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Distribution System Service Restoration Using Electric Vehicles

Swapna Ganapaneni [1], Srinivasa Varma Pinni [1,*], Ch. Rami Reddy [2], Flah Aymen [3], Mohammed Alqarni [4], Basem Alamri [5] and Habib Kraiem [6]

1 Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram 522302, India; swapna@kluniversity.in
2 Electrical and Electronics Engineering, Malla Reddy Engineering College (A), Maisammaguda, Secunderabad 500100, India; crreddy229@mrec.ac.in
3 National Engineering School of Gabès, Processes, Energy, Environment and Electrical Systems, University of Gabès, LR18ES34, Gabes 6072, Tunisia; aymen.flah@enig.u-gabes.tn
4 College of Engineering, University of Business and Technology (UBT), Jeddah 23435, Saudi Arabia; m.alqarni@ubt.edu.sa
5 Department of Electrical Engineering, College of Engineering, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia; b.alamri@tu.edu.sa
6 Department of Electrical Engineering, College of Engineering, Northern Border University, Arar 73222, Saudi Arabia; habib.kraiem@yahoo.fr
* Correspondence: pinnivarma@kluniversity.in

Abstract: Nowadays the utilization of Electric Vehicles (EVs) has greatly increased. They are attaining greater attention due to their impacts on the grid at the distribution level. However, due to the increased need for electricity, EVs are also used to serve the load in the instance of electrical failure in the distribution systems. This paper presents a new approach to a service restoration method for a low-voltage distribution network at the time of a power outage using existing EVs available in a parking place. The objective function formulated here was a constrained linear optimization model. It aimed to develop priority-based scheduling of the residential user appliances while meeting all the operational constraints if the EV's power was in a deficit at the hour of the outage. Weight factors were assigned to various residential appliances to decide their priority while scheduling. To substantiate the proposed methodology, a day load profile of a 20 kVA distribution transformer feeding eight residential users is considered. This was tested during an hour-long power outage scenario in the MATLAB and LINGO platforms, with four EVs available during the outage period. This method restored the maximum power to the residential appliances.

Keywords: Electric Vehicles; service restoration; distribution system; priority-based scheduling; residential appliances

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1. Introduction

Recently, the electricity demand has increased the utilization of power systems. As customers always expect uninterruptible quality power, it poses a challenge to power utility companies to increase their power supply to meet the additional loads. If proper planning is not done, the system gets stressed, which leads to the risk of outages and blackouts. The increased utilization of EVs becomes a promising strategy for service restoration at the distribution level. After a major outage, the distribution system generally requires a long time for maintenance. Dependency on a utility operator for its repair may not result in quick management of an outage. However, a benefit associated with EVs is that the batteries in the EVs help to serve the loads at the time of the outage.

Various potential services offered by EVs for distribution systems are mentioned in [1] and are called EV distribution system services (EVs-DSS). They categorized the services into three main groups. It was suggested that active power support from EVs can be considered for congestion management, loss minimization, peak shaving, valley filling, and voltage regulation and load shifting. Various aspects of EVs, such as technical, economical, regulatory, and user-related issues and their associated barriers, are discussed in [2].

Mixed-integer linear programming was implemented in [3] for fast restoration of a distribution system with different penetration levels of Plug-in Hybrid Electric Vehicles (PHEVs). They analyzed coordination for the restoration of transmission and distribution systems for bringing the system back to normal conditions. A decentralized multi-agent system approach was proposed in [4] for service restoration. It was used to account for uncertainty in load demand and renewable energy resources in 38 bus and 119 bus distribution systems. They highlighted the use of EVs to support the energy uncertainties at the time of restoration.

To improve the resilience of the distribution system, a two-stage optimization model was proposed by [5] for the routing and scheduling of mobile power sources (MPSs), such as EVs. This solution demonstrated its effectiveness when tested on IEEE 33-node and 123-node test systems. A resilient scheme was proposed in [6] for the proper dispatch of repair crews and MPSs for disaster recovery logistics, optimizing the distribution system restoration by forming dynamic microgrids powered by the MPSs. A smart transformer architecture for a solid-state transformer was proposed in [7] to improve the services of the electric grid and the resilience of the system by initiating a restoration procedure after a blackout.

Mobile energy resources (MERs) connected to the distribution system through the transportation system are used for dynamic service restoration to serve critical loads. MERs' dispatching schedule is obtained from a mixed-integer linear programming optimization problem in [8]. The faster self-healing process of a distribution system for reliable load pickup by PHEVs is presented in [9], where a Markov chain process was used to generate the driving behavior of PHEVs and an optimization problem was formulated to restore the maximum load.

Power system restoration was achieved in [10] by locating distributed generators (DGs) optimally. They considered this as a problem of constrained optimization and applied it to both sub-transmission and distribution systems for the minimization of the service area at the time of restoration. A hybrid multi-agent system approach with six agents was implemented for service restoration in [11], using both DGs and EVs. The optimal location of DGs was obtained by using an Open DSS network simulator and proposing an R&M algorithm for finding optimal island ranges.

A real-time household load priority scheduling algorithm was implemented in [12] based on the availability of renewable energy sources to minimize the energy cost and satisfy the comfort of the customers. Assigned priority to home appliances was achieved dynamically for hour-to-hour energy consumption of various home appliances. A strategy for service restoration at multiple levels was proposed in [13] with microgrids and EVs and a fault was created on 3 feeders and 18 nodes of an IEEE distribution system. They not only restored the service in a much quicker time but also improved the reliability of the system.

Classification of DGs and models of service restoration methods were discussed in [14]. They implemented it for an active distribution network as a complex optimization problem by considering the priority levels of users, the number of switching operations, and losses of the network after restoration. The Pareto genetic algorithm, which was implemented to choose the optimal path for service restoration, gave effective results.

Table 1 shows the comparison of computational methods of service restoration in distribution systems, along with their solution approaches, merits, and demerits. The optimal coordinated operation of dc microgrids connected to a distribution system followed by a major power disturbance to sustain the distribution system resilience was proposed in [15] as a multi-objective mixed-integer linear programming optimization problem. They considered the impact of PHEVs and demonstrated the effectiveness of different methodologies on a 34-bus test distribution system.

Table 1. Comparison of computational methods of service restoration in distribution systems.

