A Smart On-Line Centralized Coordinated Charging Strategy in Residential Distribution Networks

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Abstract- Environmental and economic aspects encourage the transition of conventional fuel-based vehicles to electric vehicles (EVs). However, the uncoordinated charging activities of EVs may increase the stress on the distribution networks. Coordination between EVs charging activities is the perfect way to avoid the negative consequences of unscheduled charging activities without reinforcing the existing network infrastructure. Many previous works proposed coordinated charging strategies but without considering some influencing factors like EV departure time and energy tariff. Some others used impractical assumptions like a very large parking period or forced the users to choose the preferred charging period before the vehicles' arrival. In this work, a centralized coordinated charging strategy is proposed to reduce EVs charging costs from users' point of view side by side with the safe operation of the distribution network considering vehicle departure time and charging prices. The proposed strategy mainly determines the proper starting instant and the suitable charger power rate of the charging process. The proper starting instant of the EV charging process is calculated by ranking the charging priority of the arrived vehicles. In contrast, the charging power rate is estimated based on the available duration from starting instant to the instant of vehicle departure. The strategy is applied to a modified IEEE 31 bus residential distribution system with 22 residential distribution feeders. The results proved the proposed strategy's effectiveness in reducing the charging costs, alleviating overloading on the main substation, improving voltage deviations, and reducing the power loss.

Keywords Coordinated charging; Electric vehicle; Centralized coordination; On-line coordination; Residential distribution networks.

1. Introduction

The escalating of the energy crisis, depleting reserves of fuel resources, and the alarming levels of carbon emissions are the main reasons for the significant increase of electric vehicles (EVs) as a credible candidate to partially overcome these problems [1]. Besides that, the continuous development of batteries technology has advanced the prevalence of EVs in distribution networks [2,3].

The widespread use of EVs has led to arising new threats in existing electrical distribution networks, wherein such technologies have a vital reliance on battery recharging activities [4]. Home charging activities of EVs are presumably the most common charging method with the scarcity of public charging facilities that support the censored charging activities [5].

Most of the charging events occur when EVs arrive home during early evening hours, which involving the peak period of the residential communities. Accordingly, the uncoordinated charging processes at homes constitute significant stresses on distribution grids in severe energy losses, excessive voltage deviation, transformer overloading, and system interruptions [6]. Hence, the coordinated charging strategies will be indispensable to suppress the adverse effects of unscheduled charging activities of EVs in distribution networks.

The coordinated scheduling of the charging times and power rates (smart charging) are anticipated to alleviate EVs' deployment effects in the power distribution networks [7]. Furthermore, the transition of distribution networks towards smart grids involving bi-directional communication features contributes to facilitating the coordination of charging activities among EV users. With the evolving concept of smart grids, a new concept arises, which is called "aggregators." The aggregators are intermediary entities between EV owners and system operators who want to coordinate the end-users vehicle charging activities [8].

EVs coordinated charging can be realized through two different control schemes, including distributed (decentralized) and centralized coordination strategies. Interested readers can further refer to reference [9] for detailed information on the two schemes. The EV owners act as independent decision-makers who have the vehicle charging authority in the distributed scheme, including charging times and power rates. In contrast, in the centralized scheme, vehicle owners submit their charging requests to an EV aggregator. The charging coordination is decided by the aggregator to balance network constraints and customer satisfaction.

The main disadvantage of the distributed coordination scheme is the risk that may occur if a large segment of users ignores the coordination of their charging activities, which may lead to system failure, thereby jeopardizing the security of the network. As each EV owner decides his charging coordination individually, the global coordination benefits like voltage deviation and transformer overloading reductions are not guaranteed. As a result, system operators prefer the centralized coordination charging scheme.

Many works have focused on the charging strategies in residential distribution networks using the two coordination schemes in the recently published research.

- References [10-16] are introduce charging strategies using a distributed coordination scheme.
- References [17-24] present centralized coordinated charging strategies in distribution networks and the associated effects with and without using coordination strategies. Many charging coordination objectives have been proposed in these works, such as minimizing the total charging cost, flatten the load curve, voltage deviation reduction, and power loss minimization.

As the proposed strategy in this paper is classified within the second category, an in-depth review will be presented with illustrating the main contributions and shortcomings in these works. Table 1 presents a comprehensive comparison between the recently published works.

It is clear from the literature that some works addressed charging EVs without considering the energy tariff that affects the financial burden on the vehicle owners [17,18,21,24]. On the other hand, the energy tariff price has been introduced in other works [23] without considering charging cost reduction. Also, the aggregated charging cost reduction in the network has been proposed without mentioning the individual users' charging cost reduction in [19,20,22]. Such calculations are more beneficial to system operators than to users. From the users' point of view, the individual charging reduction is more attractive to EV users.

Furthermore, many papers have implemented charging coordination without taking into account the vehicle departure time [17,19,24]. Some of the literature works introduce the well-known swarm optimization techniques to solve the on-line EVs charging coordination issue [19,23]. The main problem of these techniques is the calculation time which is an important factor in on-line operation, especially if there are many EVs that need to coordinate in a very small time slot. If-statement on-line algorithms based on ranking the charging priority are a promising solution that facilitates scheduling of charging activities without using swarm optimization techniques. However, impractical methods of priority ranking have been proposed in previous works that coordinate the charging activities of EVs depending on charging priority, as mentioned for references [19,22] in Table 1.

A lack of studies proposed a coordination strategy that combines important factors like EVs departure time and energy tariff with practically applicable assumptions that consider the charging priority ranking based on EV charging flexibility and the proper charging instant by the aggregator. There is a lack of studies interested in EVs charging cost reduction from the users' point of view. In this paper, a centralized coordinated charging strategy is proposed to reduce the charging costs from users' point of view simultaneously with the safe operation of the residential distribution network in terms of preventing the substation overloading, reducing system voltage violation, and reducing system power loss. The proposed strategy schedules the EVs charging activities considering the practical aspects that affect the charging coordination, such as vehicle departure time and energy prices. The proposed coordination strategy uses charging flexibility to rank the charging priority of EVs, hence specifying starting time of the charging process. Besides, the charging power rate is minimized as much as possible based on the available charging duration.

