Grid-Forming Control Design of Dynamic Virtual Power Plants

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Abstract: We present a novel grid-forming control design approach for dynamic virtual power plants. We consider a group of heterogeneous grid-forming distributed energy resources which collectively provide desired dynamic ancillary services such as fast frequency and voltage control. To achieve that, we employ an adaptive divide-and-conquer strategy which disaggregates the desired control specifications of the aggregate DVPP via adaptive dynamic participation factors to obtain local desired behaviors of each device. We then employ local controls to realize these desired behaviors. In the process, we ensure that local device limitations are taken into account. Finally, the control performance is verified via simulations on a power system testbed.

1. INTRODUCTION

We consider the recently emerged concept of dynamic virtual power plants (DVPPs), where heterogeneous distributed energy resources (DERs) are aggregated to collectively provide desired dynamic ancillary services such as fast frequency and voltage control. All of the existing control design methods for DVPPs are predominantly based on grid-following device aggregations. In this case, frequency and voltage are measured (via an explicit synchronization scheme, e.g., a phase-locked-loop (PLL)) and treated as inputs for the devices, such that their modified active and reactive power outputs sum up to the aggregated power output of the DVPP (Häberle et al. (2021); Björk et al. (2021); Zhong et al. (2021)). However, because of their dependency on the measured frequency, grid-following DVPP control setups require a stiff grid to operate. Namely, their responsiveness and PLL tracking performance can deteriorate or even result in instability when the DVPPs are integrated into weak grids with low short-circuit ratio (Wen et al. (2015)). To resolve this issue, grid-forming devices are envisioned to construct more reliable DVPP configurations which establish an independent voltage and frequency (Matevosyan et al. (2019)) while providing dynamic grid support. To the best of our knowledge, a grid-forming control design approach for DVPPs is not available in literature so far.

In this paper, we present a grid-forming control design approach for DVPPs that enables desired frequency and voltage control services on fast timescales in an aggregated fashion. Inspired by our recent grid-following DVPP control proposal (Häberle et al. (2021)), we resort to an adaptive divide-and-conquer strategy which disaggregates the desired control specifications of the aggregate DVPP via adaptive dynamic participation factors to obtain local behaviors of each device. In the following, we discuss the proposed grid-forming control strategy and demonstrate it via simulations on a power system testbed.

2. GRID-FORMING DVPP CONTROL SETUP

We consider a grid-forming DVPP as a collection of heterogeneous grid-forming DERs. We assume that all DVPP devices are connected in parallel at the same bus of the transmission grid (Fig. 1, left), which we refer to as the point of coupling (POC). While being connected at one bus, it is essential to ensure a sufficiently large electrical distance (e.g., via transformers or interconnection cables) between the grid-forming devices, since they operate as voltage sources connected in parallel, hence, cannot simultaneously impose different voltages at the POC.

We consider a desired aggregate DVPP behavior at the POC for a decoupled frequency and voltage control, specified as a diagonal MIMO transfer matrix as (Fig. 1, right)

\[
\begin{bmatrix}
\Delta f_{poc}(s) \\
\Delta v_{poc}(s)
\end{bmatrix} = \begin{bmatrix}
T_{pf}^{des}(s) & 0 \\
0 & T_{pv}^{des}(s)
\end{bmatrix} \begin{bmatrix}
\Delta p_{poc}(s) \\
\Delta q_{poc}(s)
\end{bmatrix},
\]

where \(\Delta p_{poc}\) and \(\Delta q_{poc}\) are the measured active and reactive power injection changes at the POC, respectively (deviating from the respective power setpoint). Further, \(\Delta f_{poc}\) and \(\Delta v_{poc}\) denote the imposed frequency and voltage magnitude deviation at the POC, respectively. Note that the decoupled p-f and q-v controls are specified to compensate for ancillary services conventionally provided by synchronous generators in transmission networks. It is assumed that \(T_{des}\) is provided by the power system operator and reasonably specified so that its collective realization is feasible for the devices while rendering the closed-loop power system stable (e.g., virtual inertia and droop control; see (15) later). Finally, we assume that

