Performance Evaluation of Network-Admissible Demand Dispatch in Multi-Phase Distribution Grids

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***Abstract*—As the penetration of flexible loads increases in distribution networks, demand dispatch schemes need to consider the effects of large-scale load control on distribution grid reliability. More specifically, we need demand dispatch schemes that actively ensure that distribution grid operational constraints are not violated (i.e., network-admissible) and still deliver valuable market services. For network-admissible demand dispatch schemes that depend on live 3-phase grid measurements, their overall performance and ability to manage constraints depends on the number, update rate, and multi-phase nature of the available measurements. In this context, the manuscript develops and evaluates the performance of a new network-admissible version of the device-driven demand dispatch scheme called Packetized Energy Management (PEM) within a large multi-phase distribution feeder. Specifically, this work investigates the effects of different levels and rates of grid measurements for a practical-sized, 2,522-node, unbalanced distribution test feeder with a 3000 flexible kW-scale loads operating under the network-admissible PEM scheme. The results demonstrate the value of live grid measurements in managing distribution grid operational constraints while PEM is able to effectively deliver frequency regulation services.**

***Index Terms*—Demand dispatch, distribution grid, load management, distributed energy resources, voltage control.**

I. Introduction

The number, density, and diversity of behind-the-meter (BTM) distributed energy resources (DERs) and loads, such as thermostatically-controlled loads (TCLs), deferrable loads, and battery storage systems (BSS) are increasing in today's distribution systems. Via demand dispatch approaches, these connected DERs can be aggregated to provide different energy services at the bulk power level, while ensuring quality of service (QoS) for end users [1], [2]. However, existing demand dispatch schemes often focus on coordinating devices and managing end-user device constraints and overlook the distribution grid's operational constraints. To incorporate both end-user QoS and grid constraints, one could naively construct a large (NP-hard) grid-aware device scheduling problem that embeds the distribution grid optimal power flow (OPF) problem and whose solution represents an optimal device dispatch. However, such approach generally scales poorly with the number of controllable end-points and the non-convex AC power flow constraints of large distribution networks. Furthermore, such OPF-based demand dispatch methods, which can enforce grid constraints and customers' QoS, rely on accurate and idealized network parameters and load/renewable generation forecasts, and are typically solved at minutes to sub-hourly intervals, which may not sufficiently capture the high variability on system conditions (e.g., rapid voltage fluctuations) caused by the DERs nor fast market conditions (e.g., frequency regulation) [3].

Ensuring grid feasibility is crucial for any demand-side management (DSM) activities. In this context, the authors in [4] proposed congestion and voltage profile management by estimating the expected network profiles (voltage, power flow, etc.) and energy usage variations. To ensure grid feasibility of diverse DERs, the work in [5] uses multi-period optimization models to aggregate the active power flexibility by approximating the exact feasible region of the net power injection at the substation level with an inner-box region. In [6], authors propose node-wise computation of power injection and withdrawal limits using OPF-based models. Disaggregating the net flexibility as obtained in [5] to nodal level or estimating the nodal injection bounds that ensures grid feasibility could still render challenging optimization problems [7]. Therefore, in [8], [9], the authors developed a provable convex inner approximation of the feasible region that is able to disaggregate dispatch signals to nodal level that do not violate the grid constraints. Realising the uncertainty of incoming usage request of connected flexible loads, in [10] the authors developed a control formulation for handling plug-and-play charging requests of flexible loads in a distribution system and ensured grid feasibility through a convex formulation of the distribution grid model [11]. The grid feasibility can also be ensured through the estimation of DER and flexible load hosting capacity as in [12], [13]. In [14], [15], the grid feasibility is ensured through the design of local droop settings to control active/reactive power of DERs.

Given the high computational needs, the optimization based models are intended to provide bounds at coarse time scale (sub-hourly) that may not capture high variability on grid conditions due to intermittency of DERs. To ensure robustness in managing the grid constraints, particularly for forecasting uncertainties and high variabilities of DERs, the coarse time-step, optimization-based methods can be complemented by feedback obtained from the grid measurements/state estimators [16], [17]. That is, as the deployment of low-cost sensors at the grid-edge intensifies and are combined with existing real-time automatic controllers (RTAC) and micro-phasor measurement units (μ-PMU), it opens up new data-driven applications for feedback-based coordination of DERs in power distribution

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networks that respects constraints and network limits [18].