The rest of this paper is organized as follows: the analysis of uncoordinated charging activities is presented in Section 2. In Section 3, the centralized scheme configurations are introduced. Then, the proposed coordination strategy and implemented methodologies are presented in Section 4. Afterward, the case study and results are noted in Section 5. Finally, conclusions are presented in Section 6.

2. Uncoordinated Charging Analysis

Without EVs coordination, the charging activities start immediately with full charger power once the EVs have arrived during early evening peak hours until the EV reaches the requested state of charge (SOC) regardless of the grid status. Since the uncoordinated charging activities usually coincide with the peak load period of the residential community, the peak load of the distribution network is expected to increase to alarming levels.

In these uncontrolled schemes, the charging process starts immediately once the vehicle arrives. The user in this

Table 1. Contributions and shortcomings of previous works

Ref.	Contribution	Included Factors		Additional comments
		Departure time	Energy tariff	
[17]	Investigating the conflict between coordinated charging strategies in transmission and distribution networks and the degree to operate both systems simultaneously in a safe manner			
[18]	Establishing a coordinated charging model based on a real driving data of EVs to minimize the system load fluctuations and maximize the charging capacity of EVs	✓		
[19]	Establishing a coordination strategy simultaneously with capacitor switching and substation tap changer adjustment to minimize voltage deviations and power loss		✓	Ranking the charging priority of the vehicles based on the number of charging slots is not appropriate since vehicles may have large charging slots with very late departure times (plug-out time). (Impractical ranking, especially when vehicle departure time not considered)
[20]	Proposed four coordinated charging strategies with three scenarios of loading level	✓	✓	Very large parking period about 9-14 hours per day. (impractical assumption)
[21]	Proposed a charging strategy that compatible with the system load fluctuations in the presence of high penetration renewable energy resources	✓		
[22]	Presenting a coordination strategy based on a probabilistic EVs charging model	✓	✓	Before optimization starts, the users should define the charging period. This hypothesis means the charging schedules are previously known before optimization. (impractical assumption)
[23]	Establishing an on-line scheduling optimized strategy based on EVs variable charging power rates	✓	✓	▪ Minimizing charging costs is not considered. ▪ Complete all charging activities as soon as possible regardless of the possibility of charging at a very low tariff period which may impose an additional financial burden on many users.
[24]	Controlling EVs charging points through disconnections and reconnections of charging activities based on corrective and preventive approaches			
Proposed Strategy	Considering the effect of vehicle departure time and energy tariff to reduce EVs charging costs from the user point of view simultaneously with maintaining the safe operation of the distribution network	✓	✓	▪ Minimizing charging cost from the user point of view ▪ Providing the percentage reduction in the charging cost for each user ▪ Ranking the charging priority based on EV charging more practical flexibility ▪ Fast calculation with large fleets of EVs that arrive in the same time slot

system defines the expected departure time (t_d) and SOC required at the departure time (SOC_{req}) through the user interface of the charging unit. Meanwhile, the charging unit automatically captures the values of arrival time (t_a), arrival SOC (SOC_a), vehicle battery capacity ($C_{battery}$), and charger rate power (P_{rated}). Afterward, the required charging energy (E_{ch}) can be calculated from equation (1) and then computes the total charging duration (D_{ch}) from equation (2). The end of the charging interval (t_{end}) is calculated from equation (3). The vehicle starts the charging process from the instant of t_a to t_{end} with charging power of P_{rated} as shown in Fig. 1.

$$E_{ch} = \frac{(SOC_{req} - SOC_a) \times C_{battery}}{\eta_{ch}} \quad (1)$$

$$D_{ch} = \frac{E_{ch}}{P_{rated}} \quad (2)$$

$$t_{end} = t_a + D_{ch} \quad (3)$$

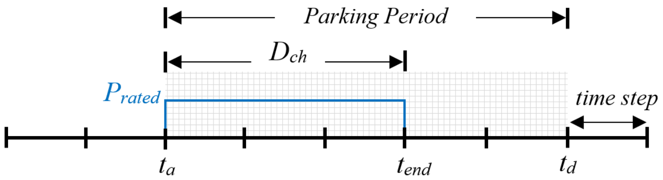

Fig. 1. Illustrated figure of the charging data.

In this paper, the calculated charging data of each arrived EV will be stored in what is called "a charging matrix." This matrix will be used in the later comparison with the proposed scheme. The charging matrix is constructed as follows:

- Initially, all the matrix elements are set to zero with a size of *m* rows and *n* columns where *m* is equal to the number of time slots per day while *n* is equal to the number of EVs in the network.
- When the vehicle *i* arrives at t_a, the values in column *i* will be updated with the value of P_{rated} from the instant of t_a to t_{end}.
- At any time instant t, the total charging load of the arrived vehicles can be calculated from the summation of *t* row. The charging matrix contents have illustrated in Fig. 2.

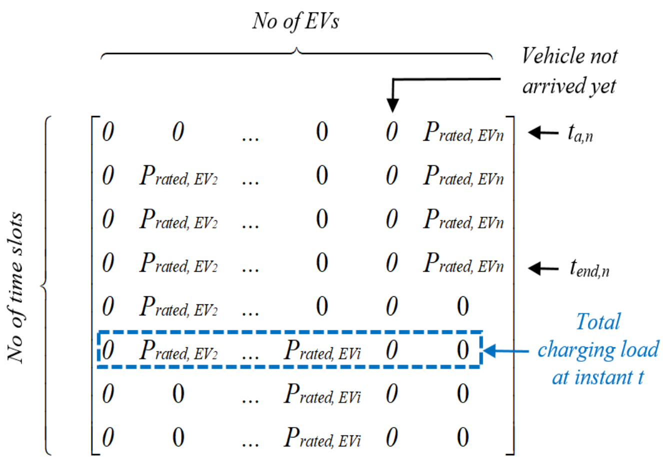

Fig. 2. Charging matrix contents.

