Optimal Fixed Charge–Rate Coordination of Plug-In Electric Vehicle Incorporating Capacitor and OLTC Switching to Minimize Power Loss and Voltage Deviation

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Incorporating Capacitor and OLTC Switching to Minimize Power Loss and Voltage Deviation

Integration of plug-in electric vehicles (PEVs) in a smart grid largely deteriorates the performances of the system. This paper proposes a two-stage optimization approach to optimize customer satisfaction as well as grid performances when fixed charge–rate PEV coordination, switching capacitor and on-load tap charger (OLTC) are coordinated simultaneously. To coordinate PEV charging, capacitor and OLTC, an efficient binary particle swarm optimization (BPSO) has been applied. The main consideration in this optimal coordination is to minimize the daily power loss and voltage deviation while maximizing customer satisfaction. Simulation results are compared with the variable charge–rate coordination that is proposed previously. © 2018 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: PEV coordination; fixed charge–rate; OLTC; capacitor; customer satisfaction

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1. Introduction

Plug-in electric vehicles (PEVs) are environment-friendly green transportation because of their pollution-free operation. PEVs are becoming the more prominent choice in recent years as a consequence of greenhouse gas (GHG) emission in the environment. Moreover, the lower daily running cost of PEVs over the conventional combustion engine has drawn the attention of the vehicle users [1].

Basically, PEVs utilize large battery capacities that require frequent charging to run high power-rated motors [2]. These vehicles are charged by plugging into electric outlets in corporate or residential car parking. A PEV’s load is considered extra large and undesirable peak electrical consumption on residential distribution systems. The charging of PEVs has a significant impact on power distribution systems. Hence, uncoordinated and random PEV charging activities can overload the system, and in many cases, it can cause power quality issues such as voltage sag as well as increase the system’s power loss [3,4]. In order to counter the massive increase in PEV loads, particularly during peak hours, many countries are introducing smart metering and smart appliances [5]. Large integration of PEVs has influenced researchers to work on developing a coordination strategy for PEV charging in distribution systems. In general, the coordination strategies for PEVs can be categorized into two types: centralized approach and decentralized approach. In decentralized coordination of PEV charging, the charging time is decided by the PEV customer based on the system capacity and constraints. Different types of decentralized methods are proposed for PEV charging, which are based on tariffs, voltage profile [6] and energy cost sharing models [7]. However, the decentralized approach cannot guarantee an optimal solution as the customer can decide on their charging patterns independently. In contrast, centralized coordination is more effective as it has a central control system with high-speed, bidirectional, smart grid communication for each PEV. The charging decision is taken by the central control system considering several system constraints as well as customer’s satisfaction. Much research on centralized PEV charging coordination has been proposed to minimize distribution system power losses [8], generation cost [9] considering time-varying market energy prices and customer priority [3]. A two-stage optimization procedure is proposed in [10] to charge the PEV optimally considering customer satisfaction as well as charging cost minimization. Moreover, an optimal variable charge–rate scheduling of PEVs is introduced [11] to ensure priority fairness for all PEVs in distribution.

Nevertheless, due to the ongoing development of smart technologies between central control and PEV charger, sometimes, the charging rate cannot be controlled precisely as required [3,12]. In addition, fixed charging of the PEV battery is considered a fast process over the variable charge–rate coordination strategy [13]. Since, the buses which are located at the end line of the distribution network have lower voltage, no PEV in that area can charge earlier even though the system has available capacity. Furthermore, end buses PEV cannot be considered a priority due to its voltage violation in the earlier stage of coordination.

According to recent literature review, numerous aspects of the PEV coordination problem in residential distribution systems have been studied. However, only a few studies [8,14] have considered power loss and voltage deviation as an objective function together. Furthermore, as far as the authors’ knowledge, no research has been conducted to improve the end buses voltage of the distribution during PEV charging by considering switching capacitors on feeder and on-load tap charger (OLTC). Therefore, an intelligent PEV
battery charging technique considering end buses’ voltage improvement during charging is needed for the distribution network.

To address this gap, this study proposes a method for fixed charge–rate PEV charging coordination while considering the optimal dispatch of switching capacitors and OLTC to minimize the power losses and voltage deviation. A binary particle swarm optimization (BPSO) has been employed to coordinate PEV charging, optimal dispatch of capacitors and OLTC. Constraints such as maximum demand, voltage limits, state of charge and number of capacitor switching and number of OLTC switching a day are considered to achieve the objective.