In this paper, we incorporate grid measurements (or estimates) with a recently-developed, bottom-up coordination scheme called packetized energy management (PEM), please see [19]. The combination of sensor measurements and coordination begets a novel grid-aware implementation of PEM. Unlike many other grid-aware coordination methods, the presented approach leverages the device-driven nature of PEM and employs 'traffic-light logic' with grid measurements and constraint violations to make real-time and local decisions about devices. At its core, PEM employs internet-like packet protocols to coordinate the energy consumption of TCLs by having each device asynchronously and probabilistically request a finite-duration, fixed-power energy packet based on its local need for energy (e.g., temperature within its deadband or its state of charge). The PEM coordinator then accepts or denies individual energy packet requests to regulate the aggregate load based on a desired reference. If the coordinator accepts more packet requests than packets that expire, then the aggregate demand increases. Otherwise, it decreases. However, to ensure that devices can meet local energy requirements, PEM also enables devices whose energy packet requests have been denied to temporarily opt-out of the scheme and consume energy, if it needs to do so to preserve the end-user's QoS. The opted out device returns to PEM once QoS has been restored (e.g., the temperature or SoC is returned strictly within deadband). Thus, we term PEM to be QoS-aware.

PEM has been developed recently and analyzed in a variety of settings. For example, PEM was initially been developed for electric water heaters and demonstrated a peak demand curtailment scenario [20], extended to consider bidirectional energy storage devices and diverse groups of DERs while providing synthetic balancing reserves [19], modeling and control [21]–[23], and characterization of demand flexibility under PEM [24], [25]. Recent work shows how the packet duration (or packet length) in PEM determines the speed of the closed-loop response and the type of grid-services PEM can provide. In particular, to effectively deliver frequency regulation, shorter packets lengths of 1-3 minutes are needed, but leads to more device on-off cycling (i.e., increased wear-and-tear) [26]. The probability-to-request in PEM determines the average number of request at the coordinator within a short time period, which represents that ability of the fleet to ramp up or down (depending on request types) and is related to the fleet's flexible capacity. This analysis has lead to the notion of randomized packet lengths, which have been shown to both improve the speed of response and reduce device cycling [26]. However, prior work on PEM has focused exclusively on grid-agnostic coordinator that effectively ignores the underlying distribution networks. As the density of devices increase in the medium/low-voltage networks, incorporating grid conditions and measurements will become important. Thus, in [27], we extended PEM by developing a 'Network-Admissible PEM', in which the grid operational constraints are respected in real time while delivering ancillary market services in the aggregate (and preserving end-user's QoS).

However, like in any measurement-based closed-loop voltage control of distribution feeders, the performance of 'Network-Admissible PEM' depends on the number of available measurements, frequency of the measurement update, and multi-phase measurement considerations. Note that placing sensors (e.g., μ-PMUs) on every node on the distribution circuits, and updating the measurements frequently incur high infrastructure costs and require extensive communication networks and bandwidth. Critically, this may not be necessary due to overall improvements in managing system-level constraints with a few additional grid measurements. Moreover, most of the works on voltage control with behind-the-meter assets focus on single-phase or phase decoupled circuits. Removal of mutual impedance from distribution circuits causes significant voltage error in the phase-decoupled models [28]. Specifically, the intra-phase dependency is not straightforward as active voltage control in one phase can worsen the voltage profiles on other phases [29]; hence, it necessities full three-phase voltage measurements for effective control of unbalanced distribution feeders. In this context, this work contributes as following,

- Building upon the Network-Admissible PEM [27], it provides practically-relevant, simulation-based analysis on the effects of the number, type, and sampling rate of grid measurement updates on the overall performance of the Network-Admissible PEM.
- Unlike the local voltage control schemes common in phase-decoupled circuits, this work considers phase-coupled unbalanced distribution grids in the Network-Admissible PEM and demonstrates the significance of intra-phase measurements on the effective voltage control of multi-phase distribution grids.

The remainder of the paper is structured as following. Section II provides preliminaries on PEM. Section III provides algorithmic description on the Network-Admissible PEM. Section IV discusses performance evaluation of Network-Admissible PEM using a 2522-bus unbalanced distribution system. Section V concludes the paper.

II. Packetized Energy Management Preliminaries

This section provides a summary of grid-agnostic PEM control logic at the device and coordinator layers.

