Cyber Physical Grid-Interactive Distributed Energy Resources Control for VPP Dispatch and Regulation

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Cyber Physical Grid-Interactive Distributed Energy Resources Control for VPP Dispatch and Regulation

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***Abstract*—This paper presents a cyber-physical algorithm for grid-interactive Distributed Energy Resource (DER) control to enable two features of Virtual Power Plants (VPPs) dispatch and grid voltage regulation, considering the communication and security impacts. We first formulate the DER dispatch problem as a real-time, iterative, and grid-interactive DER control problem. Thereafter, we consider a probabilistic traffic model to characterize packet delays and loss in a communication network, and study how the delays enter the process of information exchange among the grid measurement units, local DER controllers and the grid control center that coordinately execute this dispatch algorithm. Finally, a strategy combining delay threshold and modified message update rules is proposed to immune the asynchrony resulting from the communications network traffic and it avoids possible numerical instabilities and sensitivities of the tracking and regulation capabilities of this DER control algorithm. By implementing the proposed cyber-physical algorithm on the modified IEEE 37-node system, our preliminary results exhibit that the uncertainties of the underlying communications infrastructure must be considered for the VPP tracking and regulation capabilities of any DER in a generic Cyber-Physical System (CPS), because the delayed voltage measurements in the uplink/bi-link cases result in the off-track in VPP dispatch and jittery in voltage regulation.**

***Index Terms*—cyber-physical algorithm, distributed energy resources (DER), DER control.**

I. Introduction

The emerging concept of smart distribution networks indicate that distributed energy resources (DERs) has a high potential to support grid operations with two features: a) optimizing energy performance of DERs to address stochastic and dynamic challenges; b) supporting grid services of frequency and voltage regulation [1]. However, all these advanced applications of smart distribution systems rely heavily on new control, protection and communication systems of DERs [2]. Therefore, the DER management system (DERMS) and its cyber-physical DER monitoring and control algorithms are emerging research topics to support the grid services.

To this end, research is currently being carried out in the academic and industrial groups on the development of advanced grid-interactive DER control algorithms [3], [4], communications architectures for DER applications [2], [5], [6], and DERMS platform [7], [8]. Specifically, the increasing prevalence of DER-based CPS and their common-mode vulnerabilities may lead to cyber-threats and risk of detaching DERs due to power disruptions and operational instability. It is intuitive that it will no longer be feasible under the large deployment of DERs for the state-of-the-art algorithms to handle DER control and communication architectures separately. In particular, very little attention has been paid to perhaps two most critical consequences of these envisioned cyber-physical DER dispatch algorithms, i.e., a) theoretical formulation of DER dispatch strategies as cyber-physical algorithms, and b) investigation of regulation and tracking capabilities of these algorithms with asynchronous data flow resulting from practical communication networks. A new set of cyber-physical DER control algorithms is in a critical need to address communication and security issues.

To bridge this gap, built on the existing advanced optimal regulation of virtual power plant (VPP) algorithm in [3], this study further proposes a cyber-physical grid-interactive DER dispatch algorithm and its implementation architecture for characterizing the performance and reliability of the real DER system. It aims to meeting the increasing needs of an automated smart power distribution grid with large-scale DERs to provide the guide for the future deployment of DERs. The main contribution of this paper are: 1) identified two main delay/security-sensitive steps in DER dispatch algorithm and how these delays enter the process of information exchange between DERMS and grid edges. 2) developed a cyber-physical grid-interactive DER dispatch algorithm considering a probabilistic traffic model for modeling delays in the controllable communication network; 3) implemented the hierarchical and distributed implementation architecture; 4) conducted an assessment of impact of multiple cyber-sensitive procedures on the DER control performance in terms of tracking accuracy and voltage regulation.

