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OPTIMAL PLANNING OF A VIRTUAL POWER PLANT HOSTING AN EV PARKING LOT

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ABSTRACT

With the increasing penetration of electric vehicles (EV) in the future, VPPs can take some actions for meeting their demand. This way, VPPs can increase their income by selling electric power to EVs and utilizing the battery of EVs as energy storage to facilitate the deployment of renewable energy resources. However, investing too much in charging stations may not have an acceptable return on investment. In this paper, we study the optimal operation and planning of a VPP which is located to certain part of the network and is composed of wind turbines, PV units, as well as unidirectional and bidirectional EV charging stations. In our proposed approach, optimal planning is done considering that the system will be operated optimally. According to the simulation results, EV owners' behavior could have a significant impact on the optimal planning decision of the VPP. In addition, optimal number of the unidirectional and bidirectional EV charging stations depend on the share of the PV and wind generation and the capacity of the line between the VPP and upstream grid.

INTRODUCTION

Recently, due to environmental reasons, interest towards the exploitation of renewable energy resources in electricity networks has been constantly increasing. Nonetheless, the high penetration of renewable-based units and their intermittent behavior have caused several technical, economic, and regulatory challenges [1]. The mentioned issues could be addressed by jointly operating non-dispatchable renewable units with different types of dispatchable resources, including conventional generation units, flexible loads, and energy storage devices [2]. To facilitate the coordination of these energy sources in a single platform, a concept called virtual power plant (VPP) has been raised. Accordingly, the VPP aggregates a wide range of distributed energy resources (DERs) and systematically controls them to not only compensate for the uncertain nature of renewable energy generation but also pave the way for the participation of the integrated DERs in different energy markets or providing system support services [3]. It is clear that VPPs are willing to find a solution for promoting their profit, and in this context, an optimal planning strategy assists them to reach the highest possible amount of income.

On the other hand, over the past few years, the number of electric vehicles (EVs) has been increasing notably, having also growing effects on power systems [4]. Thanks to the high deployment of EVs at the distribution level, VPPs can take some actions to meet their demands. In this way, VPPs are able to increase their income by selling electric power to EVs and utilizing their batteries as energy storage systems to mitigate the power fluctuation resulting from the stochastic generation of renewable energy resources [5]. Thus, by adding charging stations and hosting EVs, VPPs can improve the optimal utilization of renewable-based resources. However, investing too much in charging stations may not have an acceptable return on investment. As a result, it is highly required to find the optimal operational planning for VPPs equipped with EV charging stations as well.

Various research works have been conducted to evaluate the planning strategy of VPPs taking into account operational constraints. In this regard, a bi-level programming framework has been provided in [6] to determine the optimal location and capacity of an energy storage system within the VPP. The upper level of the model deals with the planning problem aimed at maximizing the net profit of the VPP, while the lower level deals with its operational strategy. A risk-based stochastic method has been utilized in [7] for investigating the investment planning of a VPP trading power in the electricity market. In this study, the objective is to maximize the profit of the VPP, which comprises conventional and renewable generation units, storage systems as well as flexible demands. A multi-objective optimization approach has been employed in [8] for the optimal capacity allocation of the VPP, which includes EVs. The capacity allocation of the considered VPP is implemented in a way to not only promote its net revenue but also reduce pollution and overcome environmental concerns. An optimization framework has been developed in [9] for the optimal operational planning of an integrated system that aggregates multiple renewable-based resources, energy storage systems, and EV charging stations for providing services to the upstream grid. The primary objective of this study is to determine the optimal configuration of the system and maximize its profit while considering operational constraints. A mixed-integer linear programming model has been exploited in [10] for the optimal planning of an aggregator that integrates a wide range of disparate DER technologies at the distribution level. This work aims to maximize the aggregator's net present value income from providing services to the upstream network over the planning horizon. Finally, a bi-level stochastic model has been suggested in [11] for the capacity allocation of an energy storage system within a VPP. Accordingly, at the upper level, the VPP's planning problem is modeled to minimize its investment and maintenance costs. At the lower level, the VPP's operating problem is formulated to minimize the power fluctuation of the existing renewable units.