For each time slot, when EVs have arrived, the charging duration (D_{ch}) and the end of the charging period (t_{end}) are calculated from equations (1) to (3). Once these values are calculated, the charging matrix is updated. Then, load flow calculation is initiated to determine the network performance parameters such as the total power consumption at the substation, total power losses, minimum voltage magnitude of the network, and charging costs. The detailed procedures of the uncoordinated charging mode are illustrated in Fig. 3.

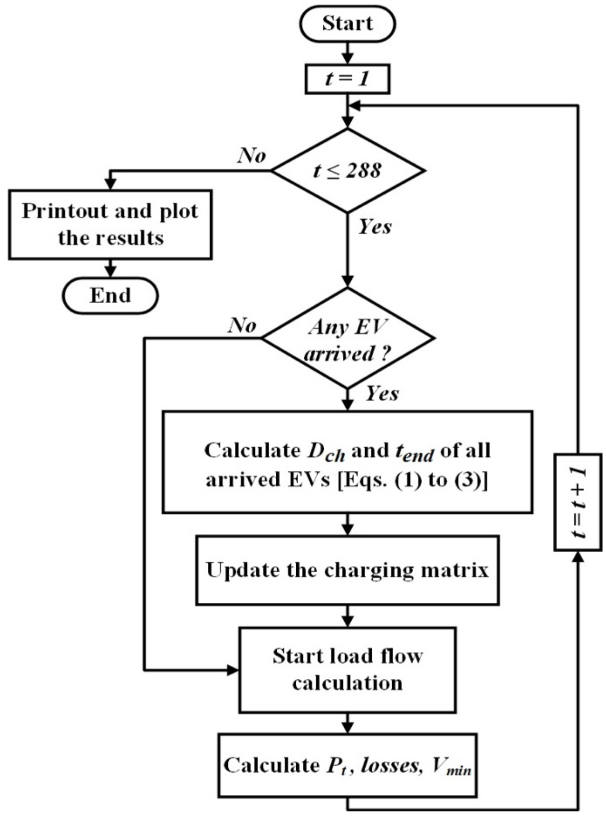

Fig. 3. Main procedures of the uncoordinated charging mode.

3. Configurations of Centralized Coordination Scheme

In this paper, a centralized coordination scheme illustrated in Fig. 4 is used to control the aggregated home charging activities. The elements involved in the centralized scheme are:

- *Main Substation:* that serves the distribution network and responsible for supplying power to the network loads.
- *EVs Aggregator:* who is responsible for:
  a. Collecting the necessary data from EV owners through communicating with the home charging control unit of each user to identify the vehicle data and user charging requirements such as charger rated power, vehicle battery capacity, arrival state of charge (SOC_a), arrival time, departure time, and required SOC at the instant of departure.
  b. Receiving the daily operation data from the network service providers.
  c. Designing and applying the coordinated charging strategy to achieve safe network operation simultaneously with satisfying user charging requirements.
- *Smart Houses:* each house contains EV charging control unit that allows the aggregators to remotely control the vehicle charging activities (charging power rates and charging times).

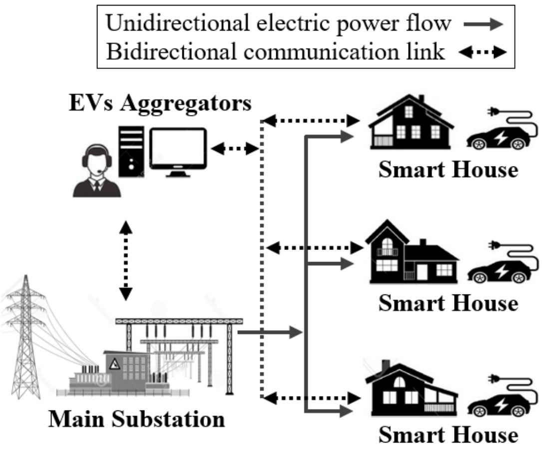

Fig. 4. Schematic diagram of the centralized coordinated charging.

4. Proposed Coordinated Charging Strategy

The proposed strategy aims primarily to alleviate the user charging costs considering the parking periods, vehicle departure time, and starting the charging process at the lowest tariff period. The proposed smart charging strategy calculations are introduced in the next four subsections.

- First, the ranking technique for the charging priority is calculated in section 4.1. This ranking is used to specify the specific EVs that need to start charging.
- Second, the charging power rate calculation based on the available period up to the vehicle departure time is presented in section 4.2.
- Third, the charging cost is estimated as per section 4.3.
- Finally, the proposed on-line coordinated charging strategy is clarified in detail in section 4.4.

4.1. Ranking of Charging Priority

Ranking of charging priority is an essential factor to decide the proper starting instant of EVs charging process. Practically, the ranking procedures should not just rely on the charging duration without considering the vehicle departure time. In this work, ranking the charging priority of each EV is determined by what is called charging flexibility [21]. The charging flexibility (f_{ch}) of EVs is affected by charging duration (D_{ch}) and the available period until departure (D_{av}). At any instant t, the available duration is equal to the difference between the departure time (t_d) and current time (t). The available duration until departure (D_{av}) and the charging flexibility (f_{ch}) are introduced in equations (4) and (5), respectively, as shown in Fig. 5.

