Joint Voltage and Frequency Regulation by EV Charging Scheduling in the Distribution Network

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***Abstract*—This paper proposes a novel electric vehicle (EV) charging scheduling mechanism by controlling active and reactive charging power of EVs to provide joint voltage and frequency regulation (JVFR) in the distribution network. The objective of the scheduling problem is to minimize the net cost of the distribution system operator (DSO) for operating the distribution grid in the presence of both wind-based renewable generation and EV charging stations. We test the method on a 34-bus radial distribution network for different levels of VAR requirements of wind DG units to demonstrate the feasibility and performance of the proposed JVFR approach. The simulation results show that this JVFR greatly reduces the cost of DSO in comparison with Volt-VAR Optimization (VVO) technique, which is traditionally used to optimize voltage and minimize losses of a distribution network.**

***Index Terms*—Electric vehicles, Frequency regulation, Voltage regulation, Reactive power.**

I. Introduction

Power system and transportation system, as two massive energy conversion systems based on fossil fuels, have a significant impact on fossil energy consumption and greenhouse gas emissions. According to U.S. Energy Information Administration, the electricity generation and transportation sector account for 39% and 29% of total energy consumption in the U.S. in 2016 respectively [1]. To promote energy conservation and environmental protection, these two massive systems start to evolve in their own ways. For power system, renewable energy is increasingly being pursued as an alternative to traditional thermal power stations. On the transportation system part, EVs, are playing an increasingly important role in the structure of automotive industry. However, the integration of increasing number of electric vehicles and large-scale deployment of renewable energy resources without proper management can impose negative impact on the power system, especially the most vulnerable part—distribution network.

We can analyze the challenges of integrating new elements to the distribution network from both the consumption and generation aspects. On the consumption side, the increasing penetration of EVs reshapes the temporal and spatial load patterns in the distribution system, leading to coexistence of congestion and under-utilization of grid components (e.g., distribution transformers and cables). Also, uncoordinated power consumption of EVs can increase power loss, bring harmful large peaks as well as cause voltage deviations [2], [3]. On the generation side, renewable energy resources (e.g. wind turbines and solar panels), due to their intermittent nature, are proved to be able to affect stability, power quality and voltage control of the grid [4], [5]. Furthermore, as the most popular and representative renewable generation form, wind-based renewable generations usually have inductive loads and can cause voltage fluctuations if there is not enough reactive power compensated for each wind turbine unit [6]. The common solution to mitigate this problem and stabilize the voltage is to install a series of reactive power compensation devices, such as shunt capacitors and SVCs, and these compensation devices could be adjusted timely according to the needs of the wind turbines [7]. However, with the increasing penetration level of wind generation, the amount of reactive power needed is also increasing, thus new devices need to be installed all the while. Nevertheless, the ever-increasing capital costs and operation costs of these devices would be an economic barrier for the integration of wind power.

Given the aforementioned impacts and analysis, an effective way for the DSO to provide reliable and economic energy delivery is to exploit the control flexibility of EVs on the consumption side, making the best use of existing assets instead of building up new supporting facilities (e.g., distribution transformers, capacitors, etc.). Hence, this paper proposes a novel idea to conduct combined active and reactive power scheduling of the EVs by the DSO, with the aim of providing both voltage regulation and frequency regulation services. The provision of these ancillary services from the EVs to the grid, has the potential to reduce the cost of distribution network operation and offer financial benefits to the DSO. Actually, there have been extensive studies talking about utilizing EV to provide frequency or voltage regulation services [7]–[12]. Reference [8] considers the problem of coordinating the overnight charging process of a fleet of electric vehicles for providing frequency regulation service. In [9], [10], the regulation capacity estimation and capacity scheduling problems for electric vehicles are investigated. In terms of voltage regulation, [11] studies a innovative Volt-VAR Optimization (VVO) problem to minimize the power loss cost and capacitor bank operation cost by employing EVs as VAR suppliers. In [7], reactive power compensation from EVs is adopted to stabilize the voltage profile.