![Fig. 1. Sketch of a DVPP connected at the POC and a desired dynamic behavior \(T_{des}(s)\) at the POC.](image-url)
where in Fig. 2 are described by the linearized power flow equations. The overall interconnected dynamics of the system (Jiang et al. (2021); Min and Mallada (2019)) inductive and tightly connected DVPP interconnection loop transfer functions. To derive the aggregated frequency response of the DVPP, we consider the coherent (synchronized) response for an inductive and tightly connected DVPP interconnection network as (Ishizaki et al. (2018); Dörfler and Bullo (2012)) of the parallel device interconnection in Fig. 1 to eliminate the algebraic constraints of the POC as shown in Fig. 3. In this regard, the input signals ∆pf,i in Fig. 2 represent the local active power injection disturbances at each DVPP device. The output signals ∆fi represent the local frequency deviations of the DVPP devices from its nominal value. The dynamics of the DVPP devices that map the local active power deviation output ∆poc to the local frequency deviations ∆fi are described by the local closed-loop transfer functions Tpf(s). Assuming constant voltage magnitudes, the active power fluctuations ∆poc,i of the inductive DVPP interconnection lines are approximated by the linearized power flow equations

\[ \Delta p_{oc}(s) = L_{dvpp} \Delta f(s), \]  

where \( L_{dvpp} \) is an undirected weighted Laplacian matrix of the Kron-reduced DVPP interconnection network (Fig. 3, right). The overall interconnected dynamics of the system in Fig. 2 are described by

\[ \Delta f(s) = (I + \text{diag}(T_{pf1}(s)) L_{dvpp}^{-1})^{-1} \text{diag}(T_{pf}(s)) \Delta p_{oc}(s). \]  

To derive the aggregated frequency response of the DVPP, we consider the coherent (synchronized) response for an inductive and tightly connected DVPP interconnection network as (Jiang et al. (2021); Min and Mallada (2019))

\[ \Delta f(s) = \left( \sum_{i=1}^{n} T_{pf1}(s) \right)^{-1} \|_n \|_n^\top \Delta p_{oc}(s), \]  

where \( \| \) is the vector of all ones. The ideal synchronized frequency dynamics at the POC can be approximated as

\[ \Delta f_{poc} = \left( \sum_{i=1}^{n} T_{pf1}(s)^{-1} \right)^{-1} \sum_{i=1}^{n} \Delta p_{di}, \]  

where \( \sum_{i=1}^{n} \Delta p_{di} \approx \Delta p_{poc} \), assuming the DVPP interconnection lines to be mainly inductive. Thus, the DVPP aggregation condition for frequency control is obtained as

\[ \left( \sum_{i=1}^{n} T_{pf1}(s)^{-1} \right)^{-1} \approx T_{pf}(s). \]  

From the aggregation condition in (6), it can be concluded that the DVPP specification \( T_{pf}^{agg} \) has to be satisfied only during synchronized conditions of the devices’ frequencies.

### 2.2 Voltage Control Architecture

In contrast to the DVPP frequency control setup, we cannot establish an analogous DVPP setup for voltage control, as the local voltage magnitudes do not naturally yield a coherent dynamic behavior. We therefore consider the voltage control setup as in Fig. 4, where all devices receive an identical input measurement, i.e., the voltage magnitude deviation \( \Delta v_{poc} \). The reactive power deviation output of each device, namely \( \Delta q_i \), sums up to the aggregate reactive power deviation output of the DVPP, namely \( \Delta q_{agg} \), i.e.,

\[ \Delta q_{agg} = \sum_{i=1}^{n} \Delta q_i. \]  

Considering the local closed-loop transfer functions \( T_{q1}^{agg}(s) \), the aggregate DVPP behavior is given by

\[ \Delta q_{agg}(s) = -\sum_{i=1}^{n} T_{q1}(s) \Delta v_{poc}(s). \]  

By approximating \( \Delta q_{poc} \approx -\Delta q_{agg} \), we can derive the DVPP aggregation condition for voltage control as

\[ \sum_{i=1}^{n} T_{q1}^{agg}(s) \approx T_{q1}^{agg}(s)^{-1}. \]  

Note that the aggregation condition in (9) requires \( T_{q1}^{agg} \) to be invertible. Otherwise, (e.g., because of unstable zeros, etc.), one might either resort to a causal and stable approximation of \( T_{q1}^{agg}^{-1} \), or alternatively (by switching inputs and outputs) consider an aggregate DVPP specification at the POC from voltage to reactive power as

\[ \Delta q_{poc}(s) = T_{q1}^{agg}(s) \Delta v_{poc}(s). \]  

Instead of the specification in (1).