A. Device Level PEM Logic

Consider device n with measured or estimated energy state over discrete time interval k of duration Δt, $x_n[k]$. This device is endowed with local control logic that relates the $x_n[k]$, its user-defined set-point x_n^{set}, and its comfort range, $[\underline{x}_n, \overline{x}_n]$, to a probability of making a request for a finite-duration, fixed-power energy packet to the coordinator (e.g., 5-minute, 4 kW or 0.33 kWh energy packet request). As an example, the probability that device n makes a request during interval Δt is illustrated in Fig. 1 via the following relation for a charging (i.e., power consumption) packet:

$$P_{\text{req}}(k) := 1 - e^{-m_R \mu_n (x_n[k]) \Delta t} \tag{1}$$

where m_R is the mean time-to-request (MTTR) when $x_n[k] = x_n^{\text{set}}$ and $\mu_n(x_n[k]) \geq 0$ is a state-dependent rate parameter given by,

$$\mu_n(x_n[k]) := \begin{cases} \frac{\overline{x}_n - x_n[k]}{x_n[k] - \underline{x}_n} \cdot \frac{x_n^{\text{set}} - \underline{x}_n}{\overline{x}_n - x_n^{\text{set}}} & \text{if } x_n[k] \in (\underline{x}_n, \overline{x}_n) \\ 0 & \text{if } x_n[k] \geq \overline{x}_n \end{cases}. \tag{2}$$

Discharging (i.e., power injection) packet request logic can be defined similarly and is also illustrated in Fig. 1. Thus, for a given local dynamic energy state (or a device's need for energy), the probability of making a request is defined. This probability is compared with an independent sample from uniform distribution to determine if a request is made from device n at time-step k.

If the request is made and accepted by the coordinator, the device switches from standby to a constant-power charging/discharging (consumes/supplies energy) state at the device's rated power level $\pm P_n^{\text{rate}}$. The constant power level is maintained for the duration of the packet length when the packet then *expires*, unless the packet is *interrupted* prematurely (to avoid exceeding the comfort range).

In addition, if a device's requests are repeatedly denied by the coordinator, the device's energy state may exceed its comfort range. Owing to the QoS-aware design of PEM, the device will then notify the coordinator that it is automatically *opting out* of PEM and will consume/supply the necessary energy to return the energy state to within its defined comfort range upon which the device updates the coordinator that it has returned to PEM mode. The use of packet-based (net) consumption and event-based device communications represents a novel, scalable approach for a centralized coordinator to estimate the aggregate demand without real-time power measurements from the entire fleet. Next, we define how packet requests are managed by the PEM coordinator to dynamically regulate aggregate (net) demand.

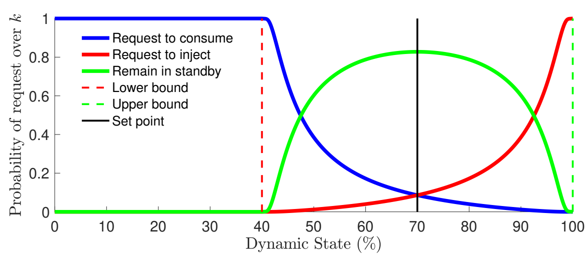

Fig. 1: Probability of a bidirectional device (e.g., ESS) requesting to the coordinator to either consume power (blue) or inject power (red) over a discrete-time interval k. If neither or both request types are made, then the device remains in standby (green). Clearly, for an electric water heater, there is no option to inject power, so device's packet request logic simplifies.

B. Coordinator Level PEM Logic

Due the asynchronous implementation of PEM, an energy packet request from any device can arrive at the coordinator at any time. This implies that over a sufficiently small time interval (e.g, 10ms, which can be different from device's interval Δt), it is reasonable to assume that the coordinator only receives a single device event. The event could be an incoming charging/discharging packet request, $u_{\text{c/d},n}[k] \in \{0,1\}$, which is either accepted or rejected (i.e., $y_{\text{c/d},n}[k] \in \{0,1\}$ with $y_{\text{c/d},n}[k] \leq u_{\text{c/d},n}[k]$). Besides packet requests, the coordinator can also receive event types related to previously accepted packets expiring ($y_{\text{c/d},n}^{\text{exp}}[k]=1$) or being interrupted ($y_{\text{c/d},n}^{\text{int}}[k]=1$) and devices opting out ($y_{\text{c/d},n}^{\text{opt}}[k]=1$). From the incoming stream of events, the coordinator can then construct an online estimate of the aggregate demand. For example, for a fleet of switch loads (i.e., with only charging packets and $P_n^{\text{rate}} > 0$), the aggregate demand at time-step k can be estimated as:

$$P_{\text{agg}}[k+1] := P_{\text{agg}}[k] + \sum_{n=1}^{N} P_n^{\text{rate}} \Delta y_{\text{c},n}[k], \tag{3}$$

where, $\Delta y_{\text{c},n}[k] := y_{\text{c},n}[k] - y_{\text{c},n}^{\text{exp}}[k] - y_{\text{c},n}^{\text{int}}[k] + y_{\text{c},n}^{\text{opt}}[k]$ and we assume that the time-step k is sufficiently small such that no more than a single device event takes place across the fleet (i.e., $\sum_{n=1}^{N} y_{\text{c},n}[k] + y_{\text{c},n}^{\text{exp}}[k] + y_{\text{c},n}^{\text{int}}[k] + y_{\text{c},n}^{\text{opt}}[k] \leq 1$ for all k). Clearly, the aggregate demand increases when packets are accepted or devices opt out and demand decreases when a packet expires or is interrupted. Note that the coordinator's only decision is whether to accept or reject a packet request (i.e., determine $y_{\text{c/d},n}[k]$), which is based on the difference between $P_{\text{agg}}[k]$ and a desired target reference power $P_{\text{ref}}[k]$.

