014	PHEV	PHEVs complete 70% of journey on electricity
[71]	2020	BEV	Proposed a probabilistic smart charging strategy with overnight charging

smart charging. In [48], the authors have developed a Markov model-based tool named bCharge for charging demand prediction and scheduling of e buses. The model was validated for the real time bus e fleet of Schenzen, China. In [49] , the authors have modelled an ideal city having e taxis for public transport and proposed a Monte Carlo based approach for charging demand prediction of the taxis.

V. SMART CHARGING PILOT PROJECTS

Pilot projects driven by academia as well as industry across the world are exploring various aspects of smart charging. The list of major pilot projects on smart charging are listed in Table 6. The pilot projects reported in Table 6 investigated different aspects of smart charging such as frequency response achieved by smart charging, smart pricing, field trials, potential of EV batteries as medium of storage, economics of smart charging.

VI. SYSTEM COST AND SMART PRICING

With increasing penetration of renewable energy and EVs, power system investments, system cost and requirements for sector integration are emerging. EVs have already early been identified as a potential new flexibility element in the system [60]. Studies on sector coupling within the European energy system have shown high benefits of the flexibility from EVs especially through balancing of solar and also wind power production [61]. The same conclusion of the synergic co-existence of high penetration of EV's and expanding solar power in power system expansion in the Chilean power system was made in [62]. Smart pricing is a sort of cost-effective alternative where pricing signals are sent to consumers regarding the net cost of generating and delivering electricity [63]. An overview of smart pricing strategies is presented in Table 7. It was observed that with two period time of use tariff, a Nissan Leaf EV user will save approximately 167 Euros per year by night charging rate [64]. In a similar type of study on plug-in hybrid vehicles with small batteries concluded that most of the end user benefits of smart EVs come from smart timing of charging although benefits are also accrued from provision of reserves and lower power plant portfolio cost. The owner benefits of smart charging of EVs were in this study estimated at 227 €/vehicle/year [65].

VII. PERCEPTIONS REGARDING SMART CHARGING

The adoption and promotion of smart charging scheme depends on different stakeholders. The views of the different stakeholders on different aspects of smart charging are systematically captured in this section. Analyzing the charging behavior of EV drivers is an important aspect for adoption of smart charging. A number of research initiatives have made attempts to analyze the charging behavior of EVs as reported in Table 8. The viewpoints of different stakeholders on Vehicle Grid Integration (V1G and V2G) in Indian context is captured in [50] as shown in Table 9.

VIII. ROLE OF ARTIFICIAL INTELLIGENCE AND BLOCKCHAIN IN SMART CHARGING

The recent popularity of Internet of Things (IoT) has paved the path of smart and connected charging infrastructure. Also, Artificial Intelligence (AI) and blockchain technology have played an impressive role in streamlining smart and secure charging infrastructure. AI and blockchain can be utilized to deal with key issues related to charging infrastructure such as security in the charging stations, charging scheduling in the charging stations. Scheduling of EV charging is a complex task involving conflicting objective functions. There has to be a tradeoff between EV drivers' convenience, and security of the power grid. The EV charging service has multiple

TABLE 9. Perceptions regarding smart charging [50].

Stakeholder	View
DISCOMs	• Futuristic concept • Not enough EVs on road for aggregation
Charging Service Providers	• Attractive proposition for DISCOMs to better manage peak demand and reduce power procurement cost • VGI can be effectively utilised to deal with the variability associated with renewable energy sources since EV batteries can be suitably employed as an energy storage
R&D organization	• Requirement of quality electronics and communication • Requirement of stable grid and a framework for integration of EVs to the grid
Fleet operators	• Sceptical regarding VGI • Fleet operators will not be much interested to feed the power back to the grid • Priority is battery swapping and battery-to-grid before considering V2G

protocols imposing additional vulnerabilities to the system. For example, Open Charge Point Protocol (OCPP) is found prone to Man-In-The- Middle Attacks (MITM) [81]. Further, having multiple entry points to the system increases the chance that all the entities and protocols within the charging system may be compromised [82].