Finally, given \( T_{des} \), the overall DVPP control design problem is to find local device-level controllers, such that the two aggregation conditions in (6) and (9) are satisfied. Furthermore, it is important to ensure that practical device limitations are not exceeded during normal operation.

The accuracy of this approximation depends on whether \( \Delta q_i \) is measured before or after the inductive transformer of each device. A solution to overcome this issue is proposed in Section 3.3.
3. ADAPTIVE DIVIDE-AND-CONQUER STRATEGY

3.1 Disaggregation of \( T_{\text{des}} \)

Given the aggregation conditions in (6) and (9), we disaggregate the desired MIMO transfer matrix \( T_{\text{des}} \) as

\[
T_{\text{des}}(s)^{-1} = \sum_{i=1}^{n} m_i^{\text{pf}}(s) s T_{\text{des}}(s)^{-1} - \sum_{i=1}^{n} m_i^{\text{qv}}(s) s T_{\text{des}}(s)^{-1},
\]

where the transfer functions \( m_i^{\text{pf}} \) and \( m_i^{\text{qv}} \) are adaptive dynamic participation factors (ADPFs), required to satisfy the participation condition

\[
\sum_{i=1}^{n} m_i^{\text{pf}}(s) = 1 \quad \text{and} \quad \sum_{i=1}^{n} m_i^{\text{qv}}(s) = 1. \tag{12}
\]

ADPF Selection: The ADPFs of the DVPP devices are selected such that the participation condition (12) is satisfied, while simultaneously respecting the heterogeneous time scales of local device dynamics as well as steady-state power capacity limitations. We thus specify the ADPFs by two parameters (see H¨aberle et al. (2021) for details): a time constant \( \tau_i^{\text{pf}} \) (or \( \tau_i^{\text{qv}} \)) for the roll-off frequency to account for different time scales of local active (or reactive) power injection dynamics, and a DC gain \( \mu_i^{\text{pf}} \) (or \( \mu_i^{\text{qv}} \)) to account for active (or reactive) device power capacity limits during steady state, similar to droop gains in traditional power systems. Based on these two parameters, we divide the ADPFs into three categories, i.e., we envision

- a low-pass filter (LPF) participation factor for devices that can provide regulation on slow time scales including steady-state contributions,
- a high-pass filter (HPF) participation factor for devices able to provide regulation on fast time scales,
- a band-pass filter (BPF) participation factor for devices able to cover the intermediate regime.

The ADPFs with a BPF or HPF behavior will always have a zero DC gain by definition. In contrast, for all devices participating as a LPF, the LPF DC gains have to satisfy

\[
\sum_{i=1}^{n} m_i^{\text{pf}}(s = 0) = 1, \quad \sum_{i=1}^{n} m_i^{\text{qv}}(s = 0) = 1 \tag{13}
\]

To meet the participation conditions in (12).

3.2 Online Adaptation of LPF DC Gains

We specify the LPF DC gains \( \mu_i^{\text{pf}} \) (or \( \mu_i^{\text{qv}} \)) such that they can be adapted online, in proportion to the power capacity limits of the devices. The latter might be time-varying based on the resource availability (e.g., weather conditions). During power system operation, the DC gains are updated in a centralized fashion where the DVPP operator continuously collects the capacity limits of the devices and communicates back the appropriate DC gains. If a distributed implementation is desired, one could alternatively use a consensus algorithm via peer-to-peer communication (see H¨aberle et al. (2021) for details).

