Exploring the Impact of EVs on the Power Grid with High Penetration of RES

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***Abstract*—Electric Vehicles (EVs) provide new opportunities for the power grid, especially with high penetration of Renewable Energy Source (RES). For instance, EVs can be utilized to store energy and then provide energy to the power grid during the high demand periods, improve power factor, and to mitigate the over/under-voltage problems. Yet, EVs introduce new challenges for the power grid, e.g., uncontrolled charging at the early evening can aggravate the peak power demand problem. This work focuses on smart strategies for charging EVs. Based on mixed integer linear programming (MILP), we introduce two smart strategies for charging the EVs, namely, the constant demand and the profit maximization approaches. Additionally, we explored the usage of rule-based control mechanisms to deal with over/under-voltage and reactive power compensation. We looked into different EV-applications in the power grid and performed comprehensive simulation experiments. We simulate the different components of the power grid as well as the data communication network. The open source power simulator (OpenDSS) was employed to simulate the power grid components and the discrete event simulator (OMNeT++) was used to simulate data communication system. These two simulators are integrated in one framework called (SGsim), which can be used to explore different ICT-based smart grid applications. The R tool has been used to solve an optimization problem to get the optimal schedule for charging EVs.**

I. Introduction

EVs are more efficient, have low greenhouse gas emissions, and lower driving cost than conventional vehicles. World-wide, the amount RES deployed in the grid is increasing. An EV would not have a sensible impact on the power grid, but a large number of EVs would have a serious impact. The EVs charging habits that don't take into consideration the current situation of the power grid, will place a substantial pressure on the grid. For example, in an uncontrolled charging of the EVs, most owners would probably plug-in their vehicles and charge when they come back to home from their last trip of the day. We call this charging pattern "dumb charge". This would probably cause a peak in demand somewhere in the evening, when there is already a peak in the base demand. In fact, depending on how we use the EVs, they can be part of the problem or part of the solution.

If the EVs used in a smart way, they can not only reduce the peak demand but also they can be utilized to solve some problems in the distribution network such as over/under voltage, power factor correction, frequency regulation, and voltage sag problems. This would improve the performance of the power grid, reduce power losses in it and reduce the investments in the grid modernization.

The electricity price is mainly determined by the balance between generation and demand of electric power, the higher the demand the higher the price. Thus, using smart charging strategies, could manage the demand and thus control the increase of electricity price. In fact, a solution to cover the high demand periods is to install new generators (e.g. new gas turbines). Yet installing new generators is costly and the generator should run for hundreds or thousands of hours yearly to pay-off. This would be difficult to achieve, in particular with high penetration of renewable energy sources. Therefore new smart approaches are needed to deal with the EVs.

It is well-known that most people around the world use the car around one hour day and the rest of the day they are parked either at home, work, shopping centers, etc. This feature could be exploited to apply Vehicle-to-Grid (V2G) power generation concept. V2G provides a means by which to engage advantage of parked EVs to supply electricity to the power grid. That is, V2G enables EVs to act as Distributed Energy Resources (DER) [13].

We have explored the economic benefits of Demand Side Management (DSM) in our previous works [1], [3], [6]. Combining DSM EV is a very promising approach because of the elastic nature of the charging process of the EV. This combination will open an intellectual gate toward higher efficiency of the power system. And this can be done by charging EVs during the low demand periods [10], [11], [7].

In this paper we introduce two approaches to deal with EV charging. In the first approach, we rely on mixed integer linear programming to hold a constant demand in the grid and to maximize the profit. Employing linear programing makes it possible to scale for a large number of nodes. In the second approach we employed rule-based approach to deal with over voltage, and reactive power.

The rest of the paper is organized as follows. At the beginning we present our approach II. Then in Section III we introduce the simulation environment. In section IV we show the implementation approach. In Section V we evaluate the proposed approaches. Section VI provides a discussion on the results. Finally, Section VII concludes the paper.