Ref. No.	Problem	Solution Approach	Merits	Demerits
[3]	Distribution system restoration using PHEVs	Mixed-integer linear programming is implemented. 100-bus test system was considered.	Coordination between transmission and distribution restoration was obtained.	The availability of a large number of PHEVs and their participation were concerns.
[4]	Service restoration using DGs	The decentralized multi-agent system (MAS) framework and service restoration was formulated as the multi-objective optimization problem.	Addressed the uncertainty in load demand and renewable distributed generators (RDGs) for service restoration.	Powerful control architecture was required for communication between the agents of the MAS.
[6]	Co-optimized distribution system restoration	Co-optimized repair crew and mobile power sources. A mixed-integer linear programming method was proposed.	Methods to reduce the computational time, the repair tasks, and MPS connection pre-processing were proposed.	Needed good coordination at every stage of implementation and involved many data variables.
[10]	Smart service restoration with distributed generation	The Tabu search approach was proposed to solve constrained objective functions.	Sub-transmission and distribution systems were considered with all crucial objectives.	Many data variables were involved and needed more input data.
[11]	Service restoration in distribution systems using a hybrid multi-agent approach	Used DGs and EVs. Multi-objective, multi-constraint, combinatorial, nonlinear optimization problem.	The optimal positions of DGs and islanding ranges were determined.	Required a powerful control architecture of a hybrid MAS. Fewer switching operations are not taken care of.
[13]	Multi-level service restoration strategy of a distribution network	Utilized the microgrid (MG) and EVs. An optimal power flow (OPF) model was constructed to minimize the net loss after the service restoration.	A potential aspect of EVs and MGs was considered.	The availability of sufficient capacity from MGs and the number of EVs to participate readily were concerns.
[14]	Service restoration of an active distribution network using DGs	A multi-objective, multiple-constraint, complex optimization problem was proposed.	Prioritized loads were restored, improved the economic benefits of the grid, and reduced the loss of the network fault recovery.	The intermittent nature of renewable DGs may not provide support all the time.

An optimal operation of the local energy community (LEC) placed in the distribution network consisting of the number of EVs, which are treated as flexible energy resources, are used for manual frequency restoration [16]. An EV Markov adequacy model was proposed in [17] to estimate the reliability of the system in both cases, i.e., home-to-vehicle and grid-to-vehicle, as well as vehicle-to-home and vehicle-to-grid, based on the mobility of EVs, capacity available from EVs, stochastic behavior of driving EVs, etc.

In [18], the authors identified the optimal location of EV charging stations, along with DGs, using artificial intelligence-based hybrid golf and particle swarm optimization methods in IEEE 33- and 69-bus systems to enhance the reliability of the distribution systems. In [19], the authors implemented a two-step, self-optimizing method for charging and discharging a large-scale fleet of EVs in a microgrid for a real-time network based on an estimated process of the Ontario energy network.

In [20], the authors developed a model for estimating the power demand of EVs while they were charging to calculate the total charging demand in a distribution system. An EVs' state of charge (SoC)-based dynamic charge coordination method in a distribution network was proposed in [21]. PHEVs were modeled as an energy storage system and their impact on power distribution systems was analyzed in [22] by considering different penetration levels, periods, and variations of load in a day. Batteries of EVs are used as energy storage devices. The different topologies of single energy storage systems and hybrid energy storage systems were presented in [23]. The lifetime of distribution components, mainly on a distribution transformer, was investigated in [24] due to the increased charging impact of EVs and PHEVs. They gave suggestions to reduce the negative impacts on a distribution transformer. Regarding PHEVs charging and discharging, their impact was studied in two areas by [25]. They evaluated the reliability indices and proposed a reliability index expected energy not charged (EENC) to find a better location for the charging station. They also presented two discharging strategies to inject power into the grid to restore the system during a power failure. Regarding the concept of vehicle-to-grid (V2G), the possible ancillary services, potential benefits, challenges, impacts, and future market penetration were discussed clearly in [26]. The role of EVs connected in V2G mode in a distribution system was analyzed by calculating the reliability indices and the proposed model estimated the energy available from EVs during a day to supply the grid during emergency conditions [27]. The results showed an improvement in the reliability of the system while EVs inject power into the grid.

Significant approaches are discussed in the literature to handle service restoration traditionally, where some of them implemented network reconfiguration, formed suitable islanding, identified best switch indices, used a graph-based method, used an optimal load shed during restoration, integrated renewable energy resources (RERs), implemented of heuristic methods to obtain optimal restoration, used PHEVs along with DGs, etc. The implementation of the above methods needs a lot of analysis and verification [28]. They pose certain technical challenges in terms of the system operating conditions, equipment availability, time to restore, and operation success rate. All these methods are heavily focused on medium- and high-voltage standard IEEE distribution networks and extended distribution systems but are not concentrated on the low-voltage distribution systems to satisfy the needs of the individual residential user.

In recent years, most studies have only focused on various issues related to EVs, such as coordinated and uncoordinated charging of EVs, demand-side management with EVs, enhancement of reliability, and voltage and frequency regulation using EVs. PHEVs and EVs are used to feed power back to the grid, i.e., V2G technology. However, its control is more complex and needs the grid operator to coordinate the operations, as well as requires good communication infrastructure [29]. The concepts of vehicle-to-building (V2B) or vehicle-to-home (V2H) technologies require simple infrastructure that feeds power to a building or home, respectively. The V2B and V2H can be used as a backup during emergencies. Therefore, for outage management, EVs can be used to restore power to a home or building and it is a good alternative for V2G during an emergency condition [30]. With the advent of the increased use of EVs, quick power restoration is possible from the side of a low-voltage distribution system during a power outage, which can avoid dependency on utility operators. We believe that no other authors have focused on service restoration from the perspective of a low-voltage distribution system, i.e., a distribution transformer serving the residential area to satisfy their individual needs solely using parked Electric Vehicles, utilizing the potential aspect of V2B or V2Hand their state of charge. Without the intervention of the grid, service restoration of residential loads is possible according to their priorities by using parked EVs during the period of a power outage. The optimization problem formulated here is a linear model to achieve priority-based scheduling of residential appliances if EVs' power is a deficit to serve the required load. The model is less complex and involves fewer computations. Thus, this studyaimed at service restoration of the residential loads served by a distribution transformer using parked Electric Vehicles in that area, according to the resident's priority for individual appliances of the residential loads.

This paper is organized as follows. Section 2 presents the description of the test system, the methodology for the priority-based schedule of appliances is explained in Section 3, Section 4 presents the discussion on the results, and finally, the conclusion is presented in Section 5.

2. Description of the Test System

At the end of 2020, 10 million electric cars were on the world's roads and there was a significant rise in the new electric car registrations, which was nearly 41%.By 2030, EV stock in all modes on the road will be around 7% [31]. Almost 95% of the time, EVs are parked at homes or parking lots in the U.S. [32]. While the vehicles are parked in the parking lot, they can be used to provide power to the grid, which helps with service restoration.

For this investigation, eight residential users served by a 20KVA distribution transformer and its residential load profile of a location in Texas, USA, in summer were considered from [33]. The residential area served by the distribution transformer and its load profile for a day is shown in Figures 1 and 2, respectively. It was assumed that each residential user had an EV, along with various appliances, such as a freezer, washing machine, refrigerator, microwave oven, various lighting loads, water heater, and air conditioners. Their wattages and power consumption, considered from [34], are tabulated in Table 2.