II. Problem Statement and Recap of VPP Dispatch

Consider a distribution feeder with DERs comprising $N+1$ nodes, denoted as $\mathcal{N} \cup \{0\}, \mathcal{N} := \{1, ..., N\}$. Node 0 denotes the secondary of the distribution transformer or feeder head. Let $V_n \in \mathbb{C}$ denote the phasor for the voltage injected into Node $n \in \mathcal{N}$, and define the N-dimensional complex vectors $\mathbf{v} := [V_1, ..., V_N]^T \in \mathbb{C}^N$ Let $P_{l,n}$ and $Q_{l,n}$ denote the active and reactive demands at Node $n \in \mathcal{N}$, and P_0 and Q_0 denote the active and reactive powers flowing into the feeder at the substation. Let $\mathcal{G} := \{1, ..., G\} \subseteq \mathcal{N}$ be a set of nodes where DERs are located, and P_i and Q_i denote the active and reactive powers injected by the DER at Node $i \in \mathcal{G}$. We denote $\mathcal{Y}_i \subset \mathbb{R}^2$ as the set of possible set points P_i, Q_i for DER i. For the PV system, let P_i^{av} denote the available active power and S_i be the rated apparent capacity. Then, the set $\mathcal{Y}_i$ is given by $\mathcal{Y}_i = \{(P_i, Q_i) : 0 \leq P_i \leq P_i^{av}, P_i^2 + Q_i^2 \leq S_i^2\}$.

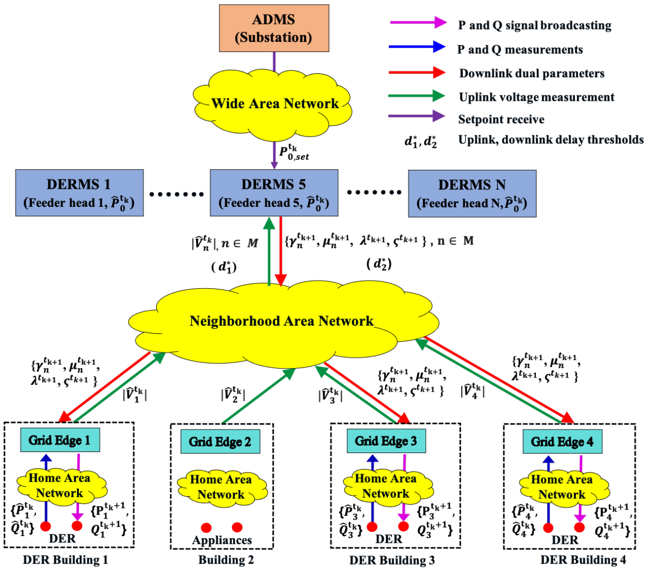


Fig. 1. Architecture for Cyber-Physical Grid-Interactive DER Control

Let $\mathbf{s}_{inj} := [S_1, ..., S_N] \in \mathcal{C}^N$ denote the net power injected at nodes $\mathcal{N}$, where $S_i = P_i - P_{l,i} + j(Q_i - Q_{l,i})$ for $i \in \mathcal{G}$, and $S_i = -P_{l,i} - jQ_{l,i}$ for $i \in \mathcal{G} \backslash \mathcal{N}$. By defining $\mathbf{v}_{nom}$ as the linearization point of the nominal-voltage vector, the so-called "LinDisFlow" linearization approach is applied to achieve the power flow approximation of the nodal-voltage magnitudes $|\mathbf{v}|$ and P_0, Q_0 as the function of the real and reactive power injections:

$$|\mathbf{v}| \approx \mathbf{A p_{inj}} + \mathbf{B q_{inj}} + \mathbf{c}, \quad [P_0, Q_0]^T \approx \mathbf{M p_{inj}} + \mathbf{N q_{inj}} + \mathbf{o} \tag{1}$$

where $\mathbf{p_{inj}} := \Re\{\mathbf{s}_{inj}\}$, $\mathbf{q_{inj}} := \Im\{\mathbf{s}_{inj}\}$ and the model parameters $\mathbf{A} \in \mathbb{R}^{N \times N}, \mathbf{B} \in \mathbb{R}^{N \times N}, \mathbf{M} \in \mathbb{R}^{2 \times N}, \mathbf{N} \in \mathbb{R}^{2 \times N}, \mathbf{c} \in \mathbb{R}^N, \mathbf{o} \in \mathbb{R}^2$ can be obtained using suitable linearization methods for the AC power-flow equations by referring the paper [3].

