

Accurate Reduced-Order Models for Heterogeneous Coherent Generators

Hancheng Min¹, Fernando Paganini², *Fellow, IEEE*, and Enrique Mallada¹, *Senior Member, IEEE*

Abstract—We introduce a novel framework to approximate the aggregate frequency dynamics of coherent generators. By leveraging recent results on dynamics concentration of tightly connected networks, and frequency weighted balanced truncation, a hierarchy of reduced-order models is developed. This hierarchy provides increasing accuracy in the approximation of the aggregate system response, outperforming existing aggregation techniques.

I. INTRODUCTION

Assessing the performance of power grid frequency control requires models which are both accurate and tractable. In large-scale networks, this goal has been sought for decades through *aggregation* based on *coherency* [1]. Generally speaking, a group of generators is considered coherent if their bus frequencies exhibit a similar response when subject to power disturbances. These generators are often subsequently modeled by a single effective machine.

Various methods for identifying coherent groups of generators have been introduced in the past [2]–[6]. The Linear Simulation Method [7] groups generators whose maximum difference in time-domain response is within some tolerance. Similarly, [3] develops a clustering algorithm based on the pairwise maximum difference in time-domain response. The Weak Coupling Method [6] quantifies the strength of coupling between two areas to iteratively determine the boundaries of coherent generator groups. The Two Time Scale Method [4], [5] computes the eigen-basis matrix associated with the electromechanical modes in the linearized network: generators with similar entries on the basis matrix with respect to low frequency oscillatory modes are considered coherent.

Once generators are grouped by coherence, an effective machine model is typically proposed for each group. Previous work [8]–[13] suggests that inertial and damping coefficients for the effective generator should be chosen as the sum of the corresponding generator parameters. However, in the presence of turbine control dynamics, the proper choice of turbine time constants is unclear. Optimization-based approaches [9], [10] minimize an error function to choose the time constant of the effective generator. Other approaches use the average [11], or the weighted harmonic

mean [12] of time constants of generators in the coherent group.

Accurate models of the coherent dynamics are applicable to the modeling of area dynamics [12], optimization of DER participation [10], and frequency shaping control [14]. Moreover, new modeling demands arise in modern-day networks where coherent groups may include grid-forming inverters [15], [16] in addition to classical synchronous generators.

In this paper, we leverage new results [17] on characterizing coherence in tightly-connected networks to propose a general framework for aggregation of coherent generators. For n coherent generators with transfer function $g_i(s)$, $i = 1, \dots, n$, the aggregate coherent dynamics are accurately approximated by $\hat{g}(s) = (\sum_{i=1}^n g_i^{-1}(s))^{-1}$. In particular, we show that $\hat{g}(s)$ is a natural characterization of the coherent dynamics in the sense that, as the algebraic connectivity of the network increases, the response of the coherent group is asymptotically $\hat{g}(s)$. Note, however, that in the general case where turbines have heterogeneous dynamics, the aggregate transfer function $\hat{g}(s)$ will be of an order which scales with the network size. We thus seek a low-order approximation.

In contrast with the conventional approach [9], [10], [12] we will not restrict the choice of low order models to the simple selection of parameters of an effective generator. Rather, we will resort to *frequency weighted balanced truncation* to develop a hierarchy of models of adjustable order and increasing accuracy. In particular, for an aggregation of n second order generator models, we find that high accuracy can often be achieved by reducing the $(n+1)$ -th order system to a 3rd order one. We note, however, that the aggregation techniques introduced in this paper apply to any linear model of generators, including those of higher order.

We further compare two alternatives: providing an aggregate model for a set of turbines, and subsequently closing the loop, versus performing the reduction directly on the closed loop $\hat{g}(s)$. The first is motivated by retaining the interpretation whereby the aggregate is represented by one or two equivalent turbines; nonetheless, we show how a similar interpretation may be available for the second, more accurate method.

