An Optimization-Based Reliability Enhancement Scheme for Active Distribution Systems Utilizing Electric Vehicles

**RASHID KHAN[1], KHAWAJA KHALID MEHMOOD[2], SYED BASIT ALI BUKHARI[2],
KASHIF IMRAN[1], ABDUL WADOOD[3], SANG BONG RHEE[4], AND SINA PARK[5]**

[1]U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan
[2]Department of Electrical Engineering, The University of Azad Jammu and Kashmir, Muzaffarabad, Azad Jammu and Kashmir 13100, Pakistan
[3]Department of Electrical Engineering, Air University Islamabad Kamra Campus, Kamra 43750, Pakistan
[4]Department of Electrical Engineering, Yeungnam University, Gyeongsan-si 38541, South Korea
[5]Department of Smart Electrical Engineering, Korea Polytechnic Colleges VI, Daegu 41765, South Korea

Corresponding authors: Abdul Wadood (wadood@au.edu.pk) and Sang Bong Rhee (rrsd@yu.ac.kr)

ABSTRACT Unanticipated faults can hinder the operation of the utility grid, consumers, and businesses. This study aims to ensure the continued power supply to the consumers during outages and peak hours from the stored energy in the batteries of electric vehicles (EVs). Considering the bi-directional charging feature, the energy capacity model of the EV-batteries in a centralized parking lot (PL) and distributed EVs is developed. Various factors that affect the energy capacity of EVs are considered and modeled. The optimal location of PL and charging/discharging time and rate are found for reliability improvement, losses reduction, and voltage regulation of the distribution system. The problem is formulated as a mixed-integer multi-objective optimization problem. The first objective function is formulated to maximize the energy output from the EVs-batteries during blackouts or to minimize the energy not supplied (ENS) to the consumers, whereas the second objective function minimizes the losses of the distribution system. Moreover, an IEEE 37 Node-Test Feeder and seven test cases are considered for this study. Simulation results show that PL of EVs could be employed as a power source during the islanded and grid-connected mode for improvement of reliability in the power systems.

INDEX TERMS Distribution system reliability, electric vehicle (EV), energy not supplied (ENS), parking lot (PL), smart charging, vehicle-to-home (V2H), vehicle-to-grid (V2G).

I. INTRODUCTION

Electricity is the main driving force behind the modern economy. It is used from household equipment to the industrial motor that drives an assembly line. Electricity outages cost billions of dollars every year in the world. It has been estimated that blackouts in a single year cost around 79 billion dollars in the United States alone in which residential, industrial, and commercial sectors face 2% ($1.5 billion), 26% ($20.4 billion) and 72% ($56.8 billion) of the total cost of blackouts, respectively [1]. Reliability issues are of great concern, especially on the distribution side. An overhead distribution system is exposed to nature; environmental hazards

The associate editor coordinating the review of this manuscript and approving it for publication was Guillaume Parent.

can harm the lines easily and consumers can suffer from frequent blackouts. Storage systems and distributed generation are used as power sources to overcome these issues [2], [3]. The arrival of EVs opens a new pathway to improve the reliability of the distribution system by utilizing EVs as a source of power for distribution systems. The transportation sector is moving from conventional fuel/gas vehicles toward EVs to reduce the emission and make the environment clean. The number of EVs is increasing exponentially around the world from 6000 in 2010 to 750000 in 2016, and the light-duty EVs are predicted to reach 150 million by 2030 [4].

The integration of EVs in the traditional electric power system will bring many challenges; hence, it demands new optimal planning approaches [5], [6]. These EVs can give benefits to the power system if smartly handled; as EVs are

different from other electrical loads, they can store energy in their batteries and can be controlled without violating the constraints and the main purpose of the EVs [7]. The EVs can be used as a source of energy for the grid in the form of vehicle-to-home (V2H) and vehicle-to-grid (V2G) by appropriate planning and modeling strategies [8]–[11]. Therefore, to enhance the reliability of the grids by suitable planning and modeling of the EVs, appropriate optimization is required to integrate the EVs and resolve the operational problems of distribution systems. After a fault, a major region may face blackouts for several hours. In some regions, distributed generation is used to supply the power to the disconnected region in the island mode. The integration of EVs in the power system also offers an opportunity to give power to the disconnected region during the blackout. Therefore, it is essential to integrate EVs with proper distributed planning methods to maximize the reliability of the grids during faults and operational difficulties.

A. LITERATURE REVIEW

In the past, different techniques have been proposed to improve the reliability of the power system and consumer satisfaction with the help of EVs. In [12], to improve the reliability, a centralized charging station for EVs-battery swapping is considered, and the stored energy in the batteries of EVs is used in parallel with the generator to fasten the restoration time after a blackout by finding out the feasible restoration path with the help of a bi-level optimization-based network model. In [13], a bottom-up restoration strategy is suggested for reliability improvement; EVs compensate the imbalance between load and generation to meet the load pickup point quickly during the restoration of the power system after an outage with the help of mixed-integer linear optimization. In [14], a sequential Monte Carlo method is adopted to evaluate the centralized and dispersed charging of EVs and the capability of V2H and V2G during the blackout. In [15], EVs-employing battery swapping is considered, and a battery exchange station is utilized as a source to supply power during the interruption for the improvement of reliability. Moreover, most of the other studies on the EVs integration in the power system are only focusing on the voltage support, load smoothing, and smart charging of EVs. A two-stage control algorithm is proposed in [16] to collaborate EVs with online load tap changing to alleviate the voltage issues produced by distributed solar generation. In [17], a smart charging algorithm for EVs based on droop controller without depending on the V2G ability regulates the charging current according to the local voltage measurements to mitigate the voltage unbalance. A multi charging station with the help of fuzzy controller is proposed in [18] to utilize EVs-batteries as an energy storage system for valley filling and peak shaving to maintain the rated voltage limit. Another control algorithm is proposed for peak shaving and valley filling in [7] to energize the grid. In [19], using a genetic algorithm (GA), an optimal site and size of the parking lot (PL) are determined for grid support to improve the voltage profile. The GA and particle swarm optimization (PSO) algorithms are proposed in [20] to enhance the availability of PL economically and reduce the losses of the distribution network. In [21], stochastic programming is used for coordinated charging which decreases the losses and increases the grid load factor compared to the uncoordinated charging of EVs which causes grid problems. In [22], an artificial intelligence algorithm is used to minimize the charging cost of EVs. In [23], EVs load management control scheme is developed for coordination of EVs charging to reduce the generation cost and system losses.

Most of the previous studies addressed the problems caused by the uneven load profiles of distribution networks. Furthermore, voltage profile, frequency regulation, and smoothing the load profile are considered using smart charging techniques for charging/discharging of EVs. In [24], a control method is proposed to use EV as a virtual power plant for providing primary frequency reserve in the grid. In [25], a control scheme is proposed to minimize the imbalance among the feeder produced by the photovoltaic generation and EVs integration. Monte-Carlo technique is used to address the variations in EVs load. In [26], the impacts of coordinated, uncoordinated, and smart charging of EVs on the microgrids are investigated with the help of deep machine learning and collective decision-based optimization algorithm. In [27], demand response load and EVs in PLs are utilized for load management to increase the system profit and grid reliability under peak hours and reducing energy not supplied to the industry. The economic and environmental performance of future buildings powered by the photovoltaic generation where EVs are considered in the system is analyzed in [28]. The surplus of electrical energy is used to charge EVs and electrical batteries. In [29], the potential integration of EV charging into large-scale district heating systems is explored. The aim is to improve the financial feasibility of the system. Via agent-based modeling, the diverse range of distributed technologies considering residential and commercial EVs charging demands are modeled. In [30], GA is used to minimize the operating cost of microgrids utilizing EVs and renewable energy resources. In [31], a demand response-based method is developed for increasing the penetration level of EVs at the power system. However, there are some major problems that have been overlooked such as faults or complete blackout in a region which decrease the reliability of the power system. The identification of a PL location in a region during planning can be significantly profitable in terms of continuous power supply if that region is disconnected from the main grid during the fault. The location of a PL with smart charging capabilities, without affecting the main purpose of EVs which will supply the power in an islanded mode, has not been studied yet.