1) VPP Dispatch Problem with Voltage Regulation: Built on the aforementioned linearized power flow model, the real time optimal VPP dispatch problem considering voltage regulation (Equation 9, [3]) has been developed by leveraging primal-dual-gradient methods to the regularized Lagrangian function. The DER dispatch actions are conducted in a discrete-time fashion at time instants $t_k, k \in \mathbb{N}$. Let $\mathcal{M} := \{1, ..., M\} \subset \mathcal{N}$ be a set of nodes where measurements of the voltage magnitudes can be obtained and the voltage regulation of $[V^{min}, V^{max}]$ are required. We define $\boldsymbol{\gamma}^{t_k} := [\gamma_1^{t_k}, ..., \gamma_M^{t_k}]^T$ and $\boldsymbol{\mu}^{t_k} := [\mu_1^{t_k}, ..., \mu_M^{t_k}]^T$ as the dual variables associated with the voltage regulation constraints. Similarly, let λ^{t_k} and ζ^{t_k} be the Lagrange multipliers associated with the setpoints tracking constraints. Thus, with $\mathbf{d} := \{\boldsymbol{\gamma}, \boldsymbol{\mu}, \lambda, \zeta\}$, the developed DER control algorithm is described as,

$$\begin{aligned}
&\max_{\mathbf{d} \in \mathbb{R}_+^{2M+2}} \min_{\mathbf{p}, \mathbf{q} \in \mathcal{Y}^{t_k}} \mathcal{L}^{t_k}(\mathbf{p}, \mathbf{q}, \mathbf{d}) \\
&\mathcal{L}^{t_k}(\mathbf{p}, \mathbf{q}, \mathbf{d}) := \sum_{i \in \mathcal{G}} f_i^{t_k}(P_i, Q_i) \\
&+ \sum_{n \in \mathcal{M}} [\gamma_n (V^{min} - |V_n^{t_k}|(P_i, Q_i)) \\
&+ \mu_n (|V_n^{t_k}|(P_i, Q_i) - V^{max})] \\
&+ \lambda [P_0^{t_k}(P_i, Q_i) - P_{0,set}^{t_k} - E^{t_k}] \\
&+ \zeta [P_{0,set}^{t_k} - P_0^{t_k}(P_i, Q_i) - E^{t_k}] \\
&+ \frac{\nu}{2} \sum_{i \in \mathcal{G}} (P_i^2, Q_i^2) - \frac{\epsilon}{2} \|\mathbf{d}\|_2^2, \forall i \in \mathcal{G}, \forall n \in \mathcal{M}
\end{aligned} \tag{2}$$

where the tracking error $E^{t_k} > 0$, $\mathbf{p} := [P_1, ..., P_G]^T$, $\mathbf{q} := [Q_1, ..., Q_G]^T$. Functions $f_i^{t_k}(\cdot)$ capture a variety of operational objectives for both DERs' owners and the utility. ν and ϵ are regularization coefficients.

III. Cyber-Physical Grid-Interactive DER Control Algorithm

To solve the optimal VPP dispatch with voltage regulation described in Equation (2) in the envisioned distribution grid considering the communication and security issues, a new algorithm with cyber-physical features is further developed. The corresponding cyber model of the communication network is described in this section.

A. Identification of Cyber Sensitivity

Based on the measurements of 1) $|\widehat{V}_n^{t_k}|$: measurement of the voltage magnitude at each node $n \in \mathcal{M}$; 2) $\widehat{P}_0^{t_k}$: measurement of the active power at the feeder head; and 3) $\widehat{P}_i^{t_k}, \widehat{Q}_i^{t_k}$: measurement of the active and reactive output powers at DER $i \in \mathcal{G}$, the hierarchical and distributed control framework, shown in Fig. 1, has been proposed in [3], [9] to execute the DER dispatch algorithm in the following steps. Consider the t_k iteration, referring to Fig. 2: **Step 1)** at time $t_k^{1,n}$, each grid edge, which could be embedded in the smart meter or DER aggregator, sends $|\widehat{V}_n^{t_k}|$ to the DERMS node embedded in the data concentrator at the feeder's control room, which also collects $\widehat{P}_0^{t_k}$ from the feeder head, and $\widehat{P}_{0,set}^{t_k}$ from the ADMS node located at the substation control room; **Step 2)** at time $t_k^{2,n}$, the DERMS node updates the dual parameter set $\mathbf{d}^{t_{k+1}} = [\gamma_n^{t_{k+1}}, \mu_n^{t_{k+1}}, \lambda^{t_{k+1}}, \zeta^{t_{k+1}}]$, individually, as follows:

$$\begin{aligned}
\gamma_n^{t_{k+1}} &= proj_{\mathbb{R}_+} \left\{ \gamma_n^{t_k} + \alpha (V^{min} - |\widehat{V}_n^{t_k}| - \epsilon \gamma_n^{t_k}) \right\}, \\
\mu_n^{t_{k+1}} &= proj_{\mathbb{R}_+} \left\{ \mu_n^{t_k} + \alpha (|\widehat{V}_n^{t_k}| - V^{max} - \epsilon \mu_n^{t_k}) \right\}, \\
\lambda^{t_{k+1}} &= proj_{\mathbb{R}_+} \left\{ \lambda^{t_k} + \alpha (\widehat{P}_0^{t_k} - P_{0,set}^{t_k} - E^{t_k} - \epsilon \lambda^{t_k}) \right\}, \\
\zeta^{t_{k+1}} &= proj_{\mathbb{R}_+} \left\{ \zeta^{t_k} + \alpha (P_{0,set}^{t_k} - \widehat{P}_0^{t_k} - E^{t_k} - \epsilon \zeta^{t_k}) \right\};
\end{aligned} \tag{3}$$

Step 3) at time $t_k^{3,i}$, the DERMS node has to finish all updates calculation and sends $\mathbf{d}^{t_{k+1}}$ to each DER grid edge; **Step 4)** at time $t_k^{4,i}$, each DER grid edge updates $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$, after receiving both $\widehat{P}_i^{t_k}, \widehat{Q}_i^{t_k}$ and $\mathbf{d}^{t_{k+1}}$, as follows:

$$\begin{aligned}
[P_i^{t_{k+1}}, Q_i^{t_{k+1}}]^T &= proj_{\mathcal{Y}_i^{t_k}} \{ [P_i^{t_k}, Q_i^{t_k}]^T \\
&- \alpha \nabla_{[P_i, Q_i]} \mathcal{L}^{t_k}(\mathbf{p}, \mathbf{q}, \mathbf{d}) |_{\widehat{P}_i^{t_k}, \widehat{Q}_i^{t_k}, \mathbf{d}^{t_{k+1}}} \};
\end{aligned} \tag{4}$$

Step 5) at time $t_k^{5,i}$, each DER grid edge dispatches $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$ to each DER device for their next update. Without considering the cyber system, the underlying assumptions include 1) every update associated with communications can be performed by the local grid edges in parallel, they are synchronized with each other; and 2) each update associated with computation can be executed by the DERMS node in parallel processes. The algorithm is, therefore, referred to as synchronous optimal grid-interactive VPP dispatch algorithm.

