Voltage Control in Smart Distribution Network with Deep Penetration of Electric Vehicle

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Abstract- The deep integration of renewable energy resources (RES) in the smart distribution network (SDN) has presented more technical challenges and uncertainties in the operation of the network system degraded protection, voltage variation, increased fault level, and two-way power flow. Hence, the high penetration of the (RES), most especially the variability of PV irradiance and wind speed will certainly affect the power distribution Network (DN) control and operation. It is therefore essential to investigate the effect of high penetration of RES on the design requirements for DN and the appropriate voltage control strategy to be taken. To accommodate the deep integration of solar PV in SDN with its fluctuating and variability characteristic, different conceptualizations based on control schemes are proposed. Hence the application of battery electric vehicles (EV) and plug hybrid electric vehicles (PHEV) are used to overcome voltage rise or variation problems with minimum network reinforcement. A modified IEEE 13-bus test feeder of total load distributed among residential and commercial electricity consumers is used as a test feeder network. The network, including all conductors, feeder regulators, service transformers, and customer loads is simulated in OpenDSS interfaced with Matlab. This is utilized to compute the random variables and regulate the execution of the procedure. The solar PVs integrated produce as much power as the available energy resources permit. Excess energy produced is stored in battery electric vehicles (EV).

Keywords Electric vehicle; OPENDSS; Renewable energy; PV; Smart distribution.

1. Introduction

The existing power system is not environmentally friendly and inefficient in terms of greenhouse gas emission (GHG) and it is not designed to accommodate distributed energy resources (DER) [1],[2]. Globally, there has been a lot of concern about climate change, reducing carbon emissions, and technological advancements. New technologies have emerged in recent years. These involve the incorporation of RES like wind, solar photovoltaic (PV), biomass, fuel cells, and distributed generation (DG) in the power system with clear advantages in the way the power systems behave environmentally. More uncertainties and technological difficulties were introduced into the operation of the network system voltage profile due to the intermittent and erratic nature of wind and PV generating. [3],[4].

For an SDN to be successful, there needs to be ongoing research into new energy sources, funding for RES development, advancement and sustainability of facilities and equipment, extension and placement of DGs where loads are served, innovation of ICT integrated with legacy infrastructure, and encouragement of customer participation [5],[6]. This in turn causes the voltage regulation mechanism in the DN to undergo considerable alterations. Electricity must be delivered to consumers' terminals within allowable limits.

Both wind and solar energy may not always be obtainable where and when they are required. Conventional sources of electrical energy are dispatchable while RES such as solar and wind are not [7]. Solar and wind energies exhibit nonlinear characteristics that necessitate the adoption of coordinated control strategies [8]. This will eventually necessitate the addition of new network control applications in order to assure the DN's proper and reliable operation.

The SDN vision aims to develop innovative products, processes, and services that will improve industrial efficiency while also utilizing cleaner energy sources. The SDN vision is critical in achieving the nation's environmental and economic goals. Within the transmission and distribution (T&D) networks, there are already several developing technologies that can help improve system operation and control [9]. Furthermore, the usage of digital communication and control, such as smart metering and enhanced grid-wide-area real-time monitoring, is increasing.

The primary goal of any SDN installation on the DN should be to enable all infrastructures to allow all desirable functions of optimizing the DN's operation to obtain maximum benefits for both utility industries and end-users [8]. These objectives can only be met with a system that allows for precise and regular monitoring of the DN in terms of system planning, using data from smart network technology (SNT) can considerably improve the planning process [9]. According to the SNT in the system, expansion plans alter under a different weighted combination of objective functions and different instances, while the objective function can also be enhanced due to the availability of SNT [10]. The use of SNT in the distribution network does have some energy-related advantages. Nonetheless, the SNT must be further developed and integrated into the grid structure. This could enable the grid's self-healing capabilities and make the incorporation of dispersed generation technologies easier. SNT, for example, can be used to speed up reactive power adjustment with dynamic VAR devices. The implementation of these SDN functions can be sped up by enabling technologies in terms of information and communications [11].

SDN is being developed as an automated, digitalized, and extensively distributed energy delivery network [12]. SDN uses digital technology to improve the electric system's stability, security, and efficiency (both economic and energy) from major generation to electricity customers, as well as a growing number of distributed generation and storage devices [11]. It will also provide homeowners and businesses with the most cost-effective way to use electricity. It's about achieving reliability, efficiency, and optimization in operations, planning, demand response, and resource usage [13]. With the SDN concept described above, the power system's power quality and dependability are greatly enhanced.