Given the importance of making strategic decisions over the planning horizon of VPPs and according to the high penetration rates of EVs, the present article focuses on the operational planning of a VPP that possesses renewable-based energy resources as well as EV charging stations which are located at a certain part of the grid. Accordingly, the main goal of the paper is to determine the optimal number of unidirectional and bidirectional EV charging stations and renewable-based units within the VPP and in the presence of operational constraints of each component. On the other hand, this research seeks to assess how the investment in the charging stations differs for VPPs with different shares of renewable generations. This analysis will pave the path toward more deployment of renewable energy resources as well as EVs and provide a green and sustainable energy sector in the future.

The rest of the paper is organized as follows: the structure of the considered VPP and the problem formulation are explained in more detail in section 2. A typical case study is implemented in section 3. Ultimately, the study is concluded in section 4.

PROPOSED VPP MODEL

In this section, we intend to explain the formulation used for modelling a VPP consisting of electric vehicle charging station, wind and photovoltaic generation, as well as load. This way, the VPP's problem is composed of its objective function for minimizing its operational cost and the constraints related to the operation of all components.

The operational objective function of the VPP is presented in (1).

$$OF_{op} = -((SOC_{ex} - SOC_{en}).\boldsymbol{\lambda}_{EVch}.(\mathbf{N}_{UDCS} + \mathbf{N}_{BDCS}) + \sum_t P_{grid}(t).\boldsymbol{\lambda}_{DA}(\mathbf{t})) \tag{1}$$

The objective function of the problem is the operational cost of the VPP. The first term in the objective function is the income gained from electric vehicle owners for charging their vehicles. $\boldsymbol{\lambda}_{EVch}$ is the price tariff for charging EVs. The second term is the total cost of the VPP for buying power from the power system.

We have considered two types of electric vehicle charging stations. The first type is the unidirectional charging station in which the electric vehicle can just be charged while it cannot be discharged to inject the power into the grid. The second type is the bidirectional charging station in which the vehicle can be both charged and discharged. Therefore, the flow of power can be both from the grid to the vehicle (G2V) and vehicle to grid (V2G).

The battery of the EVs that are located at unidirectional and bidirectional charging stations are modelled as represented in (2-6) and (7-12), respectively.

$$P^n_{ch_{min}}(t) \leq P^n_{ch}(t) \leq P^n_{ch_{max}}(t) \tag{2}$$

$$SOC^n(t+1) = SOC^n(t) + P^n_{ch}(t).\boldsymbol{\eta}_{ch} \tag{3}$$

$$SOC^n_{min}(t) \leq SOC^n(t) \leq SOC^n_{max}(t) \tag{4}$$

$$SOC^n(t_{en}) = SOC_{initial} \tag{5}$$

$$SOC^n(t_{ex}) = SOC_{final} \tag{6}$$

$$P^m_{ch_{min}}(t) \leq P^m_{ch}(t) \leq P^m_{ch_{max}}(t) \tag{7}$$

$$P^m_{dch_{min}}(t) \leq P^m_{dch}(t) \leq P^m_{dch_{max}}(t) \tag{8}$$

$$SOC^m(t+1) = SOC^m(t) + P^m_{ch}(t).\boldsymbol{\eta}_{ch} - P^m_{dch}(t)/\boldsymbol{\eta}_{dch} \tag{9}$$

$$SOC^m_{min}(t) \leq SOC^m(t) \leq SOC^m_{max}(t) \tag{10}$$

$$SOC^m(t_{en}) = SOC_{initial} \tag{11}$$

$$SOC^m(t_{ex}) = SOC_{final} \tag{12}$$

The output power of the wind turbines and the photovoltaic cell can vary between 0 and the maximum possible generation according to the hourly wind speed and solar radiation (13, 14). The maximum possible generation of the PV and wind turbine is calculated as represented in (15) and (16).