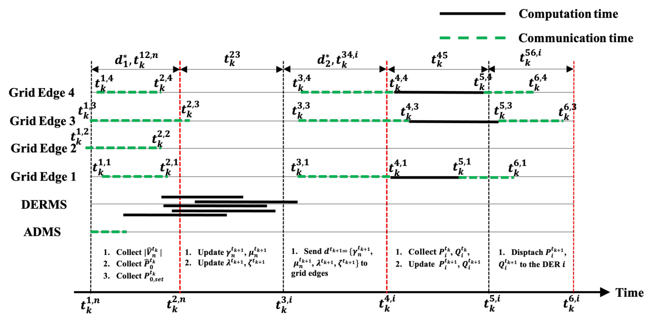


Fig. 2. Timing Diagram for Asynchronous Cyber-Physical DER Control

In practice, however, the communications between the DERMS node and local grid edges and that between local grid edges and DER devices always involve packet delays, packet loss, and malicious security attacks, thereby leading to asynchrony in message arrivals, lost message, and impaired message, respectively. The timing diagram under the particular condition of communication delays, as shown in Fig.2, consists of four main cyber-sensitive components: (1) the ADMS dispatches $\widehat{P}_{0,set}^{t_k}$ to the DERMS node. Since this communication always happens over the high-speed Wide Area Network (WAN) and $\widehat{P}_0^{t_k}$ arrives earlier than $|\widehat{V}_n^{t_k}|$ with high possibility, we ignore this communication delay throughout this paper; (2) the green dash lines between time $t_k^{1,n}$ and $t_k^{2,n}$ for grid edges show that the local voltage measurements $|\widehat{V}_n^{t_k}|$ arrive at the DERMS at different instants $t_k^{2,n}, n \in \mathcal{M}$ due to variable uplink delays through the Neighborhood Area Network (NAN); (3) the green dash lines between time $t_k^{3,i}$ and $t_k^{4,i}$ show that a set of dual parameter $\mathbf{d}^{t_{k+1}}$ arrives at each DER grid edge at different instants $t_k^{4,i}, i \in \mathcal{G}$ due to varying downlink delays on NAN; (4) each DER grid edge dispatches $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$ to the DER device with the collection of $P_i^{t_k}, Q_i^{t_k}$ through the Home Area Network (HAN). Since these two delays happen within the short-distance HAN, they are also ignored. The resulting algorithm is referred to as asynchronous VPP dispatch. One trivial way to counteract the asynchrony within the collection of $|\widehat{V}_n^{t_k}|, n \in \mathcal{M}$ and calculation of the updated $\mathbf{d}^{\mathbf{t_{k+1}}}$ would be to force the DERMS to wait till it receives all measurements and computes all parameters at every iteration. This, however, can lead to unacceptable setpoints tracking accuracy and voltage regulation performance. And depending on the congestion and security of network, this can even turn out to be very risky in the case that any message gets lost or delayed for an uncertain period of time, or gets impaired. Instead, we expect to counteract asynchrony/attacks by defining a set of *flexible deadlines*/countermeasures for message arrival at the DERMS and each grid edge, and accordingly by modifying the update rules in the synchronous VPP dispatch algorithm based on only those messages that respect these deadlines/countermeasures. In order to understand how these deadlines/countermeasures should be constructed in accordance to the network traffic and security, we first develop a probability distribution model for the communication network delays/attacks.

B. Cyber Model of Communications Network

We expect to develop the cyber model of communication network capturing both asynchrony and attack behaviors. In this paper, we start with the cyber delay model by assuming that the NAN uses the Ethernet cable as the communication technology. Referring to [10], we model the stochastic end-to-end delay experienced by a message between the DERMS and local grid edges within the NAN in terms of three components: the minimum deterministic delay, denoted by m; the Internet traffic delay with Probability Density Function (PDF), denoted by ϕ_1; and the router processing delay with PDF, denoted by ϕ_2. Then, the PDF of the total delay at any time t is given as

$$\phi(t) = p\phi_2(t) + (1-p)\phi_1(t) * \phi_2(t), t \geq 0, \tag{5}$$

with $\phi_1(t) * \phi_2(t) = \int_0^t \phi_2(u)\phi_1(t-u)du$. Here p is the probability of open period of the path with no Internet traffic, and the router processing delay can be well approximated by a Gaussian density function $\phi_2(t) = \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(t-\mu)^2}{2\sigma^2}}$, where $\mu > m$. The Internet traffic delay is modeled by an alternating renewal process with exponential closure period when the Internet traffic is on, with the PDF $\phi_1(t) = \lambda e^{-\lambda t}$, where λ^{-1} models the mean length of the closure period. The benchmark value of all parameters of this model are set as: $p = 0.58, \lambda = 1.39, \mu = 5.3, \sigma = 0.078$, following [10].

By using the partial integral method, the error function $erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$, and its first derivative $\frac{d}{ds}erf(s) = \frac{2}{\sqrt{\pi}e^{-s^2}}$, we derive the CDF of the cyber delay model as

$$\begin{aligned} P(t) = \int_{-\infty}^{t} \phi(s)ds = \frac{1}{2}\left[erf(\frac{\mu}{\sqrt{2}\sigma}) + erf(\frac{t-\mu}{\sqrt{2}\sigma})\right] \\ + \frac{(p-1)}{2}e^{(\frac{1}{2}\lambda^2\sigma^2+\mu\lambda)}e^{-\lambda t} \\ \times \left[erf(\frac{t-\lambda\sigma^2-\mu}{\sqrt{2}\sigma}) + erf(\frac{\lambda\sigma^2+\mu}{\sqrt{2}\sigma})\right]. \end{aligned} \tag{6}$$

Random delays from this CDF will next be imposed on the communication links to emulate the cyber-physical optimal VPP dispatch algorithm.