The existing papers mainly focus on EV-based voltage and frequency regulation individually. This paper, instead, proposes a joint voltage and frequency regulation framework by scheduling the active and reactive power of EVs in a distribution network with wind generation. We consider a

TABLE I
NOTATION

Indices:	
i, j	Index for buses in the distribution network
n	Index for EVs in the distribution system
t	Index for time intervals during the period
Sets:	
$\mathcal{T}$	Set of time intervals
$\mathcal{V}$	Set of buses in the distribution network
$\mathcal{V}_{\mathcal{R}}$	Set of buses which have reactive power compensation devices
$\mathcal{V}_{\mathcal{W}}$	Set of buses which have wind turbines and EV charging stations
$\mathcal{E}$	Set of lines in the distribution network
$\mathcal{N}$	Set of the EVs in the distribution network
$\mathcal{N}_i$	Set of the EVs connected to bus i
Parameters:	
Δt	Duration of each time interval
T	Number of time intervals in set $\mathcal{T}$
$v_0, v_{0,t}$	Squared voltage magnitude on substation (bus 0)
$\underline{v}_i, \overline{v}_i$	Squared Voltage limitations at bus i
r_{ij}, x_{ij}	The line impedance on line (i,j)
$p_i^c(t)$	Real power consumed by the base load on bus i
$q_i^c(t)$	Reactive power consumed by the base load on bus i
$p_i^g(t)$	Real power injected from the wind turbine on bus i
$q_i^g(t)$	Reactive power drawn by the wind turbine on bus i
$p^c_{i,max}, q^c_{i,max}$	The maximum values of active and reactive power consumed by the base load on bus i
$p^g_{i,max}, q^g_{i,max}$	The maximum values of active and reactive power drawn by the wind turbine on bus i
$m_i^c(t), m_i^g(t)$	The normalized profiles of the base load and wind turbine on bus i
a'_n, d'_n	Regularized EV arrival and departure times
e_n^{min}, e_n^{max}	Minimum and maximum energy demand of EV n
s_n	EVs' maximum apparent power capacity
$q^r_{i,max}$	Maximum reactive power from traditional reactive power compensation devices at node i (kVAR).
w_E	Electricity price (\$/kW·h)
w_R	Operating cost of VAR injection from reactive power compensation devices (\$/MVAR·h).
w_F	Capacity price for providing frequency regulation service to the grid (\$/MW-h)
r_t	The normalized regulation signal during time interval t, i.e. $r_t \in$ [-1,1]
ε	A small value to control the allowable error when offering frequency regulation service
Variables:	
$v_i(t)$	Squared voltage magnitude on bus i
$l_{ij}(t)$	Squared current magnitude of line $(i, j) \in \mathcal{E}$
$p_i(t), q_i(t)$	Real and reactive power drawn from bus i at time t
$p_i^v(t), q_i^v(t)$	Total real and reactive power consumed by the EVs connected to bus i
$p_n^v(t), q_n^v(t)$	Real and reactive power consumed by EV n during time interval t
$q_i^r(t)$	Reactive power injected from traditional reactive power compensation devices
P_t^v	Total real power consumed by EVs during time t (i.e. the sum of $p_n^v(t)$ for all EVs)
C_F	The capacity of the regulation service
P_{ij}, Q_{ij}	Power flow of line (i, j)

scenario of a distribution network where wind turbines are co-located with EV charging stations. Inside this distribution network, conventional reactive power compensation devices and base loads are also considered. The main aim of this study is to reduce the net cost of the DSO for operating the distribution network, by coordinating EVs to offer joint voltage and frequency regulation services.