$$0 \leq P_{PV}(t) \leq P^{max}_{PV}(t) \tag{13}$$

$$0 \leq P_{wind}(t) \leq P^{max}_{wind}(t) \tag{14}$$

$$P^{max}_{PV}(t) = G_{PV}(t).\boldsymbol{\eta}_{PV}.A_{PV} \tag{15}$$

$$P^{max}_{wind}(t) = \begin{cases} 0 & if\ v(t) < v_{cutin} \\ \frac{(v(t)-v_{cutin})}{(v_{rated}-v_{cutin})}.P^{max}_{w} & if\ v_{cutin} \leq v(t) \leq v_{rated} \\ P^{max}_{w} & if\ v_{rated} \leq v(t) \leq v_{cutout} \\ 0 & if\ v_{cutout} \leq v(t) \end{cases} \tag{16}$$

The power balance of the VPP is formulated as presented in eq. (17). In addition, the traded power between VPP and the upstream grid (in both directions) in each hour must not exceed the capacity of the line between the VPP and the grid (18).

$$P_{wind}(t) + P_{PV}(t) - \sum_m P^m_{dch}(t) + \sum_m P^m_{ch}(t) + \sum_n P^n_{ch}(t) - Load(t) = P_{grid}(t) \tag{17}$$

$$-P^{max}_{grid} \leq P_{grid}(t) \leq P^{max}_{grid} \tag{18}$$

In addition, the charge and discharge power of each bidirectional charging station cannot be nonzero simultaneously in each hour (19). This constraint causes the problem to be nonlinear. To prevent nonlinearity, by utilizing the big M method, equations (20) and (21) are used instead of (19) where M is a large enough number and $u(t,m)$ is a binary variable. Then the problem would be converted to mixed-integer linear programming (MILP).

$$P^m_{ch}(t).P^m_{dch}(t) = 0 \tag{19}$$

$$P^m_{ch}(t) \leq u(t,m).M \tag{20}$$

$$P^m_{dch}(t) \leq (1 - u(t,m)).M \tag{21}$$

For the planning problem, the objective function is the total cost of the plan that equals the summation of the investment cost and the net present value of the total operational cost of the VPP over its lifecycle (22). In addition, all of the mentioned constraints for the operational problem are also the constraints of the planning problem. Because the optimal planning is done considering that the system will be operated optimally.

$$OF_{pl} = NPV(\sum_{lifecycle} OF_{op}) + \mathbf{N}_{UDCS}.\mathbf{C}_{UDCS} + \mathbf{N}_{BDCS}.\mathbf{C}_{BDCS} + \mathbf{N}_{WT}.\mathbf{C}_{WT} + \mathbf{N}_{PV}.\mathbf{C}_{PV} \quad (22)$$

The net present value of the operational cost of the year i is calculated using Eq. (23), in which IR is the interest rate, and C_i is the operation cost at year i. Therefore, the net present value of the operation cost should be calculated for all years of the lifecycle separately. The summation of the net present value of each year gives the net present value of the total operational cost over the lifecycle.

$$NPV(C_i) = C_i/(1 + IR)^{\,i} \quad (23)$$

SIMULATION RESULTS

This section consists of four subsections. At first, the case study used for the simulation is introduced. Then, the operational performance of the VPP for scheduling the charging of EVs is investigated. The third subsection studies the optimal planning of the VPP for hosting unidirectional and bidirectional EV charging stations. The fourth part investigates the comprehensive planning of the VPP for adding the capacity of wind power plants and PV units as well as unidirectional and bidirectional EV charging stations.