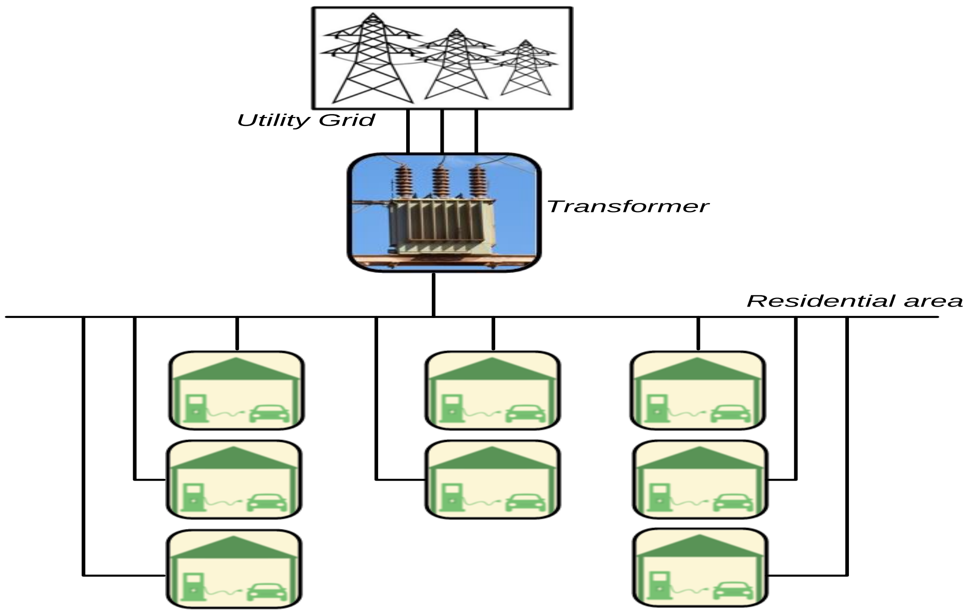

Figure 1. Distribution transformer serving residential loads.

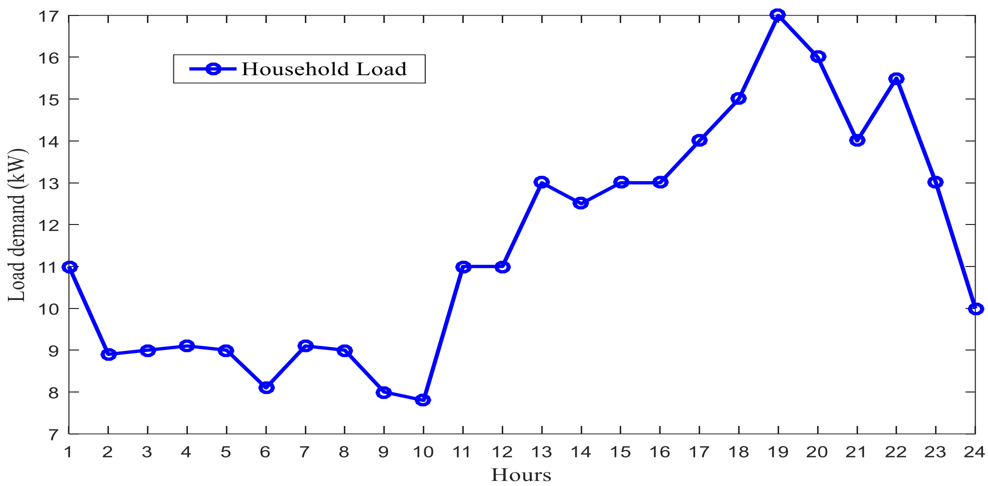

Figure 2. Residential load profile during the day.

Table 2. Wattage and quantity of various appliances in the residences.

S.No.	Appliances	Wattage(W) × Quantity							
		Residential User-1	**Residential User-2**	**Residential User-3**	**Residential User-4**	**Residential User-5**	**Residential User-6**	**Residential User-7**	**Residential User-8**
1	Refrigerator	100 × 1	150 × 1	100 × 1	130 × 1	130 × 1	130 × 1	150 × 1	100 × 1
2	freezer	500 × 1	400 × 1	400 × 1	500 × 1	50 × 1	50 × 1	50 × 1	400 × 1
3	Tube lights	None	22 × 3	22 × 3	22 × 3	22 × 3	22 × 3	22 × 3	22 × 3
4	Lamps	15 × 4	15 × 3	15 × 3	15 × 3	15 × 3	15 × 3	15 × 3	15 × 3
5	LED TV	85 × 1	116 × 1	120 × 1	110 × 1	60 × 1	85 × 1	90 × 1	110 × 1
6	Desktop	150 × 1	150 × 1	150 × 1	150 × 1	200 × 1	150 × 1	150 × 1	200 × 1
7	Laptop	60 × 1	60 × 1	60 × 1	-	60 × 1	60 × 1	100 × 1	60 × 1
8	Phones	25 × 2	25 × 2	25 × 2	25 × 2	25 × 2	25 × 3	25 × 1	25 × 1
9	Blender	250 × 1	250 × 1	250 × 1	250 × 1	250 × 1	250 × 1	250 × 1	-
10	Electric kettle	-	-	1200 × 1	1200 × 1	1200 × 1	1200 × 1	1200 × 1	1200 × 1
11	Microwave	900 × 1	900 × 1	900 × 1	900 × 1	900 × 1	600 × 1	900 × 1	900 × 1
12	Iron	1000 × 1	1000 × 1	1000 × 1	1000 × 1	800 × 1	1000 × 1	1000 × 1	1000 × 1
13	Security light	25 × 6	25 × 6	25 × 6	25 × 6	25 × 6	25 × 6	25 × 6	25 × 6
14	Waterpump	750 × 1	750 × 1	750 × 1	750 × 1	750 × 1	750 × 1	750 × 1	750 × 1
15	Waterheater	1000 × 1	1000 × 1	1000 × 1	1000 × 1	-	1000 × 1	1000 × 1	1000 × 1
16	Washing Machine	900 × 1	900 × 1	900 × 1	900 × 1	900 × 1	500 × 1	900 × 1	900 × 1
17	Dishwasher	1200 × 1	1200 × 1	1200 × 1	1200 × 1	1200 × 1	1200 × 1	1200 × 1	1200 × 1
18	Electricstove	2000 × 1	2000 × 1	2000 × 1	2000 × 1	2000 × 1	2000 × 1	2000 × 1	2000 × 1
19	ElectricpressureCooker	1000 × 1	1000 × 1	1000 × 1	1000 × 1	1000 × 1	1000 × 1	1000 × 1	1000 × 1
20	Coffee maker	1400 × 1	1400 × 1	1400 × 1	1400 × 1	1400 × 1	1400 × 1	800 × 1	1400 × 1
21	Air Conditioner	1500 × 1	1500 × 1	1500 × 1	1500 × 1	1000 × 1	1000 × 1	1000 × 1	1000 × 1
22	Internet Router	-	15 × 1	15 × 1	15 × 1	15 × 1	15 × 1	15 × 1	15 × 1
23	Waterpurifier	100 × 1	100 × 1	100 × 1	100 × 1	100 × 1	100 × 1	100 × 1	100 × 1

The EV model considered was the Nissan Leaf 2016, which has a 24 kWh battery capacity. Generally, the driving behavior of EVs decides the available SoC in the EVs. To retain a high life for batteries, the SoC must be maintained in the range of 20 to 80% of its capacity. In the present work, it was assumed that EVs were initially available in the range of 30 to 60% of SoC. Therefore, the percentage of SoC available from each EV was estimated in the range of 10% to 40% by using a random function in the PYTHON platform for every hour. Further, it was assumed that at least one EV was available in the parking lot at any instant.