2. Problem Formulation

2.1. Objective function

The PEV charging coordination in a distribution system is considered a real-time optimization problem. PEV charging coordination in the presence of switching capacitors and OLTC are determined based on minimum system power loss and voltage deviation over 24 h while considering the maximum demand of the system. The PEV coordination is divided into 288 time slots of 5-min intervals. Consideration of capacitor switching and OLTC during the PEV charging coordination splits the proposed method into two parts. One is fixed charge–rate PEV coordination, and another is optimal dispatch of capacitors and OLTC. Moreover, a set of constraints are taken into account to obtain the objective function. The objective function can be formulated as (1).

\[
\min f = \sum_{h=1}^{24} (P_{\text{loss}} + V_d) \tag{1}
\]

As the objective function has different units, the final power loss is calculated as the ratio of total system power loss after and before coordination.

\[
P_{\text{loss}} = \frac{P_{\text{coord}}}{P_{\text{uncord}}} \tag{2}
\]

The power loss equation for the distribution system is presented by:

\[
P_{\text{loss}} = \sum_{j=1}^{\text{timeslot}} (I_{\text{A}}^2 * R_{\text{n}}) \tag{3}
\]

Voltage deviation \( (V_d) \) can be defined as the difference between the nominal voltage and the actual voltage. The smaller the deviation of the bus voltage from the nominal voltage, the better the voltage condition of the system.

\[
V_d = \text{Max}_{m=2}^{m} \left( \frac{V_{\text{rated}} - V_i}{V_{\text{rated}}} \right) \tag{4}
\]

where \( V_{\text{rated}} \) is the nominal voltage of the system that is 1.0 pu, and \( V_i \) is the voltage at the \( i \)th node. \( m \) is the total number of nodes of the system.

2.2. Constraints

A series of constraints have to be satisfied to achieve the objective function. The constraints are described below:

2.2.1. Maximum demand

\[
P_{\text{max}} \geq \sum_{i=2}^{m} (P_{\text{load}, i} + P_{\text{PEV}, i}) \tag{5}
\]

here, \( n \) is the number of branches, \( P_{\text{load}, i} \) refers to the residential load, \( P_{\text{PEV}, i} \) denotes the PEV load on \( i \)th node, and \( P_{\text{max}} \) demand is the maximum demand from the substation transformer of the system within 24 h.

2.2.2. Bus voltage

\[
V_{\text{min}} \leq V_i \leq V_{\text{max}} \tag{6}
\]

Here, \( V_{\text{min}} \) and \( V_{\text{max}} \) denote the minimum and maximum allowable voltage range, respectively. In this work, the voltage limits are specified to ±10% (considered 0.9–1.1 pu for this distribution system).

2.2.3. State of charge (SOC)

\[
SOC_{\text{int}} \leq SOC_{\text{curr}} \leq SOC_{\text{req}} \tag{7}
\]

here, \( SOC_{\text{int}} \) is the initial state of charge when the battery is plugged in, \( SOC_{\text{req}} \) is the requested maximum charge by the customer, and \( SOC_{\text{curr}} \) is the state of charge after each \( \Delta t \) time slot.

2.2.4. Operation number for capacitor

Although capacitors along the feeder are allowed to switch on and off once a day, the switching of a capacitor at secondary bus can occur more than once. It is worth mentioning that the maximum allowable number of capacitors at secondary bus is perceived as constrained [15]. The daily number of switching operations for a capacitor is given by (8).

\[
\sum_{h=1}^{24} (C_{i,h} \otimes C_{i,h-1}) \leq C_{\text{m}} \tag{8}
\]

here, \( C_{i,h} \) is the status of the capacitor, and \( C_{\text{m}} \) is the maximum allowable switching number for capacitor ‘i’ in a day.

2.2.5. Daily switching number of OLTC

OLTC cannot be switched frequently due to higher maintenance costs and reduction of life expectancy. Therefore, the daily number of switching operation is limited by a constraint.

\[
\sum_{h=1}^{L} |T_{\text{ap}, h} - T_{\text{ap}, h-1}| \leq T_{\text{ap}, \text{max}} \tag{9}
\]

here, \( L \) is the number of load levels in a day. The maximum number of allowable switching operations of OLTC is 30 times a day [16].