Our contributions in this paper can be summarized as follows: 1) A JVFR framework is proposed in a distribution network scenario where EV changing stations, wind turbines, base loads and reactive power compensation devices co-exist. 2) We formulate the EV charging scheduling problem as an optimization problem with the objective of minimizing the net economic cost of DSO for operating the distribution network, which includes the power loss cost of the distribution line, operation cost of the reactive power compensation devices and benefits from providing frequency regulation service to the ISO. A Volt-VAR Optimization problem under this scenario is also formulated to serve as the benchmark problem for performance comparison with the proposed JVFR strategy. 3) Performance evaluation and comparison are conducted under different VAR requirement scenarios of wind turbines in a 34-bus radial distribution network.

All the notation and symbols used in this paper are given in Table I.

II. SYSTEM MODEL

A. Distribution System Model

As shown in Fig. 1, EV charging stations, wind turbines, base loads and compensation devices co-exist in the distribution system. The DSO schedules the active and reactive charging power of EVs to provide voltage regulation to the distribution system and frequency regulation service to the ISO according to the regulation signal r_t sent by the ISO. Meanwhile, the DSO gets rewards from the ISO according to amount of regulation service provided. The objective of the DSO is to minimize the net cost for the operation of the distribution network.

We consider a discrete-time system with a finite regulation horizon, which is divided into T intervals (with each interval of Δt). We focus on a radial distribution system modeled by a tree graph $(\mathcal{V}, \mathcal{E})$. The tree is rooted at the substation bus indexed by $i = 0$. Note that the squared voltage $v_{0,t}$ at bus station remain constant across all the regulation period considered (i.e., $v_{0,t} \equiv v_0$). We assume that the scenarios of the EV charging stations (e.g., arrival time, departure time, charging requirement and maximum apparent power) can be known in advance according to historical data analysis. a'_n and d'_n denote the regularized arrival and departure time. More precisely, if EV n arrives before the beginning of the regulation period, a'_n will be assigned the value 1. Similarly, if EV n departs after the end of the regulation period, the value T will be assigned to d'_n. In other cases, a'_n and d'_n denote the specific time slot when EV n arrives and departs, respectively. Regarding the charging stations and wind turbines, it is assumed that they are co-located at the bus set

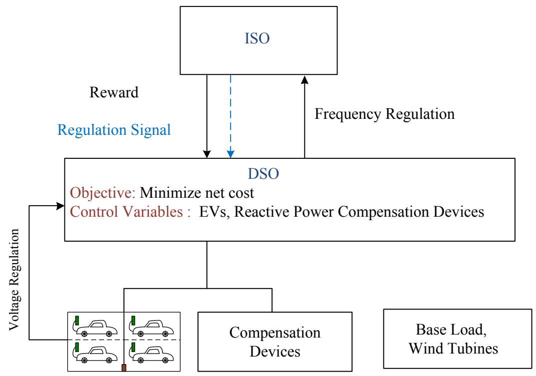


Fig. 1. An illustration of the system model

$\mathcal{V}_{\mathcal{W}}$. The compensation devices are assumed to be located at bus set $\mathcal{V}_{\mathcal{R}}$, which is a subset of $\mathcal{V}$.

B. Power Flow Model

We assume that the accurate values of $\{p_i^c(t), q_i^c(t), p_i^g(t), q_i^g(t), \forall i \in \mathcal{V}, \forall t \in \mathcal{T}\}$ can be known to the DSO in advance by some prediction methods. We can represent these parameters by their normalized profile multiplied by their maximum values:

$$p_i^c(t) = p_{i,max}^c m_i^c(t),\ q_i^c(t) = q_{i,max}^c m_i^c(t), \tag{1}$$
$$p_i^g(t) = p_{i,max}^g m_i^g(t),\ q_i^g(t) = q_{i,max}^g m_i^g(t). \tag{2}$$

$p_i(t)$ and $q_i(t)$ denote the real and reactive power drawn from bus i at time t. Then we can obtain their relationships with the base loads, wind turbines and EVs as follows.