In the integration of RES with DN, efficiency, dependability, and power quality (PQ) are critical factors to consider, as is the cost of energy conversion, appropriate load, management, safety, and security [14]. Due to the fluctuating properties of many of these resources, the substantial penetration of RES into the network system has been a cause of concern for utility companies [7]. Wind and solar energy have the greatest influence, although biomass, hydropower, and geothermal energy resources are more dependable and have a little problem integrating with the DN [15].

Due to their intermittency and varying characteristics, renewable energies bring additional challenges to the utility system compared to centralized predictable generation [16], [17]. Electricity consumers may be impacted in a variety of ways in terms 1of power system quality, reliability [18], efficiency, and operational reliability. With the integration of RES into the DN close to customers, the typical flow of power is changed from a unidirectional to a bidirectional flow, resulting in an imbalance in energy production and consumption], as well as low CO_2 emissions [19]. As a result, essential operational parameters in the DN including voltage, frequency, and reactive power regulation may be affected. Many methods based on control strategies have been proposed to mitigate voltage changes owing to RES penetration. When a significant portion of the electricity output is dependent on distributed generations (DGs), an examination of transformer voltage management is carried out. The technological issues faced by SDN due to DG, such as substantial wind generation intermittence and fluctuation, were highlighted by Shi, L. et al [20].

An optimization approach for day-ahead scheduling was proposed in [21]. The proposed solution has a flaw in that it requires daily load and power output forecasts from RE. Vacecaro et al. [22] used a decentralized non-hierarchical voltage control architecture based on intelligent and cooperative smart entities, whereas Jauch [23] focused on substation transformer chores using Load Tap Changers (LTCs) on SDNs. Amedeo Andreotti et al. [24] developed a method for increasing the efficiency of voltage regulation in DNs by utilizing the potential of SDNs. However, [25] presented a voltage control pattern in SDN, which also controls the placement and capacity of Volt-Var control (VVC) equipment via the SDN. A new strategy for improving voltage regulator function in multiple feeds with DGs was given in [26]. By compromising reduced communication equipment needs and reducing calculations performed by RTUs using a coordinated online voltage management method, YifeiGuo, QiuweiWu, HouleiGao and FeifanShen [27] revised [26].

When the requirements are met, the method illustrated on the IEEE 34-bus distribution test system indicates that voltage fluctuation can be kept below acceptable limits. Energy storage [ES] systems deployed across the grid from generation to end-user [28], [29] present a chance to break free from the power balance paradigm by storing energy during off-peak hours and redistributing it when needed. When combined with other smart grid control technologies like demand-side integration, ES increases network performance. The level of contribution of the ES system is determined by the event definitions and fluctuating network behaviour on both long and short-time scales. Furthermore, ES has the potential to improve grid dependability and asset utilization. Congestion and constraints are alleviated with ES facilities. They facilitate the connecting of RES and allow for islanding, as well as load levelling and peak shaving.

Ferrendez-Pastor et al. [30] proposed an intelligent energy management strategy to assess power-sharing amidst hydrogen and storage batteries in a hybrid standalone system based on operational costs, which produced greater outcomes than simplistic state-based energy management techniques. To include power balancing equality constraints in the energy management strategy, Chatelain et al. [31], used PSO with a roulette wheel distribution mechanism. The energy management technique penalizes charging and discharging based on SOC, which accounts for the effects of battery storage depth of discharge and promotes longer battery life. Battery electric vehicles (EV) can have a smooth load curve for utilities, as well as stability and frequency control if utilities can handle EVs loads using rate advantages or direct signals. Again, this is highly reliant on utility-provided smart charging strategies.

The realization of V2G technology has become more realistic as the EV industry has grown exponentially over the last few years. However, as the number of EVs on the road grows, so does the difficulty of supplying electricity to charge EV batteries without negatively impacting the energy grid or creating problems for electric utilities. Many solutions have been suggested to date, but due to the margin for growth, there is already a lot of emphasis on developing even improved smart charge strategies. [32] The structure of EVs and its structure of V2G are depicted in the network and are captured in [33].