As shown in this figure, charging flexibility is reduced as the charging process is delayed. Therefore, the EVs with lower flexibility must have precedence to charge compared with the vehicles with higher flexibility. In other words, the EVs with low flexibility have a high charging priority, while the EVs with high flexibility have a low charging priority. In this proposed strategy, the starting time of the charging process is assigned depending on the charging flexibility of EVs and the tariff situation, as will be explained in section 4.4.

$$D_{av} = t_d - t \tag{4}$$

$$f_{ch} = D_{av} - D_{ch} \tag{5}$$

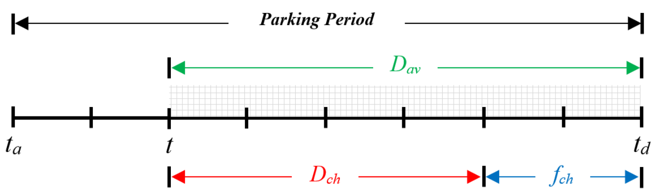

Fig. 5. EV Charging flexibility.

4.2. Charging Power Rate Calculation

To alleviate the effects of the aggregated charging activities, the charging power rate should be reduced to a level not overloading the distribution transformer while allowing fulfilling the required SOC before vehicle departure. The main idea of choosing the most proper charging power rate is to extend the charging period along the available duration (D_{av}) to reduce the value of charging power. For example, as shown in Fig. 6, if an EV requires a 1.5 hour with a charging power of 6.6 kW to reach the required SOC, it will take about 3 hours with approximately 3.3 kW charger power to fulfill the charging requirements before the vehicle departure time. The minimum controlled charging power (P_c) that can be used to charge EV during the available duration is calculated by dividing the required charging energy calculated previously in equation (1) by the available duration before the vehicle departure time, as shown in equation (6).

$$P_c = \frac{E_{ch}}{D_{av}} \tag{6}$$

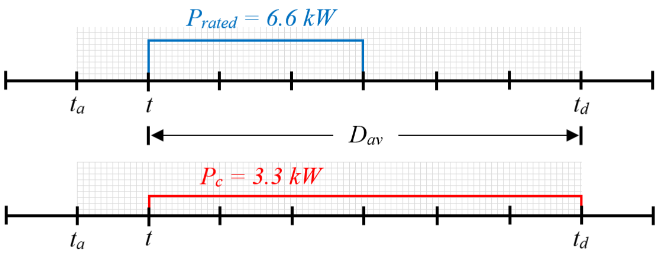

Fig. 6. Controlled charging power.

4.3. Charging Cost Calculation

Previously, published works had intended to display the reductions of the aggregated charging cost in the network without mentioning the percentage reduction of various individual users. Typically, the user is not interested in the total charging cost reduction in the network but in the charging percentage reduction reflected on his electricity bill. Therefore, this paper concentrates on the individual percentage cost reduction of EV charging activities for different users. The individual EV charging cost per day ($Cost_{EV\text{-}charge}$) is calculated utilizing the value of charging power of EV ($P_{EV,t}$) and the real-time energy price (RTP) as shown in equation (7), where *s* is the number of time slots per day.

$$Cost_{EV\text{ - }charge} = \sum_{t=1}^{s} \left(P_{EV,t} \times RTP_t \right) \tag{7}$$

4.4. The proposed algorithm

The proposed strategy aims to coordinate the charging activities from a two-sided perspective, including users' preferences (charging at very low tariff period) and safe operation of the distribution network simply and easily. The main outlines of the proposed strategy are:

1. Network service providers send a day-ahead energy tariff data at the beginning of each day to the aggregators.
2. The home charging unit is powered with a remotely variable charging control system to adapt the output power of the unit.
3. The aggregators are connected with each home charging unit in the network through a bi-directional communication link.
4. The aggregators automatically capture the vehicle's data like arrival SOC, battery capacity, and maximum charger power once the vehicle is plugged into the charging control unit.
5. After the arrival of the EV, the user should submit the following data
   - The expected departure time.
   - The value of SOC is required at departure instant.

The strategy procedure comprises four stages, as explained in Fig. 7. These stages are summarized as follows:

Stage I. Gathering the distribution network initial data, receiving the day-ahead tariff, initialized the EVs charging matrix, and finally starts the daily time sweep with a time resolution of 5 minutes. (288-time slots).

Stage II. The coordinated charging data, including starting time and the value of charging power, are determined as follows:

Step 1. The aggregators collect the EVs data by communicating with the home charging units and calculate the charging flexibility (f_{ch}) from equations (1), (2), (4), and (5). Finally, sorting the calculated flexibility of all arrived vehicles.

Step 2. The EVs' priorities are ranked in this step (high, moderate, low) based on the charging flexibility. The low charging priority is chosen if the charging flexibility is large enough to delay the charging process to the very low tariff period (users' preferences). The moderate charging priority is chosen if the charging flexibility is suitable to delay the charging process to the off-peak period (decreasing tariff). Finally, if the two previous conditions are not satisfied, the vehicle will be ranked as a high charging priority.

Step 3. The starting time and power rate of the charging process are determined for three separate cases:

- ***Case 3.a (low priority)*** the starting time is determined depending on the relation between the arrival time and the low tariff starting instant and then calculate the charging power from equation (6).
- ***Case 3.b (high priority)*** the charging process starts immediately, and the charging power is calculated from equation (6).
- ***Case 3.c (moderate priority)*** the starting time is determined depending on the relation between the arrival time and the off-peak starting instant. Then the charging power is calculated from equation (6).

Stage III. This stage is dedicated to preventing the total load consumption (P_t) on the substation from exceeding the substation capacity limit (SCL). Initially, the substation's total load consumption is estimated by the applied load flow program. If the total load exceeds the SCL limit, the algorithm will start delaying the lowest priority vehicle one by one and updating the charging matrix until P_t goes below SCL.