II. Approach

An optimization problem is provided to identify the optimum charging strategy to be followed by EVs. We will explore two approaches. The first approach focuses on the power losses. It is known that the power losses is a non linear problem. In this work we provide a linear approach to reduce the power losses. We introduce an objective function that tries to hold the power consumption constant. This will reduce the losses. Therefore the objective functions can be written as in Equation 1

$$min \left\{ \sum_{t=1}^{T} |P(t) - P_{av}| + P_d(t) + P_c(t) \right\} \tag{1}$$

The second Optimization problem includes demand response such that the EVs can be charged when the electricity price is low. Moreover, the optimizer try to increase the revenue by selling the power generated from the renewable energy sources.

$$min \left\{ \sum_{i=1}^{T} C(t) * P_b(t) - 0.18 * P_s(t) \right\} \tag{2}$$

The above minimization problems is subjected to system constraints. Equation 3 represents the power balance in the grid.

$$P_b(t) + P_{di}(t) - P_{ci}(t) - P_s(t) = P_{load}(t) + P_{ren}(t) \tag{3}$$

where $P(t)$ is the power demand, P_{av} is the average of power demand, $P_{di}(t)$ denotes power discharged from the battery, $P_{ci}(t)$ is the power charged in the battery, 0.18 is the electricity selling price in euro (0.18EUR≈ 0.72NIS), C is the electricity price, $P_b(t)$ denotes the amount of power bought from the network, $P_s(t)$ denotes the amount of power sold to the network, $P_{load}(t)$ represents the load power,$P_{ren}(t)$ is the power generated by RES.

The following constraints ensures that buy and sell can't be done simultaneously.

$$0 \leq P_b(t) \leq x(t) * P_{b,max} \tag{4}$$
$$0 \leq P_s(t) \leq (1 - x(t)) * P_{s,max} \tag{5}$$
$$x(t) \in (0, 1) \tag{6}$$
$$\tag{7}$$

$x(t)$ is a binary value to prevent buying and selling in the same time, $P_{b,max}$ is maximum bought power, $P_{s,max}$ is maximum sold power,

The following equations represent the constraints on the capacity of the battery, i.e. the battery instantaneous charging and discharging can't exceed the maximum rating power of the battery.

$$P_{d,max} \geq P_d(t) \tag{8}$$
$$P_{c,max} \geq P_c(t) \tag{9}$$

name	value	unit
V_{low}	210	volt
V_{high},	249	volt
V_{th1},	215	volt
V_{th2}	244	volt
$T_{voltage}$	15	second

TABLE I
SGSIM CASE STUDY PARAMETERS

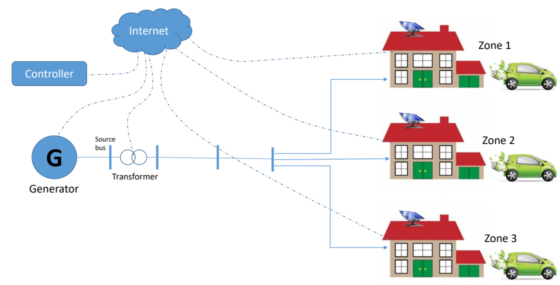

Fig. 1. The optimization case study model which consist of three zones each zone has loads, EVs and PVs

$P_{d,max}$ is maximum discharge power, and $P_{c,max}$ is maximum charge power.

The hourly energy balance in the battery can be modeled as,

$$E(t+1) = E(t) + E_{di}(t) - E_{ci}(t) \tag{10}$$
$$where; E_{di}(t) = \tau P_c(t) \eta_c \tag{11}$$
$$E_{ci}(t) = \tau \frac{P_d(t)}{\eta_d} \tag{12}$$
$$E(0) = E_{start} \tag{13}$$
$$E(T) = E_{end} \tag{14}$$
$$E_{max} \geq E(t) \tag{15}$$

Where $E(t)$ the energy storage level in the battery at each hour, E_{start} and E_{end} are the initial and final energy storage levels respectively, E_{max} the maximum energy storage level in the battery, η_c and η_d are the charge and discharge efficiency of the battery respectively. The optimization problem above is for one day with time step$\frac{1}{4}$ hour ($\tau = 0.25$) , thus we need 96 samples ($T = 96$ samples) [2], [9].

III. Simulation environment

This section presents a network description and the parameters for each case.

A. Case I: Optimization case study

The network consists of three zones, each zone includes load (houses), EVs and PV cells, as it is shown in the Figure 1.