The rest of the paper is organized as follows. In Section II, we provide the theoretical justification of the coherent dynamics $\hat{g}(s)$. In Section III, we propose reduced-order models for $\hat{g}(s)$ by frequency weighted balanced truncation. We then show via numerical illustrations that the proposed models can achieve accurate approximation (Section IV). Lastly, we conclude this paper with more discussions on the implications of our current results. A preliminary one-and-half page abstract of this work was presented in [18].

¹H. Min and E. Mallada are with the Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, MD 21218, USA {hanchmin, mallada}@jhu.edu.

²F. Paganini is with Universidad ORT Uruguay, Montevideo, Uruguay paganini@ort.edu.uy.

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II. AGGREGATE DYNAMICS OF COHERENT GENERATORS

Consider a group of n generators, indexed by $i = 1, \dots, n$ and dynamically coupled through an AC network. Assuming the network is in steady-state, Fig.1 shows the block diagram of the linearized system around its operating point.

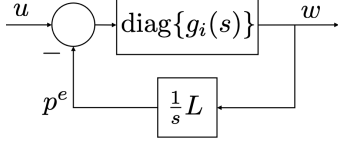


Fig. 1. Block Diagram of a Linearized Power Network.

Due to space constraints, we refer to [19] for details on the linearization procedure. The signals $w = [w_1, \dots, w_n]^T$, $u = [u_1, \dots, u_n]^T$, $p^e = [p_1^e, \dots, p_n^e]^T$ are in vector form. For generator i , the transfer function $g_i(s)$ has input $(u_i - p_i^e)$, the net power deviation at its generator axis, resulting from disturbances u_i in mechanical power minus variations in electrical power p_i^e drawn from the network, relative to their equilibrium values. The output w_i is the angular frequency deviation relative to equilibrium frequency.

The network power fluctuations p^e are given by a linearized (lossless) DC model $p^e(s) = \frac{1}{s} L w(s)$ of the power flow equation. Here L is the Laplacian matrix of an undirected weighted graph, with its elements given by $L_{ij} = \frac{\partial}{\partial \theta_j} \sum_{k=1}^n |V_i| |V_k| b_{ik} \sin(\theta_i - \theta_k) \Big|_{\theta=\theta_0}$, where θ_0 are angle deviations at steady state, $|V_i|$ is the voltage magnitude at bus i and b_{ij} is the line susceptance. Without loss of generality, we assume the steady state angular difference $\theta_{0i} - \theta_{0j}$ across each line is smaller than $\frac{\pi}{2}$. Moreover, because L is a symmetric real Laplacian, its eigenvalues are given by $0 = \lambda_1(L) \leq \lambda_2(L) \leq \dots \leq \lambda_n(L)$. The overall linearized frequency dynamics of the generators is given by

$$w_i(s) = g_i(s)(u_i(s) - p_i^e(s)), \quad i = 1, \dots, n, \quad (1a)$$

$$p^e(s) = \frac{1}{s} L w(s). \quad (1b)$$

Generally, a group of generators coupled as in Fig. 1 is considered *coherent* if their response in frequency is the same/similar under a disturbance u of any shape. We are interested in characterizing the dynamic response of coherent generators, which we term here the *coherent dynamics*. With this aim, we seek conditions on the network (1) under which the entire set of generators behave coherently. The same approach can be used on subgroups of generators.

To motivate our results, we start with summing over all equations in (1a) to get

$$\sum_{i=1}^n g_i^{-1}(s) w_i(s) = \sum_{i=1}^n u_i(s) - \sum_{i=1}^n p_i^e(s) = \sum_{i=1}^n u_i(s). \quad (2)$$

Notice that the term $\sum_{i=1}^n p_i^e(s) = \mathbf{1}^T \frac{L}{s} w(s) = 0$ since $\mathbf{1} = [1, \dots, 1]^T$ is a left eigenvector of $\lambda_1(L) = 0$.