3. Algorithm and Implementation

In this study, BPSO, introduced by Kennedy and Eberhart [17], was applied to solve the proposed EV charging method. Binary PSO is very identical to the continuous PSO. The principal difference is in a particle position change equation. The velocity and the position of each particle in d-dimensional space can be presented by the (10) and (12), respectively.

\[
V_{\text{it}} = W * V_{\text{it}} + C_1 * m_1 \times (P_{\text{it}} - X_{\text{it}}) + C_2 * m_2 \times (P_{\text{g}, \text{it}} - X_{\text{it}}) \tag{10}
\]

here, \( m_1 \) and \( m_2 \) are two different random values, \( V_{\text{it}} \) is particle velocity, \( X_{\text{it}} \) is the current particle, \( P_{\text{it}} \) is the best previous position, and \( P_{\text{g}, \text{it}} \) is the best among all the particles. Each \( V_{\text{it}} \) performs the probability of new position of particle \( X_{\text{it}} \) and is limited in the range of \( [V_{\text{min}}, V_{\text{max}}] \).

\[
\text{Sig}(V_{\text{it}}) = \frac{1}{1 + e^{-V_{\text{it}}}} \tag{11}
\]

\[
X_{\text{it}}(t+1) = \begin{cases} 
1 & \text{if } \phi < \text{Sig}(V_{\text{it}}) \\
0 & \text{if } \phi \geq \text{Sig}(V_{\text{it}}) \end{cases} \tag{12}
\]

here, Sig(V_{\text{it}}) is a logistic function transformation, and \( \phi \) is a quasi-random number between ‘0’ and ‘1’.

BPSO is chosen in this study because the nature of the solution in EV charging scheduling required a binary form; ‘1’ for charging and ‘0’ for off-charging. Furthermore, BPSO has been proven to offer better optimal solutions compared to the other optimization techniques for problems with a limited number of parameters [18].
3.1. PEV coordination

The PEV charging algorithm selects the time slot for all vehicles, that is, what time it will start to charge. The required input data from the PEV charger for coordination, such as arbitrary arriving time of PEV, charger capacity, battery capacity, current SOC and requested SOC, can be acquired using smart metering [3].

At the very first time, the coordination algorithm has been executed to schedule the arrived PEV on the basis of minimum system power loss and voltage deviation using BPSO. Each $\Delta t = 5$ min, the input data are updated, and the coordination algorithm is executed to find the schedule for those PEVs that are newly arrived and not connected in the previous time slot due to voltage limitation. Then, the previous scheduled status is updated by the new schedule at $\Delta t$ time. Once a vehicle has started to charge, it will continue until it reaches its requested SOC. To avoid overloading of the substation transformer, all the scheduled PEVs will be disconnected when the residential load reaches the maximum demand. These PEVs will be connected again when the residential load decreases and when the transformer is available to connect more loads. Fig. 1 shows the flow chart of the proposed BPSO algorithm for fixed charge–rate PEV coordination based on (1).

![Fig. 1. Flowchart of the proposed fixed charge–rate PEV coordination](image)

3.2. Capacitor and OLTC

Conventionally, the involvement of a load tap changer of the substation transformer and switchable capacitor installed at the distribution feeder can improve voltage profiles for all end buses’ customers [19],[20] and reduce system loss and increase system efficiency [21]. The capacitors location on feeder and its sizing are obtained from [20]. Capacitor scheduling will take place prior to OLTC operation to reduce the daily switching numbers of OLTC.

In this section, the same objective function has been utilized to perform an optimal dispatch of capacitors and OLTC in the smart grid in the presence of PEV charging. For this purpose, BPSO has been adopted, similar to the previous section. Because of the arbitrary and uncertainty nature of the PEV load on residential distribution, it could be construed as a daily load curve based on previous day data of PEV load. The optimization algorithm finds the optimal dispatch sequence of capacitor and OLTC. The results obtained from the BPSO indicate the status of each capacitor in the specific hour, where ‘0’ and ‘1’ indicate the status of capacitor off and on, respectively. Furthermore, OLTC is a significant part of the distribution system in voltage control. Most of the OLTC has 17 tap positions, which can change the voltage from $-5$ to $+5\%$ [22]. The operation of OLTC is not frequent as it reduces the lifetime and increases repairing cost. The tap changer adjustment is determined in terms of predefined voltage, which represents its tap position. Fig. 2 shows the flow chart of the proposed BPSO.