Network description:

- Photo voltaic cells: The PVs is modeled through its fundamental parameter that are: $Pmpp$, $irrad$, KVA and

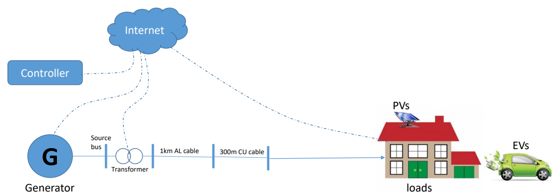

Fig. 2. The SGsim case study model which consist of loads, EVs and PVs

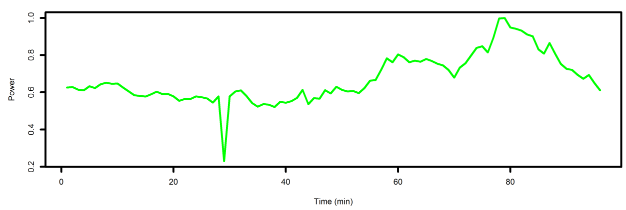

Fig. 3. Load: a 15 min resolution power consumption of Birzeit housing in Al-Tira

pf. The size of PV is 100 KVA and we adjusted the PV to produce the maximum active power. We used data for irradiation from a weather station at the university.

- we assumed a number of EVs are available in each zone.
  - Zone1: $capacity = 235$ kWh, 85 kW rated.
  - Zone2: $capacity = 318$ kWh, 114 kW rated.
  - Zone3: $capacity = 394$ kWh, 142 kW rated.
- Electric load: we used a load profile form Birzeit housing in Al-tira as shown in Figure 3. This load is a 15 min resolution power consumption of Birzeit housing in Al-Tira which was measured on a summer day.
- Transmission lines:
  - Underground cable that specification: AL 240 mm^2 cable, approximately length 1.95 km, AC resistance at $45C^o$ $R_{AC} = 0.14\Omega/km$, and series reactance $X = 0.078\Omega/km$ [12].
  - 75m of Cu 16 mm^2 cable with AC resistance at $45C^o$ $R_{AC} = 1.26\Omega/km$ and series reactance $X = 0.076\Omega/m$ [12].
- Transformer $10/0.4$ KV, 900 kVA.

the electricity cost is based on the following equation:

$$C(t) = (P_l(t)/max(P_l))^2 * 0.6 - (P_v(t)/max(P_v))^2 * 0.2 + 0.2 \quad (16)$$

B. Case II: SGsim case study

In this case, a simple network was designed as shown in Figure 2. The controller was used to monitor the behavior of grid. And to take the correct action by sending an order to the electric vehicle to charge or discharge based on the data available. The `Voltage` messages are transmitted periodically or in case of over voltage ($voltage \geq V_{high}$) or under voltage (($voltage \leq V_{low}$)). Upon receiving such messages, the controller sends appropriate message to the EVs. Algorithm 1 depicts the handling of `Voltage` messages. If the voltage is above V_{high}, the controller sends $CHARGE$ message and if the voltage is below V_{low}, the controller sends $DISCHARGE$ message. The controller sends a message to stop charge or discharge, when the voltage returns to normal value $V_{th1} \leq V \leq V_{th2}$ and a time period $T_{voltage}$ is elapsed. This time period is used to avoid oscillations. Table I shows the parameters which have been used in the simulation.

Algorithm 1 Controller behavior: handle `Voltage` messages

Require: Locally stored state of voltage from different power grid components
Ensure: Send appropriate message to the EVs

```
Receive voltage messages V
Emergency=0
if V ≤ V_low then
    Send DISCHARGE Message
    Emergency=1
    OldTime=Time()
else if V ≥ V_high then
    Send CHARGE Message
    Emergency=1
    OldTime=Time()
end if
if Emergency == 1 AND V_th1 ≤ V ≤ V_th2 AND (Time() − OldTime) > T_voltage then
    Send IDLE Message
    Emergency=0
end if
```

Network description:

- Photo voltaic cells:The size of the PV=20 KVA and rated at maximum active power and we used the same irradiation profile as in the previous network.
- Battery energy storage: we used 25 kWh with 15 kW rated power.
- Electric load: we used the same load profile
- Transmission lines:
  - Underground cable that specification: AL 240 mm^2 cable, approximately length 1 km, AC resistance at $45C^o$ $R_{AC} = 0.14\Omega/km$, and series reactance $X = 0.078\Omega/km$ [12].
  - Cable that specification: Cu 16 mm^2 cable, approximately length 300m, with AC resistance at $45C^o$ $R_{AC} = 1.26\Omega/km$ and series reactance $X = 0.076\Omega/m$ [12].
- Transformer $11/0.4$ KV, 250 kVA [12].
- Controller: it receives the voltage messages and sends decisions based on the value of the voltage.