A pragmatic approach to obtain a model of coherent behavior is to simply *impose* the equality $w_i(s) = \hat{w}(s)$ between the frequency outputs. Solving from (2) we obtain:

$$\hat{w}(s) = \left(\sum_{i=1}^n g_i^{-1}(s) \right)^{-1} \sum_{i=1}^n u_i(s) =: \hat{g}(s) \sum_{i=1}^n u_i(s); \quad (3)$$

the group of generators is aggregated into a single effective machine $\hat{g}(s)$, responding to the total disturbance.

A. Coherence in Tightly Connected Networks

To properly justify the use of (3) as an accurate descriptor of the coherent dynamics, we state here a precise result. Our analysis will highlight the role of the algebraic connectivity $\lambda_2(L)$ of the network as a direct indicator of how coherent a group of generators is.

For the network shown in Fig.1, the transfer matrix from the disturbance u to the frequency deviation w is given by

$$T(s) = (I_n + \text{diag}\{g_i(s)\}L/s)^{-1} \text{diag}\{g_i(s)\}, \quad (4)$$

where I_n is the $n \times n$ identity matrix. We establish that the transfer matrix $T(s)$ converges, as the algebraic connectivity $\lambda_2(L)$ increases, to one where all entries are given by $\hat{g}(s)$.

We make several assumptions: 1) $T(s)$ is stable; 2) $\hat{g}(s)$ in (3) is stable 3) all $g_i(s)$ are minimum phase systems. All generator network models discussed in this paper (Section II-B, II-C) satisfy these assumptions. In particular, the stability of $T(s)$ is guaranteed by passivity of the network [20]. We state the following result.

Theorem 1: Given the assumptions above, the following holds for any $\eta_0 > 0$:

$$\lim_{\lambda_2(L) \rightarrow +\infty} \sup_{\eta \in [-\eta_0, \eta_0]} \|T(j\eta) - \hat{g}(j\eta) \mathbf{1} \mathbf{1}^T\| = 0,$$

where $j = \sqrt{-1}$ and $\mathbf{1} \in \mathbb{R}^n$ is the vector of all ones.

The transfer matrix $\hat{g}(s) \mathbf{1} \mathbf{1}^T$ has the property that for an arbitrary vector disturbance $u(s)$, the response is $w(s) = \hat{g}(s) \mathbf{1} \mathbf{1}^T u(s) = (\hat{g}(s) \sum_{i=1}^n u_i(s)) \mathbf{1}$; this says the vector of bus frequencies responds in unison, with all entries equal to the response \hat{w} in (3). Theorem 1 states that in the limit of large connectivity, the true response $T(s)u(s)$ is approximated by the one in (3) for disturbances in the frequency band $[-\eta_0, \eta_0]$. Due to space constraints, we refer to [21] for the proof.

The limit of high connectivity analyzed in the theorem is a good assumption for many cases of tightly connected networks, but one may wonder about the relevance of $\hat{g}(s)$ in a less extreme case. We explore this through a numerical simulation on the Icelandic Power Grid [22], of moderate connectivity. As shown in Fig.2, the step response has incoherent oscillations from individual generators. Nevertheless, if one looks at the Center of Inertia (CoI) frequency $w_{\text{coi}} = (\sum_{i=1}^n m_i w_i) / (\sum_{i=1}^n m_i)$, a commonly used system-wide metric, we see it is very closely approximated by the coherent dynamics $\hat{g}(s)$. Thus we will proceed with this model of aggregate response. For certain generator models, however, the complexity of $\hat{g}(s)$ motivates the need for approximations.

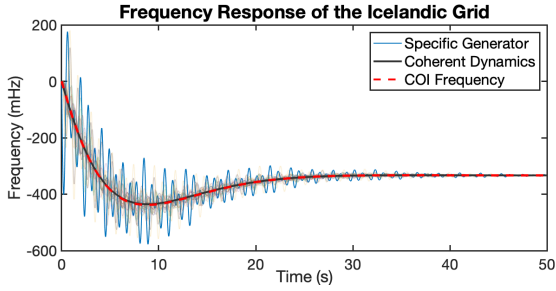


Fig. 2. Step response of the Icelandic grid. Individual responses appear in light font in the background, with a specific one highlighted in blue. We also show the COI frequency response, and step response of the coherent dynamics $\hat{g}(s)$. The Iceland network has Algebraic connectivity $\lambda_2(L) = 0.0915$.