Therefore, the total power available from EVs in the parking lot could be aggregated based on their SoC and could be treated as a single source of generation to serve the residential loads instantly at the time of an outage. The aggregated power of all EVs in an hour is the sum of the power of the individual vehicle and is given as P_{agg}.

$$P_{agg} = \sum_{i=1}^{N} P_i \tag{1}$$

where P_i is the power available from ith EV during the hour of outage in kW.

3. Problem Formulation and Methodology

The restoration problem was formulated as a constrained linear programming problem. It aimed to serve maximum power to the residential users who were served by a distribution transformer at the time of the outage based on the availability of EVs. In the case of deficit power from the EVs, appliances in the individual house were served based on the priorities assigned by that resident. The weight factor assigned to appliances decided the priority of the appliance during the hour of restoration. The higher the value of the weight factor, the higher the priority of the appliance.

Therefore, the objective function was formulated as shown in Equation (2) to restore maximum available power to the connected appliances. Further, it was subjected to various operational constraints, such as power available from EVs, limits on the bus voltage, connectivity of the appliance at the time of the outage, and power ratings of the appliance, as shown in Equations (3)–(5).

$$\text{Max} \sum_{i=1}^{N} \sum_{j=1}^{K} W_{ij} * P_{ij} * C_{ij} \tag{2}$$

$$\text{Subjected to } \mathrm{V_i min} \leq \mathrm{V_i} \leq \mathrm{V_i max}\ \forall\ \mathrm{i} \ldots \tag{3}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{K} P_{ij} * C_{ij} \leq\ P_{agg}\ \forall \mathrm{i}, \mathrm{j} \ldots \tag{4}$$

$$P_{ij} \leq\ R_{ij} \forall\ \mathrm{i}, \mathrm{j} \ldots \tag{5}$$

where P_{ij} is the power scheduled for the *i*th residential user's *j*th appliance in kW.

W_{ij} is the priority factor of the *i*th residential user's *j*th appliance.

C_{ij} indicates the on or off condition of the jth appliance for the *i*th residential user.

$C_{ij} = 1$ when the *j*th appliance is turned on by the *i*th residential user at the time of restoration.

$C_{ij} = 0$ when the *j*th appliance is turned off by the *i*th residential user at the time of restoration.

$\mathrm{V_i}$ is the *i*th bus voltage in pu.

$\mathrm{V_i min}$ and $\mathrm{V_i max}$ are the lower and upper limits of the bus voltage, which are considered as 0.9 pu and 1 pu, respectively.

The values of bus voltages were obtained from the power flow analysis.

R_{ij} is the power rating of the *i*th residential user's *j*th appliance in kW.

The distribution transformer serving the eight residential users was modeled as a 9-bus radial distribution system. Its single-line diagram is represented in Figure 3 before the outage. The system shows that the transformer fed the nine buses B1 to B9, out of which, buses B2 to B9 represent the residential users 1 to 8, respectively, and their corresponding loads are represented as L1 to L8. As shown in Table 2, the list of appliances, their wattages, and the quantity used by each residential user was considered. The power rating of every appliance of a residential user (R_{ij}) can be obtained from Table 2. It was considered that residential users separated from each other by 10 m, the resistance was 20 ohms per kilometer, and the reactance was twice the value of the resistance.

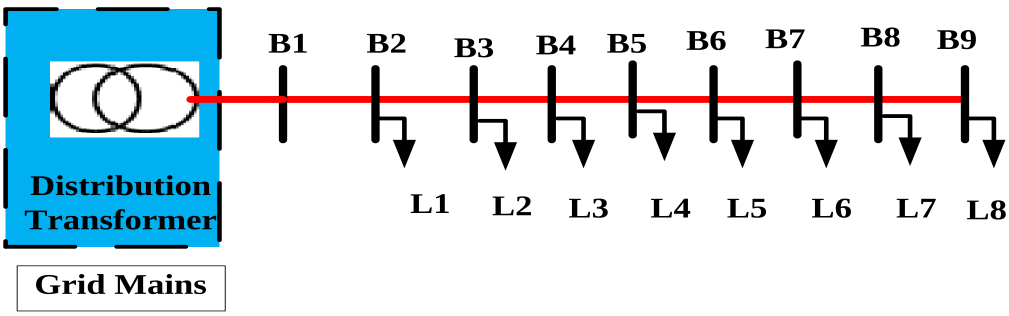

Figure 3. Single-line diagram of the radial distribution system under consideration.

At the time of the blackout, for the service restoration, the EVs' total energy was aggregated as per their availability in the parking lot. Then, the aggregated power from EVs was treated as a source of generation to serve the residential loads. The test system at the time of restoration is shown in Figure 4. The base MVA of the system was considered as per the availability of the number of EVs at the hour of the outage. First, the residential load profile of every resident was estimated using the residential load profile for a day.

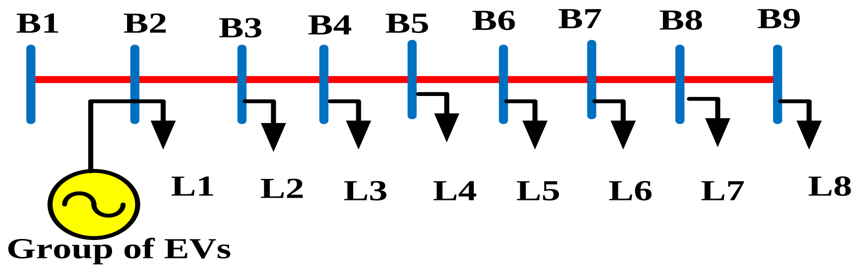

Figure 4. Single-line diagram of the radial distribution system at the time of restoration.

Later, Newton's method of power flow was implemented in the test system to identify the voltage violations in the MATLAB/MATPOWER environment. If no violations were found, appliances were powered per their requirements. If violations existed, then prioritization of appliances was required. Every appliance in all residences was indexed and their corresponding weight factors were assigned according to the individual residential user priorities. The sum of the weight factors assigned to connected appliances of every residential user must be equal to 1. Figure 5 shows the flowchart of the methodology to follow for implementing priority-based scheduling of the appliances using EVs in this study.