3.3 Local Model Matching

Finally, we need to find local feedback controls for the DVPP devices to ensure their closed-loop transfer matrices \( T_i^{\text{pf}} \) and \( T_i^{\text{qv}} \) match their desired behaviors, i.e.,

\[
T_i^{\text{pf}}(s)^{-1} = m_i^{\text{pf}}(s) T_{\text{des}}(s)^{-1}, \quad T_i^{\text{qv}}(s)^{-1} = m_i^{\text{qv}}(s) T_{\text{des}}(s)^{-1}. \tag{14}
\]

4. TEST CASE

We perform an electromagnetic transients simulation using Simscape Electrical in MATLAB/Simulink to verify the performance of the grid-forming DVPP controls in the IEEE 9-bus system, using nonlinear network and device models. We investigate a DVPP consisting of a wind power plant, a PV system, and a STATCOM with supercapacitors (Fig. 5) that replaces the fast frequency and voltage control of a thermal-based generator. Further, we exploit the complementary nature of wind and solar energy to compensate their fluctuations via online adaptation of the ADPFs, while not affecting the overall DVPP response.

4.1 Converter Model and Control Architecture

We consider a uniform converter system topology for all DVPP devices as in Fig. 6. The employed converter model represents an aggregation of multiple commercial converter modules, and is based on a state-of-the-art cascaded control scheme, which receives the angle and voltage reference from the local DVPP controls to satisfy the matching conditions in (14). We model the primary energy sources by a generic controllable dc current source with delayed response time to account for resource dynamics, communication, or actuation delays (Tayyebi et al. (2020)).

As indicated in Fig. 6, there are different options for measuring the local active and reactive powers. Depending on the application, a measurement either before (option A) or after (option B) the LV/MV transformer might be desired. In the first case, an additional affine control term \( q_{\text{loss}} \) is added to the local DVPP \( q \cdot v \) control, thus accounting for the reactive losses dominantly associated with the
transformer impedance. The active power difference at the two measurement points is assumed to be negligible. In what follows, we resort to option B.

4.2 Numerical Case Studies

We specify a p-f and q-v control for the DVPP in Fig. 5 as

\[
\begin{bmatrix}
\Delta f_{\text{poc}}(s) \\
\Delta v_{\text{poc}}(s)
\end{bmatrix} = T_{\text{des}}(s) \begin{bmatrix}
\Delta f_{\text{poc}}(s) \\
\Delta v_{\text{poc}}(s)
\end{bmatrix},
\]

where \( H_p \) and \( D_p \) are the normalized virtual inertia and droop coefficients for the p-f control, and \( D_s \) is a high gain droop for the q-v control. The magnitude Bode plots of the ADPFs for the wind, PV and STATCOM (st) during nominal power capacity conditions are shown on the left of Fig. 7, where the active power injection bandwidth of each device is selected according to the dc time-constant \( \tau_{\text{dc},f} \) of the associated converter-model in Fig. 6.

We first simulate a 21 MW load increase at bus 2 and investigate the POC’s frequency and voltage response during nominal power capacity conditions. The wind and PV are operated under deloaded conditions with respect to their maximum power point. Based on the left of Fig. 8, it is apparent how the aggregate DVPP accomplishes an accurate matching of the desired frequency and voltage dynamics at the POC (dashed lines).

To investigate the online adaptability of the ADPFs towards time-varying capacity fluctuations of weather-driven DERs, we simulate a sudden decrease of the wind active power capacity limit. This causes a change in the wind active power setpoint, thereby inducing an equivalent active power generation deficiency of 21 MW as during the previous load increase at bus 2. Apparently, by comparing the aggregate DVPP response during the local wind generation decrease (right of Fig. 8) with the aggregate DVPP response during the load increase causing an equal generation deficiency at bus 2 (left of Fig. 8), we can see how the overall DVPP response behavior remains nearly unaffected. In particular, the PV and STATCOM ADPFs are adapted online to compensate of the missing DVPP control provided by the wind power plant (see magnitude Bode plots on the right of Fig. 7 in comparison to the magnitude Bode plots on the left of Fig. 7.)

5. CONCLUSION

We have proposed a novel grid-forming control design approach for DVPPs, with the objective to provide dynamic ancillary services such as fast frequency and voltage control in an aggregated fashion. We have discussed the adaptive divide-and-conquer strategy that takes into account the individual device characteristics, and can additionally handle temporal variability of weather-driven DERs. We proved the successful performance of our controls via simulations on a power system testbed.

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