B. Aggregate Dynamics for Different Generator Models

Having characterized how, the *coherent dynamics* given by $\hat{g}(s)$, represent the network's aggregate behavior, from now on we will use with no distinction the terms “aggregate” and “coherent” dynamics. Now we look into the explicit forms these dynamics take for different generator models.

Case 1: Generators with 1st order model, of two types:

1) For synchronous generators [13], $g_i(s) = \frac{1}{m_i s + d_i}$, where m_i, d_i are the inertia and damping of generator i , respectively. The coherent dynamics are $\hat{g}(s) = \frac{1}{\hat{m}s + \hat{d}}$, where $\hat{m} = \sum_{i=1}^n m_i$ and $\hat{d} = \sum_{i=1}^n d_i$.

2) For droop-controlled inverters [15], $g_i(s) = \frac{k_{P,i}}{\tau_{P,i}s + 1}$, where $k_{P,i}$ and $\tau_{P,i}$ are the droop coefficient and the filter time constant of the active power measurement, respectively. The coherent dynamics are $\hat{g}(s) = \frac{\hat{k}_P}{\hat{\tau}_P s + 1}$, where $\hat{k}_P = \left(\sum_{i=1}^n k_{P,i}^{-1}\right)^{-1}$, $\hat{\tau}_P = \hat{k}_P \left(\sum_{i=1}^n \tau_{P,i}/k_{P,i}\right)$.

Notice that both dynamics are of the same form; by suitable reparameterization, we may use the “swing” model $g_i(s) = \frac{1}{m_i s + d_i}$ to model both types of generators. In this case no order reduction is needed: the aggregate model given in Case 1 is consistent with the conventional approach of choosing inertia \hat{m} and damping \hat{d} as the respective sums over all generators. Theorem 1 explains why such a choice is indeed appropriate.

The aggregation is more complicated when considering generators with turbine droop control:

Case 2: Synchronous generators given by the swing model with turbine droop [13]

$$g_i(s) = \frac{1}{m_i s + d_i + \frac{r_i^{-1}}{\tau_i s + 1}}, \quad (5)$$

where r_i^{-1} and τ_i are the droop coefficient and turbine time constant of generator i , respectively. The coherent dynamics are given by

$$\hat{g}(s) = \frac{1}{\hat{m}s + \hat{d} + \sum_{i=1}^n \frac{r_i^{-1}}{\tau_i s + 1}}. \quad (6)$$

When all generators have the same turbine time constant $\tau_i = \hat{\tau}$, then $\hat{g}(s)$ in (6) reduces to the typical effective machine model of the form (5) with parameters $(\hat{m}, \hat{d}, \hat{r}^{-1}, \hat{\tau})$,

where $\hat{r}^{-1} = \sum_{i=1}^n r_i^{-1}$, i.e., the aggregation model is still obtained by choosing parameters as the respective sums of their individual values. However, if the τ_i are heterogeneous, then $\sum_{i=1}^n \frac{r_i^{-1}}{\tau_i s + 1}$ is generally of high-order because the summands have distinct poles. As a result, the closed-loop dynamics $\hat{g}(s)$ is a high-order transfer function and cannot be accurately represented by a single generator model. The aggregation of generators thus requires a low-order approximation of $\hat{g}(s)$.

C. Aggregate Dynamics for Mixture of Generators

We have shown the aggregate dynamics for generators of three different types. When a mixture of these different types is present¹, we adopt (5) as a general representation of the three types; in particular, the first order models can be regarded as (5) with $r_i^{-1} = 0$. Therefore, (6) provides a general representation of the aggregate dynamics resulting from a mixture of generators. Again, high-order coherent dynamics arise when heterogeneous turbines exist.