![Fig. 2. Flowchart of optimal dispatch of capacitor and OLTC during PEV charging coordination](image)
algorithm for optimal dispatch of feeder capacitor and OLTC based on (1), (8) and (9).

4. Results and Discussion

The proposed method is tested on the IEEE 31 bus 23 kV distribution test system [23] with 22 residential 415 V networks as shown in Fig. 3. All the low voltage residential feeders have the same configurations with household loads. The residential feeder node data and daily load curve have been taken from [3]. The daily peak power consumption is considered to be 2 kW maintaining the power factor 0.9. The switchable capacitors are located at bus number 4, 14, 16, 20 and 27 bearing the size 50, 100, 100, 50 and 50 kVAr, respectively. However, the PEV battery capacities are high and generally range from few kWh to over 50 kWh [8]. Therefore, the charger capacities are also large enough to charge the battery in an acceptable time frame. For this analysis, all the chargers are considered to have fixed charging rate. In this research, backward forward sweep load flow proposed in [24] has been employed to determine the power flows and voltages of each node. The backward forward sweep load flow calculates the node currents, line currents and node voltages of the tested distribution system. However, the charger capacities, initial SOC and requested SOC for the weakest and best feeders at 63% penetration are shown in Table I.

![Fig. 3. IEEE 31 node 23 kV system with 22 low-voltage feeders and detailed diagram of one feeder populated by 63% PEV penetration](image)

![Fig. 4. Uncoordinated PEV charging with different penetration.](image)

(a) Voltage profile for weakest node, (b) total system power loss, (c) total system power consumption

Table I. Detailed system input data and customer satisfaction status for the weakest and best feeder at 63% penetration

<table>
<thead>
<tr>
<th></th>
<th>n2</th>
<th>n4</th>
<th>n6</th>
<th>n7</th>
<th>n8</th>
<th>n10</th>
<th>n11</th>
<th>n13</th>
<th>n15</th>
<th>n17</th>
<th>n18</th>
<th>n19</th>
<th>Feeder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charger capacity (kW)</td>
<td>3.3</td>
<td>7.2</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
<td>6.6</td>
<td>7.2</td>
<td>7.2</td>
<td>6.6</td>
<td>7.2</td>
<td>6.6</td>
<td>7.2</td>
<td>DT14</td>
</tr>
<tr>
<td>Initial SOC (%)</td>
<td>3.3</td>
<td>7.2</td>
<td>7.2</td>
<td>3.3</td>
<td>6.6</td>
<td>3.3</td>
<td>7.2</td>
<td>7.2</td>
<td>3.3</td>
<td>6.6</td>
<td>7.2</td>
<td>6.6</td>
<td>DT17</td>
</tr>
<tr>
<td>Requested SOC (%)</td>
<td>17</td>
<td>25</td>
<td>9</td>
<td>19</td>
<td>7</td>
<td>19</td>
<td>28</td>
<td>12</td>
<td>5</td>
<td>16</td>
<td>22</td>
<td>15</td>
<td>DT14</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>6</td>
<td>11</td>
<td>11</td>
<td>24</td>
<td>7</td>
<td>26</td>
<td>14</td>
<td>11</td>
<td>24</td>
<td>14</td>
<td>13</td>
<td>DT17</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>72</td>
<td>83</td>
<td>66</td>
<td>78</td>
<td>59</td>
<td>61</td>
<td>80</td>
<td>82</td>
<td>74</td>
<td>68</td>
<td>81</td>
<td>DT14</td>
</tr>
<tr>
<td>Customer satisfaction</td>
<td>sat</td>
<td>uns</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>uns</td>
<td>uns</td>
<td>uns</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>uns</td>
<td>DT14</td>
</tr>
<tr>
<td></td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>sat</td>
<td>DT17</td>
</tr>
</tbody>
</table>

DT14 = weakest feeder, DT17 = best feeder, sat = satisfied, uns = unsatisfied.
Table II. Impact of PEV charging on distribution systems in different cases