B. CONTRIBUTION

In this paper, a new approach is presented for improving the reliability of the distribution system with the help of EVs. Several factors that have an enormous impact on the distribution system and EVs energy capacity such as

charging/discharging rate and time, daily traveling distance, departure and arrival times are considered for modeling. An intelligent mixed-integer multi-objective optimization scheme is developed for the integration and utilization of EVs in grid-connected mode or in the standalone mode of operation in the distribution system. The first objective is to reduce the ENS, which improves the system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI). The second objective is to minimize the losses of the distribution system. Furthermore, EVs are employed in peak shaving to reduce the impact of peak load on the generating station and improve the voltage of the distribution system. First, the stored energy and location of the EVs are optimized. The power is supplied from the EVs to the disconnected consumers of the distribution system during the fault in standalone mode. Second, the remaining potential of EVs is utilized during grid-connected mode for loss reduction and peak clipping. The proposed scheme is tested on the IEEE 37 Node-test Feeder and the results of different cases are compared.

The major contributions of this paper are summed up as follow:

- Capacity contribution of EVs: This paper has proposed the capacity contribution of EVs in PL or dispersed in a distribution system taking all the constraints into the consideration.
- Reliability indices improvement: The EVs are utilized in standalone mode to supply power to the disconnected region of the distribution system to improve the SAIDI and SAIFI.
- Losses reduction: Smart charging strategy for the EVs is developed to reduce the losses of a distribution system.
- Voltage regulation: A smart discharging scheme during grid-connected mode is employed which improves the voltage of the distribution system.

C. ORGANIZATION OF PAPER

This paper is organized as follow: Section 2 illustrates the modeling of EVs and PL. The optimization problem and constraints are demonstrated in Section 3. Section 4 explains the optimization algorithm. The test system and cases are discussed in Section 5. The results are discussed and explained in Section 6 and the challenges and future work is discussed in Section 7. Finally, the paper is concluded in Section 8.

II. MODELLING OF EVs AND PARKING LOT

The increasing number of EVs are providing storage and load smoothing opportunities for distribution systems. Personal vehicles remain idol in PL most of the time of day. In [32], it is analyzed that at maximum 10% of personal vehicles are on roads during the rush hours. The vehicles in the PL can be modeled as an aggregated load or a generator.

One of the issues in the planning of power systems in the presence of EVs is the unavailability of EVs data. In this paper, an assumption of the same behavior of the electrical and conventional fuel-based vehicle is made and vehicles

TABLE 1. Nomenclatures.

P_{PLchr}	Charging rate of PL
V_{PLn}	Voltage of the node where PL is connected
Chr_{rate}	Charging factor
TEVs	Total number of EVs availible at any time t
B_{cap}	Charging factor
P_{PLdis}	Discharging rate of PL
Dis_{rate}	Discharging factor
P_{lf}	Disconnected load
E_{PL}	Availible energy in PL at time 't'
E_{PLini}	Initial energy in PL
β	Energy of EVs leaving PL at time 't'
α	Energy of arrived EVs at time 't'
$NEVs_{Dep}$	Aggrigate of total EVs departure at time 't'
$NEVs_{Arr}$	Aggrigate of total EVs arrived at time 't'
ε_{EV}	Capacity of EV battery
λ	SOC at the time of departure
μ	Energy consumed by EVs
D	Distance traveled
ν	Average traveled distance per 100 Kwh
$TEVs_{Dep}$	Number of EVs departure
$TEVs_{Arr}$	Number of EVs arrived
C_c	Charging cost
E_c	Charged energy
C_{fc}	Fixed cost per unit of charging
C_{vc}	Variable cost per unit of charging
C_{cf}	Charging cost factor
C_d	Discharging cost
E_d	Discharged energy
C_{fd}	Fixed cost per unit of discharging
C_{vd}	Variable cost per unit of discharging
C_{df}	Discharging cost factor
C_T	Total cost

with the daily trip distance equal to or less than 30 miles are considered only. The data of the 2017 national household survey is used for the vehicle arrival, departure times, and daily traveling distance [33].

A. CHARGING AND DISCHARGING RATES
1) CHARGING RATE
One of the important decisions to be made after the EVs integration in the power system is: when an EV should be

charged and how much should be the charging rate. The load of the distribution system is varying. Therefore, the EVs are charged during off-peak hours, and the priority is given to those EVs whose trip starting time is the nearest. Equation (1) shows the charging rate of EVs:

$$P_{PLchr}(t) = (V_{PLn}(t) - 1) * Chr_{rate} \quad (1)$$

$$SOC_{new} = SOC_{old} + \frac{(V_{PLn}(t) - 1) * Chr_{rate}}{TEVs * B_{cap}} * \Delta t \quad (2)$$

where P_{PLchr} shows the rate of charging power. V_{PLn} is the voltage of the PL bus, and Chr_{rate} is the charging factor obtained via the proposed algorithm. Equation (2) shows the aggregated state of charge (SOC) of the EVs in PL, and SOC_{new} represents the updated SOC of the EVs in PL. SOC_{old} is the previous aggregated SOC of EVs in PL. TEVs is the total number of EVs, and B_{cap} is the capacity of the EV battery.

2) DISCHARGING RATE

When EVs are utilized for reliable power flow, smart discharging should be performed without affecting the main purpose of the EVs. Those EVs which stay long in the PL are considered as a power source for the grid or islanded mode of operation.

$$P_{PLdis}(t) = (1 - V_{PLn}(t)) * Dis_{rate} \quad (3)$$

$$P_{PLdis}(t) = \sum_{i=1}^{n} P_{lfi} \quad (4)$$

The discharging rates for voltage support and standalone mode are different. Equation (3) shows the PL rate of discharging during grid-connected, where Dis_{rate} is the discharging factor obtained via the proposed algorithm. Equation (4) represents the rate of discharging during fault conditions, where P_{lfi} is the load at any node 'i' supported by the parking lot. In these conditions, SOC of the parking lot is given as:

$$SOC_{new}$$
$$= \begin{cases} SOC_{old} - \dfrac{\sum_{i=1}^{n} P_{lfi}}{TEVs * B_{cap}} * \Delta t, & \text{if fault} \\ SOC_{old} - \dfrac{(1 - V_{PLn}(t)) * Dis_{rate}}{TEVs * B_{cap}} * \Delta t, & \text{otherwise} \end{cases} \quad (5)$$

B. ENERGY CAPACITY OF PL

The capacity of the PL is varying due to the varying numbers of EVs in the PL. Equation (6) is a general equation without any charging and discharging that shows the aggregated energy available in the PL at any time. In equation (6), E_{PLini} is the initial energy of the PL. β and α are the arrays of the energy of EVs departure and arrival for the whole day, respectively.

$$E_{PL}(t) = E_{PLini} - \beta(t) + \alpha(t) \quad (6)$$

$$\beta(t) = \sum_{i=1}^{t} NEVs_{Dep}(i) * \varepsilon_{EV} * \lambda \quad (7)$$

$$\alpha(t) = \sum_{i=1}^{t} (NEVs_{Arr}(i) * \varepsilon_{EV} * \lambda) - \mu(i) \quad (8)$$

$$\mu(i) = NEVs_{Arr}(i) * \frac{D * v}{100} \quad (9)$$

$$NEVs_{Dep}(i) = \sum TEVs_{Dep} \quad (10)$$

$$NEVs_{Arr}(i) = \sum TEVs_{Arr} \quad (11)$$

$$E_{PL}(t) = E_{PLini} - \beta(t) + \alpha(t) + \sum_{i=1}^{t} P_{PLchr} - \sum_{i=1}^{t} P_{PLdis} \quad (12)$$

$$SOC_{PL}(t) = SOC_{PL}(t-1) + \frac{\alpha(t) - \beta(t)}{TEVs * B_{cap}} + \frac{P_{PLchr} - P_{PLdis}}{TEVs * B_{cap}} * \Delta t \quad (13)$$

The PL acts as a smart charging station, it should give priority to EVs that are leaving. The energy for standalone and grid support is taken from EVs which are staying long in the PL, so that smart charging of the PL had enough time after the fault to charge the EV batteries to the required SOC level for the coming trips. The energy available and the SOC of PL after smart charging and discharging are shown in equations (12) and (13), respectively.