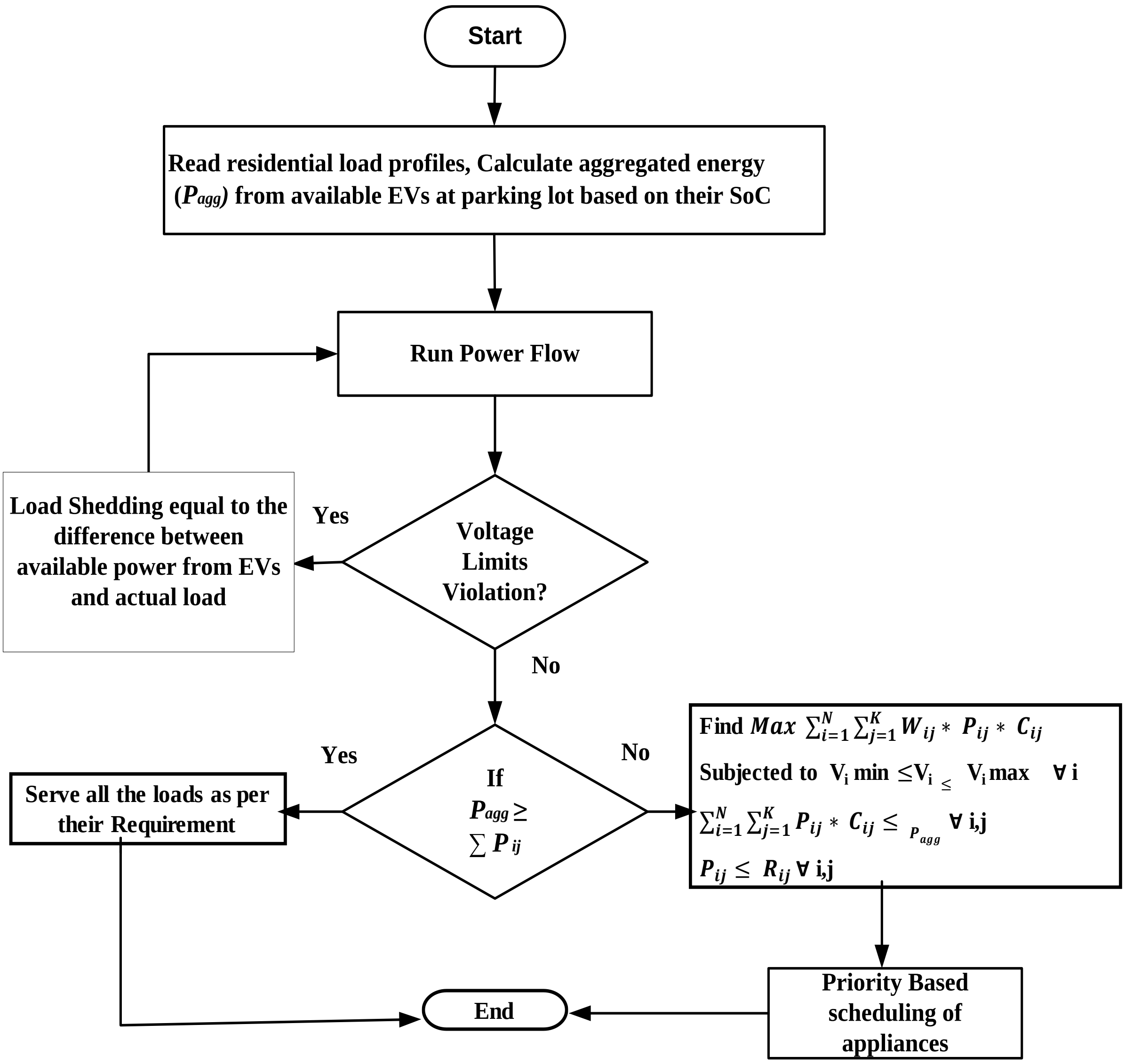

Figure 5. The flowchart of the priority-based scheduling of the appliances.

If the voltage magnitudes were within the limits, it implied that the power available from EVs was more abundant than the actual load. Otherwise, load shedding was made equivalent to the difference between the available EVs' power and the actual residential need for power at the time of restoration. Thereby, the load shedding ensured that the bus voltages were within the limits and the objective function was calculated, which gave the schedule for maximum energy restored to the appliances according to their weight priority factors for every residence by using LINGO optimization modeling.

4. Results and Discussions

The proposed methodology was implemented in the distribution system, as shown in Figure 4. The total residential load profile at any given time was considered as k based on [35]; then the residential load profile of k, individual residents was determined as 0.15 k times for the residential users 1 to 4 and 0.1 k times for residential users 5 to 8. In the instance of a blackout, the number of EVs available in the parking lot was considered to estimate the available energy from EVs based on their SoC. A random function was used to generate the random number of EVs available for 24 h in PYTHON. Power flow was implemented with the estimated power from EVs to observe the voltage deviations. Table 3 shows the randomly generated number of EVs, their estimated power, and the status of the voltage limits after the power flow with available EVs power for each hour. It was observed that the voltage magnitudes were in bounds if the available power from the EVs was higher than the total load. While the voltage magnitudes were within the limits, there was no need to provide weight factors for the appliances and the required load could be served as it is. Prioritization of appliances was required in the case of bus voltage limit violations. To validate the effectiveness of the proposed methodology, a scenario was considered to implement service restoration when the EVs' power was insufficient and the load shedding was done based on the priorities assigned to appliances and voltages to satisfy the limits.

The Scenario at Hour 16

Under an outage condition at hour 16, it was estimated that the total power available from EVs was 9.41 kW and the residential load to meet was 14.09 kW. Power flow was run with a base MVA of 0.096 MVA, as four EVs were available whose battery capacity was 24 kWh each. It was observed that the voltage at buses 6–9 had deviated from the limits. Therefore, load shedding was required. The amount of load shedding was calculated as the difference between the total residential load and the available power from EVs here, it was 4.68 kW. Afterload shedding power flow resulted from the imposed voltage at every bus. Figure 6 shows the voltage profiles before and after the load shedding conditions at hour 16. It is seen that those bus voltages were within the specified limits after the load shedding.

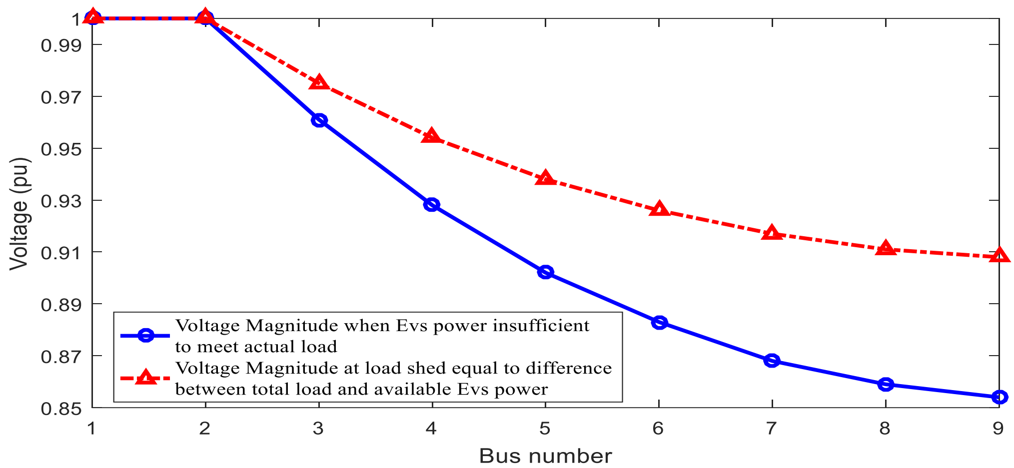

Figure 6. Voltage profile at hour 16 before and after load shedding.