This gives rise to the coordinator's control policy, whose objective is to minimize the tracking error $e[k] := P_{\text{ref}}[k] - P_{\text{agg}}[k]$ and is defined as follows for a fleet of switch loads:

$$y_{\text{c},n}[k] := \begin{cases} 1, & \text{if } u_{\text{c},n}[k] = 1 \ \wedge \ e[k] \geq P_n^{\text{rate}}/2 \\ 0, & \text{else} \end{cases} . \tag{4}$$

Generalizing the above to the case of coordinating a fleet with both charging and discharging requests is straightforward. For further details on modeling and control of a fleet under PEM, please see prior works [19], [22], [23], [26]. Note that the coordinator's control policy is similar to a relay controller that accepts a packet when the tracking error is above a threshold ("green light") and reject otherwise ("red light"). However, unlike traditional relay control from a single plant, the coordinator responds to asynchronous, stochastic requests from N plants, which permits accurate tracking.

The key contribution in this manuscript is to extend the coordinator's control policy in (4) to incorporate and understand the effect of distribution grid measurements into the packet acceptance/rejection logic. These measurements enable PEM to be cognizant of the network's nodal voltage and transformer apparent power limits and only accept packet request if they reduce tracking error **and** do not exacerbate any network violations, which gives rise to a *Network-Admissible PEM* and is described next.

III. Network-Admissible PEM

A. Overall Approach

The overall Network-Admissible PEM approach is illustrated in Fig. 2, where the PEM coordinator as in [19], [20] is integrated with a (grid) Constraint Coordinator. In regular PEM scheme, energy packet requests are made by the devices to the PEM coordinator, which are accepted or rejected by the coordinator in real time to track desired reference setpoints (as explained in Section II). The accepted requests are handled by the Constraint Coordinator in the next step, which checks the grid constraints based on live grid measurements to generate traffic-like logic to determine, in real time, whether packets requests are network admissible. The details of Network-Admissible PEM is provided in [27].

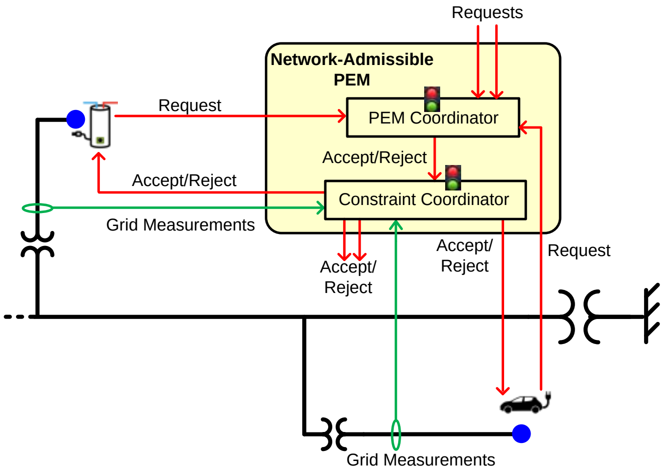

Fig. 2: Network-Admissible PEM-based demand dispatch scheme.

B. Multi-Phase Measurement Considerations

The local voltage control schemes in literature (e.g., [30]) use voltage measurements only from the controlled node. Refer to Fig. 3, where a local controller at node i_a (which is phase-a of three-phase bus i) takes the voltage measurements only from the same node, i.e., V_{i_a}, while the voltage measurements of other two phases of the same bus, i.e., V_{i_b} and V_{i_c} are not used. Such voltage control schemes are applied to three-phase unbalanced feeders with strong assumption that improvement in voltage performance on one phase of a multi-phase bus does not worsen the voltage profile of other phases of the same bus. The assumption would be that a load of I_{i_a} causes voltage drop on all three phases of the bus i with respect to bus j, i.e., $|V_{i_a}| \leq |V_{j_a}|$, $|V_{i_b}| \leq |V_{j_b}|$, and $|V_{i_c}| \leq |V_{j_c}|$. However, a closer look at voltage drop model in three-phase circuit suggests that the mutual coupling among phases may impact the voltages of other phases differently. The voltages on two ends (bus j and i) of three-phase distribution feeder with a load of I_{i_a} can be modelled as,

$$\begin{bmatrix} V_{i_a} \\ V_{i_b} \\ V_{i_c} \end{bmatrix} = \begin{bmatrix} V_{j_a} \\ V_{j_b} \\ V_{j_c} \end{bmatrix} - \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_{i_a} \\ 0 \\ 0 \end{bmatrix}. \quad (5)$$