C. COST ANALYSIS

Cost is the most important factor in assuring EVs owners to enable their EV for bi-directional energy flow. Because the lifespan of EVs battery is affected by various factors such as the depth of discharge, the frequency of charging/discharging, and the magnitude of charging/discharging currents [34]. Utilizing EVs for demand response will degrade the battery of EVs. The policymakers are focusing to give incentives to EV owners for utilizing EVs for frequency control, losses reduction, demand response, and reliability improvement. The cost model in this paper consists of fixed and variable costs. In peak hours the cost of energy will be more compared to the off-peak hours, convincing EV owners to participate in demand response. The variable cost of charging and discharging motivates EV owners to whether sell or power. The cost of charging and discharging are calculated by equations (14) and (15), respectively. The first part of these equations is fixed while the second part is variable depending upon the level of load on the grid. The total cost of the EVs energy consumption is shown in equation (16).

$$C_c = E_c C_{fc} + E_c (C_{vc} - C_{cf}(V_{PLn} - 1)) \quad (14)$$

$$C_d = E_d C_{fd} + E_d (C_{vd} + C_{df}(1 - V_{PLn})) \quad (15)$$

$$C_T = C_c - C_d \quad (16)$$

III. OPTIMIZATION PROBLEM
A. OBJECTIVE FUNCTION

Typically, there are a large number of vehicles and nodes in a distribution system. Picking the best region of the island within an island where PL will provide power after a fault,

the location of PL, charging/discharging rate, and time for improving reliability are difficult to select manually or with a hit and trial method. Thus, the problem of the island within an island, location of PL, and charging/discharging of EVs is formulated as an optimization problem. Fig. 1 shows the objectives of our proposed scheme. The first objective for the minimization of the fault duration or ENS to consumers is shown in equation (17). This objective will improve the SAIDI and SAIFI of the system. Whereas Equation (18) shows the objective function of line losses. This objective will improve the voltage of the system.

Minimize:

$$f_1(T, P) = \sum_{k=m}^{n} T_{fault} * P_{lk} \qquad (17)$$

$$f_2(p, s) = \sum_{h=1}^{D} \sum_{m=1}^{H} \sum_{i=1}^{N} \left(\frac{P_{i,m,h} + Q_{i,m,h}}{V_{i,m,h}} \right)^2 * R_{ij} \quad (18)$$

where T_{fault} is the duration of fault, and P_{lk} is the load that is disconnected during the fault. k represents the set of loads not supplied during the fault. P and Q are the real and reactive powers, respectively. V is the node voltage, and R is the line resistance. Equation (17) is the main objective function for improving reliability, and the minimization of Equation (17) directly minimizes Equations (19) and (21). Therefore, Equation (17) can be transformed into Equations (19) and (21).

$$SAIDI = \frac{\sum r_i * N_i}{N_t} \qquad (19)$$

$$SAIFI = \frac{\sum N_i}{N_t} \qquad (20)$$

where r_i, N_i and N_t represent the restoration time in minutes, the total number of customers interrupted and the total number of customers served, respectively.

B. CONSTRAINTS
1) VOLTAGE LIMITS
During the charging/discharging, the voltage of each node should be within the specified limits. The voltage will start dropping if the load is too high, and the voltage starts rising if we decrease the load; therefore, we are limiting the rates of charging and discharging so that the voltage does not violate the voltage standard.

$$V_{min} < V_n < V_{max} \qquad (21)$$

2) LINE CAPACITY
The current flowing in each line should not exceed the maximum current carrying capacity of the conductors. The flow of current in a line depends on the load connected to it. The load should be within the limits to avoid the capacity issues of the line and any other damages to the line. The current in the line can be calculated as follow:

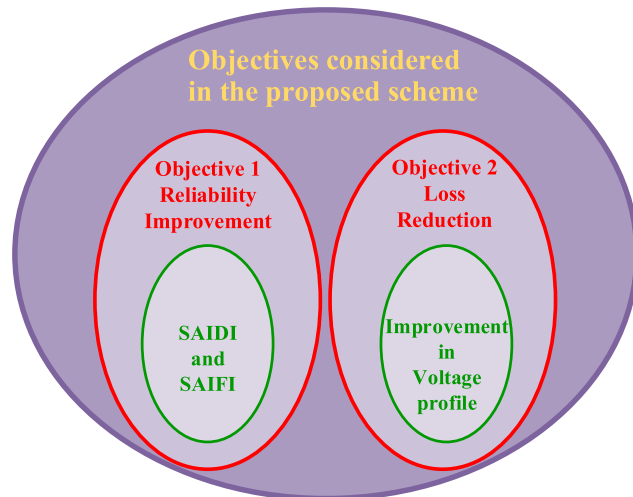$$I_{lx} = \sum_{i=x}^{m} \frac{S_n(i)}{V_n(i)} \qquad (22)$$

FIGURE 1. Objectives of the proposed algorithm.

where I_{lx} represents the total current in any line x. S_n is the array of the total load connected to the nodes and V_n is the array of the node voltage. If we place a PL in any region with the help of optimization, the lines within that region should be capable enough to withstand the flow of current. The placement of the PL will increase the load on that line and all the other lines which are in between PL and the substation. In that case, the current in line is:

$$I_{lx} = \sum_{i=x}^{m} \frac{S_n(i)}{V_n(i)} + \frac{P_{PL}}{V_{PL}} \qquad (23)$$

3) SOC OF EVs BATTERIES
The main purpose of a vehicle is to provide easiness in traveling. In order to not affect the main purpose of EVs, we are maintaining the same SOC of the batteries at the end of the day as it was at the beginning of the day.

$$SOC_{end} = SOC_{start} \qquad (24)$$

Furthermore, only those vehicles are considered for the discharging which have extra SOC and are staying long in the parking lot, so that it should be charged back to the same level of SOC as it was before the discharging.

4) PL SELECTION AS A POWER SOURCE
After the fault, only the PL of the disconnected zone will be employed to supply the power to some portion of the disconnected load. The equation below further explains the constraint:

$$S_s = PL_i \qquad (25)$$

S_s is the power source of an islanded zone and PL_i is the PL, where i represents the disconnected zone.