C. Cyber-Physical Optimal DER Control Algorithm

To counteract message asynchrony, we propose two update strategies. In Strategy I, both the DERMS node and local DER grid edges use internal memory to replace messages that do not arrive within a chosen deadline with their values from

Algorithm 1 Cyber-Physical Optimal DER Control

procedure DERMS(ν, ϵ, α)
  initialization: $t_k = 1, d_1^*, V^{min}, V^{max}, n \in \mathcal{M}$
  repeat
    update E^{t_k}
    wait
    receive the setpoint: $\widehat{P}_{0,set}^{t_k}$
    receive measurements: $|\widehat{V}_n^{t_k}|$, $\widehat{P}_0^{t_k}$,
  until timer $\geq d_1^*$ or all measurements received
  if $|\widehat{V}_n^{t_k}|$ received within d_1^* **then**
    update $\mathbf{d}^{t_{k+1}}$ by (3)
  else
    update $\mathbf{d}^{t_{k+1}}$ by (3) with Strategy I or II
  end if
  broadcast $\mathbf{d}^{t_{k+1}}$ to all DER grid edges
  $t_k = t_k + 1$
end procedure
procedure LOCAL DER GRID EDGE $i(\alpha)$
  initialization: $t_k = 1, d_2^*, \mathcal{Y}_i^{t_k}$
  repeat
    receive $\widehat{P}_i^{t_k}, \widehat{Q}_i^{t_k}$
    wait
  until timer $\geq d_2^*$ or receive $\mathbf{d}^{t_{k+1}}$
  if $\mathbf{d}^{t_{k+1}}$ received within d_2^* **then**
    update $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$ by (4)
  else
    update $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$ by (4) with Strategy I or II
  end if
  dispatch $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$ to the DER device
  $t_k = t_k + 1$
  send $|\widehat{V}_n^{t_k}|$ to the DERMS
end procedure
procedure LOCAL NON-DER GRID EDGE n
  initialization: $t_k = 1$
  while do
    send $|\widehat{V}_n^{t_k}|$ to the DERMS
    $t_k = t_k + 1$
  end while
end procedure

previous iteration. We define two deadlines or *delay thresholds*, namely $d_1^* > 0$ and $d_2^* > 0$ in milliseconds, for the uplink and downlink delays, respectively. Without loss of generality, we assume that the counting of these deadlines start from the instant at which the DERMS or any grid edge *sends out* any message at any iteration. For simplicity of notations, we also assume that every grid edge is assigned the same threshold d_2^* although same analysis will hold for different threshold values at different grid edges. Following the timing diagram in Fig.2, if any local voltage measurement $|\widehat{V}_n^{t_k}|$ does not arrive at the DERMS within time d_1^*, the DERMS uses $|\widehat{V}_n^{t_{k-1}}|$ to compute the dual parameters $\lambda_n^{t_{k+1}}, \mu_n^{t_{k+1}}$. On the other hand, if any DER grid edge $i, i \in \mathcal{G}$ does not receive $\mathbf{d}^{t_{k+1}}$ within d_2^*, it updates $P_i^{t_{k+1}}, Q_i^{t_{k+1}}$ using $\mathbf{d}^{t_k}$.

In Strategy II, the DERMS and each DER grid edge *skip* updating when messages do not arrive within the respective deadline. With any delayed local voltage measurement $|\widehat{V}_n^{t_k}|$, the DERMS skips parameter updating, namely updates $\lambda_n^{t_{k+1}} = \lambda_n^{t_k}, \mu_n^{t_{k+1}} = \mu_n^{t_k}$. Similarly, with the delayed $\mathbf{d}^{t_{k+1}}$, any local grid edge updates $P_i^{t_{k+1}} = P_i^{t_k}, Q_i^{t_{k+1}} = Q_i^{t_k}$. In a practical Internet, these two modified update strategies are suitable for scenarios that involve exceptionally long delays or possible packet loss. The resulting cyber-physical optimal DER control algorithm with the modified update strategy I or II is listed in Algorithm 1.