Case study

The data related to the wind speed, solar radiation, the day-ahead (DA) electricity price, and load pattern is presented in Table. 1. In addition, the technical characteristics of the wind turbine and PV are available in Table. 2. Moreover, the data related to the maximum charging and discharging power, the initial and final state of charge (SOC), as well as the entrance and exit time of the EVs are represented in Table. 3. Furthermore, the investment costs used in our simulation are presented in Table 4. We simulated the operational problem by coding in Python. The solver Ipopt has been used for optimization. Then, for the planning, the objective function of each planning scenario is calculated using Ipopt solver, and the planning scenario with the least planning objective function is the optimal planning decision. It is noteworthy that the plan's life cycle in our case study is 15 years. Moreover, for the planning problem, it has been assumed that the data for all days in the lifecycle is similar to the data presented in Table 1.

Table. 1. Hourly wind, solar, DA price, and load data

Hour	Wind speed	Solar radiation	DA price	Load
1	19.60	0	0.031	68.35
2	13.50	0	0.025	57.7
3	22.00	0	0.021	57.94
4	6.80	0	0.012	44.74
5	9.60	0	0.015	66.18
6	11.50	0	0.022	78.51
7	9.90	0.052	0.056	103.55
8	7.10	0.272	0.078	125.28
9	9.90	0.329	0.108	129.3
10	15.40	0.45	0.128	143.39
11	11.00	0.519	0.12	131.91
12	11.90	0.53	0.135	145.22
13	5.30	0.601	0.128	149.07
14	8.80	0.638	0.104	130.58
15	11.20	0.551	0.068	119.98
16	9.20	0.427	0.039	110.71
17	2.00	0.22	0.034	128.15
18	4.20	0.052	0.046	118
19	13.20	0	0.064	120.62
20	7.50	0	0.073	129.06
21	14.20	0	0.066	116.3
22	11.20	0	0.055	101.47
23	8.00	0	0.044	92.94
24	12.60	0	0.034	83.35

Table. 2. The technical characteristics of the wind turbine and PV

P_w^{max}	V_{cutin}	V_{rated}	V_{cutout}	A_{PV}	η_{PV}
150	5	14	25	700	0.14

Table 3. Data related to the EVs

P_{ch}^{max}	P_{dch}^{max}	t_{en}	t_{ex}	SOC_{init}	SOC_{final}	Battery capacity
20	20	7	16	50%	100%	20

Table. 4. Investment costs and interest rate data

$\mathbf{C}_{UDCS}$	$\mathbf{C}_{BDCS}$	$\mathbf{C}_{WT}$	$\mathbf{C}_{PV}$	IR
5000€	13000€	1475€/kW	1625€/kW	0.02

Optimal Operation of the VPP hosting EV charging stations

In this subsection, the operational performance of the VPP in presence of one unidirectional and bidirectional charging station is studied. The charge and discharge power of the bidirectional station, the charge power of the unidirectional charging station, as well as the day-ahead electricity price are shown in Fig. 1. As expected, charging at the unidirectional and bidirectional stations is done at those hours when the electricity price is low. Accordingly, discharging at the bidirectional charging station is done in hours that electricity price is high. Therefore, the bidirectional EV charging station acts as an energy storage system and gains income by smart charging and discharging. The total operational cost of the VPP over the lifecycle is 258097 €. We also did the simulation for 3 other scenarios to study the impact of EV entrance and exit time on the total operational cost of the VPP over a 15-year lifecycle. The results are presented in Table. 5.

When EVs enter the parking earlier and quit later, the total operation cost is less because EVs charging and discharging could be scheduled with more freedom. In addition, indicate that earlier entrance is more effective than later exit in reducing the cost. Because when EVs enter at 7 and leave at 15, the total operational cost is 258478 €, which is less than the operational cost when EVs enter at 8 and leave at 16, while the staying time of the EVs in the two scenarios are similar. Therefore, for the VPP owner, it is preferred that EVs enter earlier in the day. Furthermore, it is clear that the entrance and exit time has a major impact on the results. In future studies, the behavior of the EV owners (entrance and exit time) and potential uncertainties and risks should be further studied and modelled in a probabilistic manner.