Table 3. Available number of EVs, power from EVs, total actual load, and status of voltage limits during each hour.

Sl.No.	Hour Number	Number of EVs Available	Available Power from EVs (kW)	Total Load (kW)	Status of Voltage Limits before Load Shedding
1	1	2	7.49	10.33916	Violated
2	2	5	24.19	9.7942246	Not violated
3	3	5	18.62	9.2970252	Not violated
4	4	3	15.56	8.885042	Not violated
5	5	3	12.29	8.5883301	Not violated
6	6	3	15.74	8.4295185	Not violated
7	7	4	20.35	8.4238109	Not violated
8	8	5	22.85	8.5789847	Not violated
9	9	2	12.67	8.8953919	Not violated
10	10	2	11.33	9.3659586	Not violated
11	11	5	25.73	9.9761853	Not violated
12	12	3	11.72	10.704147	Violated
13	13	5	11.52	11.520491	Violated
14	14	2	10.18	12.388442	Violated
15	15	3	12.1	13.263797	Violated
16	16	4	9.41	14.094927	Violated
17	17	2	7.3	14.822779	Violated
18	18	5	11.52	15.380871	Violated
19	19	5	12.1	15.6953	Violated
20	20	2	8.07	15.684732	Violated
21	21	2	10.95	15.260411	Violated
22	22	4	12.1	14.326153	Violated
23	23	5	11.52	12.778351	Violated
24	24	3	10.75	10.505969	Violated

Subsequently, the individual residential load was approximated to be 2.115 kW for the residents 1 to 4, which was 0.15 times the 14.09 kW, and for residents 5 to 8, it was 1.409 kW, which was 0.1 times the 14.09 kW, as per our assumption. While a sufficient load was shed, priority-based scheduling was implemented by running the objective function in the LINGO platform. LINGO is an inclusive tool that solves the linear, nonlinear, quadratic, quadratically constrained, second-order cone, semi-definite, stochastic, and integer optimization models with fast built-in solvers. Thus, the maximum power was restored to the appliances from the available EVs. The actual individual residential load profiles, weight factor assigned for priority of appliances, and power restored to appliances from EVs after load shedding are shown in Figures 7–14 for residential users 1–8, respectively.

The amount of load shedding for individual residential users was done as their percentage of the actual load. Hence, the load shedding required for residents 1 to 4 and residents 5–8 was 0.702 kW and 0.468 kW, respectively. Based on the weight factors assigned to the appliances, it was observed that appliances with higher weight factors were scheduled first and the appliances with lower weight factors were scheduled later. Thus, the load shedding for a particular appliance happened according to its priority index. Since there was a deficit of power from EVs compared to the actual load, not all appliances were scheduled as per their requirements. The power restored to the eight residential users was 1.36 kW, 1.4 kW, 1.219 kW, 1.4 kW, 0.945 kW, 0.91 kW, 0.94 kW, and 0.942 kW, respectively. The power restored to individual residents was according to the load pattern of their actual loads. However, maximum power was restored from the available EVs' power. Tables 4 and 5 show the actual power needed during the period of the outage and the power restored from the four available EVs. Therefore, the load served by a low voltage distribution system could be met with the help of parked EVs without any help from the grid during emergency power outages. An abundant number of EVs at the hour of the outage would further meet the total load required during the outage period.

Table 4. Status of the test system during an outage without EVs.

Number of residential users interrupted	8
Duration of the power outage	1 h
Power needed in kW	14.09
Total residential appliances to run	69

Table 5. Status of the test system during the outage with EVs.

Number of residential users interrupted	0
Duration of the power outage	1 h
Power restored from EVs in kW	9.116
Total residential appliances served	39

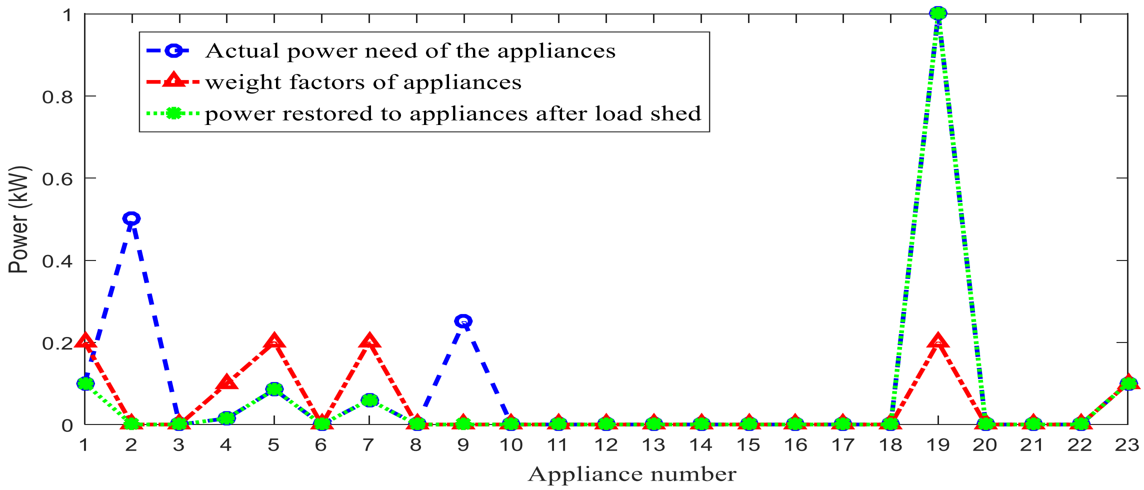

Figure 7. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 1.