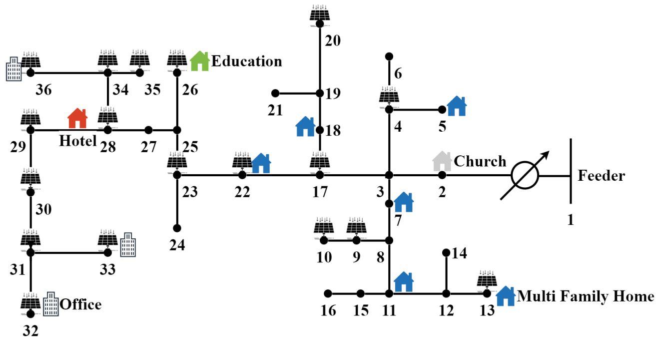
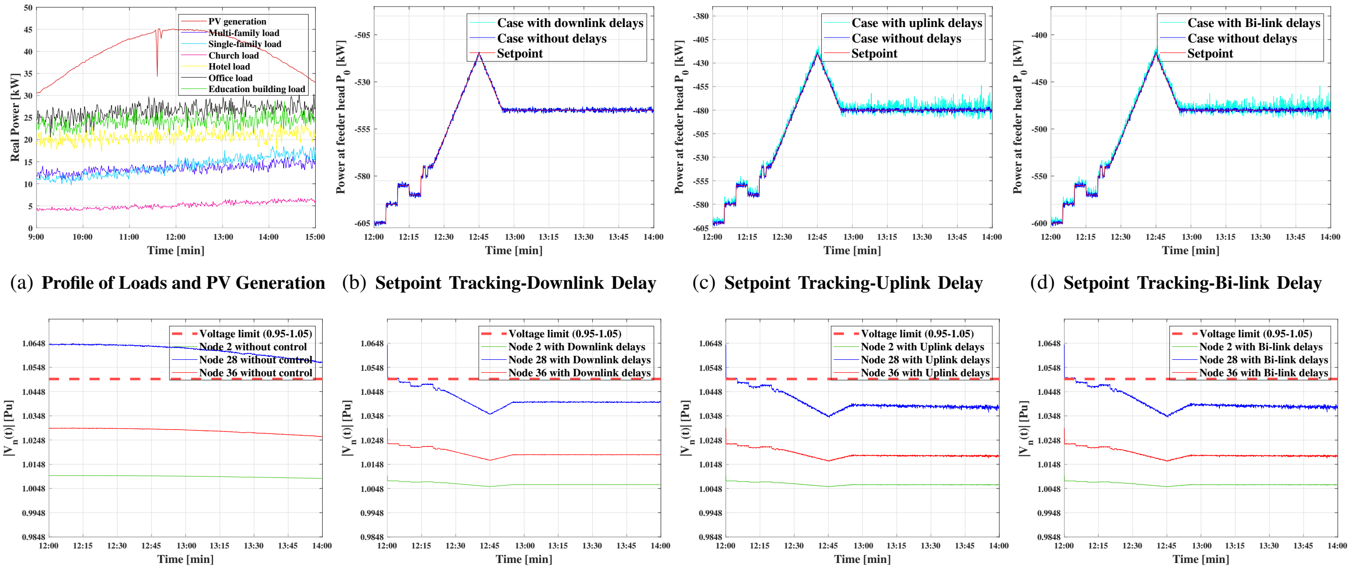