Sheik et al. [34] suggest a system for optimized EV charging power in their paper "Towards an optimal EV charging scheduling scheme with V2G and V2V energy transfer." Their schemes use real-life data from Belgian photovoltaic (PV) panels to effectively utilize electricity to meet consumer demands in a situation where the only energy supply is the electric grid. Yuntao et al. [35], suggest a charging system for electric vehicles that is dependent on autonomous scheduling. This paradigm combines renewable energy resources and electric vehicles with the delivery network, treating them as distributed energy sources. Shahid et al. [36], concentrate on the demand and availability of 25 domestic electric appliances and use integer linear programming (ILP) to solve the scheduling problem. Furthermore, M. Alonso et al. (2014), [37] investigate a charging schedule for active and reactive power supports using V2G technology using heuristic algorithms.

This paper aims to show the role of Electric vehicles in mitigating the variability and fluctuating characteristics of renewable energies integrated into the distribution network, to improve the voltage profile, and reduce energy losses in the distribution network. The paper develops an integrated framework using the PSO optimization approach for VAr control devices and EV batteries over a multiperiod time simulation of 24 hours. PSO is adopted so as to integrate the PSO exploitation ability to synthesize the strength of the algorithms. The solution renders the hourly optimal settings of the LTC transformers, the status of switched capacitors, location and size of EV energy storage as well as consumer 24-hour electricity scheduling.

2. Methodology

The RES is considered to be of unity power factor mode distributed at different optimal locations in IEEE 13 bus feeders. The internal impedance matrix of the generator is included in the load flow calculation. A constraint about power ramps of PV and wind is also considered. RES connected to the grid is expected to inject as much energy as the energy resources allow. Batter EV devices store energy that exceeds the primary load. Dispatch strategies and limitations are included in a generic node with generation and storage.

A modeled IEEE 13 test feeder of a real 115kV/4.16kV 50Hz distribution circuit with a total load of roughly 3.46 MW spread among different energy consumers. The IEEE 13 test feeder, as modified in Fig. 3.1, consists of a three-phase primary line with numerous feeder regulators in series. At the system buses that reflect a typical peak load day, customers load with different load shapes such as constant current, constant impedance, and constant power. It is assumed that there is no existing RES in the circuit under examination. The power factor for the feeder is expected to be one. As a result, the RES' power injections have been represented by voltage-independent active injections with zero reactive power in the simulation work, and the ideal RES size has been integrated into the best distribution feeder placement. The loss sensitivity and voltage sensitivity coefficients, which make up the sensitivity index, were calculated using the base case power flow on the feeder (SI). Based on the analytic expression, the SI of the PV is determined for each bus in the test system. As shown in Fig. 1 and 2 the circuit is constructed in Open distribution system simulation (OpenDSS), an electric utility DN simulation tool that can be used as a stand-alone executable program or a Matlab Com interface. The random variables are calculated with Matlab, and the method is controlled with Matlab. Intermittent PVs and load curves can be created using offline technologies.