$$p_i(t) = p_i^c(t) - p_i^g(t) + p_i^v(t), \tag{3}$$
$$q_i(t) = q_i^c(t) + q_i^g(t) - q_i^r(t) + q_i^v(t), \tag{4}$$
$$p_i^v(t) = \sum_{n\in\mathcal{N}_i} p_n^v(t),\ q_i^v(t) = \sum_{n\in\mathcal{N}_i} q_n^v(t), \forall i \in \mathcal{V}, \forall t \in \mathcal{T}. \tag{5}$$

Based on [13], the power flows in the radial distribution network are characterized by the following branch flow model, where each equation holds $\forall (i,j) \in \mathcal{E}, \forall t \in \mathcal{T}$.

$$P_{ij}(t) = r_{ij} l_{ij}(t) + p_j(t) + \sum_{k:(j,k)\in\mathcal{E}} P_{jk}(t), \tag{6a}$$
$$Q_{ij}(t) = x_{ij} l_{ij}(t) + q_j(t) + \sum_{k:(j,k)\in\mathcal{E}} Q_{jk}(t), \tag{6b}$$
$$v_j(t) = v_i(t) + (r_{ij}^2 + x_{ij}^2) l_{ij}(t) - 2(P_{ij}(t) r_{ij} + Q_{ij}(t) x_{ij}), \tag{6c}$$
$$v_i(t) = \frac{1}{l_{ij}(t)} (P_{ij}(t)^2 + Q_{ij}(t)^2). \tag{6d}$$

III. Problem Formulation

We formulate two problems in this section: the first one is the traditional VVO problem without reactive power compensation or frequency regulation from EVs; the second one is the proposed JVFR formulation. The VVO formulation will be treated as a benchmark approach for performance comparison with JVFR approach.

A. Volt-VAR Optimization

Define the decision variables by $\mathbf{x} = \{p_n^v(t), q_n^v(t), q_i^r(t), P_{ij}(t), Q_{ij}(t), l_{ij}(t), v_i(t) | i \in \mathcal{V}, j \in \mathcal{V}/\{0\}, t \in \mathcal{T}\}$. Then, the VVO formulation is given as follows.

$$\begin{aligned}
\min_{\mathbf{x}} \quad & w_E(\sum_{t\in\mathcal{T}} \sum_{(i,j)\in\mathcal{E}} r_{ij} l_{ij}(t))\Delta t + w_R(\sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{V}} q_i^r(t))\Delta t \\
\text{s. t.} \quad & 0 \le p_n^v(t) \le s_n, \forall n \in \mathcal{N}, \forall t \in \mathcal{T} && (7)\\
& p_n^v(t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}/\{a_n', ..., d_n'\} && (8)\\
& q_n^v(t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T} && (9)\\
& \sum_{t=a_n'}^{d_n'} p_n^v(t)\Delta t \ge e_n^{min}, \forall n \in \mathcal{N}, && (10)\\
& \sum_{t=a_n'}^{d_n'} p_n^v(t)\Delta t \le e_n^{max}, \forall n \in \mathcal{N}, && (11)\\
& \underline{v}_i \le v_i(t) \le \overline{v}_i, \forall t \in \mathcal{T}, \forall i \in \mathcal{N} && (12)\\
& 0 \le q_i^r(t) \le q_{i,max}^r, \forall i \in \mathcal{V}_{\mathcal{R}} && (13)\\
& q_i^r(t) = 0, \forall i \in \mathcal{T}/\mathcal{V}_{\mathcal{R}} && (14)\\
& \text{constraints (3),(4),(5), and (6).}
\end{aligned}$$

In this formulation, the objective has two terms. In the first term, $\sum_{t\in\mathcal{T}} \sum_{(i,j)\in\mathcal{E}} r_{ij} l_{ij}(t)$ represents the total power loss of the distribution network. In the second term, $\sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{V}} q_i^r(t)$ denotes the total VAR injected by the compensation devices. After being multiplied by the price information and time interval, the sum of these two terms stands for the sum of the power loss cost and operation cost of the compensation devices. For the constraints, first, power flow constraints are included in (3)–(6). Constraints (7)–(9) indicate that unidirectional charging of EVs is adopted, and there is no reactive power support from EVs. Constraints (10) and (11) refer to the minimum and maximum charging demand during $[a_n', d_n']$. Constraints (12) represent the voltage regulation requirements. The reactive power compensation is restricted by constraints (13) and (14).