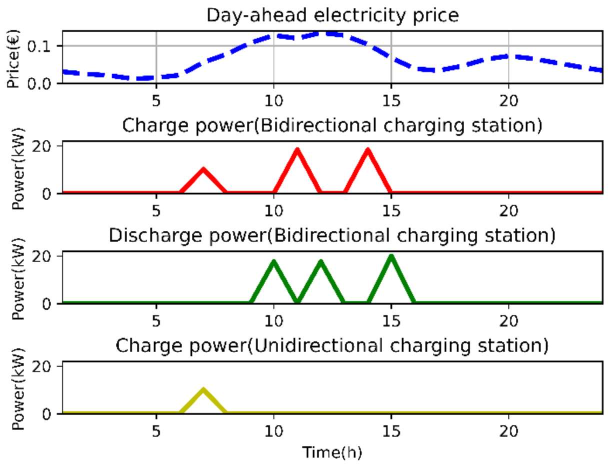

Fig. 1. Charge and discharge power as well as day-ahead electricity price

Table. 5. Operational cost for different entrance and exit time of the EVs

t_{en}	t_{ex}	Total operational cost
7	16	258097 €
7	15	258478 €
8	15	261636 €
8	16	263704 €

Optimal Planning of a VPP for hosting EV charging stations

In this part, we want to define the optimal number of unidirectional and bidirectional charging stations to be utilized at the EV parking lot owned by the VPP. We consider that VPP possesses one wind turbine and one PV introduced in the section "Case study". At first, we consider five different VPPs with different capacities of the line between the VPP and the upstream grid (all other characteristics are the same). Fig. 2. shows that for VPPs with the greater capacity of the line between the VPP and the grid the number of optimal bidirectional charging stations is more. The reason is that when the VPP can trade more power to the grid in each hour, the possibility of buying power in low price hours by charging and selling power in high price hours by discharging in bidirectional EV charging stations increases. Therefore, bidirectional EV charging stations could gain more benefits.

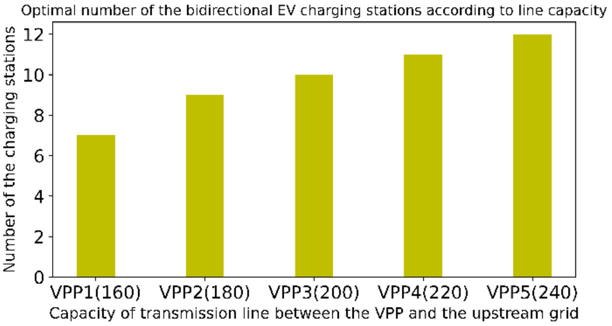

Fig. 2. Optimal number of the bidirectional EV charging stations for different line capacities

In addition, seven scenarios have been considered for the initial SOC of the EVs entering the VPP. As shown in Fig.3, if the initial SOC of the VPP is 10% and 20%, the optimal number of the unidirectional and bidirectional EV charging stations are 2 and 10, respectively. If it is 30%, 40%, or 50% the optimal number of the unidirectional and bidirectional EV charging stations are 0 and 10. For the more initial SOC the optimal number of bidirectional charging stations decreases. The reason behind this is that when the initial SOC is low, there is more potential for gaining income from EV owners for charging their EVs, and the greater initial SOC will result in less potential for gaining income. Therefore, EV charging stations would have a less return on investment as the initial SOC increases.