III. REDUCED ORDER MODEL FOR COHERENT GENERATORS WITH HETEROGENEOUS TURBINES

As shown in the previous section, the coherent dynamics $\hat{g}(s)$ are of high-order if the coherent group has generators with different turbine time constants. This suggests that substituting $\hat{g}(s)$ with an equivalent machine of the same order as each $g_i(s)$ may lead to a substantial approximation error. In this section we propose instead a hierarchy of reduced models with increasing order, based on balanced realization theory [23], such that eventually an accurate reduced model is obtained as the order of the reduction increases. An additional avenue of improvement is: instead of the standard approach [9], [10], [12] of reducing the aggregate of turbines, to apply the reduction methodology over the closed-loop coherent dynamics.

We use frequency weighted balanced truncation [24] to approximate $\hat{g}(s)$. Frequency weighted balanced truncation identifies the most significant dynamics with respect to particular LTI frequency weight by computing the weighted Hankel singular values, which decay fast in many cases, allowing us to accurately approximate high-order systems. Importantly, the reduction procedure favors approximation accuracy in certain frequency range specified by the weights. Due to space constraints, we refer to [21] for the detailed procedure of frequency weighted balanced truncation. Given a SISO stable proper transfer function $G(s)$, and a stable frequency weight $W(s)$, the k -th order weighted balanced truncation returns

$$\tilde{G}_k(s) = \frac{b_{k-1}s^{k-1} + \dots + b_1s + b_0}{a_k s^k + \dots + a_1s + a_0}, \quad (7)$$

which is guaranteed to be stable [24], and such that the weighted error $\sup_{\eta \in \mathbb{R}} |W(j\eta)(G(j\eta) - \tilde{G}_k(j\eta))|$ is upper bounded, with an upper bound decreasing to zero with

¹Generally, when considering a mixture of synchronous generators and grid-forming inverters, our network model is valid only when synchronous generators make up a significant portion of the composition.

the order k . For our purposes, $W(s)$ must have a high gain in the low frequency range, so that the DC gains of the original and the reduced dynamics are approximately matched, i.e., $G(0) \simeq \tilde{G}(0)$. Our two proposed model reduction approaches for high-order $\hat{g}(s)$ in (6) are both based on frequency weighted balanced truncation.

A. Model Reduction on Turbine Dynamics

Our first model is based on applying balanced truncation to the turbine aggregate. Essentially, $\hat{g}(s)$ in (6) is of high order because it has high-order turbine dynamics $\sum_{i=1}^n \frac{r_i^{-1}}{\tau_i s + 1}$; we seek to replace it with a reduced-order model. This is akin to the existing literature [9], [10] which replaces an aggregate of turbines in parallel by a first order turbine model with parameters obtained by minimizing certain error functions.

We denote the aggregate turbine dynamics as $\hat{g}_t(s) := \sum_{i=1}^n \frac{r_i^{-1}}{\tau_i s + 1}$. We also denote the $(k-1)$ -th reduction model of $\hat{g}_t(s)$ by frequency-weighted balanced truncation as $\tilde{g}_{t,k-1}(s)$. Then the k -th order reduction model of $\hat{g}(s)$ is given by

$$\tilde{g}_k^{tb}(s) = \frac{1}{\hat{m}s + \hat{d} + \tilde{g}_{t,k-1}(s)}, \quad (8)$$

with, again, $\hat{m} = \sum_{i=1}^n m_i$, $\hat{d} = \sum_{i=1}^n d_i$. We highlight two special instances of relevance for our numerical illustration.