B. Joint Voltage and Frequency Regulation

Define the decision variables by $\mathbf{y} = \{\mathbf{x}, C_F\}$. We formulate the JVFR problem as an EV charging scheduling problem as follows.

$$\begin{aligned}
\min_{\mathbf{y}} \quad & w_E(\sum_{t\in\mathcal{T}} \sum_{(i,j)\in\mathcal{E}} r_{ij} l_{ij}(t))\Delta t + w_R(\sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{V}} q_i^r(t))\Delta t \\
& - w_F C_F T \Delta t \\
\text{s. t.} \quad & \sqrt{(p_n^v(t))^2 + (q_n^v(t))^2} \le s_n, p_n^v(t) \ge 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T} && (15)\\
& p_n^v(t) = 0, q_n^v(t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}/\{a_n', ..., d_n'\} && (16)\\
& |P_t^{ref} - P_t^v - C_F r_t| \le \varepsilon \cdot C_F \cdot |r_t|, \forall t \in \mathcal{T} && (17)\\
& C_F \ge 0 && (18)\\
& \text{constraints (3) – (6), (10) – (14),}
\end{aligned}$$

where $P_t^v = \sum_{n \in \mathcal{N}} p_n^v(t)$.

For the objective of JVRF problem, compared with VVO, an extra term representing the revenue of providing frequency regulation service is added. Thus the objective is to minimize the net cost of the DSO during the regulation period.

For the constraints, in addition to the power flow, charging demand, voltage regulation and compensation devices constraints which are the same as the VVO problem, constraints (15) and (16) indicate that both the active and reactive power of EVs can be scheduled; constraints (17) and (18) denote the requirements for offering frequency regulation service to the grid. In (17), ε is a small value to control the allowable error when offering frequency regulation service. P_t^{ref} is a parameter denoting the reference charging power at time t for frequency regulation, in other words, the difference between P_t^{ref} and P_t^v (i.e., $P_t^{ref} - P_t^v$) should follow the variation of the regulation signal $C_F r_t$ when providing frequency regulation services. In this scenario, we adopt the reference charging power by assuming each EV is charged with a constant charging power $p_n^{v,ref}(t)$ during its stay in the charging station. Mathematically, we have,

$$P_t^{ref} = \sum_{n \in \mathcal{N}} p_n^{v,ref}(t) \tag{19}$$

$$p_n^{v,ref}(t) = \frac{(e_n^{min} + e_n^{max})}{2(d_n' - a_n' + 1)\Delta t}, \forall t \in \{a_n', ..., d_n'\} \tag{20}$$

Eq. (20) means each EV will be charged to the average of its maximum and minimum energy demand with a constant charging rate.

The difficulty in solving the VVO and JVFR problems comes from the quadratic equality constraint (6d), which causes the whole problem to be non-convex. However, based on the advances in solving the OPF problem by convex relaxation [14], we propose to solve VVO and JVFR problem via convex relaxation, namely replacing constraint (6d) by

$$v_i(t) \geq \frac{1}{l_{ij}(t)}(P_{ij}(t)^2 + Q_{ij}(t)^2), \forall (i,j) \in \mathcal{E}, \forall t \in \mathcal{T} \tag{21}$$

The relaxed problems are second-order cone program (SOCP) problems which can be solved optimally and efficiently. And the relaxed constraint can be shown to be binding after verification at the end of Section IV. Thus, solving the relaxed problems is equivalent to solving the original problems.