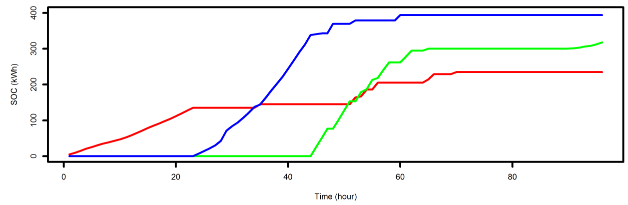

Fig. 4. state of charge of the EVs groups in constant demand scenario

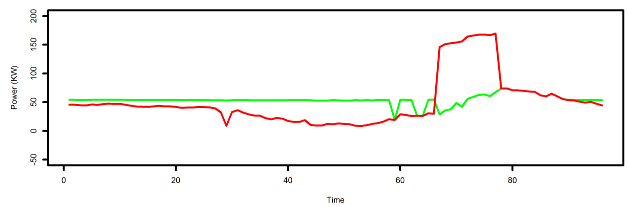

Fig. 5. comparison between power demand in constant demand and dumb charge scenarios

IV. Implementations

There are many Simulation tools which can be used to implement and analysis grid with renewable energy source. SGsim [4], [5], [14] which is a multi-simulator framework has been used to evaluate the approach. Mainly, it is based on two simulators: OpenDSS [8] to simulate the power grid and OMNeT++ [15] to simulate the data communication grid. Additionally OMNeT++ is used to control the behavior of the different components. We used R tool to get an optimal schedule of charging EVs. Then the SGsim simulator was used to apply different scenarios on the grid. In the voltage regulation scenario, when the voltage exceeds upper limit (249 V), the controller sends a massage to EVs that required to charge EVs battery at this time. But when the voltage exceeds the lower limit (212V) the controller sends a message to EVs that required to discharge EVs battery at this time. In the reactive power scenario, is The EVs produce reactive power to improve the power factor load when it exceeds lower limit.

V. Results

In this section we present different scenarios to explore the impact of EVs on the power grid with high penetration of RES.

A. Case I: Optimization Approach

This subsection presents the first case study which consists of two optimization scenarios, constant demand and profit maximization scenario.

1) Scenario I: Constant Demand: In this scenario, we use the system shown in Figure 1 and the objective function in Equation 1 to hold a constant power demand as much as we can. The results are shown in Figure 4, Figure 5 and Figure 6.

Figure 4 shows the state of charge of each storage zone using smart charging. It distributes the charging of EVs along the day and this distribution depends on the load and the power generated by the PV system at each hour along the day. Figure 5 shows the power demand on the grid by EVs and the loads along the day. The red line shows the power demand on the grid in case of dump charge. As can be seen, a peak power demand has occurred from $17:00$ to $19:00$ as a result of dump charge. It aggravates the high peak problem. The green line shows the power demand when applying smart charge. It is clear that the demand is almost constant. Figure 6 shows the voltage on the load along the day, the red line shows the voltage on the load as a result of dump charge which it decreases in the peak power demand period below the standard value. The green line shows the voltage profile when applying smart charge. as it can be seen, the voltage profile is much better than the case of dump charge and there is no under-voltage situations.

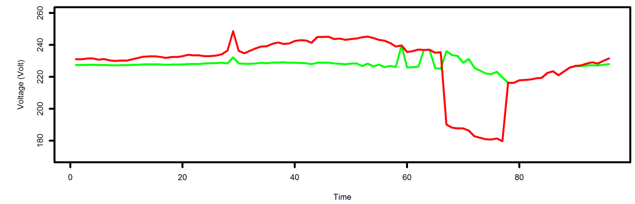

Fig. 6. comparison between the voltage in constant demand and dumb charge scenarios

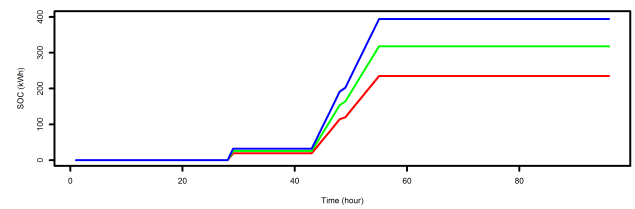

Fig. 7. state of charge of the EVs groups in profit maximization scenario

2) Scenario II: Profit Maximization: In this scenario, we have been used the system shown in Figure 1 and the objective function in Equation 2 to maximize the profit. The results are illustrated in Figure 7 , Figure 8 and Figure 9.