Stage IV. This stage is a voltage support stage supposed to be used by the aggregators to maintain the network minimum voltage (V_{min}) in the acceptable limit (assumed to be 0.9 in this work). In distribution networks, many techniques are used to maintain the minimum system voltage within the acceptable limit [25]. In the proposed strategy, two sequential techniques are used to support the minimum voltage magnitude [19]. In the first step, capacitors are switched to raise the voltage. If the added capacitors failed to raise the minimum voltage to an acceptable limit (this is expected in case of having large numbers of EVs), the transformer's substation tap changer is applied with the capacitors.

5. Tests and Results

5.1. Case Study Data

The selected network is a modified IEEE 31 bus 23 kV distribution network [26] with 22 low voltage residential feeders, as portrayed in Fig. 8. Each residential feeder contains 19 nodes that are populated with residential customers and supplied from 23/0.415 kV, 100 kVA distribution transformer [27]. The detailed diagram of the residential feeder with 63% EV penetration levels is illustrated in Fig. 9 [23]. The system is also comprised of five capacitors of 50, 100, 100, 50, and 50 kVAR located at buses of 4, 14, 16, 20, and 27, respectively [28]. In addition, the substation transformer tap changer is assumed to have five tap positions of [-2 -1 0 1 2] which vary the voltage magnitude by ± 5 %. The typical residential daily load curve and the real-time energy prices tariff are illustrated in Fig. 10 [23].

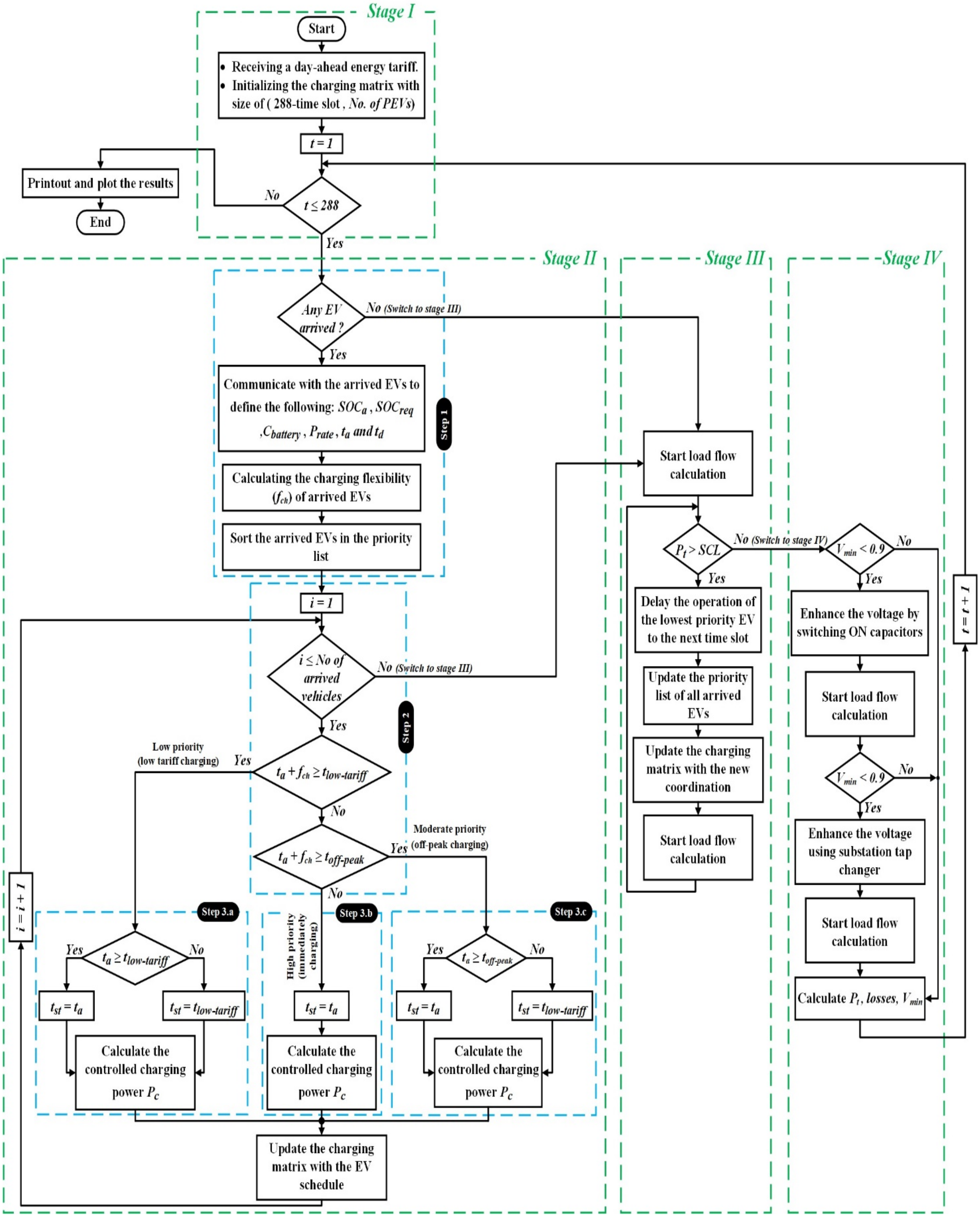

Fig. 7. The proposed coordinated charging strategy.