Blockchain networks can be utilized for enhancing the security within the charging infrastructure. Blockchain has the capacity to enable safe and secure trading of energy and allow homeowners to trade their energy and make their EVCS open to public. Different companies have taken initiatives to build Blockchain-enabled EV charging networks within P2P framework of energy trading. For example, Oxygen Initiative has extended already existing EV charging protocols (ISO-15118) and proposed a Blockchain network that enables either the utilities or any EVCS to offer pricing and grid conditions for EVs [81]. Also, a company named Charg offers an Uber-like service, through the Ethereum network, for energy trading by allowing anyone to lease their EVCSs to EV drivers [82]. AI can be effectively used for predicting the charging demand and driver behavior that in turn will assist in planning and operation of smart charging infrastructure.

IX. SMART EMERGENCY EV-TO-EV PORTABLE BATTERY CHARGER

Charging EVs on the road during emergency is still a challenge. To overcome this challenge in recent years, researchers have proposed an innovative EV-to-EV Portable Battery Charger (EPBC) [83]. This smart charger has the capability to charge another EV by examining the SoC and other battery specifications in a reliable manner. The charger can also control the output voltage and injected current to the EV at the same time. The charger uses a non-linear integral backstepping control to regulate the output voltage of the battery charger. The proposed smart charger can share up to 15% of the stored energy while taking into consideration the state of charge (SoC), capacity, and important technical specifications of the EV's battery. By using a bidirectional dual active bridge (DAB) dc-dc converter, the proposed EPBC can regulate the output voltage and the injected current to the EV simultaneously.

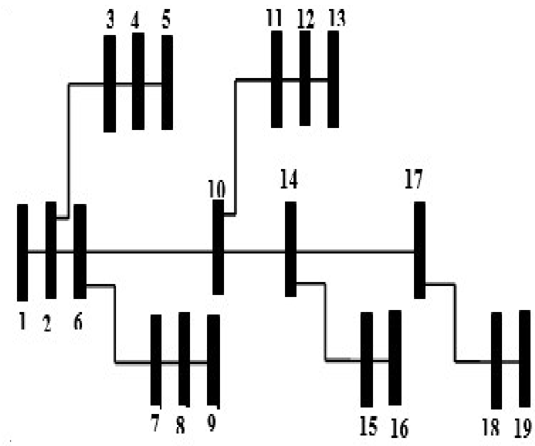

FIGURE 1. Test system [73], [74].

X. CASE STUDIES

A. CASE STUDY 1

A case study to illustrate the benefits of smart charging is illustrated in this section. The test system is as shown in Fig.1. The test system resembles the distribution network of a highway in Guwahati, India. In ref [72], [73] the planning of charging infrastructure for this network was performed considering cost, VRP index, accessibility index, and waiting time as objective functions. Six planning schemes were obtained after solving the multi-objective optimization [72], [73]. In this work, we tried to compare the impact of unmanaged charging with smart charging schemes (Coordinated charging and V2G) on VRP index as shown in Fig.2. The advantages of coordinated charging and V2G over uncoordinated charging is prominent from the simulation results.

B. CASE STUDY 2

A case study assessing the cost effectiveness of smart charging is elaborated in this section. ERDF in France compared the cost of smart charging with uncoordinated charging for 1 million EVs traversing globally for charging at multi

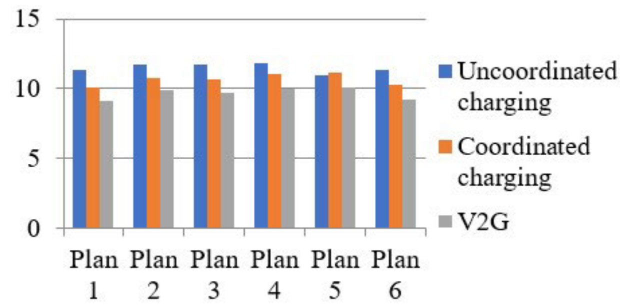

FIGURE 2. VRP index value for three scenarios in case of distribution network of Guwahati [73], [75].