1) *2nd order reduction*: When $k = 2$, the reduced model $\tilde{g}_{t,1}(s)$ can be interpreted as a first order turbine model

$$\tilde{g}_{t,1}(s) = \frac{b_0}{a_1 s + a_0} = \frac{b_0/a_0}{(a_1/a_0)s + 1} := \frac{\tilde{r}^{-1}}{\tilde{\tau} s + 1},$$

with parameters $(\tilde{r}^{-1}, \tilde{\tau})$ chosen by the weighted balanced truncation method. Then the overall reduced model $\tilde{g}_2^{tb}(s)$ is of second order, which is a single generator model.

Unlike [9], [10], there is a DC gain mismatch between $\tilde{g}_2^{tb}(s)$ and the original $\hat{g}(s)$ since $\tilde{r}^{-1} \neq \hat{r}^{-1} = \sum_{i=1}^n r_i^{-1}$. Later in the simulation section, by choosing a proper frequency weight $W(s)$, we effectively make the DC gain mismatch negligible. However, as we will see in the numerical section, $k = 2$ may not suffice to accurately approximate the coherent dynamics.

2) *3rd order reduction*: To obtain a more accurate reduced-order model, one may consider $k = 3$ as the next suitable option. In fact, as we see in the later numerical simulation, a 2nd order turbine model $\tilde{g}_{t,2}(s)$, i.e., $k = 3$, is sufficient to give an almost exact approximation of $\hat{g}_t(s)$.

We can also interpret $\tilde{g}_{t,2}(s)$, by means of partial fraction expansion, i.e.,

$$\tilde{g}_{t,2}(s) = \frac{b_1 s + b_0}{a_2 s^2 + a_1 s + a_0} = \frac{\tilde{r}_1^{-1}}{\tilde{\tau}_1 s + 1} + \frac{\tilde{r}_2^{-1}}{\tilde{\tau}_2 s + 1},$$

assuming the poles are real. Then the reduced dynamics $\tilde{g}_{t,2}(s)$ can be viewed as two first order turbines in parallel with parameters $(\tilde{r}_1^{-1}, \tilde{\tau}_1)$ and $(\tilde{r}_2^{-1}, \tilde{\tau}_2)$. In Section IV-A, we show such interpretation is valid for our numerical example.

B. Model Reduction on Closed-loop Coherent Dynamics

Our second proposal is to apply weighted balanced truncation directly on $\hat{g}(s)$, instead of reducing the turbine dynamics (8). Thus, we denote $\tilde{g}_k^{cl}(s)$ as the k -th order reduction model, via frequency weighted balanced truncation, of the coherent dynamics $\hat{g}(s)$. Again, DC gain mismatch can be made negligible by properly choosing $W(s)$.

As compared to the one in Section III-A, this reduced model might not be easy to interpret. Nevertheless, the procedure described below often leads to a practical interpretation.

1) *2nd order reduction*: When $k = 2$, we wish to interpret $\tilde{g}_2^{cl}(s)$ in terms of a single generator with a first order turbine of the form in (5), with parameters $(\tilde{m}, \tilde{d}, \tilde{r}^{-1}, \tilde{\tau})$. Given

$$\tilde{g}_2^{cl}(s) = \frac{b_1 s + b_0}{a_2 s^2 + a_1 s + a_0} := \frac{N(s)}{D(s)},$$

obtained by the proposed method, we write the polynomial division $D(s) = Q(s)N(s) + R$, where $Q(s)$, R are quotient and remainder, respectively. This leads to the expression

$$\tilde{g}_2^{cl}(s) = \frac{N(s)}{Q(s)N(s) + R} = \frac{1}{Q(s) + \frac{R}{N(s)}}.$$

Here the first order polynomial $Q(s)$ can be matched to $\tilde{m}s + \tilde{d}$, and $\frac{R}{N(s)}$ to $\frac{\tilde{r}^{-1}}{\tilde{\tau}s + 1}$. Provided the obtained constants $(\tilde{m}, \tilde{d}, \tilde{r}^{-1}, \tilde{\tau})$ are positive, the interpretation follows.