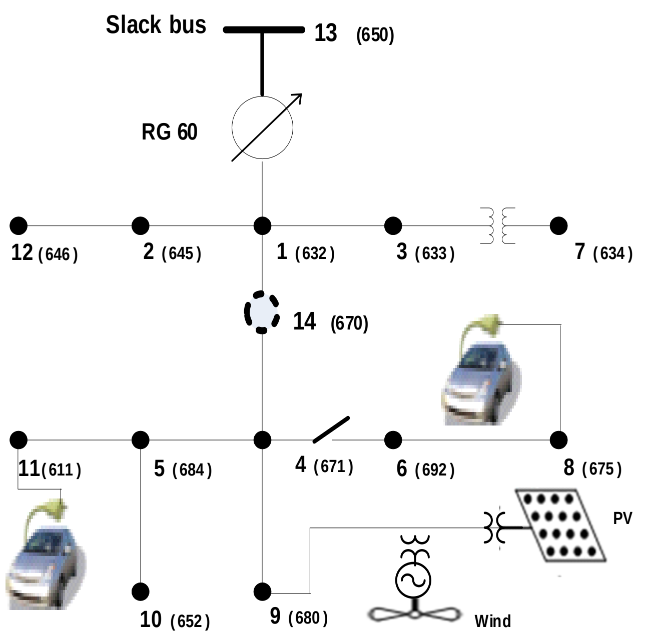

Fig. 1. IEEE 13 Bus test feeders

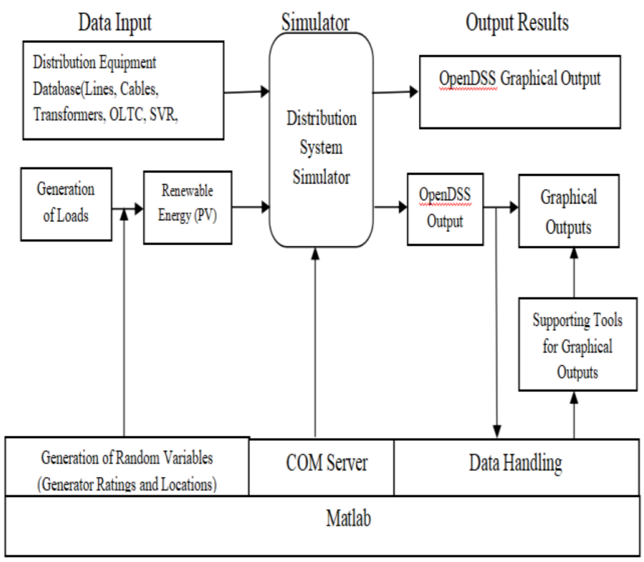

Fig.2. Block diagram of the implemented procedure

During the off-peak period when voltage rise takes place, the on-load tap changer (OLTC) responds first. After which the state of charge (SOC) controllers receive a signal from the centralized coordination controller. Enabling the SOC controllers to charge the battery EV to minimize the OLTC operation stress by absorbing the reverse power flow. In the same vein, the centralized coordination controller sends a signal to the SOC controller during the peak period so as to enable the ES to inject power to the feeders. The tap changer is controlled by the centralized coordination controller. It makes use of line droop compensation (LDC) with communication capability to take necessary action based on the signal receives from the coordination controller to regulate bus voltage within acceptable limits during voltage rise. Figures 3 and 4, respectively, depict the control scheme and the flow diagram of the tap changer regulator, coordination controller, and SOC controller.

The SOC controller sends a charge signal command to the ES in order to mitigate the reverse power flow. This reduces additional tap changing operations as a result of voltage rise. The OLTC/SVR employs the traditional method to maintain the distribution feeders within acceptable limits in the absence of voltage rise. The charging operation is issued whenever any bus exceeds the voltage limits due to voltage rise but the discharging operation takes over when the voltage During the off-peak period when voltage rise takes place, the on-load tap changer (OLTC) responds first. After which the state of charge (SOC) controllers receive a signal from the centralized coordination controller. Enabling the SOC controllers to charge the battery EV to minimize the OLTC operation stress by absorbing the reverse power flow. In the same vein, the centralized coordination controller sends a signal to the SOC controller during the peak period so as to enable the ES to inject power to the feeders. The tap changer is controlled by the centralized coordination controller. It makes use of line droop compensation (LDC) with communication capability to take necessary action based on the signal receives from the coordination controller to regulate bus voltage within acceptable limits during voltage rise. Figures 3, 4a, 4b and 4c, respectively, depict the control scheme and the flow diagram of the tap changer regulator, coordination controller, and SOC controller. The detailed flowchart of each step in carrying out the simulation in this research is shown in Fig. 5.