The phasor diagram in Fig. 3 shows that the load of I_{i_a} can lead to voltage rise on node i_b (with respect to node j_b), i.e., $|V_{i_b}| \geq |V_{j_b}|$ due to mutual coupling of the phases. We can arrive at similar observations if loads are connected at nodes i_b or i_c. This clearly indicates that a local control scheme that improves voltage on one phase can negatively impact the voltages on other phases of the same bus. Therefore, for any measurement based control approach, voltage measurements of other phases of the same bus is required for effective voltage management of a single phase node. Therefore, in the proposed Network-Admissible PEM scheme, we consider intra-phase measurements in the Constraint Coordinator (see Fig. 2).

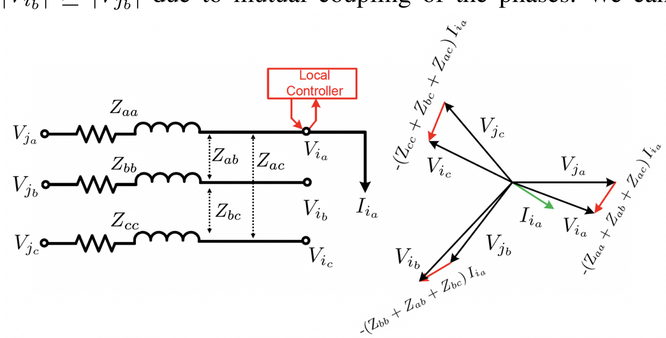

Fig. 3: Equivalent circuit and voltage drop model of three-phase unbalanced distribution feeder.

C. Network-Admissible PEM Algorithm

Consider i_p represents index for a single phase node at bus i, i_{p+} represents all phases of the same bus where node i is connected to, and $M[i_p] \in \{0,1\}$ is a parameter that represents if voltage at node i_p is measured or not. $\underline{V}[i_p]$ and $\overline{V}[i_p]$ are the prescribed minimum and maximum voltage magnitude bounds. Based on the overall approach shown in Fig. 2 and the multi-phase voltage measurement consideration as described earlier, we build the proposed Network-Admissible PEM algorithm as shown in Algorithm 1. Note that Algorithm 1 is provided with respect to charging packet requests only; however, similar logic can be readily developed for discharging packet request in the Network-Admissible PEM.