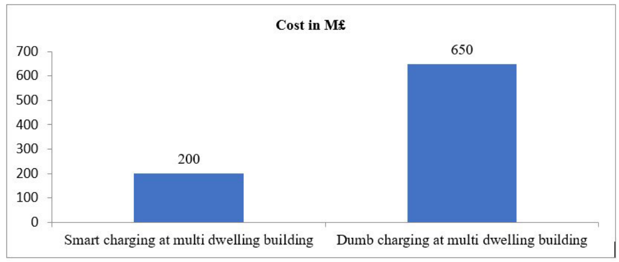

FIGURE 3. Cost comparison for charging at multi dwelling buildings [76].

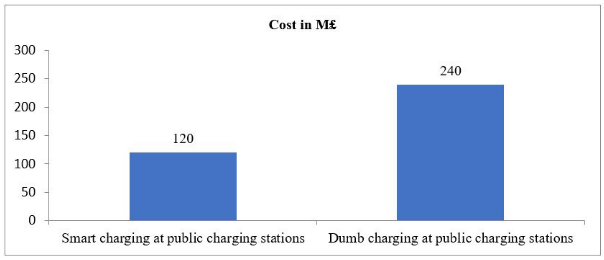

FIGURE 4. Cost comparison for charging at public charging stations [76].

dwelling buildings and public charging stations [76]. The cost for charging at multi-dwelling buildings for the two scenarios of smart charging and dumb charging is as shown in Fig. 3. And the cost for charging at public charging stations for the two scenarios of smart charging and dumb charging is as shown in Fig. 4. The cost effectiveness of smart charging as compared to dumb charging is clearly revealed from Fig.3, and Fig.4.

C. CASE STUDY 3

Nordpool Day-ahead Market (DAM) hourly price data [77] were used to analyze potential end user cost benefits from smart charging. Day-ahead hourly spot prices from 2019, 2020 and 2021 were downloaded and analyzed for four areas in the Nordic countries: Finland, SE3 from Sweden, Oslo area from Norway, and DK1 from Denmark. To illustrate the DAM hourly spot price dependency on the time of charging, three different six-hour periods were isolated from the hourly data for each year: mid-day charging during office hours (9am - 3 pm), afternoon-evening charging (4pm - 10 pm), and night hours (0am - 6 am) and compared with 0-24 h 'dumb' or 'random' charging involving no informed or forced decision-making on when to charge. The hourly DAM spot prices were averaged for the said time slots and plotted for each month of the yeas as well as the all-year average for yeas 2020 and 2021 and for the four market areas mentioned. The results are shown in Fig. 5 - 12. Additionally, the graphs in the figures show by dotted lines the relative DAM hourly price difference (%) for each of the three 6-hour periods as compared to 'dumb' charging 0-24h. This illustrates the relative savings potential for the smart end user who can choose the timing for charging.

As the data shows, 2020 was a more stable year for the market whereas towards the end of 2021 both price and its volatility increased; this trend is still continuing in 2022. Generally, Finland and SE3 show more intra-day variations in hourly spot price, whereas Oslo and DK1 are somewhat more stable. The end-user potential for cost savings through smart timed charging emerges during the night hours 0am-6am. In the analyzed dataset, this potential is largest in Finland: up to −50% year average night charging vs 24h average in 2020, and −40% in 2021). The same year average numbers, night hours vs 24h, are for SE3 −44% (2020) and −38% (2021), for