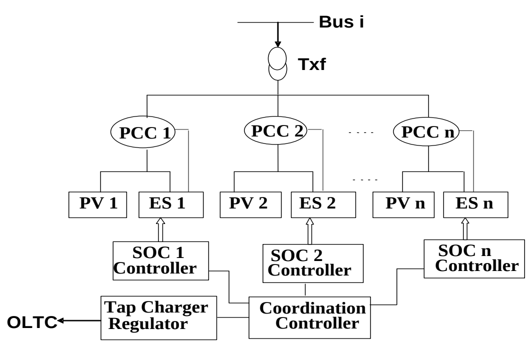

Fig. 3. SOC control system

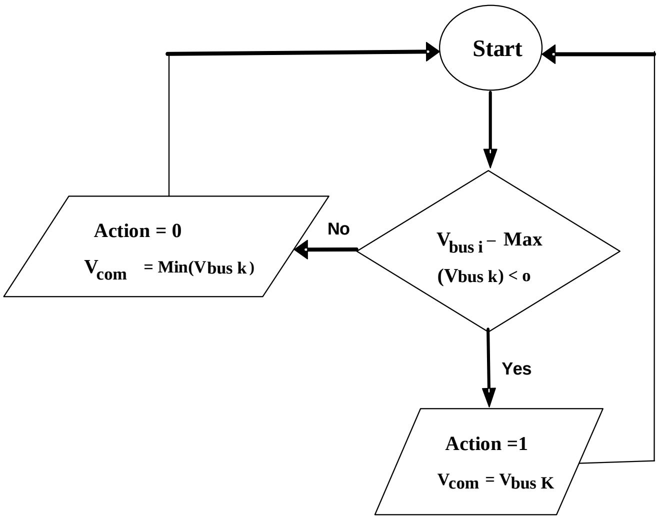

Fig. 4a. Tap changer controller

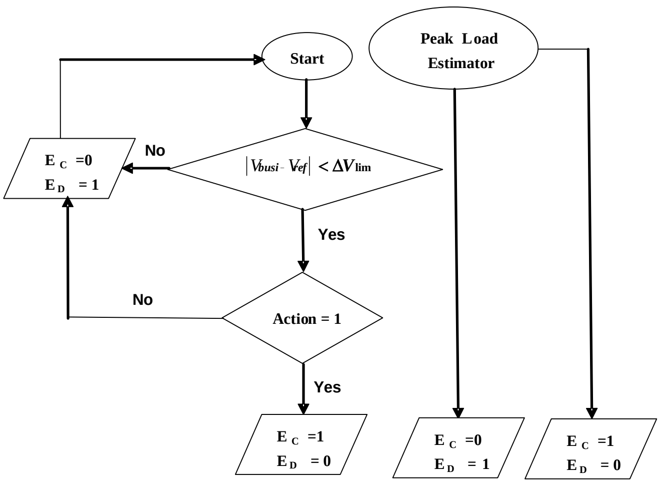

Fig. 4b. Coordination controller

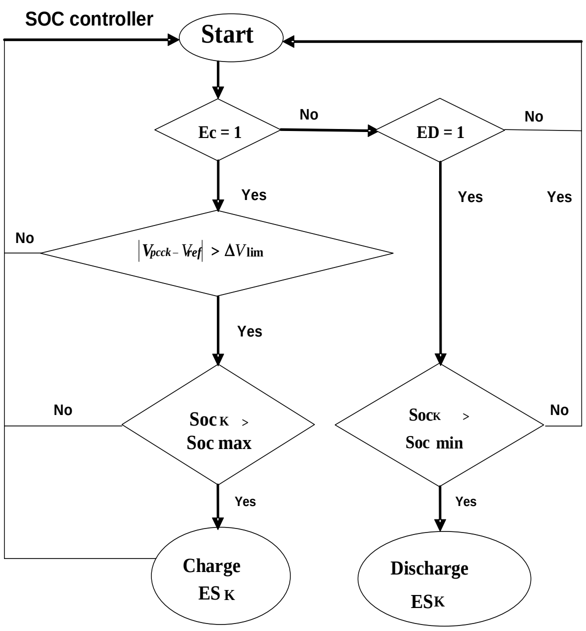

Fig. 4c. SOC controller

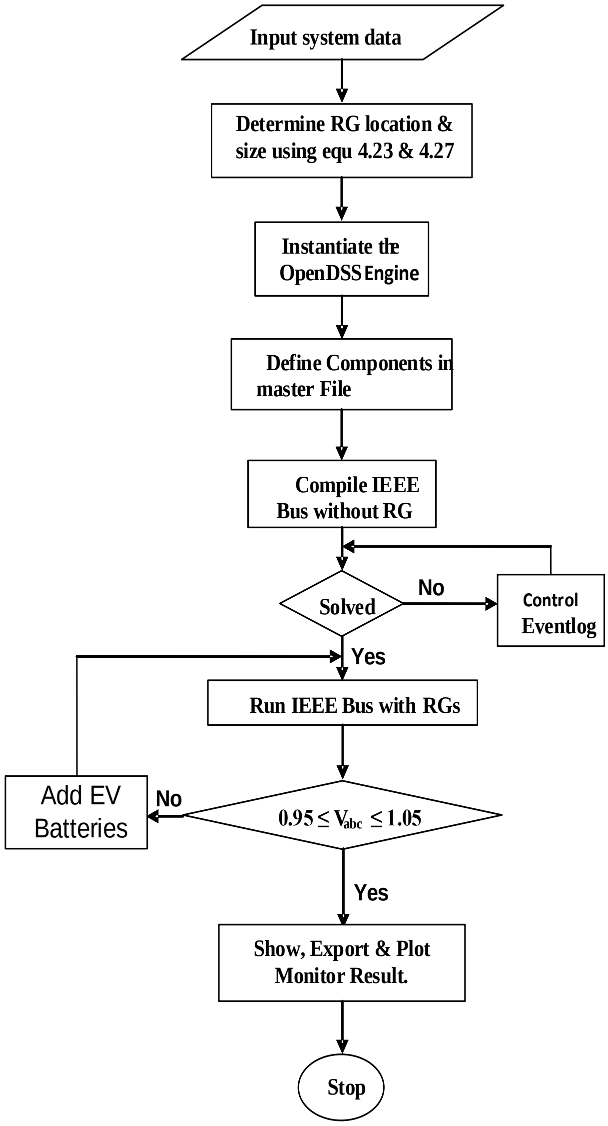

Fig. 5. Simulation flowchart

3. Results and Discussions

The effectiveness of the proposed method is tested on a modelled IEEE 13 bus feeder, shown in Fig 3.1 of an actual 5MVA, 115kV/4.16kV 50-Hz distribution network representing SDN feeder. The feeder model is at MV/LV level. The generation unit used is both stochastic and deterministic, that is, intermittent PV, and dispatchable battery EVs respectively. The total load is 3466 kW 2102 kVAr of 8 spot loads and one concentrated load (150 kW 116 KVAr) at bus 670 distributed between bus 632 and bus 671. These loads are distributed among residential, commercial, and industrial energy consumers. Details of the data used in this study are contained in [39], [40], [41]. Different types of loads modelled in constant current, constant impedance, and constant power are at the feeder buses.

The PV energy integrated into the feeder is considered to be of unity power factor mode. The PV energy is designed to inject as much power as the energy resources permit. Excess energy harvested is stored in the EVs for re-dispatching when needed. PV energy is injected into the grid as voltage-independent active injections with no reactive power. Different penetration levels of PV energy at different networks. Although, the conventional wisdom of selecting the optimal size and location of PVs or RES in the network is annulled in this paper. Therefore, the solar PV energy is integrated in the feeder at a location where it is assumed that PV irradiance may be available as shown in Fig. 1.

3.1. Voltage Profile and Power Losses in IEEE 13 Bus Feeders at Normal Load