Fig. 3. IEEE 37-node Feeder with PV System and Load Deployment

IV. VALIDATION AND RESULTS

We consider the IEEE 37-node test feeder with modification, shown in Fig. 3. In the modified network, twelve load profile data from Sacramento of California is obtained at the EPRI [11], replacing the loads on Phase C specified in the original dataset. Through the random interpolation method, time-series load data have a granularity of 1 second and are plotted in Fig. 4(a). Referring to Fig. 3, eighteen rooftop PV systems are located at nodes 4, 9, 10, 13, 17, 20, 22, 23, 26, 28, 29, 30, 32, 33, 34, 35, and 36. The generation profile data is simulated based on the real solar radiation data of Sacramento, CA at August 15, 2012 from NREL Measurement and Instrumentation Data Center (MIDC) with a granularity of 1 second after processing and capacity 50kW, shown in Fig. 4(a). Other parameters are set as $V^{min} = 0.95, V^{max} = 1.05, \nu = 10^{-3}, \epsilon = 10^{-4}, E^{t_k} = 0.001, \alpha = 0.1$, and the PV system optimization objective (2) is set as $f_i^{t_k}(P_i, Q_i) = c_p(P_{av,i}^{t_k} - P_i^{t_k})^2 + c_q(Q_i^{t_k})^2$, where $c_p = 3, c_q = 1, i \in \mathcal{G}$. We consider the setpoints $P_{0,set}^{t_k}$ from 12:00 to 14:00, consists of 5-minute economic dispatch commands, 1-minute automatic generator control setpoints, ramp signals and a commands to keep it constant for 65 minutes, depicted in red in Fig. 4(b).

We firstly consider a fundamental comparison of synchronous DER control and cyber-physical asynchronous DER control with Strategy I. Referring to our delay model, we note that $P(X \leq 6.48) = 0.9704$, meaning that $d_1^* = d_2^* = 6.48$ ms will lead to 3% of the message being delayed. We implement IEEE-37 test case in OpenDSS and the cyber-physical DER control with Strategy I in Matlab with a granularity of 1 second, and results of the tracking and voltage regulation performance is shown in Fig. 4. The strategy is subdivided into



(a) **Profile of Loads and PV Generation** (b) **Setpoint Tracking-Downlink Delay** (c) **Setpoint Tracking-Uplink Delay** (d) **Setpoint Tracking-Bi-link Delay**

(e) **Voltage without DER Control** (f) **Voltage Regulation-Downlink Delay** (g) **Voltage Regulation-Uplink Delay** (h) **Voltage Regulation-Bi-link Delay**

Fig. 4. Profile of Loads and PV Generation, Voltage w/o DER Control, and Performance of Cyber-Physical DER Control Algorithm

three cases, namely: 1) Downlink case, where the cyber delay model is only applied to the downlink, but uplink deadlines are always met; 2) Uplink case, where the reverse happens; and 3) Bi-link case, which is the usual cyber-physical optimal DER control with Strategy I.

From Fig. 4, three observations of the setpoints tracking and voltage regulation performance are: 1) *Downlink case*: the downlink delay of dual parameters has limited impact on the tracking performance, because the $P_0(t)$ closely tracks $P_{0,set}^{t_k}$ from Fig. 4(b). Compared to the smooth voltage performance of the case of no DER control in Fig. 4(a), Fig. 4(b) shows that the voltage behaviors of the cyber-physical DER control correspondingly drop when $P_{0,set}^{t_k}$ changes oppositely and return to the stable value when $P_{0,set}^{t_k}$ is kept to a fixed value for a time period. 2) *Uplink case*: the voltage magnitudes are delayed and the dual parameters are updated with previous voltage magnitudes. Compared to Downlink case, both tracking and regulation behaviors of Uplink case become jittery as more asynchrony is added. It indicates that the downlink delay dominates the overall performance of proposed cyber-physical optimal DER control with Strategy I. And 3) *Bi-link case*: as we expect, it has the similar performance with that of Uplink case. With limited space, the results of Strategy II is not included in this paper.

V. Conclusion

In this paper, we developed a cyber-physical optimal grid-interactive DER control algorithm for two outstanding features of VPP and voltage regulation. Our algorithm demonstrates how multitudes of geographically dispersed DERMS and grid edges can communicate with each other, and how the various binding factors can pose bottlenecks for their communication. We construct a suite of methods that one may choose to eliminate asynchrony in the DER control. The results provide valuable insights and guidance in deploying future DERMS infrastructures. Our future work will focus on extension of the proposed cyber model to include both asynchrony and cyber-attack behaviors in communication network and their corresponding countermeasures.

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