Algorithm 1 : Network-Admissible PEM

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Incoming Packet Request u_{c,n}[i_p, k]
if ¬(u_{c,n}[k] = 1 ∧ e[k] ≥ P_n^rate/2) then    ▷ Refer to (4).
    Reject Packet: y_{c,n}[i_p, k]=0.
else                                              ▷ Grid Constraint Management.
    if M[i_p] = 1 then                            ▷ Node i_p is measured.
        if V_lower[i_{p+}] ≤ |V[i_{p+}, k]| ≤ V_upper[i_{p+}] then
            Accept Packet: y_{c,n}[i_p, k]=1.
        else                                      ▷ Voltage violation.
            Reject Packet: y_{c,n}[i_p, k]=0.
        end if
    else
        Accept Packet: y_{c,n}[i_p, k]=1.
    end if
end if
```

IV. Numerical Simulation

In this section, we study the impact of varying PEM packet length (P_t) and grid voltage measurement update rate (S_t) on the Network-Admissible PEM scheme. We also evaluate the performance of Network-Admissible PEM scheme with single-phase versus multi-phase voltage measurements. Additionally, we study the impact of the number of voltage measurements on the performance of Network-Admissible PEM scheme.

A. Simulation Setup

A 2522-bus (3,817 single-phase nodes) test system as shown in Fig. 4, which is extracted from MV-side of the IEEE 8500-node test feeder [31], is used for numerical case studies. The test system has total of 1,413 single-phase load nodes, where TCLs and ESSs devices are connected and are controlled through Network-Admissible PEM scheme. Total of 3,000 PEM controlled devices (2,100 TCLs and 900 ESS) are connected to the load nodes. Each load has up to three PEM devices (TCL or ESS), and each device has $P_n^{\text{rate}} = \pm 5$kW.

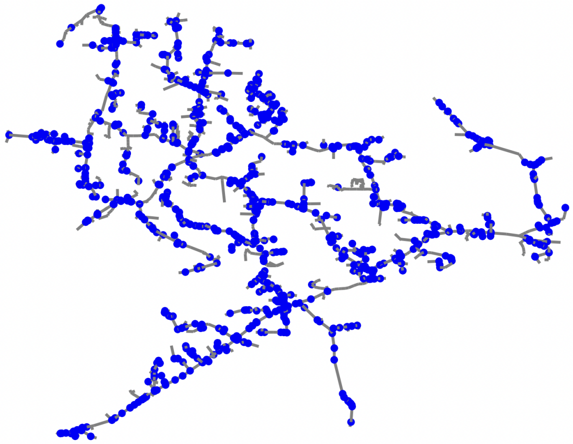

Fig. 4: A 2522-bus test feeder, modified from the original IEEE 8,500-node feeder, with 3,000 TCL and ESS devices.

Different packet lengths are used in the simulation and MTTR is kept same as the packet length. The simulations are run for 1 hour with time step of 2 seconds (i.e., 1,800 time steps).

B. Performance Metrics

We adopt the following metrics to evaluate the performance of the Network-Admissible PEM.

Composite Performance Score (x_c): This score is used in industry by system operator PJM and measures the overall performance of a grid resource to regulate to the AGC reference signal. The performance score is the average of three distinct scores namely, accuracy, delay, and precision scores. For details on scores, please see e [26].

Voltage Violation Metrics: At the system level, we propose to use the following three voltage violation metrics. Please see [27] for more details on these grid violation metrics.

- **Maximum Duration of Contiguous Voltage Violation** (D_m): This metric looks at any node on distribution feeder that exhibits the longest duration of voltage violation, i.e., $\big|V[i_p,k]\big| \geq \overline{V[i_p]} \vee \big|V[i_p,k]\big| \leq \underline{V[i_p]}$.
- **Maximum Cumulative Duration of Voltage Violations** (D_t): Since there exists multiple instances of continuous voltage violation on distribution feeders, D_m alone is not sufficient to capture the temporal distribution of voltage violation. Thus, we propose to use D_t that is the maximum of the cumulative duration of nodal voltage violation.
- **Maximum Area under the Voltage Violation** (A_m): Metrics D_m and D_t defined above only capture the duration of voltage violation; however, these metrics are not able to capture the magnitude of voltage violations. Therefore, we propose to use maximum of cumulative area under the nodal voltage violation function (i.e., area under the voltages above or below the thresholds).

C. Performance Evaluation