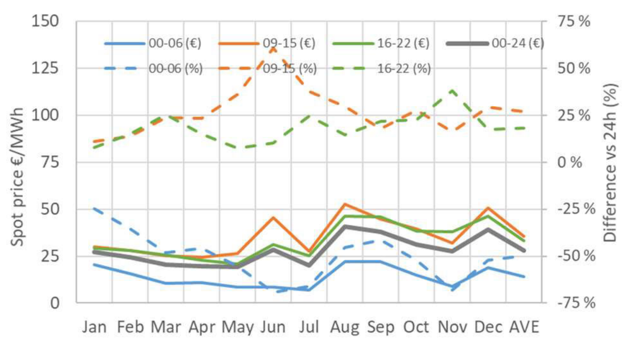

FIGURE 5. Nordpool day-ahead hourly spot prices per month in 2020 for Finland. Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

Oslo region −11% (2020) and −13% for 2021, and for DK1 −30% (2020) and −22% (2021). While the annual averages already show significant financial savings potential through smart charging, it should be noted that the momentary savings potential is still higher than the annual averages. Also, year 2019 was analyzed, the results for all areas show similar trends but a more stable spot price variation during the 24h of the day, and therefore slightly less smart charging potential end user gain.

Summarizing, all four Nordic market areas show potential gain for the EV user from timing charging to night hours and using the DAM spot tariff. The potential gain is significant and naturally dependent on the EV user's driving patterns. The largest potential gain for the analyzed years is in Finland and the smallest in Norway. Volatility of the spot market has increased during recent months, but the trend remains for December 2021 with peaking prices. Secondly, charging from the spot market during the mid-day hours (9am-3pm) is more

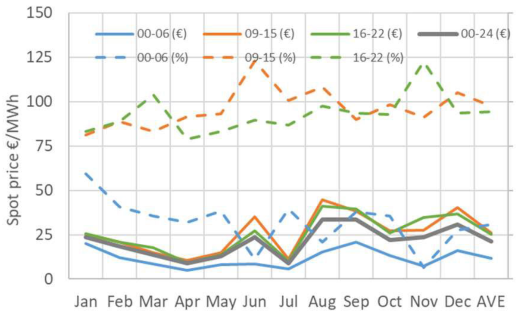

FIGURE 6. Nordpool day-ahead hourly spot prices per month in 2020 for Sweden SE3. Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

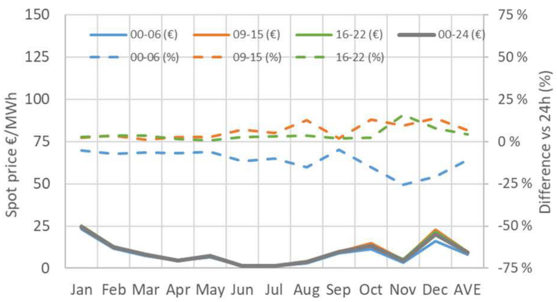

FIGURE 7. Nordpool day-ahead hourly spot prices per month in 2020 for Norway (Oslo area). Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

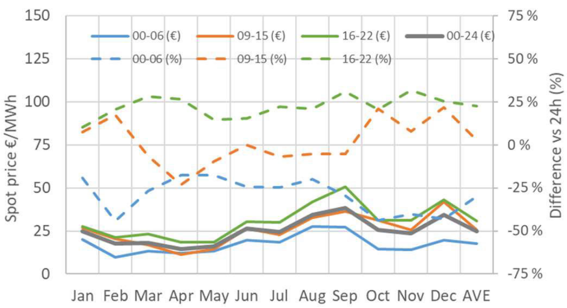

FIGURE 8. Nordpool day-ahead hourly spot prices per month in 2020 for Denmark (DK1). Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

expensive than the 24h average. This is true especially in Finland and SE3, and to a lesser extent in Oslo region and DK1. This indirectly implies an improved business case for (local) PV production to support mid-day charging.