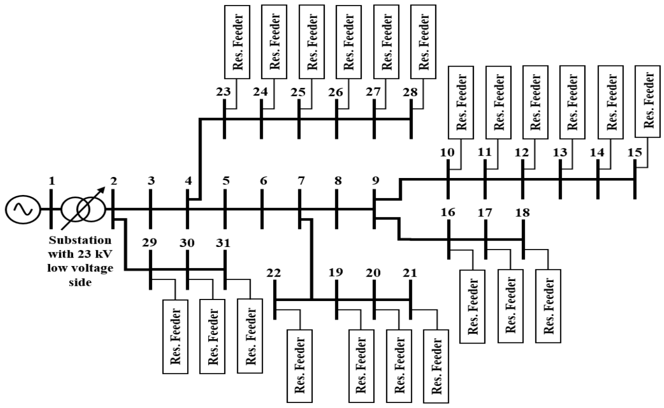

Fig. 8. Modified IEEE 31 bus distribution network.

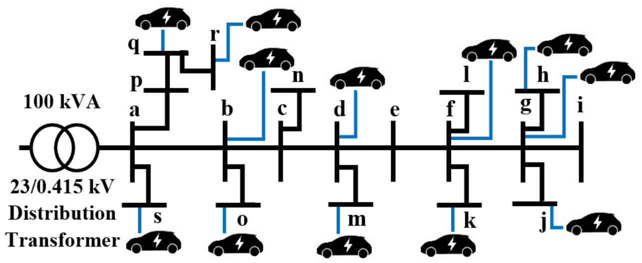

Fig. 9. Residential feeder with 63% EV penetration level.

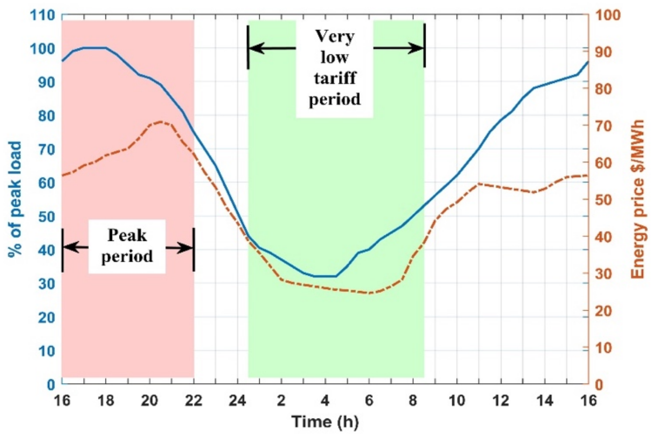

Fig. 10. Residential load profile and the energy tariff.

For reality simulation in this study, the EV battery capacity and the charger rated power are assumed to be varied from one user to another. The battery capacities are taken as 6, 16, and 19.2 kWh, while the chargers rated power are 3.3, 6.6, 7.2 kW. The simulation input data of the vehicles driving pattern are provided in [23], such as arrival time, departure time, SOC at EV arrival, and requested SOC for 63% penetration of EV. A sample of the detailed input parameters of EVs is presented in Table 2.

5.2.Analysis and Discussions

In this work, analysis and algorithm implementation have been carried out using MATLAB script, while OpenDSS program has been used to simulate distribution network and perform load flow analysis for 24 hours with 5 minutes time resolution. In addition, the simulation horizon is taken for one day (from 16:00 to 16:00 of the next day), and it is assumed that the input data is to be the same for any other day. To provide a simple demonstration of the calculation procedures, a sample of the calculation process for a one-time slot is demonstrated in Table 3. In this table, the calculation of arrived vehicles at a random time slot 43 (at 19:35) is presented. The vehicles that arrived at this instant have different charging flexibility.

Once the vehicles arrived, the users have to define the vehicle's next departure time and the required SOC at departure instant. The charger unit detects the other data like arrival battery SOC. The calculation procedures are introduced step by step (in Table 3) to determine the charging instant and the controlled charging power. Finally, after applying the steps shown in Table 3, the charging matrix is updated with the charging instant values and the controlled charging power of arrived EVs at this time slot. At time slot *t*, the EVs charging loads defined in the updated charging matrix are added to the baseload of each house in the network. Afterward, the load flow calculation starts to calculate the system performance parameters in terms of the total substation load demand, voltage deviation, and system losses. These calculations are repeated for each time slot per day.

In the next subsections, the simulation results of the proposed coordinated charging strategy are presented from two points of view included system operators who want to provide the safe operation of the network and the vehicle owners' view who want to reduce the costs of charging activities as much as possible.

A. System Operators Requirements (Network safe operation)

The proposed strategy achieves safe operation requirements of the distribution network in terms of suppressing the substation's excessive loading, maintaining the network voltage deviations in acceptable limits, and reducing the overall system power loss. As shown in Fig. 11, the uncoordinated charging activities increased the substation loading to 1.22 MW while the SCL is 0.84 MW (about 45% overloading). In contrast, the proposed charging strategy prevents the total substation loading from exceeding SCL by applying precaution procedures through controlling the EVs charging activities as following:

Table 2. Sample of detailed input parameters of EVs [23].

EV ID	*SOC* at vehicle arrival (%)	Requested *SOC* at departure (%)	Battery capacity (kWh)	Charger rated power (kW)	Arrival time slot	Departure time slot
EV31	8	54	6	3.3	51	187
EV32	19	74	19.2	7.2	39	179

Ev33	2	88	16	6.6	57	191

Table 3. Calculation sample at time slot 43 (19:35).