At a normal peak load of 3.466MW, a 30% (1.04MW) PV penetration is integrated on IEEE 13 bus feeder at bus 680 and at a normal peak load of 3.866MW, and a time series 24-hour simulation is carried out on each feeder with and without PV. The results of both feeders are shown in Table 1. The effect of PVs in multiple locations in the feeders is investigated with the PVs of the same capacity integrated in bus 633, 692, and 680 of the IEEE 13 bus feeder.

Table 1. Voltage profile and power losses in IEEE 13 bus feeders at normal Load

	IEEE 13 Bus Feeder		
	Without PV	Single PV	Multiple PV
Tap step	1.03750	1.04375	1.04375
Tap operation	2	8	7
Total iteration	2	4	4
Maximum pu. Voltage	1.0240	1.0302	1.0297
Minimum pu. Voltage	1.0240	1.0244	1.0244
Voltage deviation	-	0.0058	0.0053
Total active losses (MW)	0.1091 (3.05 %)	0.0895 (2.88 %)	0.0881 (2.84 %)
% loss reduction	-	17%	21%

It is observed in the 13 bus feeder as depicted in Table 1.1 that the tap operation moves from 1.03750 without PV to 1.04375 with the integration of PV. The voltage profile improved from 1.0240 pu without PV to 1.0302 pu with PV in IEEE 13 bus feeder. There is an increase in tap operations as a result of the voltage rise caused by the integration of the PV. However, there is a reduction in system losses and a better improved voltage profile when the PV is integrated into the feeder as compared to without PV. Although the PV integrated in one location demonstrated a higher voltage profile, however, the distributed PV demonstrated lower voltage deviation and lower losses than the PV in one location. This demonstrated the potential benefits of PV distributed in SDN as an alternative to conventional capacity enhancement.

3.2. Voltage Profile, Number of Taps and Losses with Control Devices

A 30% solar PV energy is integrated in bus 9 in the modified peak load feeder of 2.4 MW. With the ideal configurations of LTCs, shunt capacitors, and EV batteries, system real energy losses are derived by simulation in the OpenDSS Com Matlab interface.