<table>
<thead>
<tr>
<th>Scenario</th>
<th>PEV (%)</th>
<th>ΔV (%)</th>
<th>Increase in loss&lt;sup&gt;a&lt;/sup&gt; (%)</th>
<th>Satisfaction ratio&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>No PEV</td>
<td>0</td>
<td>7.35</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>Case 1: uncoordinated</td>
<td>16</td>
<td>7.61</td>
<td>6.97</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>47</td>
<td>17.27</td>
<td>14.59</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>19.16</td>
<td>33.85</td>
<td>—</td>
</tr>
<tr>
<td>Case 2: coordinated</td>
<td>16</td>
<td>7.43</td>
<td>6.96</td>
<td>18/4</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>7.47</td>
<td>13.67</td>
<td>15/7</td>
</tr>
<tr>
<td></td>
<td>47</td>
<td>8.61</td>
<td>12.32</td>
<td>8/14</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>9.91</td>
<td>17.53</td>
<td>3/19</td>
</tr>
<tr>
<td>Case 3: coordinated with capacitor and OLTC switching</td>
<td>16</td>
<td>4.96</td>
<td>5.53</td>
<td>22/0</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>4.99</td>
<td>11.86</td>
<td>22/0</td>
</tr>
<tr>
<td></td>
<td>47</td>
<td>6.32</td>
<td>17.28</td>
<td>22/0</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>7.34</td>
<td>23.03</td>
<td>22/0</td>
</tr>
</tbody>
</table>

<sup>a</sup>Increase in loss compare to no PEV case.

<sup>b</sup>Number of satisfied feeders/number of unsatisfied feeders.

Fig. 5. Fixed charge-rate PEV coordinated for different penetration level. (a) Voltage profile for weakest node, (b) total system power loss, (c) total system power consumption

Fig. 6. Battery state of charge for 63% penetration level (PEV coordinated only). (a) State of charge for weakest feeder, (b) state of charge for best feeder

In this proposed system, there are 30% of PEVs with a 3.3 kW and 6 kWh charger and battery size, respectively; 40% of PEVs with a 6.6 kW and 16 kWh charger and battery size, respectively; and 30% of PEVs with a 7.2 kW and 19.2 kWh charger and battery size, respectively. To validate the accuracy of the proposed method, a case study based on the use of a variable charge-rate coordination (VCC) strategy [11] is adopted. In addition, three different cases are investigated.

The following cases are:

**Case 1**: Uncoordinated and random PEV charging.

**Case 2**: Coordinated PEV charging with all the system constraints.

**Case 3**: Optimal dispatch of capacitor and OLTC during coordinated PEV charging.

Simulation results with 16, 32, 47 and 63% PEV penetration for three cases can be explained as follows.

**Case 1**: In this case, the charging process will be started as soon as the vehicle connects to the charger. This vehicle will charge randomly and never follow the system constraints. Therefore, the distribution system has to face more problems such as overloading, huge power loss and unacceptable voltage deviation. The weak node voltage drastically drops beyond the permissible lower limit for 47 and 63% as shown in Fig. 4(a). From Fig. 4(c), it can be observed that the power consumption exceeds the maximum demand as there is no control over the charging schedule. As a consequence, the power losses are extremely high and cause greater economical burden for all the penetration levels. The impacts of uncoordinated charging on distribution systems are shown in Table II and Fig. 4(b).

**Case 2**: To overcome the devastating impacts of uncoordinated charging of PEVs on distribution networks, a real-time PEV charging coordination approach based on 5-min interval is proposed in this paper. Once a vehicle plugs in with a charger, it will not start to charge as long as the charging decision is not taken by the central control. The implemented BPSO algorithm optimally schedules the
arrived PEV and satisfies all the system constraints. This strategy is more beneficial for the distribution system compared to case 1. As shown in Table II and Fig. 5(a) and (b), for 63% PEV penetration, total system power loss and voltage deviation at weak node were reduced to 17.53 and 9.91%, respectively. The total power consumption did not exceed the maximum demand as shown in Fig. 5(c). However, for the high PEV penetration, in some feeders, this strategy failed to satisfy all the customers equally due to the distribution system voltage limitation. From Table II, it can be seen that, for all penetration levels, some feeders are not satisfied in terms of customers. In Fig. 6 and Table I, at node n4, n10, n11, n13, n19 for 63% PEV penetration, the final SOC of the battery remain the same as the initial SOC because of the excessive voltage drops of those points, even though the substation transformer capacity is not fully utilized. Note that there are still some vehicles that have not started to charge during the whole day as in Fig. 6(b). As a result, the customers are not satisfied with those feeders and do not want to use a coordination strategy.