5) ISLAND SIZE
To supply the continued power to the island within the disconnected region of the distribution system, the size of the
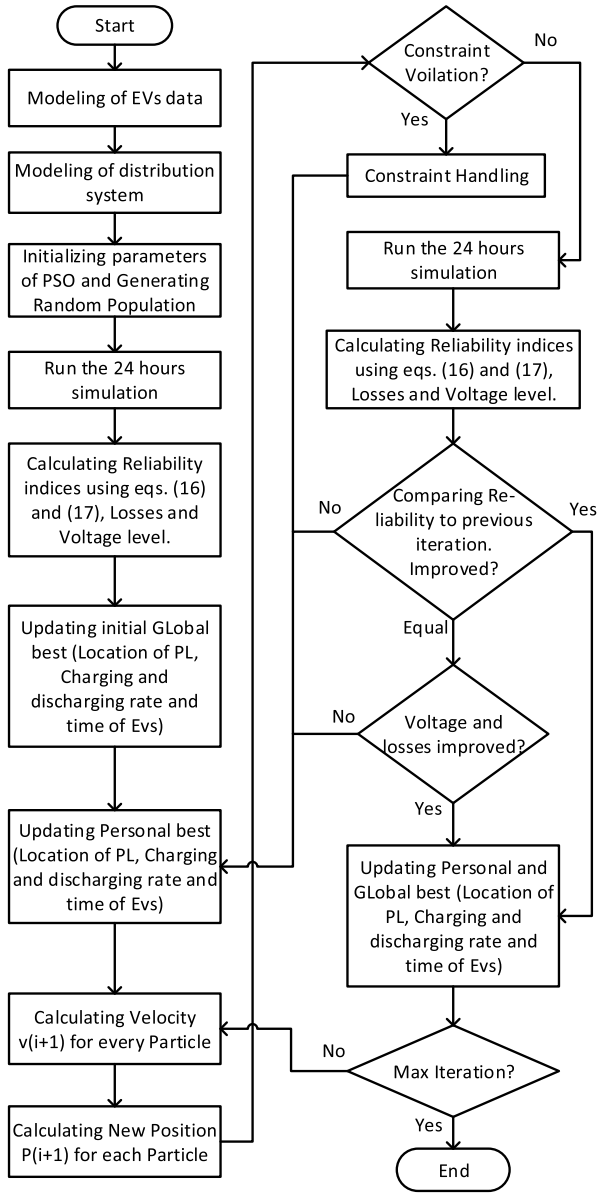
FIGURE 2. Flowchart of the proposed algorithm.

island should be within the limits so that the load does not exceed the available energy of EVs in PL. The mathematical expression is as follow:

$$\sum_{i=j}^{k} P_{Li}(t) <= E_{aPL} \qquad (26)$$

where P_{Li} represents the load at any node and E_{aPL} is the available energy to utilize during the fault.

IV. THE OPTIMIZATION ALGORITHM

The optimal location and charging/discharging of EVs in PL is a problem of the class known as non-deterministic polynomial-time problems. The heuristic algorithms such as PSO is recommended to solve such types of mixed-integer

non-linear problems. The PSO is a population-based intelligent search algorithm introduced by Kennedy and Eberhart in 1995 for non-linear functions [35] and is inspired by the social behavior of the animals such as birds and folks. The PSO is a simple and powerful optimization algorithm, and it is applicable to different applications in science and engineering such as machine learning, image processing, data mining, and many other fields. A PSO algorithm search in a space called search space to find the optimal solutions. This search space can be one dimension or multi-dimension. The PSO is an iterative algorithm. The position of the particle in the search space is represented by the n-dimension vector. The next position of the particle is determined by its n-dimension velocity vector. The velocity and position vectors are updated in every iteration with the help of personal best (Pbest) and global best positions (Gbest). Pbest is the best position of the particle which has the best value so for, and Gbest is the best position of the particle which has the best value in the whole swarm so for. The iteration stops when it converges to an optimal solution.

Fig. 2 shows the flowchart of the complete implementation pattern of the proposed algorithm for finding the best location of PL, calculating charging/discharging rates and times, and finding the region to supply the power after a fault. First, the EVs data and the distribution system are modeled. Second, the parameters of PSO are initialized and the random population is generated. Third, 24-hour simulation is performed and reliability indices SAIDI, SAIFI, losses, and voltage level are calculated. Next, the personal and global best solutions are updated. In the next step, the updated personal and global best solutions are used to find the velocity of each particle which updates the position of each particle. If a particle violated the constraint, a constraint handling method is applied. In which according to the degree of constraints violation, the worst values of objective functions are assigned to the solution of that particle. Next, the 24-hour simulation is performed again and the values of objective functions are calculated. If the values of reliability indices of the distribution system are not improved, the process is repeated and if they are improved, the global and personal best solutions are updated as shown in Fig. 2. If the values of reliability indices are equal to the previous values, the values of voltage and distribution system losses are compared to previous values. If they are not improved, the global best remains the same and the process is repeated again and if they are improved, the global and personal best solutions are updated in the next step. Finally, the process repeats itself until the maximum value of iteration is reached.

V. TEST SYSTEM AND TEST CASES

To verify the proposed methodology, IEEE 37 Node-test Feeder is considered as a test system as shown in Fig. 3. The specification of the test system can be seen in [36]. In this case study, the system is divide into three zones as shown in Fig. 3 and there will be a single PL in each zone. Seven cases have been considered to observe the required results.
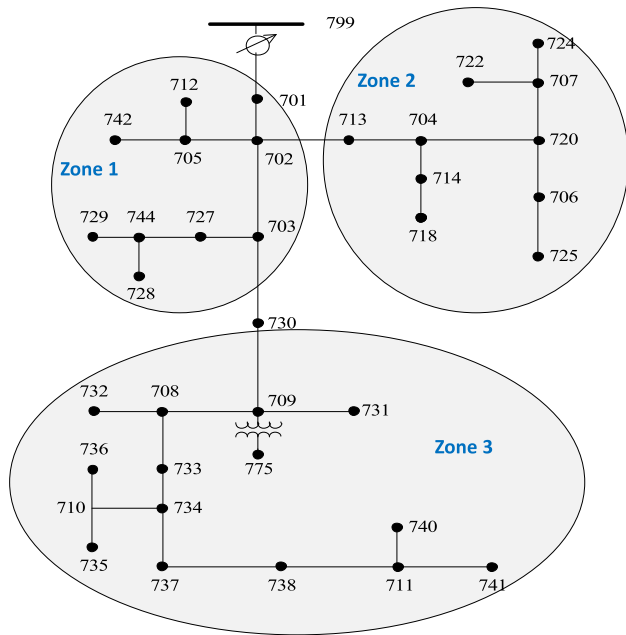
FIGURE 3. IEEE 37 NodeTest Feeder.

- Case 1: No EVs in the distribution system

Distributed EVs:

- Case 2: EVs as a load in the distribution system
- Case 3: EVs as a source for islanded mode
- Case 4: EVs as a source for islanded and grid-connected modes

Centralized EVs:

- Case 5: EVs as a load in the distribution system
- Case 6: EVs as a source for islanded mode
- Case 7: EVs as a source for islanded and grid-connected modes

In Cases 2–4, the EVs are considered as a distributed load or source and are connected in every home in the distribution system. Moreover, in Case 2, EVs are considered as a load in the distribution system and only the charging time and rate for EVs are found. In Cases 3 and 4, the EVs are utilized as a storage source for the distribution system. In Case 3, the charging/discharging times, rates, and energy provided to the consumers in islanded mode are found. In Case 4, an addition of energy provided during peak hours in grid-connected mode is found. In Cases 5–7, EVs are considered as a centralized load or source in a PL of each zone. The location of PL is found in Cases 5–7. The only differences between Cases 5–7 and Cases 2–4 are the EVs charging/discharging scheme and the point of connection in the distribution system.

VI. RESULTS AND DISCUSSION

The obtained results with non-linear PSO for Cases 1–7 are shown in Table 2. A fault is considered on a line from Bus 730 to 709, with the duration of 2 hours from 11:45 AM to 1:45 PM. Case 1, where no EV is considered in the system, the results in Table 2 show the highest value of SAIDI, SAIFI, and ENS. In Case 2, the results are the same as in Case 1 but here EVs are considered in the system, and the

TABLE 2. Losses, SAIDI, SAIFI and ENS of all the cases.

Cases	SAIDI	SAIFI	ENS (Kwh)
Case 1	36.8127	0.3068	992.65
Case 2	36.8127	0.3068	992.65
Case 3	13.8048	0.3068	383.13
Case 4	13.8048	0.3068	383.13
Case 5	36.8127	0.3068	992.65
Case 6	11.9522	0.0966	324.47
Case 7	11.9522	0.0966	324.47

TABLE 3. Location of PL in all zones.