Utilizing EV batteries efficiently helps to harness sporadic solar energy, reduce energy loss, and enhance voltage profiles. Additionally, the usage of EV batteries highlights their ability to address the issue of voltage depression in a smart distribution network when other control devices' coordination was insufficient to bring the voltage back within the required range. Table 2 Voltage profile, No. of Taps and losses with Control Devices.

Table 2. Voltage profile, no. of taps and losses with control devices.

	LTC	SC	EV Batteries
Maximum Voltage (pu)	0.9734	0.9891	1.014
Minimum Voltage (pu)	0.9213	0.9386	0.9854
Voltage deviation	0.0521	0.0523	0.0132
Number of Tap	1	5	3
Tap position	12	7 to 9	1 to 3
Losses (kW)	1810.48	1391.46	1169.39
(%) Loss Reduction	-	23.14	35.41

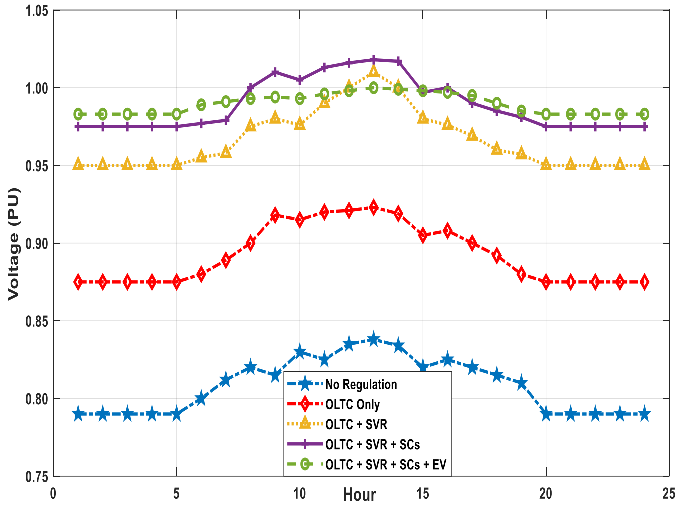

Fig. 6. Effect of control devices on system voltage

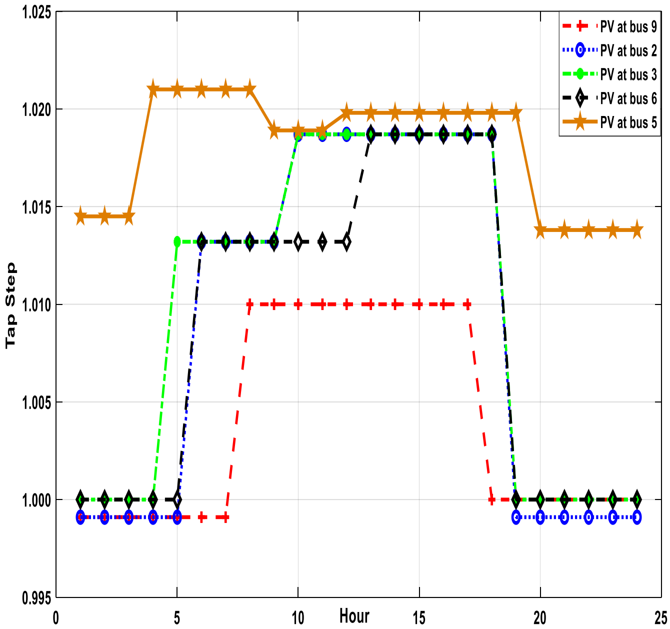

Fig.7. PV Regulators at different buses

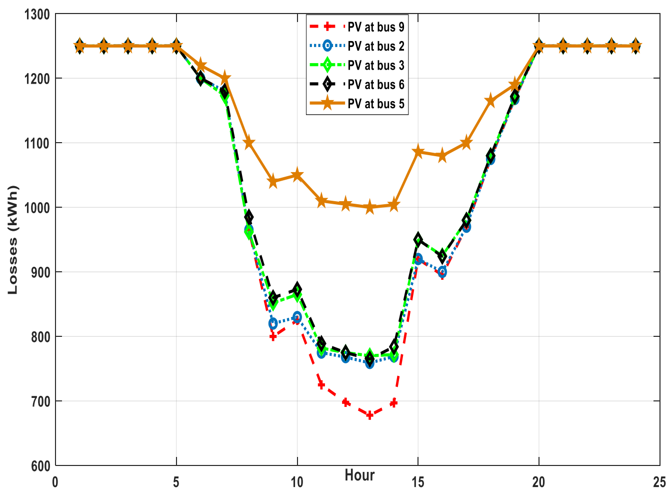

Fig. 8. PV energy losses at different buses

The results of the voltage profile from the PV energy are as depicted in Fig. 6 with the related LTC regulator action in Fig. 7 while Fig. 8 shows the energy loss on an hourly basis. However, bus 5 produces the lowest voltage profile, highest energy loss, and five (5) LTC tap setting operations while bus 9 gave the highest voltage profile, and lowest energy losses, and only three (3) LTC tap operations among the buses investigated. This implies that bus 9 is the most sensitive bus that can respond promptly to any changes in network situations and more energy can be harvested. It is observed that the coordination of the VAr control devices is efficient and effective in bringing the voltage within permissible limits where ever the PV is located in the network. In power balance analysis, the load power is expected to be balanced with the power injected into the grid by the PV and the power from the grid. The power from the grid is non-PHEV load – PV power. That is, PGrid = PLoad - Ppv.

3.3. Electric vehicles charging/discharging for voltage levelling

A 30% solar PV energy is located in the modified peak load feeder of 2.4 MW as shown in Fig. 1. Fleet of PHEVs is to charge and discharge at least one-fifth of their load capacity in the network. Charging is to be done during the day while discharging at night with proportions. The VAr control devices are coordinated with the PHEVs. The voltage limits considered in this study are +/- 6%. The