The monetary and business impact and opportunities from smart charging and pricing through use of the dynamic DAM depend on the use case and ownership or business model related to the charger. For EV owners with private chargers behind own metering the potential financial benefits can be directly cashed in through choice of tariff and smart

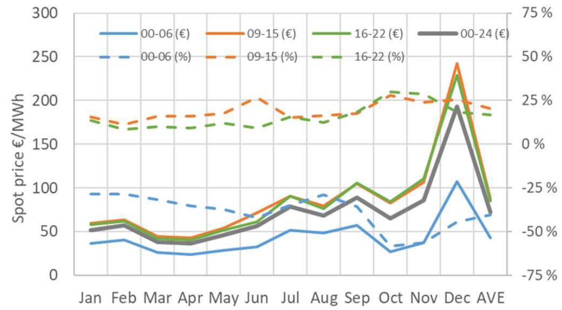

FIGURE 9. Nordpool day-ahead hourly spot prices per month in 2021 for Finland. Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

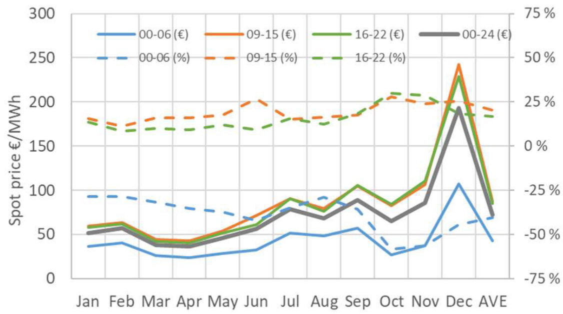

FIGURE 10. Nordpool day-ahead hourly spot prices per month in 2021 for Sweden SE3. Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

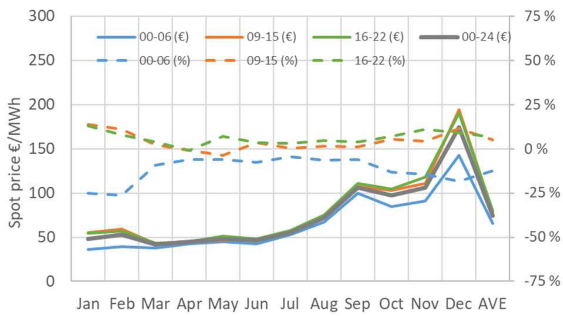

FIGURE 11. Nordpool day-ahead hourly spot prices per month in 2021 for Norway (Oslo area). Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

charging. For public chargers, the DAM offers the possibility for the charging point operators (CPO) and e-mobility service providers (EMSP) to offer dynamic pricing models utilizing smart charging, in addition to fixed prices.

D. CASE STUDY 4

The Electric Buses (EBs) impact on the power grid were studied. In this analysis, two scenarios were investigated. Scenario 1 includes standard charging, and Scenario 2 includes

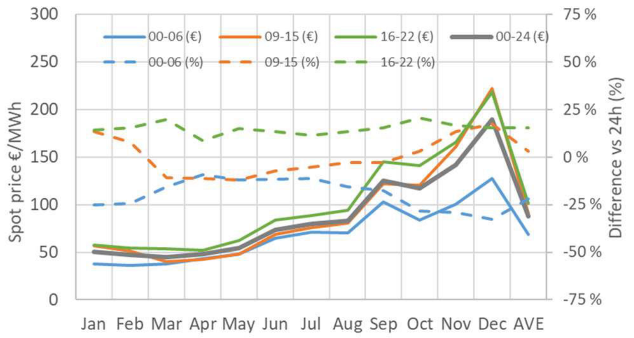

FIGURE 12. Nordpool day-ahead hourly spot prices per month in 2021 for Denmark (DK1). Averaged hourly prices for 0-24h as well as isolated average prices for mid-day charging (9am-3pm), evening charging (4pm-10pm) and night charging (0am-6am). The dashed lines show the difference (%) of the three timed slots vs the 24h average.

smart charging. The EBs were charged with depot charging (CCS2) of max power of 128kW and opportunity charging based on pantograph of max power of 320kW. The depot happens when the EBs parked for several hours, usually at night. Pantograph charging usually happens when the EBs are stopped for short time, 5–7 min to collect the passenger or a bit longer according to their working schedule [78], [79].