The combined impact of varying packet lengths P_t and grid measurement update rate S_t on the performance metrics are analysed next. To obtain average performance metrics, each case is run 200 times that ensures randomness in the packet requests from TCLs and ESSs. Nodal voltage measurement update rate S_t is varied between 2 seconds, 30 seconds, 2 minutes, and 5 minutes for each of the packet length P_t of 30 seconds, 2 minutes, and 5 minutes.

Fig. 5 presents a sample case (one out of 200 runs) in tracking a real AGC signal with varying packet lengths with S_t =2 seconds. As we can see from the Figure, with the 30-second packet length the tracking performance is superior, which degrades gradually with 2-minute and 5-minute packet lengths. Fig. 6 shows another sample case in tracking AGC by varying measurement update rates (with $P_t = 5$ minutes). As we can see from the Figure, tracking starts deteriorating as S_t is increased gradually from 2 seconds to 5 minutes.

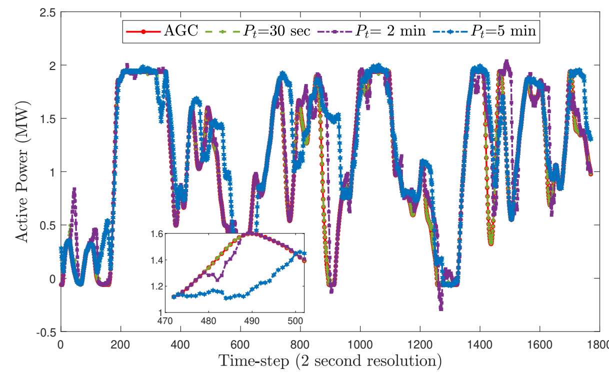

Fig. 5: Impact of packet length P_t on tracking performance of Network-Admissible PEM with $S_t = 2$ seconds.

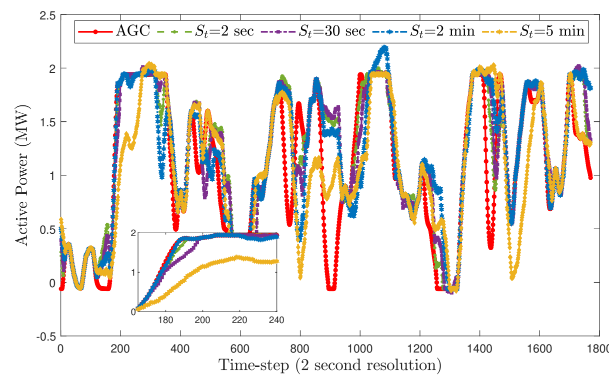

Fig. 6: Impact of measurement update rate S_t on tracking performance of Network-Admissible PEM with $P_t = 5$ minutes.

The impact of S_t on system-wide voltage performance is shown in Fig. 7 for the sample case of Fig. 6. The simulation comprises of 6,870,600 instances of voltage that correspond to 1,800 time steps simulation (1 hour) of 3,817 single-phase nodes of the test feeder. For $S_t = 2$ seconds, 130 nodes (5,405 voltage instances) experienced voltage over 1.05 p.u. As S_t is increased to 30 seconds and 2 minutes, the overvoltage instances increased. With $S_t = 5$ minutes, the total nodes with overvoltage increased to 483 (with 62,584 voltage instances).

Fig. 8 (a) shows comparison of the maximum duration of continuous voltage violation (D_m), which is averaged over 200 runs for each value of P_t and S_t. For each packet length, as we increase S_t, the duration D_m increases. For example, with $P_t = 30$ seconds, D_m varies from 18 seconds to 240 seconds

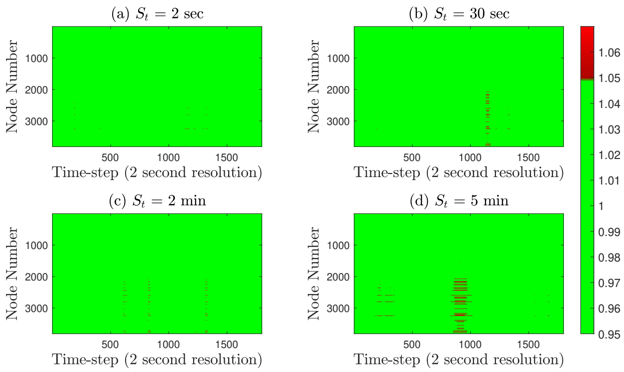

Fig. 7: System-wide voltage violation on the distribution feeder with varying level of measurement update rate S_t.

(out of 3,600 seconds of simulation) by varying S_t. With a coarse P_t (5 minutes), and measurement update rate of $S_t = 5$ minutes, D_m is 372 seconds, which is about 10% of total simulation duration and is significant overvoltage duration. We observed similar trend on maximum cumulative duration of voltage violation metric (D_t) (see Fig. 8 (b)) and the area under the voltage violation metric (A_m) (see Fig. 8 (c)). We observed from the case studies that both packet length (P_t) and measurement update rate (S_t) impact the voltage performance metrics considerably.

Fig. 8 (d) shows the composite score (x_c) in tracking the sample AGC signal. Value of x_c degrades as P_t and S_t are increased. However, the tracking performance is more dependent on the choice of P_t, and less impacted by S_t for a given value of P_t. Though it is preferred to use finer packet length for improved x_c, a packet length of $P_t = 2$ minutes in the Network-Admissible PEM schemes provided acceptable composite score and voltage performance metrics. This observation on composite score corroborates with the findings in previous work with PEM scheme (without grid constraints) [26]. Though x_c has acceptable value even with $P_t = 5$ minutes, this is not advisable from voltage performance point of view. However, if we compliment the coarse packet length with faster grid measurement update rate (e.g., $P_t = 5$ minutes and $S_t = 2$ seconds) we can achieve acceptable voltage performance. Similarly, if PEM uses fine packet length (e.g., $P_t = 30$ seconds), the grid measurements can be updated at slower rate for an acceptable voltage performance.