Item	Arrived vehicles ID at time slot 43 (19:35)							
	EV 123	*EV 126*	*EV 129*	*EV 136*	*EV 140*	*EV 148*	*EV 153*	*EV 252*
P_{rated} * (kW)	3.3	7.2	7.2	7.2	6.6	6.6	6.6	6.6
$C_{battery}$ * (kWh)	6	19.2	19.2	19.2	16	16	16	16
SOC_a * (%)	6	26	14	23	28	8	8	23
SOC_{req} ** (%)	70	62	73	94	65	85	67	92
S_{in} *	43 (19:35)	43 (19:35)	43 (19:35)	43 (19:35)	43 (19:35)	43 (19:35)	43 (19:35)	43 (19:35)
S_{out} **	181 (07:05)	80 (22:40)	182 (07:10)	69 (21:45)	88 (23:20)	182 (07:10)	81 (22:45)	183 (07:15)
Parking period [a]	138	37	139	26	45	139	38	140
E_{ch} (kWh) Eq.(1)	4.2667	7.6800	12.5867	15.1467	6.5778	13.6889	10.4889	12.2667
f_{ch} Eq.(5)	122	24	118	0	33	114	18	117
Priority rank Stage II-Step. 2	Low	High	Low	High	Moderate	Low	High	Low
Charging status	Low tariff charging	Immediately starting	Low tariff charging	Immediately starting	Off-peak charging	Low tariff charging	Immediately starting	Low tariff charging
Charging instant Stage II-Step.3	102 (00:30)	43 (19:35)	102 (00:30)	43 (19:35)	72 (22:00)	102 (00:30)	43 (19:35)	102 (00:30)
Available charging slots [b] (D_{av})	79	37	80	26	16	80	38	81
P_c (kW) Eq.(6)	0.65	2.5	1.9	7.2	5	2.06	3.4	1.82
The calculation time of this time slot is 0.0229 sec								

* Detected by charging unit.
** Defined by the user.
[a] The parking period is the number of slots from the arriving to the departure time slots.
[b] The available charging slots are calculated from the starting instant of the charging process to the vehicle departure time slot. One time slot = 5 min (0.0833h).

- During the peak period (orange region), the charging activities are restricted except for the EVs with high charging priority (low charging flexibility). The proper charging power rates of the high-charging priority vehicles are determined as presented in section 4.2.
- After the end of the peak period, previously arrived EVs with a moderate priority will be started. For currently arrived vehicles, vehicles with insufficient charging flexibility for delaying a very low tariff period will also start.
- In the very low tariff period (green region), all vehicles (delayed charging and currently arrived) will start charging immediately with a controlled power P_c.

Figure 12 illustrates the overall network power loss in various cases. The losses extremely increase during the peak period, which reaches double the original values with the uncoordinated charging activities. The proposed coordination strategy successfully reduced the overall losses compared with uncoordinated charging. With uncoordinated charging activities, the network minimum voltage decreases to immensely low levels (about 0.81 p.u.), as shown in Fig. 13. In contrast, with the assistance of capacitors switching and substation tap changer adjustment, the proposed strategy maintained the minimum voltage over 0.9 p.u.

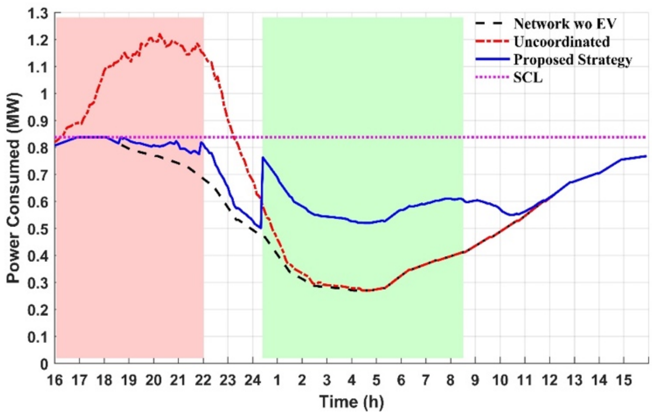

Fig. 11. Total network power consumption at the substation.

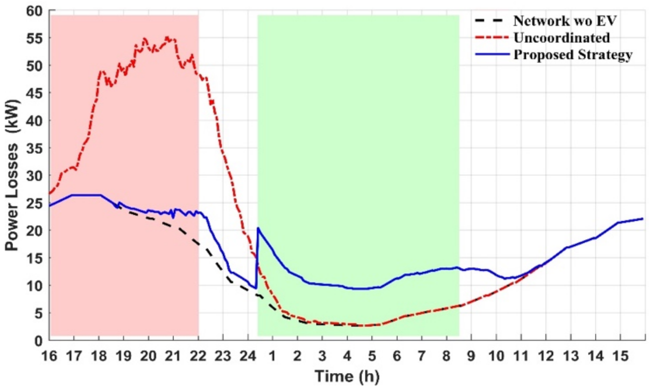

Fig. 12. Network overall power loss.

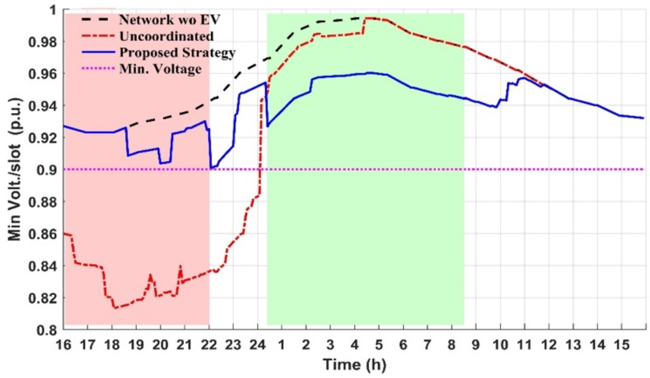

Fig. 13. Network minimum voltage magnitude.

B. EV Users Requirements (charging costs)

To figure out the effect of the proposed strategy on the charging costs from the user point of view, cost analysis has been separately calculated for each user. For the sake of comparison, the charging costs have been analyzed for both uncoordinated charging activities and the proposed coordination strategy. Referring to Eq. (7), based on the energy tariff (RTP), the charging cost of each EV in the network is calculated with and without utilizing the proposed coordination charging strategy. The percentage of charging cost reductions of all EVs is then determined and listed in Fig. 14. In this figure, the proposed strategy successfully reduces the individual charging cost of 94% of users (248 EVs) with different percentages according to the period in which the charging process has been activated of each user (peak, off-peak, or very low tariff period). The cost reductions increase for vehicles that delaying the charging activities toward the very low tariff period. The charging activities that occur during the peak period have gained a small cost reduction. Still, in urgent charging cases that occur during the peak period, this percentage of reductions is acceptable.