EV integration has risen considerably over the past few years. Generally, EVs' impact on the grid depends on the grid infrastructure. In some grids, a 20% EV penetration has no impact on the DSO networks. On the other hand, some grids tolerate no more than 10% standard (uncoordinated) load charging, which could reach 40% in the case of smart charging. In reality, it appears that every DSO grid is a special case requiring an autonomous study to explore the issues and limits of EV charging load [80].

In this work, the single-phase subsystem was modeled and simulated in pandapower library (Python software) to study various factors that influence the charging infrastructure on the system capacity and the ability to host the EVs' loads.

In order to show the impact of conventional normal charging and fast charging on the DSO grid, a small spot (terminal EBs stop) that includes both CCS2 and pantograph solutions was modeled and simulated. This spot area had 20 plug-in charging solutions and 7 pantograph charging stations with a distance between them of less than 350 m.

The standard charging is where EBs plug-in to the charger and start charging with the maximum chargers' supplied power until fully charged (100% SoC) without taking into account the impact on the grid infrastructure. In the case of a high number of EBs connected to be charged simultaneously, there would be a high impact on the grid in terms of the DSO transformer load profile, the voltages on the bus bars, and line rating. Furthermore, the energy price is not taken into account, which increase the charging cost since the energy price in peak loads is higher than the price in off-peak hours.

Smart charging of EBs is done based on load shaving and charging cost optimization. The peak shaving mainly depends on minimizing the charging power in order to minimize its impact on the DSO grid. The cost optimization is based on

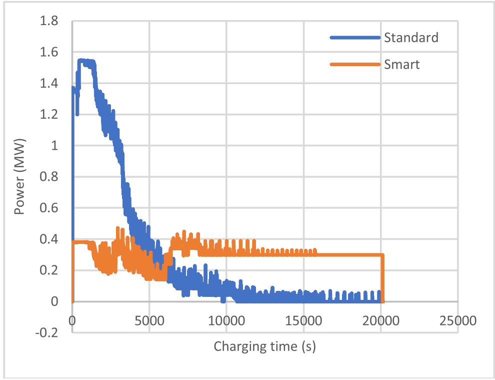

FIGURE 13. Charging load profiles for standard and smart charging.

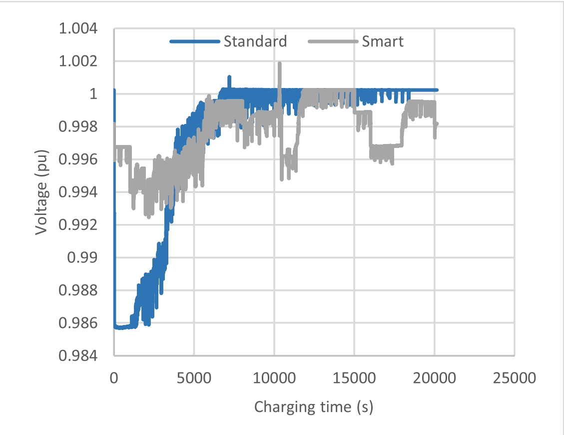

FIGURE 14. Voltage profile for standard and smart charging.

Day-ahead Market (DAM) energy price. The aim of smart charging is to flatten the load profile. This practice offers direct and indirect benefits to the DSO utilities in generation of costs, line and transformer loss reduction, and voltage support. The cost optimization aims to optimize the energy cost based DAM.