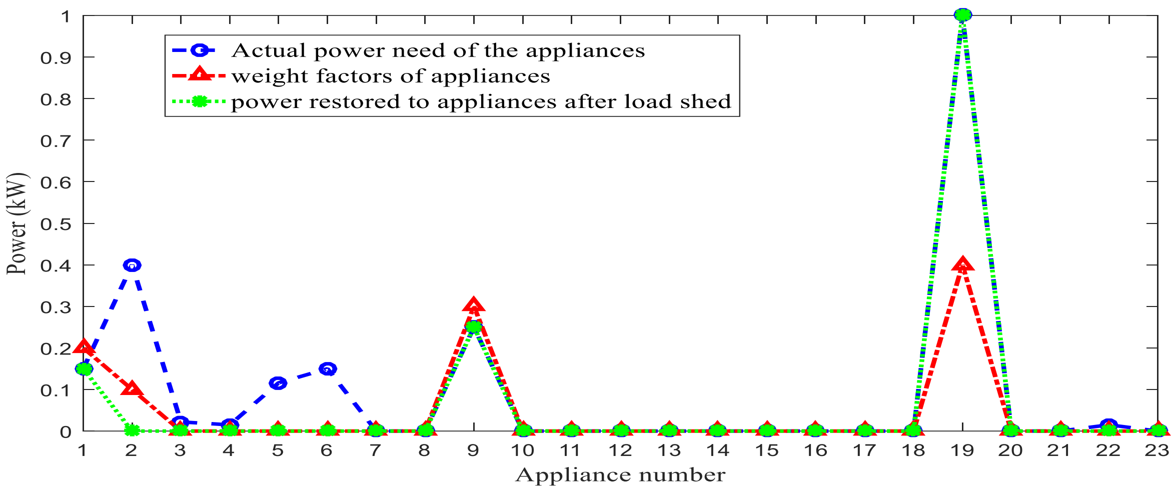

Figure 8. Actual load to meet, factors assigned for priority of appliance, and power restored due to EVs for residential user 2.

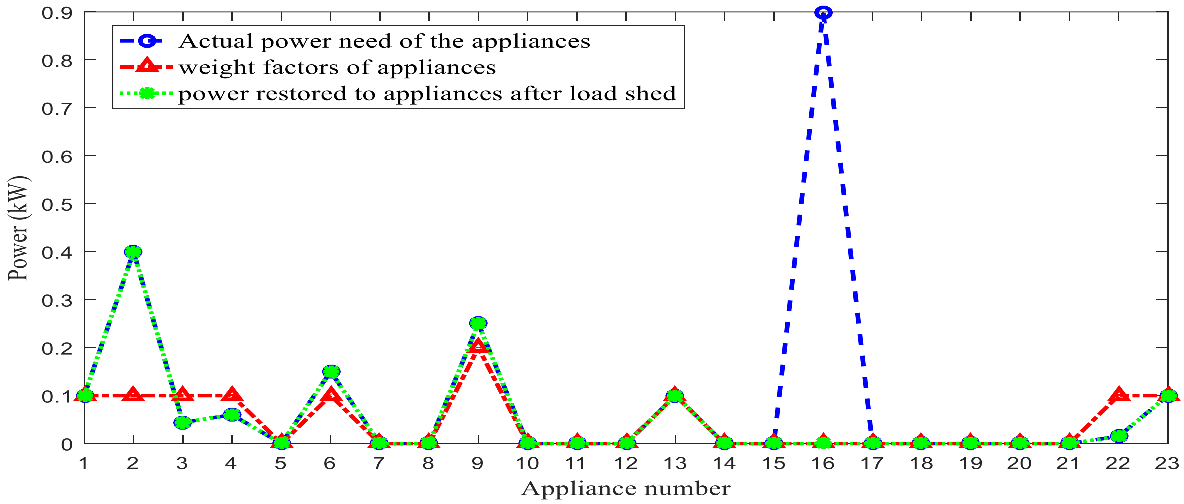

Figure 9. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 3.

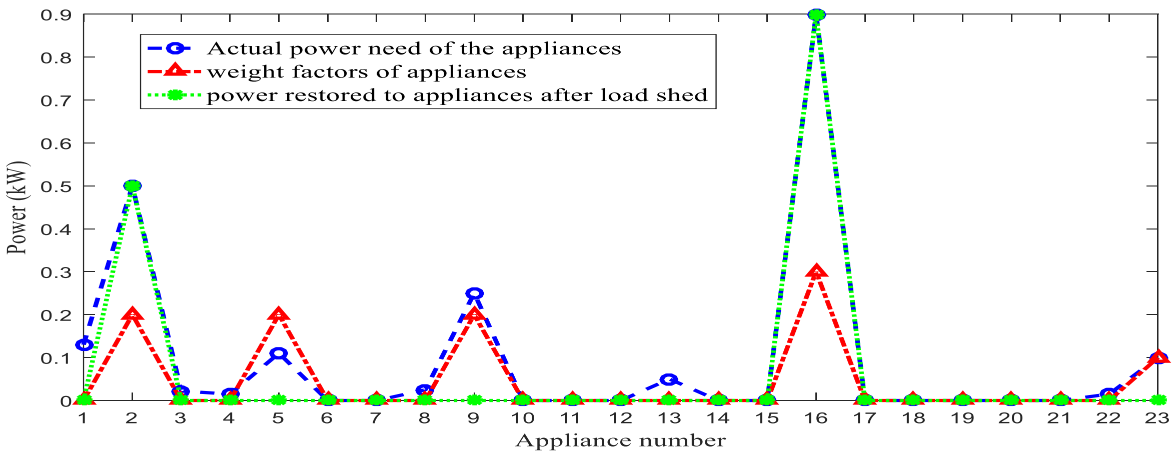

Figure 10. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 4.

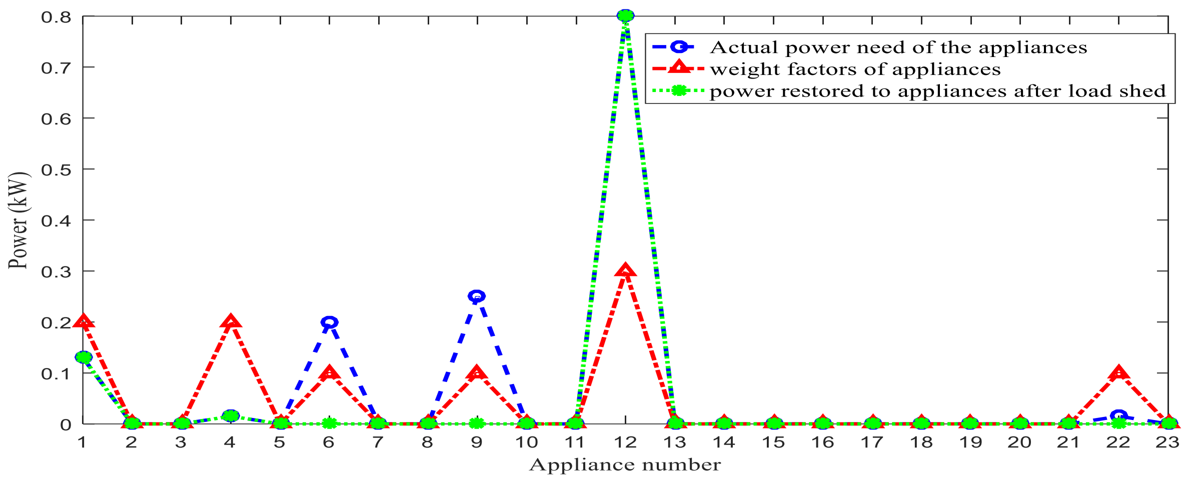

Figure 11. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 5.