Cases	Zone 1	Zone 2	Zone 3
Case 5	705	713	741
Case 6	712	713	733
Case 7	728	722	709

proposed algorithm optimizes the charging time and rate of EVs in the home to reduce the impact of EVs integration on the grid. In cases 3 and 4 where EVs are scattered in the system and utilized as a source for the distribution system. During a fault, EVs provide power back to the distribution system as V2H in island mode. The results of SAIDI and ENS show improvement with the reduction of 62.5% and 61.4% respectively as shown in Table 2.

In Cases 5–7, EVs are considered as a cluster in the PL of each zone, the optimal location, charging, and discharging are optimized for best results. In Case 5, EVs are integrated into the distribution system from the best location of the PL in each zone, but it does not provide power back to the consumers. The results of SAIDI, SAIFI, and ENS show no improvement by looking at Table 2. Cases 6 and 7 show the best results in all the cases by providing power back to the system during islanding mode from the optimized location, charging, and discharging. By looking at Table 2, comparing to Case 5 the results of Cases 6 and 7 showed great improvement with the reduction of 67.53%, 68.51%, and 67.31% in SAIDI, SAIFI, and ENS, respectively.

The line losses of the test system in all the zones and grid transformer during Cases 1–7 are shown in Table 4. The line losses in Case 1 are due to load current flowing in lines as can be seen in Table 4. After integration of EVs in Case 2, where EVs only get charged and cover the need of daily trips, the charging of EVs is optimized to charge in off-peak load duration which reduces the impact on the grid by not contributing to the increase of peak load hours; hence the

| Zones	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Zone 1	80.58 Kwh	81.46 Kwh	81.86 Kwh	67.61 Kwh	81.42 Kwh	81.84 Kwh	66.70 Kwh
Zone 2	19.37 Kwh	19.59 Kwh	19.59 Kwh	14.88 Kwh	19.42 Kwh	19.42 Kwh	13.23 Kwh
Zone 3	27.12 Kwh	27.37 Kwh	27.55 Kwh	25.39 Kwh	27.46 Kwh	27.68 Kwh	27.25 Kwh
Xtrans	1034.30 Kwh	1042.61 Kwh	1045.48 Kwh	881.11 Kwh	1042.64 Kwh	1045.56 Kwh	879.21 Kwh
Total Losses	1164.40 Kwh	1171.04 Kwh	1174.50 Kwh	989.00 Kwh	1170.96 Kwh	1174.51 Kwh	986.40 Kwh
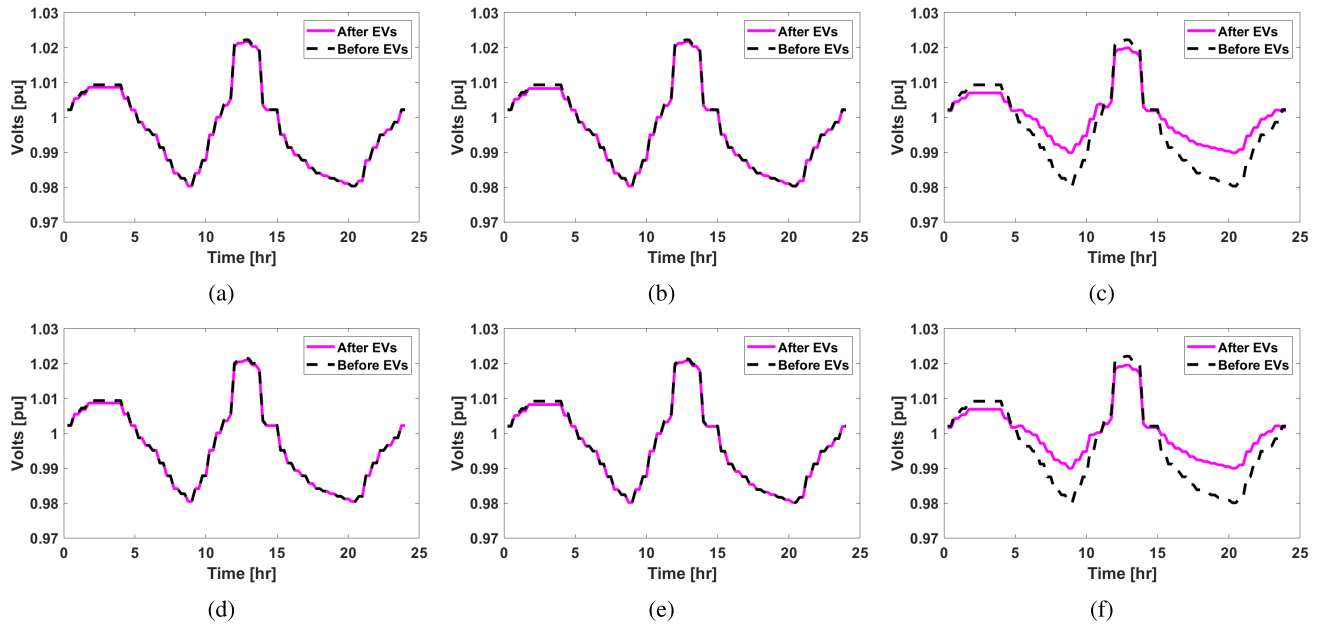
FIGURE 4. RMS voltage of a bus in Zone 1 (a) Case 2 (b) Case 3 (c) Case 4 (d) Case 5 (e) Case 6 (f) Case 7.

line losses do not increase heavily in that case. By looking at Table 4, the losses in Case 3 increase further; it is due to the extra charging of EV-batteries to store the reserve energy for providing the power in islanding mode to the distribution system. In case 4, the losses are reduced significantly due to the support from EVs in the peak load duration. EVs charge in the off-peak load duration and provide power back to the distribution system in peak hours; hence, the reduction in the losses of around 15% can be seen in Table 4. In Cases 5–7, the proposed methodology not only optimize the charging/discharging rates and times but also give us the optimal location of EVs PL as shown in Table 3, which further increase the benefits from EVs in terms of SAIDI, SAIFI, and ENS as in Table 2 and losses in Table 4. By looking at Table 4, the losses of all the three Cases 5–7 are better compared to Cases 2–4.

Figs. 4 and 5 show the voltage curves of Zones 1 and 2 in all Cases 1–7. In Cases 2-3 and Cases 5 and 6 of Zones 1 and 2 EVs only get charged in the off-peak load hours. Figs. 4 and 5 illustrate that voltage level reduces in off-peak duration due to the increase in load by EVs charging. During Cases 4 and 7

in Zones 1 and 2, EVs are improving voltage levels by supporting the grid in peak hours. Figs. 4 and 5 show the reduction of voltage in off-peak hours due to charging of EVs and improvement in the voltage levels due to the discharging in peak hours. The proposed algorithm gives us the optimized rate and time of charging/discharging without violating the constraints to benefit the utility grid and consumers.