In this section, real data were used to simulate smart and standard charging with 100% EB integration in the PKM depot charging station. The standard and smart charging load profiles are shown in Fig. 13. Based on both scenarios, in the case of standard charging, there are valleys and peaks in the load profile. This results in no impact on the grid during a period of time and huge impact during a different period. To minimize the impact on the grid, the smart charging could be adopted, where the EBs connect to the grid to be charged and take into account the other factors that have an impact on the grid.

Fig.13. shows how the charging load profile could be coordinated to lessen the impact on the grid by flattening the load profile instead of having some peaks and valleys. The corresponding impact of standard and smart charging on the busbars' voltages are shown in Fig.14. As can be seen in Fig.14. the standard charging has notorious impact on the busbars' voltage, which could be increased as more

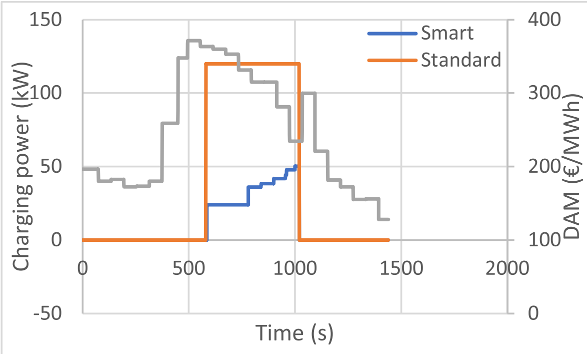

FIGURE 15. Charging cost optimization based on DAM.

EBs' integrated unlike the smart charging, which support the voltages on the busbars [79].

The charging cost optimization based on DAM was simulated according to CCS2 in depot charging (see Fig.15). The standard charging starts charging with max allowed power i.e. 120kW without taking into account the energy price during the charging time. On the other hand, the smart charging takes the DAM energy price into account to optimize the EBs' charging cost, where the supplied power by the charger is start with low level i.e. 25kW when the energy price is high, then the supplied power increase gradually as the DAM decrease. This results in a cost saving of no less than 10% for full charge EBs' with battery capacity of 220kWh. The consumer naturally also has to evaluate and make the choice between a DAM spot tariff and fixed rate electricity tariffs available.

XI. CONCLUSION

Adoption of EVs call for development of sustainable and accessible charging infrastructure. Management of charger load has become a matter of concern for the power system engineers. Uncoordinated charging can be detrimental to the smooth operation of the power grid. Smart charging gives certain amount of control over the charging process. Adaptivity of the charging process of EVs in smart charging assists to meet the needs of power system as well as EV users. Further, smart charging enables EVs to act as flexible grid resources thereby providing ancillary services to the grid in case of emergency. Flexibility from smart charging can provide benefits to power and transmission system investments and system cost, as well as cost benefits to the end users through optimized timing of charging. This work presents a comprehensive overview of smart charging thereby explaining its perception, impact, user acceptance, global status and pilot projects. An investigation highlighting the benefits of smart charging in case of EVs is presented. In smart charging, the EBs load profiles are distributed almost evenly. In reality, this could be done by shifting the charging of the EVs in a way that takes into consideration the transformer and line load profiles, and could also be done by decreasing the charging power, which prolongs the charging time while taking into consideration the user comfort and expectation, including the charging period, departure time and targeted SoC. In this study, smart charging was adopted by minimizing the charging of the EVs that were parked for a longer time and giving charging priority to other EVs parked less time. The aim of smart charging is to flatten the load profile. This practice offers direct and indirect benefits to the DSO utilities in generation of costs, line and transformer loss reduction, and voltage support. The cost optimization was also simulated based on DAM, which aims to optimize the energy cost. In terms of potential cost savings for end users who can time their EV charging from mid-day, evening or day-round random average to the night hours, can potentially save several tens of % through use of hourly spot prices and optimized timing for charging.

This detailed elucidation of smart charging will assist the researchers, and experts of power industry as well as transport to find research initiatives on smart charging at one platform thereby promoting adoption of smart charging.

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