D. *Impact of Number of Voltage Measurement Buses*

The number of voltage measurement buses are changed from 0% (no measurements) to 100% (i.e., all buses with TCLs and ESSs) at a step of 20%. The impact of the number of measurement on the performance metrics is shown in Fig. 9 with $P_t = 5$ minutes and $S_t = 2$ seconds for varying number of measurement buses. With no voltage measurement (i.e., equivalent to regular PEM schemes as in [19], [20]), D_m is 374 seconds (out of 3,600 seconds of simulation), which is significant voltage violation, and reduces to 58 seconds when the grid is fully measured (at TCL and ESS locations). We observed similar trend on D_t and A_m metrics. However, the composite score x_c in tracking AGC almost remained the same with the number of grid measurements.

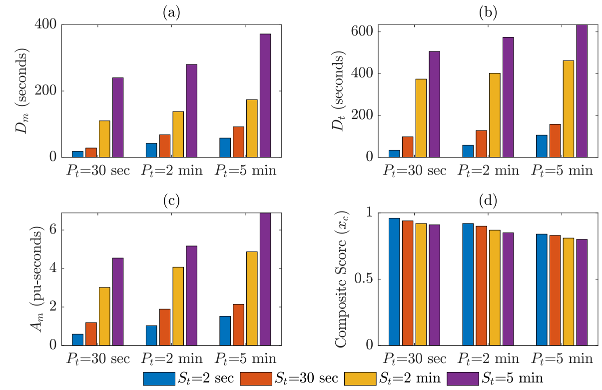

Fig. 8: Voltage violation metrics (D_m, D_t, and A_m) and composite performance score (x_c) for different values of packet length (P_t) and measurement update rate (S_t).

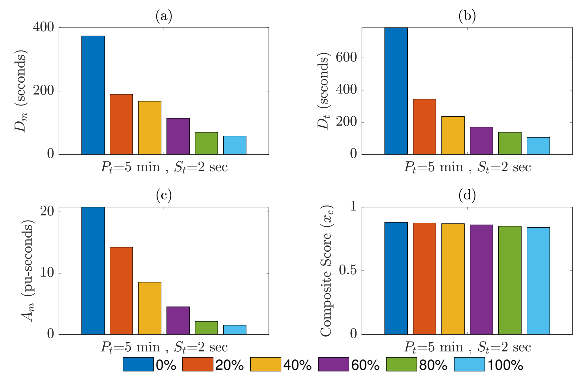

Fig. 9: Voltage violation metrics (D_m, D_t, and A_m) and composite performance score (x_c) for different number of voltage measurement buses.

E. *Impact of Multi-Phase Measurements*

As emphasized in section III B, this work evaluates significance of intra-phase voltage measurements on the effective voltage control on single-phase nodes of multi-phase unbalanced feeders. To do so, we have simulated cases with voltage measurements obtained only from the node where PEM devices are connected and compared with multi-phase voltage measurement consideration. The results in Fig. 10 shows the comparison of performance metrics with $P_t = 2$ minutes and $S_t = 2$ seconds. Figure shows that all voltage violation metrics

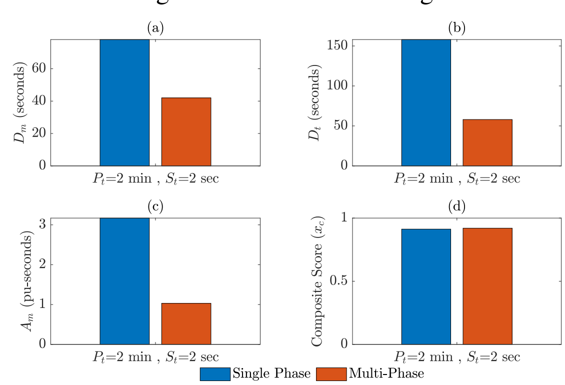

Fig. 10: a) Voltage violation metrics (D_m, D_t, and A_m) and composite performance score (x_c) for single-phase vs. multi-phase voltage measurements.

are significantly improved when multi-phase measurements are considered. However, like in the other cases, the voltage measurement did not considerably impact the composite score x_c in tracking the reference AGC signal. This case study clearly shows that the single-phase measurement based local voltage control approach as in [30] is not effective in managing voltages in three-phase unbalanced systems due to the phase coupling effect, whereas intra-phase measurements can ensure better voltage performance in multi-phase distribution feeders.

V. Conclusion

This paper provided comprehensive performance evaluation of a Network-Admissible demand dispatch algorithm in maintaining grid voltages and tracking reference (e.g., AGC signals). The Network-Admissible demand dispatch represents a generalization of PEM scheme by incorporating new grid constraint management algorithm. This work demonstrated the impact of packet length (in PEM), grid voltage measurement update rate, the number of voltage measurement buses, and multi-phase measurements in managing the grid voltages and in tracking the power reference signal. Based on the simulation-based analysis carried out in a 2522-bus three-phase unbalanced distribution feeder, we observed that a) the tracking performance is less dependent on grid measurements and is more dependent on the packet length, b) voltage performance depends on both grid measurements and packet length, c) coarse packet length if complemented by fast grid measurement update rate can provide acceptable voltage performance, and d) multi-phase measurements are essential for effective voltage control of multi-phase distribution feeders. Future work will leverage OPF-based methods to derive time-varying nodal supply/demand capacity limits, which can reduce the number of measurements required.

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