Figure 7 presents the state of charge of the storage in the

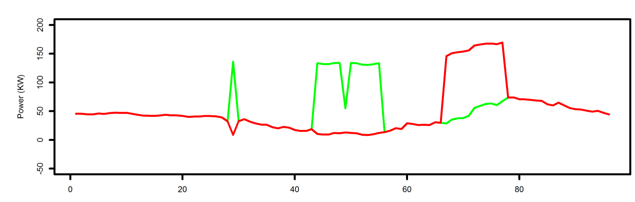

Fig. 8. comparison between power demand in profit maximization and dumb charge scenarios

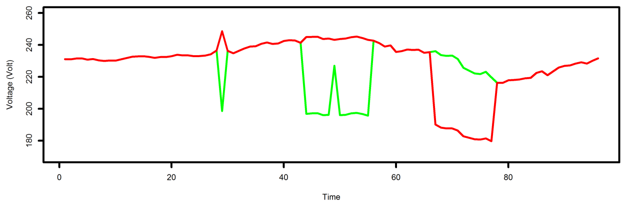

Fig. 9. comparison between the voltage in profit maximization and dumb charge scenarios

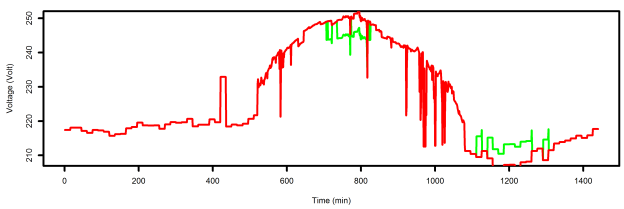

Fig. 10. voltage on the transformer with and without Voltage Regulation Scenario

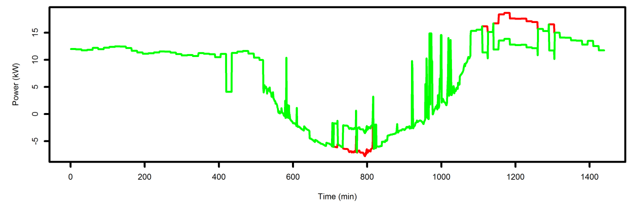

Fig. 11. power on the transformer with and without Voltage Regulation Scenario

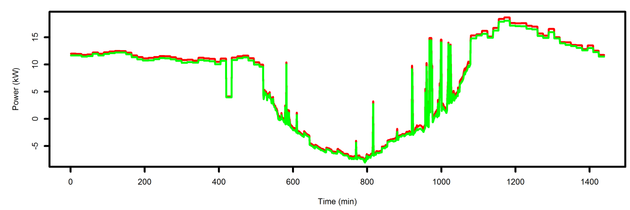

Fig. 12. power on the transformer with and without Reactive power injection Scenario

different zone as results of smart charging. The smart charging distribution depends on the price of the kWh. Figure 8 shows the power demand on the grid by EVs and the loads along the day, the red line shows the power demand on the grid in case of dump charge. As can be observed in the figure, the dump charge has caused aggravated the peak problem from $17:00$ to $19:00$. The price in this period is high and therefore, the smart charge doesn't allow the EVs to charge in this period. Figure 9 shows the voltage profile on the load along the day, the red line shows the voltage on the load as a result of dump charge which decreases the voltage below the standard values in the peak power demand period. The green lines depicts the voltage profile when applying smart charging. It can be identified from the figure that there is no voltage violations along the day.

B. Case II: Rule-Based Approach

This subsection presents the second case study which consist of two SGsim scenarios, voltage regulation and reactive power injection scenario.