2) *3rd order reduction*: Similarly, when $k = 3$, the reduced model is $\tilde{g}_3^{cl}(s) = \frac{N(s)}{D(s)}$, with $N(s)$ of 2nd order and $D(s)$ of 3rd order. The polynomial division $D(s) = Q(s)N(s) + R(s)$, still gives a first order quotient $Q(s)$, which is interpreted as $\tilde{m}s + \tilde{d}$; the second order transfer function $\frac{R(s)}{N(s)}$ can be expressed, by partial fraction expansion, as two first order turbines in parallel, provided the obtained constants remain positive. We explore this in the examples studied below.

IV. NUMERICAL SIMULATIONS

We now evaluate the reduction methodologies proposed in the previous section, and compare their performance with the solutions proposed in [9], [10]. In our comparison, we consider 5 generators forming a coherent group². All parameters are expressed in a common base of 100 MVA.

The test case: 5 generators, $\hat{m} = 0.0683(\text{s}^2/\text{rad})$, $\hat{d} = 0.0107$. The turbine and droop parameters of each generator are listed in Table I. In all comparisons, a step change of -0.1 p.u. in disturbance power is used.

TABLE I
DROOP CONTROL PARAMETERS OF GENERATORS IN TEST CASE

Index	1	2	3	4	5
Parameter					
droop r_i^{-1} (p.u.)	0.0218	0.0256	0.0236	0.0255	0.0192
time constant τ_i (s)	9.08	5.26	2.29	7.97	3.24

²More specifically, we assume sufficiently strong network coupling among these generators such that the frequency responses are coherent. The numerical simulation will only illustrate the approximation accuracy with respect to the coherent response rather than individual ones.

Remark 1: In the test case, we only aggregate 5 generators and report all parameters explicitly in order to give insight on how the distribution of the time constant τ_i affects our approximations. It is worth noting that similar behavior is observed when reducing coherent groups with a much larger number of generators. In particular, the accuracy found below with 3rd order reduced models is also observed in these higher order problems.

As mentioned in the previous section, one of the drawbacks of the balanced truncation method is the DC gain mismatch, which leads to a steady-state error. In our simulation, the DC gain mismatch is effectively cancelled by picking proper frequency weights for different reduced models. Due to space constraints, we refer to [21] for the comparison between reduced models with and without frequency weights.

A. Effect of Reduction Order k in Accuracy

We now evaluate the effect of the reduction order on the accuracy. That is, we compare 2nd and 3rd order balanced truncation on the turbine dynamics, $\tilde{g}_2^{tb}(s)$ (BT2-tb), $\tilde{g}_3^{tb}(s)$ (BT3-tb), as well as balanced truncation on the closed-loop coherent dynamics $\tilde{g}_2^{cl}(s)$ (BT2-cl), $\tilde{g}_3^{cl}(s)$ (BT3-cl). The frequency weights are given by $W_{tb}(s) = \frac{s+3 \cdot 10^{-2}}{s+10^{-4}}$ and $W_{cl}(s) = \frac{s+8 \cdot 10^{-2}}{s+10^{-4}}$, respectively.

The step response and step response error with respect to $\hat{g}(s)$ are shown in Fig. 3.

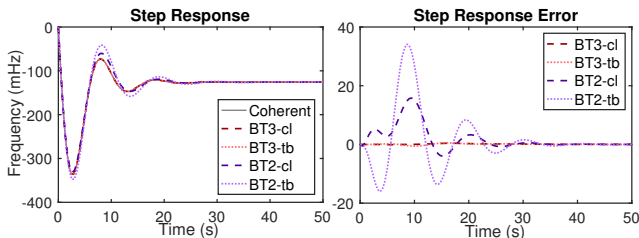


Fig. 3. Comparison of all reduced-order models by balanced truncation

Compared to 2nd order models, 3rd order reduced models give a very accurate approximation of $\hat{g}(s)$. While it is expected that the approximation error goes down with the order, it is not trivial that a 3rd order model would provide this level of accuracy for an intrinsically high order system.