Fig. 6 shows the voltage of all cases in Zone 3 where the fault is considered. It can be seen in Fig. 6, in Cases 2 and 5, EVs do not supply power in the islanded mode so the consumers of that region face total shut down during the fault. In Case 3, by looking at Fig. 6b, the duration of shut down reduces because EVs provide power for some time to the whole disconnected region. Fig. 6c, shows the result of case 5, besides providing power in islanded mode, EVs improved voltage level as well with optimized charging and discharging. In Case 6 EVs provide power throughout the fault to most of the consumers as can be seen in Fig. 6c. The voltage is maintained around 1pu during the fault. Furthermore, in this case, the algorithm makes an optimized island within the island to minimize SAIDI, SAIFI, and ENS as
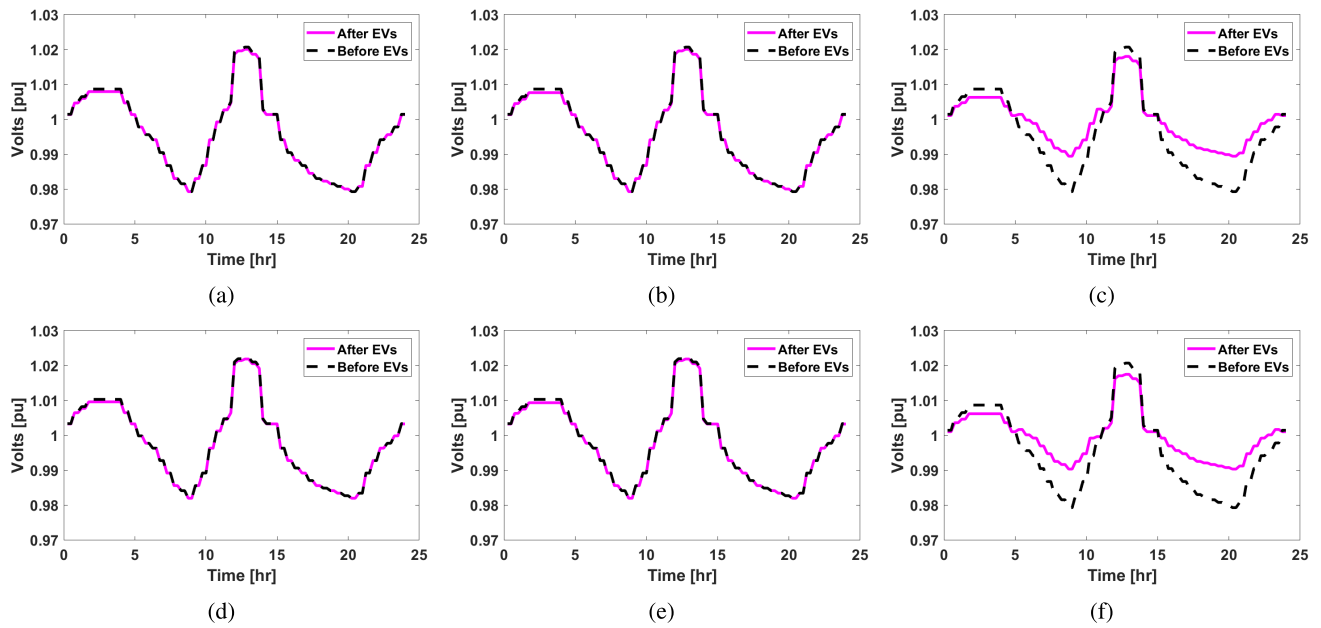
FIGURE 5. RMS voltage of a bus in Zone 2 (a) Case 2 (b) Case 3 (c) Case 4 (d) Case 5 (e) Case 6 (f) Case 7.
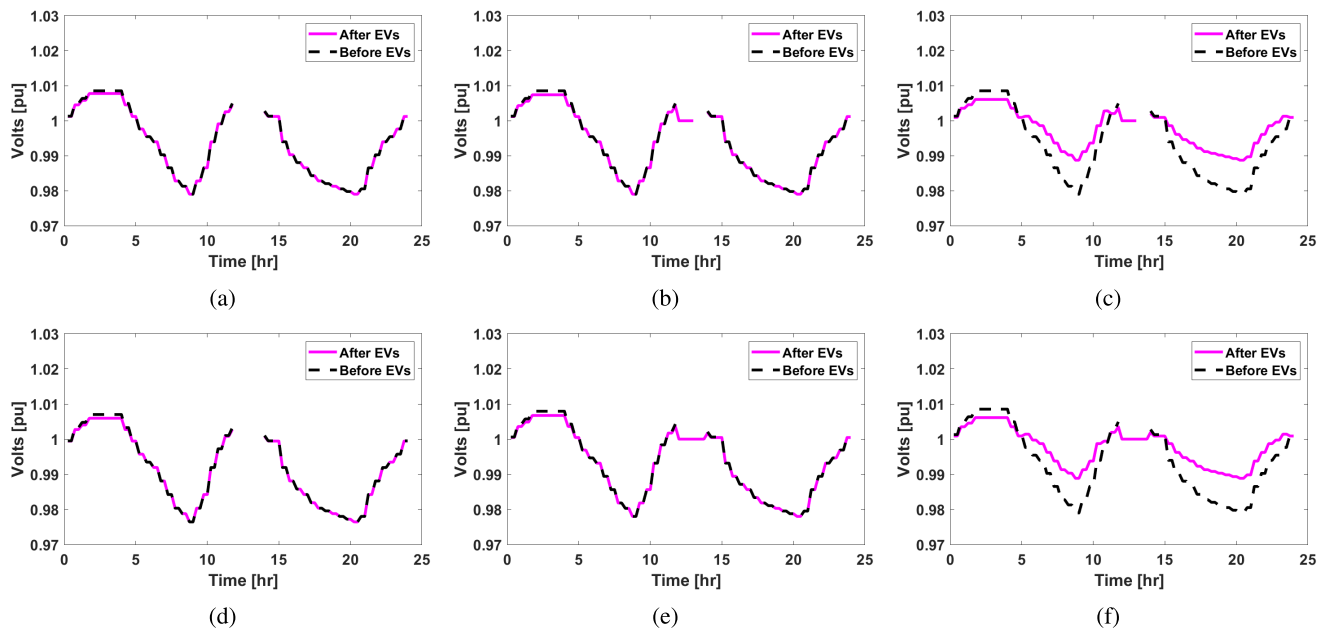

FIGURE 6. RMS voltage of a bus in Zone 3 (a) Case 2 (b) Case 3 (c) Case 4 (d) Case 5 (e) Case 6 (f) Case 7.

much as possible. Fig. 6f shows the results of Case 7 where EVs regulate voltage besides providing power to the island within the island.

Fig. 7 shows the SOC of EVs in each case for all the zones. Figs. 7a and 7d show the lowest maximum SOC because EVs use energy for their trip purpose only. In Figs. 7b and 7e, the SOC of EVs in Zone 3 exceeds 0.8 because of keeping the reserve capacity for supply during the fault in Zone 3. Figs. 7c and 7f show the SOC of each zone charged to the

maximum value in all the cases. It is due to the maximum utilization of the EV-batteries for the islanded mode and grid support in voltage regulation and losses reduction.