IV. Performance Evaluation

The performance evaluation is implemented in a 34-bus radial distribution network as shown in Fig. 2. We have $\mathcal{V}_\mathcal{W}$ = {3, 8, 18, 23}, $\mathcal{V}_\mathcal{R}$ ={ 2, 5, 6, 9, 20, 24}. The maximum reactive power value $q_{i,max}^r$ for every $i \in \mathcal{V}_\mathcal{R}$ is set to 100 kVAR. $\underline{v}_i$ and $\overline{v}_i$ are set as $(0.9)^2 v_0$ and $(1.1)^2 v_0$, respectively. A simulation period of 2 hours is divided into 12 time intervals with a length of 10 minutes (i.e., T = 12, Δt = 10 mins).[1]

[1]Note that the reason why we set Δt as 10 minutes rather than a few seconds (e.g., 2s for PJM, 4s for CAISO) in the simulation is because we want to reduce the computational time and simplify the simulation. And under this parameter configuration, the scheduling mechanism can be explained clearly in the simulation as well.

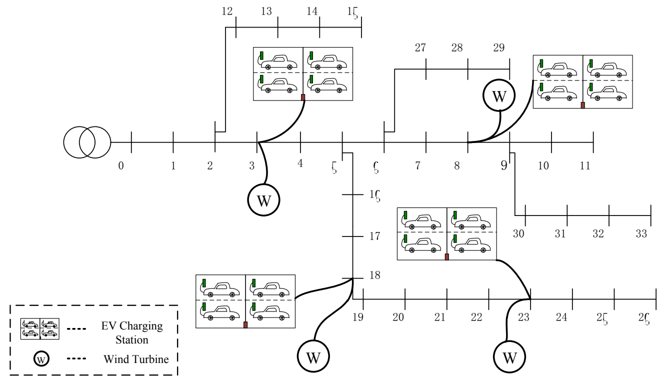


Fig. 2. 34-bus distribution network

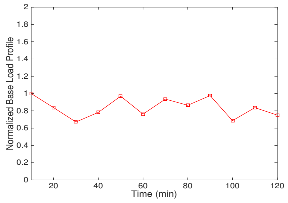
Real regulation signal data from PJM [15] on a day from 14:00 p.m. to 16:00 p.m. is used as the regulation signal by averaging it every 10 minutes.[2] We assume that all the base loads have the same variation trend in the simulation. The normalized base load and wind profiles (i.e., $m_i^c(t), m_i^g(t)$) are given in Fig. 3. We use the distribution system data (including $p_{i,max}^c$, $q_{i,max}^c$, r_{ij}, x_{ij}) from [16]. $p_{i,max}^g$ is set as 143.9 kW for all wind turbines. w_E, w_R and w_F are set as 0.06 \$/kWh, 0.2283 \$/MVARh and 43.70 \$/MW-h, respectively. We use an M/G/S/S loss queue to generate the arrival and charging process of EVs at each charging station.[3] The arrival rate parameter λ is set as 1/3. The charging times of arrived EVs are assumed to follow normal distribution with mean μ and standard deviation σ equal to 90 and 20, respectively. The capacity of each EV charging station equals 20, (i.e. S =20). The minimum and maximum energy demand data in the simulation is obtained based on the charging times of the EVs. AC Level 2 charging is adopted in the simulation (s_n = 7.68 kVA). ϵ is set as 0.1. We simulated JVFR and VVO formulations under different VAR requirements of wind turbines, $q_{i,max}^g$, from 10 kVAR to 110 kVAR.

First, we evaluate the annualized cost of the DSO for JVFR and VVO approaches under different VAR requirements of the wind turbines. It can be shown in Fig. 4 that the cost is increasing with the increase of VAR requirements. The result shows that the performance of JVFR is always better than VVO in terms of net cost, power loss cost and operation cost.

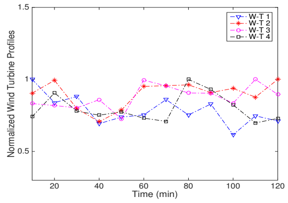
The voltage deviations of JVFR and VVO are compared in Fig. 5. Here we the average sum of deviations of squared voltage from the squared voltage at substation v_0 as the performance metric for voltage regulation (i.e., $\sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{V}} (v_i(t) - v_0)/(T \cdot v_0)$). It is clear to observe that the performance of JVFR for voltage regulation is better than that of VVO under different scenarios.