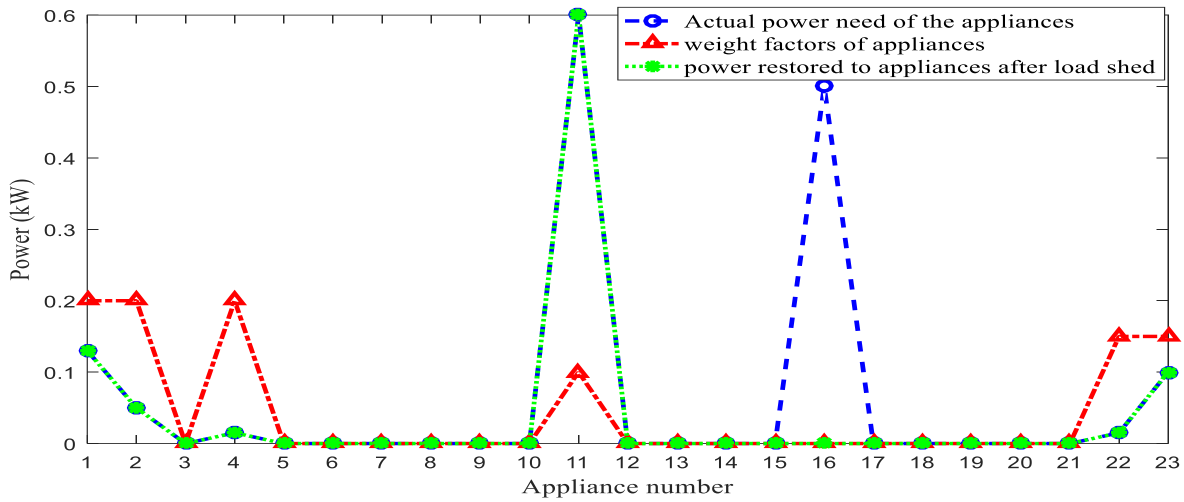

Figure 12. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 6.

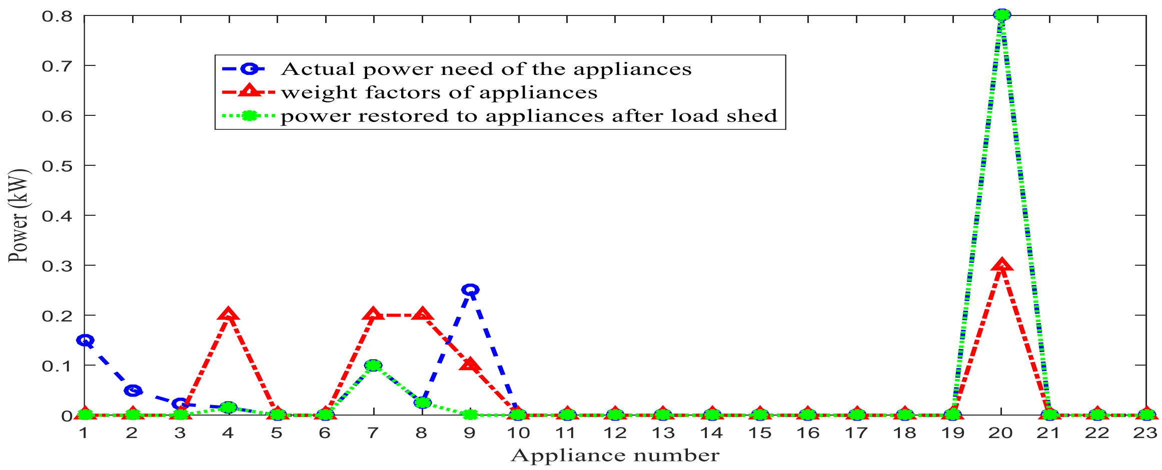

Figure 13. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 7.

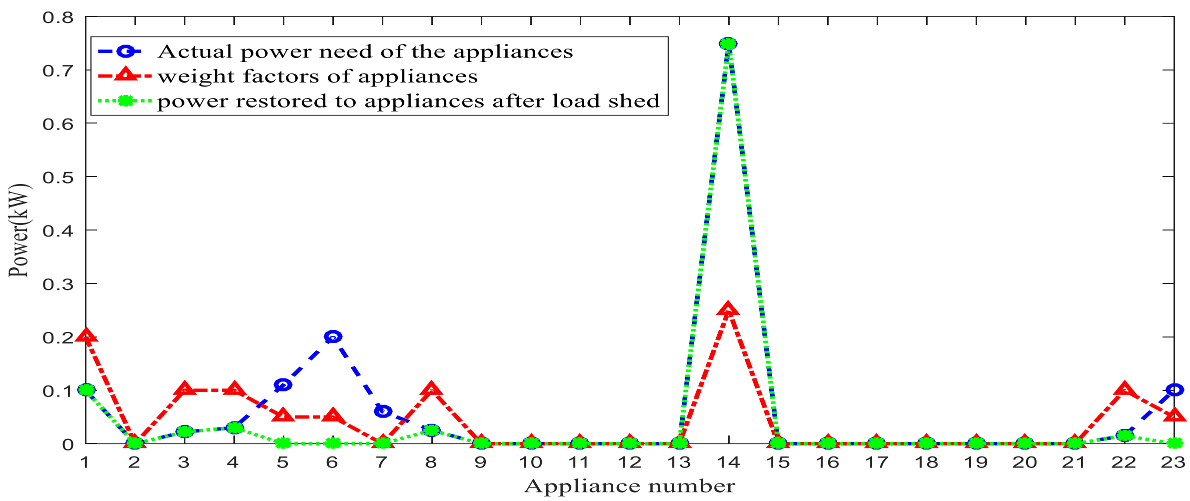

Figure 14. Actual load to meet, weight factors assigned for priority of appliance, and power restored due to EVs for residential user 8.

5. Conclusions

This study proposed a restoration strategy for LT distribution systems by tapping into the potential of parked EVs in a residential area served by a distribution transformer. The proposed methodology was tested on eight residential users by considering a 24 h residential load profile served by a 20 KVA distribution transformer. With the accessible power from EVs, at the time of the outage, priority-based scheduling of the residential appliances at every residence was performed. The results obtained exhibited the need for load shedding when the EVs' predicted power was lower than the actual load and scheduling of appliances was required according to the assigned priorities of each residential user. However, a significant number of EVs contributed to the maximum load restoration. Thus, the restoration strategy using the parked EVs in the LT distribution system improved the resilience and reliability of the distribution system. The uncertainty in the availability of EVs during power outages and a willingness to participate in the service restoration by EVs, the dynamics of EV batteries, and a multi-agent system approach can be implemented in the future to improve the efficiency and stability of the system.

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