voltage output of the network without PHEVs is shown in a dashed line in Fig. 9, with a maximum voltage of 1.0223 pu and a minimum voltage of 0.9781 pu. The effect of the PHEVs distributed with the PV in the network is depicted with a solid line in Fig 9, with a maximum voltage of 1.0038 pu and a minimum voltage of 0.9950 pu. Evidently, the PHEVs brought great improvement to the voltage profile, especially when the generation is low at night as reported in [26] where wind energy is distributed on IEEE 34 bus feeder. Voltage deviations are reduced from 0.04842 to 0.0088.

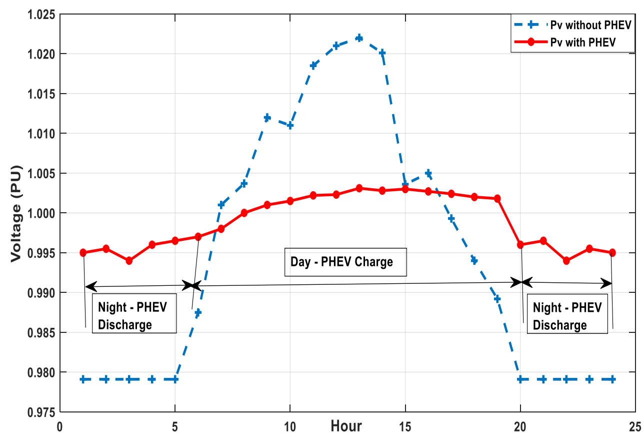

Fig. 9. PHEVs charging/discharging for voltage flattening

4. Conclusion

RESs such as PV and electric vehicles or plug-in hybrid electric vehicles are qualitatively different from types of generation and loads that have been integrated into the network system in the past. Widespread integration of these technologies will change the requirements of the smart distribution network. The inherent intermittent and uncertainty of PV integrated into a smart distribution network (SDN) can potentially cause an overall voltage profile deviation from permissible limits, reverse power flow, and disruption of the normal operation of VAr control devices. The smart coordination of the VAr control devices is used in this paper to keep the voltage within statutory limits no matter where the PV is located. The study also presents a proposed framework that is suggested for successfully integrating the aggregated EV into the network as distributed energy storage devices to act as controllable loads to balance the network's demand during off-peak hours and as a generator to provide capacity and energy services to the network during peak hours. The results show that the system's ability to maintain voltages within the statutory limits and reduce network losses is improved by the smart coordinated operation of VAr control devices including Load Tap Changing (LTC) transformers and capacitors with EVs. The use of EVs battery effectively assists to harness the variability of PV resources, improve the voltage profile, and reducing energy loss. It also provides additional flexibility to the network to hedge against the uncertainty of PV energy. Electric vehicles are sure to become a necessary tool for grid support, leading to a higher synergy between distribution networks and customers encompassing large proportions of solar PV.

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