[2]Note that the scheduling mechanism can also work in practical use (i.e., with real regulation data, Δt = 2 or 4s). With the help of powerful computing resources, the scheduling problem can also be solved in a short time.

[3]In queueing theory, an M/G/S/S loss queue is a queue model where customers arrive to the system according to a homogeneous Poisson process with rate parameter λ, service times have a General distribution. There are S available servers in the system. If a customer arrives when all the servers are occupied, that customer is lost.

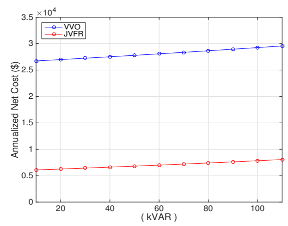


(a) Base Load Profile

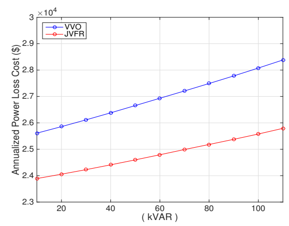


(b) Wind Profiles

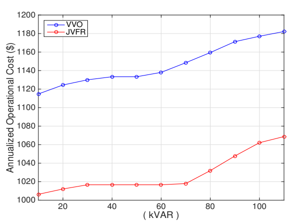
Fig. 3. Normalized Base Load Profile and Wind Profiles



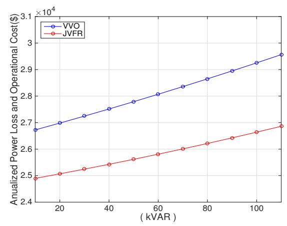
(a) Net Cost



(b) Power Loss Cost



(c) Operation Cost



(d) Power Loss and Operation Cost

Fig. 4. Annualized Costs of the DSO

When $q_{i,max}^{g} = 50$ kVAR, the performance of JVFR for providing regulation service is shown in Fig. 6. In Fig. 6(a), the real reference charging power P_t^{ref} and total charging power P_t^v are depicted. Moreover, the difference between these two (i.e., $P_t^{ref} - P_t^v$) acts as the response signal. And it is shown with the regulation signal in Fig. 6(b). It can be seen that the response signal follows the regulation signal accurately.

In Section III, we used convex relaxation to transform the original problems into SOCP problems. Here we calculated the convex relaxation gaps of constraint (6d) for time slots and found they are always below 0.01%, therefore perfect relaxation is almost achieved.

V. Conclusion

In this work, we studied how to schedule EV charging for providing JVFR in the distribution network with wind-based renewable generations. We formulated the scheduling problem as a non-convex optimization problem to minimize the net cost of the DSO, and solved it by transforming the problem into an SOCP problem. By simulating our model on a 34-bus distribution network with different VAR requirements from wind turbines, it is found that the proposed JVFR approach can reduce the net cost of DSO for operating the distribution network when comparing its performance with the traditional VVO approach, which can benefit the distribution grid a lot.

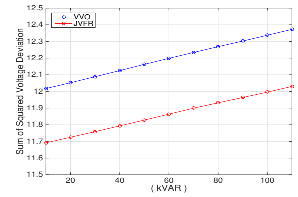
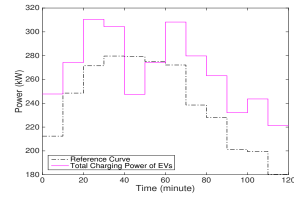
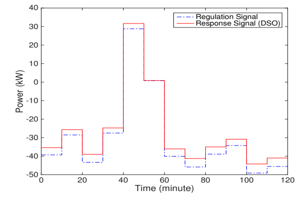


Fig. 5. Voltage Deviation Comparison



(a) Total Charging Power of EVs vs Reference Curve



(b) Response Signal vs Regulation Signal

Fig. 6. Frequency Regulation Service

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