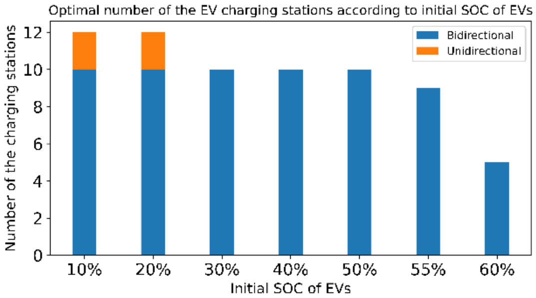

Fig. 3. Optimal number of charging stations according to EV initial SOC

Comprehensive Planning of a VPP for defining the capacity of wind and PV generation as well as EV charging stations

In this section, we intend to investigate the optimal planning of the VPP when the number of PV units, wind turbines, and EV charging stations are the decision variables of the planning problem. To this end, we have considered five different VPPs with different capacities of the line between the VPP and the upstream grid (all other characteristics are the same) and found the optimal plan for each VPP. The results are illustrated in Fig. 4.

The results depict that for VPP1, with the 180kW line capacity, the optimal number for wind turbines, PV units, and unidirectional as well as bidirectional EV charging stations would be 2, 4, 6, and 5, respectively. However, for the VPP2 (the line capacity is 200kW), the optimal number of unidirectional and bidirectional EV charging stations would be 1 and 7, respectively, while the optimal number of wind turbines and PV units are similar to the VPP1.

From these results, it can be understood that the greater line capacity of VPP2 makes the bidirectional EV charging station a more profitable option than the unidirectional EV charging station. Because the possibility for utilizing from bidirectional EV charging station as an energy storage system to charge at low price hours and discharge at high price hours is more available. This operational profit outweighs its high investment cost. Furthermore, VPP3 (with 220kw capacity line) allows for the deployment of one more PV unit, and subsequently, the optimal number of the unidirectional EV charging station would be 10, which is more than VPP3. These results reveal that more PV generation paves the way for the deployment of the more unidirectional EV charging station. In this regard, the additional PV generation could be used for EV charging.

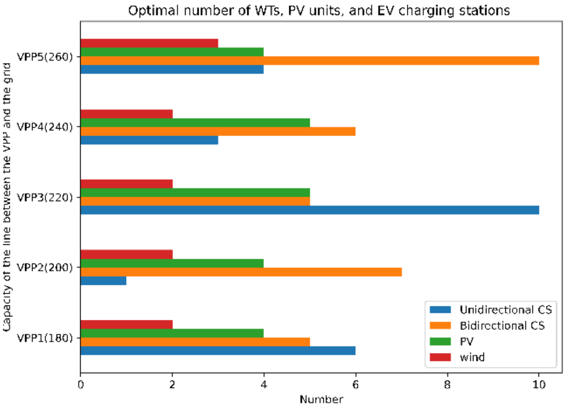

Fig. 4. Optimal number WTs, PV units, and EV charging stations

Comparing VPP4 and VPP3 shows that the optimal number of PV units and wind turbines is similar, while unidirectional EV charging stations are a more profitable choice for VPP4 compared to VPP3. This is similar to what has been described in the comparison between VPP1 and VPP2. The other important point is that the 260kw capacity line in VPP5 makes wind turbines more profitable and makes PV a less profitable planning option compared to VPP4. The results show that the higher share of wind generation in VPP5, causes the bidirectional EV charging station to be a more profitable planning option than the unidirectional EV charging station. In fact, the results show that when the share of the wind generation is more, the bidirectional EV charging station is of more interest to the VPP owner.

CONCLUSION

In this paper, we investigated the optimal operation and planning of the VPP for the deployment of unidirectional and bidirectional EV charging stations. In this way, comprehensive planning has been done where the optimal number of PV units, wind turbines, and EV charging stations have been defined for our case study VPP. The results of our case study show that when the share of PV generation increases, the profitability of the PV cells may also increase. On the other hand, the greater share of wind generation encourages the deployment of the bidirectional EV charging station. The other important point is that the behavior of EV owners for entering and exiting the parking lot and the initial SOC of the EV while entering the parking have a major impact on the results. Therefore, the uncertainty related to the mentioned issues should be considered in future studies to make a more reliable planning decision.

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