**Case 3:** In this section, the fixed charge–rate PEV coordination’s simulation results are presented with optimal dispatch of capacitor and OLTC. The voltage limitation issue has been solved, and the voltage profile has been greatly improved by using capacitor and OLTC. The improvement of the voltage to permissible limits of that period using capacitor and OLTC switching allows the charging coordination algorithm to consider those nodes fairly. Table II (column 3) shows the reduction of voltage deviation for different penetration levels, noticeably, only 7.34% voltage deviation for 63% penetration. However, this strategy not only improves the voltage profile, it also decreases the total power loss significantly. Compare to case 2, in case 3, the power loss has been observed to be a little bit high as no PEV is left to charge, as shown in Fig. 7. The fixed charge–rate coordination strategy with capacitor and OLTC switching is faster than [11]. From the Fig. 7(a), it can be seen that the last vehicle of the weakest feeder started to charge at 2:10, and all the vehicles were fully charged by 3:50 at 63% PEV penetration. Compare to variable charge–rate coordination (Table I, case B) [11], this proposed method with fixed charge–rate improves the voltage profile of the weakest node remarkably, particularly during peak hours, as shown in Fig. 8(a) and Table II.

Much research has been conducted to coordinate PEV charging in distribution systems. For comparisons with the proposed method, some of the latest studies are shown in Table III. From the comparison, it can be seen that the previous studies do not consider any power system instruments to improve the system performances during the PEV charging. Therefore, in our proposed method, the capacitor and OLTC have been adopted to improve the voltage profile at far buses from the distribution transformer. For these instruments, the optimal switching combinations are determined in the proposed method. It can be seen that by using this proposed method, PEV charging is completed at 3:50 am as shown in Fig. 8(c), which is faster compared to other methods.

The bar chart in Fig. 9 shows the effectiveness of this proposed method in terms of satisfaction level. In case 1, all the PEV customers are satisfied, although the satisfaction level in terms of the utility side is very less. After applying case 2, only three feeders’ PEV customers are satisfied. The achievement of this method is to satisfy both the customer and utility sides together with fixed charge–rate PEV coordination as presented in Fig. 9.
Table III. Comparison of the proposed method over similar conventional method

<table>
<thead>
<tr>
<th>Applied algorithm/strategy</th>
<th>Objective function</th>
<th>Customer satisfaction</th>
<th>Different charge and battery size</th>
<th>Different SOC</th>
<th>Voltage improvement using Capacitor and OLTC switching</th>
<th>Charging termination time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic program [8]</td>
<td>Power loss and voltage deviation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td>MSS [3]</td>
<td>Minimize energy cost</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>6:10 am</td>
</tr>
<tr>
<td>Valley filling [25]</td>
<td>Mitigate surplus power</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td>CAPSO [11]</td>
<td>Maximize customer satisfaction</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>5:50 am</td>
</tr>
<tr>
<td>GA [26]</td>
<td>Minimize substation load deviation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td>Proposed method (BPSO)</td>
<td>Power loss and voltage deviation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>3:50 am</td>
</tr>
</tbody>
</table>

Fig. 9. Comparison of customer and utility sides’ satisfaction for three different cases at 63% PEV penetration

5. Conclusion

The performances of the distribution system have been deteriorated by the uncoordinated PEV charging on the system. Hence, an optimal PEV charging coordination is required to ensure the power quality of the distribution network. However, PEV charging coordination alone is not sufficient to fulfill the customer and utility requirements. Therefore, this paper proposes an effective fixed charge-rate PEV coordination with optimal dispatch of capacitors and OLTC. The proposed method is proven by comparing with variable charge-rate coordination. As this strategy considers fixed a charge-rate, the charging process becomes faster than the variable charge-rate approach. With this method, customers are found to be satisfied from all the feeders as the vehicle is being charged quickly. Moreover, the minimization of the system power loss and voltage deviation offers a better operation for the distribution network. Therefore, to achieve the satisfaction of PEV customer and utility sides together, this proposed method is suitable.

Although, in this research, the simulation results are shown for 1 day only, the method can be used for planning PEV charging as well. However, datasets of the PEV charging pattern, arrival and departure time are required.

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