1) Scenario I: Voltage Regulation: In this scenario, we have used the system shown in the Figure 2, the main idea of this scenario is to hold the voltage profile within the acceptable limits. This can be achieved by utilizing the EVs charging and discharging capabilities. When the voltage on the load is less than 212, the EVs should provide electricity to the network. It will stop discharging when the voltage reaches 215. If the voltage becomes higher than 249, the EVs should start charging until the voltage drops below 244. Figure 10 and Figure 11 show the voltage and the power on the grid respectively. The red line represents the case of there's no usage of EVs and the green line represent the effect of using EVs. The red line depicts two period of voltage limit violations. The first one happens at midday when the voltage reaches higher than 253 volt and the second violation occurred in the evening when the voltage drops below 207. the green line illustrates the voltage profile when utilizing the EVs. We can see that the EVs are charging approximately from $12:00$ to $14:00$ as a result of high voltage. This occurs as a result of high power production from the PV and low demand at the midday. In the evening the EVs performs discharging from $18:00$ to $21:00$ as a result of low voltage. This happens because of the high demand at the evening.

2) Scenario II: Reactive power injection: In this scenario, we have used the system shown in Figure 2, the main idea of this scenario is to achieve the reactive compensation on the grid by using the EVs to produce reactive power plus the reactive power come from the main transformer to compensate the negative reactive power produced by the load. Figure 12 shows the power at the transformer. As can be seen, the green line is lower than the red line which indicates that the power consumption when applying reactive power compensation reduces the demand.

VI. Discussion

As can be seen from the results section, there is a peak power demand period in each scenario due to EVs and high demand. To avoid this problem or to alleviate it, there are many possible methods. Power grid development by building new generators or upgrading the generators to meet the new demand. This solution is expensive and might not economically feasible due to the penetration of renewable energy resources. For instance, building new generator would require that the generator should work for a large number of hours to pay-off. This can be challenging with high penetration of renewable energy sources. Therefore, building a new generator just to

Scenario	Total losses (kWh)	Demand (kWh)
Dumb charge	544	3000
Constant demand	399	3123
Profit maximization	507	3055

TABLE II
A COMPARISON BETWEEN DUMB CHARGE, CONSTANT DEMAND AND PROFIT MAXIMIZATION SCENARIOS FOR ENERGY DEMAND AND LOSSES

Scenario	Total losses (kWh)	Demand (kWh)
Without EVs	124	531
Voltage regulation	118	515
Reactive power rejection	88	503

TABLE III
A COMPARISON BETWEEN WITHOUT EVS, VOLTAGE REGULATION AND REACTIVE POWER REJECTION SCENARIOS FOR ENERGY DEMAND AND LOSSES

run in few hours makes this solution not economically feasible. We presented several approaches that rely on ICT to alleviate power grid problems such as over and under voltage. In the following, we present some numerical results.

A. Case I: Optimization case study

A comparison between constant demand scenario, profit maximization scenario and the dump charge for energy demand and losses is shown in Table II, this table shows that the EVs dump charge leads to the highest losses. Constant Demand has the lowest losses. We can see in the table that dumb charge has the lowest demand. To explain this, we have to look at the load model in the OpenDSS simulator. This simulator uses ZIP load model which can be used to explore smart grid applications such as Conversation Voltage Reduction (CVR). In this model, lower voltage leads to lower power consumption. In the dump charge, the voltage is very low at the peak hour and therefore the power consumption at that time is very low.

B. Case II: SGsim case study

Table III presents comparison between voltage regulation scenario, reactive power injection and without using EVs. Without using EVs introduces the highest energy demand and losses. It can be observed from the table, that the voltage regulation method doesn't only hold the voltage within the accepted limits, but also reduces the losses and demand. The reactive power compensation approach has the lowest energy losses demand. This approach reduces the current in the transmission lines and hence reduces the losses.

VII. CONCLUSION

Exploring the impact of EVs on the power grid is very important. This enables us to answer questions such as can the generators cover the demand at high power demand period? What can be done to mitigate the problems of charging the EVs? And how can the EVs be used to improve the performance of the power grid? We proposed mixed integer linear programming to formulate optimization problems to find the optimal charging periods. A rule-based approach is used to deal with over-voltage and reactive power compensation. We have used simulation techniques in our study to explore the impact of EVs on the power grid. We have built two networks and explored different scenarios on the power grid. The results show that dump charging may lead to failure of the generators to cover the demand at high peak power demand period. However, smart charging strategies can be used to improve the performance of the power grid and to reduce the investments in the grid modernization. Optimization unit can encourage the customers to charge their EVs using smart charging strategies by maximizing their discharging profit and minimize their charging cost. EVs can contribute to regulating the grid voltage by discharging when the voltage is low and charging when the voltage is too high to reduce it to a suitable value. EVs can be used to compensate the reactive power to reduce the impact of reactive power on the grid.

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