Table 5 shows the cost of energy consumed by EVs. It can be seen that utilizing EVs as a source can reduce the daily cost of EVs energy consumption. During distributed EVs, comparing Case 2 to Case 4 the daily aggregated cost of EVs reduces significantly by 32%. By comparing distributed EVs bi-directional behavior in Case 4 to the centralized
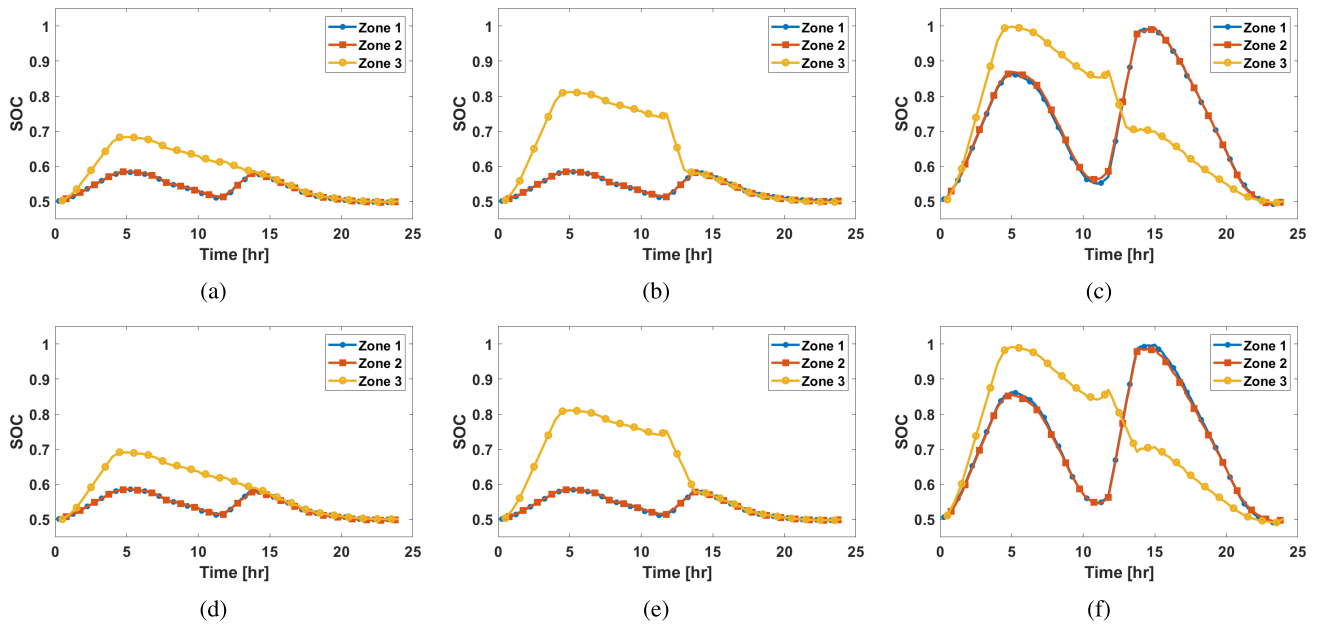
FIGURE 7. Aggrigated SOC of EVs in Zone 3 (a) Case 2 (b) Case 3 (c) Case 4 (d) Case 5 (e) Case 6 (f) Case 7.

TABLE 5. Charging cost of EVs per day.

Zones	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Zone 1	$516.14	$525.51	$286.37	$521.98	$516.81	$279.31
Zone 2	$625.80	$632.00	$287.72	$621.56	$621.22	$287.13
Zone 3	$1041.96	$976.93	$897.93	$1031.61	$859.33	$723.15
Total Cost	$2183.90	$2134.44	$1472.02	$2175.15	$1997.36	$1289.59

behavior of bi-directional EVs in Case 7, the daily cost further reduces around 13%. The bi-directional behavior of EVs charges the energy during off-peak and during peak hours or blackouts it provides energy to grid or consumers.

VII. CHALLENGES AND FUTURE WORK

EVs are getting popular both in terms of environmental and economic benefits. Tax incentives provided by the government and reduced fuel cost per mile are the motivation for increasing EVs in the market. EVs promise enormous benefits to both electric power utilities and consumers. However, the traditional distribution system lacks advanced techniques to enable bi-directional power flow to EVs. Integrating EVs in the current distribution system for grid support and reliability improvement needs advanced protection, control, and communication techniques. The uncontrolled charging of EVs can affect the operation of the electric power system in terms of increased peak load, abrupt voltage deviation, increased losses, and price volatilities. Furthermore, battery degradation is a great concern of EV owners. The tariff policies need regulations to provide incentives and motivation for participating in demand response (DR) programs.

Integration of EVs with power grid called V2G technology and this area is getting a lot of research interest. Designing PL and charging stations with renewable energy sources is also practicable in the future. Providing secondary services to the electric grid in terms of frequency control is an encouraging application of EVs. Future work will focus on gathering real-time data of EVs behavior, customer participation in DR programs, and considering a customer satisfaction parameter in the objective function. Moreover, designing coordinated charging, control, and communication algorithms for systems such as charging at home and PL needs to be focused on.

VIII. CONCLUSION

In this paper, the problem of charging/discharging of the EVs and the location of PL to increase the reliability of the distribution system is presented. Different factors that are associated with the EVs such as number of EVs, daily trip distance, daily trip time, starting/ending time of the trip, charging/discharging time and rate were considered and modelled. The problem was formulated as the mixed-integer non-linear programming to maximize the reliability, minimize the losses and regulate the voltage of the distribution system. The

optimal solution is calculated with the help of PSO. Seven cases were designed for this paper. The results provided the optimal time and rate of charging/discharging and the optimal location of PL while increasing reliability, reducing losses and regulating the voltage of the distribution system. In summary, the algorithm proposed in this paper can be used for the computation of the rate and time of charging/discharging and the location of PL to maximize the reliability of the distribution system to satisfy the consumers.

REFERENCES

[1] K. Lacommare and J. Eto, "Cost of power interruptions to electricity consumers in the United States (U.S.)," *Energy*, vol. 31, no. 12, pp. 1845–1855, Sep. 2006.

[2] H. Saboori, R. Hemmati, and M. A. Jirdehi, "Reliability improvement in radial electrical distribution network by optimal planning of energy storage systems," *Energy*, vol. 93, pp. 2299–2312, Dec. 2015.

[3] E. Biju, "Reliability improvement and loss reduction in radial distribution system by reconfiguration using black hole algorithm," Annamalai Univ., Tamil Nadu, India, Tech. Rep., Aug. 2017.

[4] Global EV, "Outlook 2016: Beyond one million electric cars," Int. Energy Agency, Paris, France, 2016.

[5] G. S. Lakshmi, R. Olena, G. Divya, and I. Hunko, "Electric vehicles integration with renewable energy sources and smart grids," in *Advances in Smart Grid Technology*. Singapore: Springer, 2020, pp. 397–411.

[6] K. K. Mehmood, C.-H. Kim, S. U. Khan, and Z. M. Haider, "Unified planning of wind generators and switched capacitor banks: A multiagent clustering-based distributed approach," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6978–6988, Nov. 2018.

[7] Z. Wang and S. Wang, "Grid power peak shaving and valley filling using vehicle-to-grid systems," *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1822–1829, Jul. 2013.

[8] D. P. Tuttle and R. Baldick, "The evolution of plug-in electric vehicle-grid interactions," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 500–505, Mar. 2012.

[9] W. Yao, J. Zhao, F. Wen, Y. Xue, and G. Ledwich, "A hierarchical decomposition approach for coordinated dispatch of plug-in electric vehicles," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2768–2778, Aug. 2013.

[10] Z. Liu, F. Wen, and G. Ledwich, "Optimal planning of electric-vehicle charging stations in distribution systems," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 102–110, Jan. 2012.

[11] H. Huang, C. Y. Chung, K. W. Chan, and H. Chen, "Quasi-Monte Carlo based probabilistic small signal stability analysis for power systems with plug-in electric vehicle and wind power integration," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3335–3343, Aug. 2013.

[12] L. Sun, X. Wang, W. Liu, Z. Lin, F. Wen, S. P. Ang, and M. A. Salam, "Optimisation model for power system restoration with support from electric vehicles employing battery swapping," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 3, pp. 771–779, Feb. 2016.

[13] W. Sun, N. Kadel, I. Alvarez-Fernandez, R. R. Nejad, and A. Golshani, "Optimal distribution system restoration using PHEVs," *IET Smart Grid*, vol. 2, no. 1, pp. 42–49, Mar. 2019.

[14] N. Z. Xu and C. Y. Chung, "Reliability evaluation of distribution systems including vehicle-to-home and vehicle-to-grid," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 759–768, Jan. 2015.

[15] H. Farzin, M. Moeini-Aghtaie, and M. Fotuhi-Firuzabad, "Reliability studies of distribution systems integrated with electric vehicles under battery-exchange mode," *IEEE Trans. Power Del.*, vol. 31, no. 6, pp. 2473–2482, Dec. 2015.

[16] L. Cheng, Y. Chang, and R. Huang, "Mitigating voltage problem in distribution system with distributed solar generation using electric vehicles," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1475–1484, Oct. 2015.