However, about 6 % of users (16 EVs out of 264) incur some additional charging costs (negative reduction) compared with their uncoordinated charging costs due to delaying their charging to a high tariff period to maintain safe operation. Referring to Fig. 10, the energy tariff is not completely compatible with the residential load curve during the peak period, which means that the charging costs during the load crest between hours of 17 to 18 are lower than charging after 18 to 22. For safe operation aspects, the charging activities during load crest are prohibited from limiting the total power consumption, and hence all charging activities are delayed after this period. Thus, some vehicles will be charged at a higher cost than if they are charged at load crest. Occasionally, in very few cases, the user may incur the same uncoordinated charging cost, while in most cases, the charging costs will reduce up to 60%.

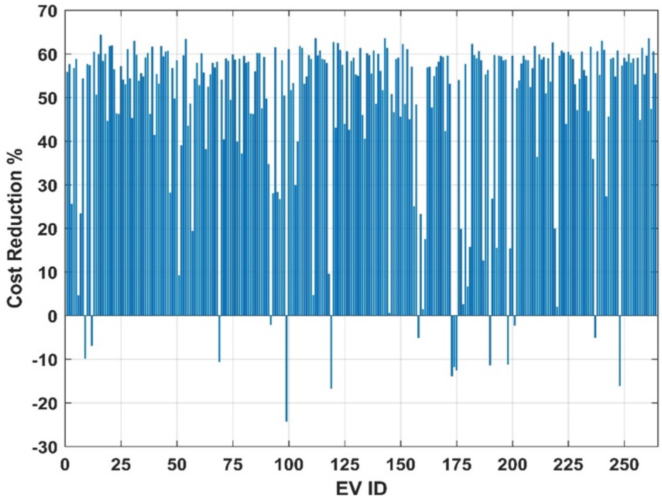

Fig. 14. Charging cost percentage reduction.

5.3.Evaluation of the Proposed Technique

The simulation input data, including EVs input data, are introduced in Table 2. The residential load curve and the energy RTP data introduced in Fig. 10 are taken from [23]. Referring to this data, there are no arrived vehicles in the period between 6:00 to 15:59. According to vehicle owners traveling surveys like National Household Traveling Survey, small numbers of vehicles arrive in the period between 6:00 to 16:00 while the largest number of vehicles arrive at homes in the early evening hours after 16:00. Before the peak period of the residential community (from 6:00 to 16:00), the difference between the actual load and SCL is large, as shown in the shaded area in Fig. 11. Since the numbers of vehicles that usually arrive in this period are typically small, the network can handle it without the need for any coordination strategies, especially with the low energy tariff during this period. Thus, the charging activities during this period do not have any noticeable effect on the distribution network performance.

Unlike most previous studies that use optimization techniques to solve the EVs coordination problem, this work uses an if-statement algorithm. Most of the optimization techniques, in general, have major drawbacks. For example, the optimal results are strongly affected by the technique coefficients (like c1 and c2 in PSO). Thus, the optimal results may be changed if different coefficient values are used. In addition, in many complex optimization problems, the optimization technique needs a large number of iterations to converge, which may lead to an increase in the calculation time (not suitable for on-line applications). The obtained results are compared with the particle swarm optimization technique (PSO) introduced in [23] to validate the obtained results with the optimal coordination solution. Table 4 illustrates a comparison of results between the proposed algorithm and the PSO-based optimization algorithm. Furthermore, the proposed strategy result is also compared with [19] as this reference has the same EVs input data (except vehicle departure time). The optimal solutions presented in [19] are determined by using PSO and grey wolf optimization techniques. The proposed strategy success in limiting the substation power consumption below the SCL with a daily voltage deviation of about 6.12%. While this value is 7.34% and 9.73% in [19] and [23], respectively. Also, the calculation time in any time slot did not exceed 0.023 seconds while it was 0.035 seconds in [23]. The cost reduction value is not reported in [23], while reference [19] uses a different type of energy tariff.

Table 4. Comparison of the proposed strategy with [23].

Item	Ref. [23]	Proposed Strategy
Used technique	PSO	If statement
ΔV[a]	9.73 %	6.12 %
Calculation time (sec.)	0.035	0.023
Average cost reduction	Not reported	47.65 %

[a] Average voltage deviation over 24 h.

Finally, in this work, the time window is simulated by only one day, while this data is assumed to be the same for any other day. As a future business, the proposed strategy could be upgraded by using a moveable simulation time window (3, 10, or more days) in order to achieve more practical simulation.

6. Conclusions

This paper proposes an on-line centralized coordinated charging strategy considering different practical parameters such as vehicle departure time and energy tariff that affect the charging coordination of EVs. The charging coordination is implemented by calculating both the charging instant and the minimum charging power rate. Unlike most previous studies, the charging period is assigned to reduce the EV charging cost according to the input data imposed by the user. A charging flexibility technique is used for ranking the charging priority of EVs in order to calculate the suitable starting instant of the charging process. Consequently, based on the calculated charging instant and the vehicle departure time, the proper minimum charging power rate is estimated for each EV to relieve the aggregated charging effects. The proposed strategy aims to reduce the charging costs from the user point of view simultaneously with providing the safe operation of the distribution network in terms of maintaining the substation loading limits, voltage limits, and overall power loss. The proposed strategy successfully deals with the harmful uncoordinated charging effects of EVs with achieving charging cost reductions for about 94% of users. Additionally, the recommendation that was concluded is that the network operators should support some of the extra charging costs that may occur due to the scheduling of EVs charging. This financial support will facilitate users' participation in the coordination processes.

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