[17] S. Martinenas, K. Knezović, and M. Marinelli, "Management of power quality issues in low voltage networks using electric vehicles: Experimental validation," *IEEE Trans. Power Del.*, vol. 32, no. 2, pp. 971–979, Apr. 2016.

[18] M. Singh, P. Kumar, and I. Kar, "A multi charging station for electric vehicles and its utilization for load management and the grid support," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1026–1037, Jun. 2013.

[19] M. Moradijoz, M. P. Moghaddam, M. R. Haghifam, and E. Alishahi, "A multi-objective optimization problem for allocating parking lots in a distribution network," *Int. J. Electr. Power Energy Syst.*, vol. 46, pp. 115–122, Mar. 2013.

[20] M. H. Amini, M. P. Moghaddam, and O. Karabasoglu, "Simultaneous allocation of electric vehicles' parking lots and distributed renewable resources in smart power distribution networks," *Sustain. Cities Soc.*, vol. 28, pp. 332–342, Jan. 2017.

[21] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 371–380, Feb. 2009.

[22] T. Sousa, Z. Vale, J. P. Carvalho, T. Pinto, and H. Morais, "A hybrid simulated annealing approach to handle energy resource management considering an intensive use of electric vehicles," *Energy*, vol. 67, pp. 81–96, Apr. 2014.

[23] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011.

[24] H. H. Alhelou, P. Siano, M. Tipaldi, R. Iervolino, and F. Mahfoud, "Primary frequency response improvement in interconnected power systems using electric vehicle virtual power plants," *World Electr. Vehicle J.*, vol. 11, no. 2, p. 40, May 2020.

[25] J. Su, T. T. Lie, and R. Zamora, "Integration of electric vehicles in distribution network considering dynamic power imbalance issue," *IEEE Trans. Ind. Appl.*, vol. 56, no. 5, pp. 5913–5923, Sep. 2020.

[26] M. Dabbaghjamanesh, A. Kavousi-Fard, and J. Zhang, "Stochastic modeling and integration of plug-in hybrid electric vehicles in reconfigurable microgrids with deep learning-based forecasting," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 7, pp. 4394–4403, Jul. 2020.

[27] Z. Azimi, R.-A. Hooshmand, and S. Soleymani, "Optimal integration of demand response programs and electric vehicles in coordinated energy management of industrial virtual power plants," *J. Energy Storage*, vol. 41, Sep. 2021, Art. no. 102951.

[28] A. Buonomano, F. Calise, F. L. Cappiello, A. Palombo, and M. Vicidomini, "Dynamic analysis of the integration of electric vehicles in efficient buildings fed by renewables," *Appl. Energy*, vol. 245, pp. 31–50, Jul. 2019.

[29] A. Chakrabarti, R. Proeglhoef, G. B. Turu, R. Lambert, A. Mariaud, S. Acha, C. N. Markides, and N. Shah, "Optimisation and analysis of system integration between electric vehicles and U.K. Decentralised energy schemes," *Energy*, vol. 176, pp. 805–815, Jun. 2019.

[30] R. Sabzehgar, M. A. Kazemi, M. Rasouli, and P. Fajri, "Cost optimization and reliability assessment of a microgrid with large-scale plug-in electric vehicles participating in demand response programs," *Int. J. Green Energy*, vol. 17, no. 2, pp. 127–136, Jan. 2020.

[31] M. Kamruzzaman and M. Benidris, "A reliability-constrained demand response-based method to increase the hosting capacity of power systems to electric vehicles," *Int. J. Electr. Power Energy Syst.*, vol. 121, Oct. 2020, Art. no. 106046.

[32] W. Kempton, J. Tomic, S. Letendre, A. Brooks, and T. Lipman, "Vehicle-to-grid power: Battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California," UC Davis Inst. Transp. Stud., Distrib. Electr. Power California, CA, USA, Tech. Rep., 2001. [Online]. Available: https://escholarship.org/uc/item/0qp6s4mb

[33] *National Household Travel Survey*, US. Dept. Transp. Federal Highway Admin., 2017.

[34] K. K. Mehmood, S. U. Khan, S. Lee, Z. M. Haider, M. K. Rafique, and C. Kim, "Optimal sizing and allocation of battery energy storage systems with wind and solar power DGs in a distribution network for voltage regulation considering the lifespan of batteries," *IET Renew. Power Gener.*, vol. 11, no. 10, pp. 1305–1315, Aug. 2017.

[35] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. IEEE ICNN*, vol. 4, Nov./Dec. 1995, pp. 1942–1948.

[36] *Distribution Test Feeders*. Accessed: Jun. 7, 2021. [Online]. Available: https://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html

RASHID KHAN received the bachelor's degree in electrical engineering from COMSATS University, Abbottabad, Pakistan. He is currently pursuing the master's degree in electrical engineering with the National University of Sciences and Technology, Islamabad. His research interests include the power system planning and design, optimization in power systems, machine learning in power systems, and smart grid.

KHAWAJA KHALID MEHMOOD received the B.Sc. degree in electrical power engineering from the Mirpur University of Science and Technology, Mirpur, Pakistan, in 2012, and the Ph.D. degree in electrical power engineering from Sungkyunkwan University, South Korea, in 2019. He is currently working as an Assistant Professor with the Department of Electrical Engineering, The University of Azad Jammu and Kashmir, Muzaffarabad. He has also served as an Assistant Professor with the U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, Islamabad, Pakistan. His research interests include planning and operations of active distribution systems, machine learning applications in distribution systems, electric vehicles, and battery energy storage systems.

SYED BASIT ALI BUKHARI received the B.Sc. degree from The University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan, the master's degree in electrical power engineering from the University of Engineering and Technology, Taxila, Pakistan, and the Ph.D. degree in electrical power engineering from Sungkyunkwan University, South Korea. He is currently working as an Assistant Professor with the Department of Electrical Engineering, The University of Azad Jammu and Kashmir. He has worked as an Assistant Professor with the U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, Islamabad, Pakistan. His research interests include protection and islanding detection of active distribution systems, machine learning applications in distribution systems, microgrid, and smart grid.

KASHIF IMRAN received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Engineering and Technology (UET), Lahore, in 2006 and 2008, respectively, and the Ph.D. degree in electrical engineering from the University of Strathclyde, in 2015. He worked with the Transmission and Distribution Division, Siemens Pvt. Ltd., and the Power Distribution Design Section, NESPAK, from 2006 to 2007. He worked as a Faculty Member with UET and COMSATS University, Lahore. He has been the Head of the U.S.-Pakistan Center for Advanced Studies in Energy, Department of Electrical Power Engineering, National University of Sciences and Technology, Islamabad, since 2018. He received the Commonwealth Scholarship for his Ph.D. degree from the University of Strathclyde.

ABDUL WADOOD received the B.S. degree in electronic engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2012, and the master's degree in electrical engineering from the Sarhad University of Science and Information Technology, Peshawar, in 2015, and the Ph.D. degree from the Department of Electrical Engineering, Yeungnam University, Gyeongbuk, South Korea, in 2019. He is currently an Assistant Professor with the Department of Electrical Engineering, Air University, Islamabad, Pakistan. His research interests include power system relaying, power system protection, energy management systems, renewable energy, and evolutionary and metaheuristic algorithms.

SANG BONG RHEE received the B.S., M.S., and Ph.D. degrees from Hanyang University, South Korea, in 1994, 1999, and 2004, respectively. He was a Research Professor with the School of Electrical and Computer Engineering, Sungkyunkwan University, South Korea. He is currently a Professor with the Department of Electrical Engineering, Yeungnam University, Gyeongbuk, South Korea. His research interests include distribution system control and operation, and artificial intelligence applications for power system protection.

SINA PARK received the master's degree from the Department of Electrical, Electronic and Information System Engineering, Ulsan University, and the Ph.D. degree in electrical engineering from Yeungnam University. Her research interests include optimization systems, renewable energy source, power systems, and distributed power system connection.

● ● ●