Moreover, when we examine the transfer function given by $\tilde{g}_3^{tb}(s)$ (from input u in p.u. to output w in rad/s), we find an interesting interpretation. That is, the turbine model for $\tilde{g}_3^{tb}(s)$ is given by

$$\tilde{g}_{t,2}(s) = \frac{0.0266s + 0.0057}{s^2 + 0.5046s + 0.0489} = \frac{0.0473}{2.68s + 1} + \frac{0.0684}{7.64s + 1},$$

where the latter is obtained by partial fraction expansion and can be viewed as two turbines (one fast turbine and one slow turbine) in parallel, and the choices of droop coefficients for these two turbines reflect the aggregate droop coefficients of fast turbines (generators 3 and 5) and slow turbines (generators 1,2, and 4), respectively, in $\hat{g}(s)$.

B. Reduction on Turbines vs. Closed-loop Dynamics

Another observation from Fig. 3 is that reduction on the closed-loop is more accurate than reduction on the turbine. For a more straightforward comparison, we list in Table II the approximation errors of all 4 models in Fig 3 using the following metrics: 1) \mathcal{L}_2 -norm of step response error³ $e(t)$ (in rad/s^{1/2}): $(\int_0^{+\infty} |e(t)|^2 dt)^{1/2}$; 2) \mathcal{L}_∞ -norm of $e(t)$ (in rad/s): $\max_{t \geq 0} |e(t)|$; 3) \mathcal{H}_∞ -norm difference between reduced and original models (from input u in p.u. to output w in rad/s).

TABLE II
APPROXIMATION ERRORS OF REDUCED ORDER MODELS

Model \ Metric	\mathcal{L}_2 diff. (rad/s ^{1/2})	\mathcal{L}_∞ diff. (rad/s)	\mathcal{H}_∞ diff.
Guggilam [10]	7.2956	3.8287	10.2748
Germond [9]	3.9594	1.9974	5.1431
BT2-tb	4.3737	2.1454	7.5879
BT2-cl	2.0376	0.9934	2.0381
BT3-tb	0.0967	0.0361	0.1315
BT3-cl	0.0704	0.0249	0.0317

We observe from Table II that for a given reduction order, balanced truncation on the closed-loop dynamics ($\tilde{g}_2^{cl}(s)$, $\tilde{g}_3^{cl}(s)$) has smaller approximation error than balanced truncation on turbine dynamics ($\tilde{g}_2^{tb}(s)$, $\tilde{g}_3^{tb}(s)$) across all metrics. Such observation seems to be true in general. For instance, Fig. 4 shows a similar trend by plotting the same configuration (metrics and models) of Table II for different values of the aggregate inertia \hat{m} , while keeping all other parameters the same.

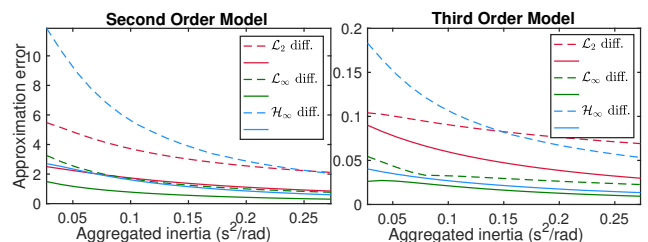


Fig. 4. Approximation errors of second order models (left) and third order models (right) by balanced truncation in different metrics. Approximation errors of reduced-order models $\tilde{g}_2^{tb}(s)$, $\tilde{g}_3^{tb}(s)$ are shown in dashed lines; Approximation errors of reduced-order models $\tilde{g}_2^{cl}(s)$, $\tilde{g}_3^{cl}(s)$ are shown in solid lines. The approximation errors are in their respective units.

It can be seen from Fig. 4 that reduction on closed-loop dynamics improves the approximation in every metric, uniformly, for a wide range of aggregate inertia \hat{m} values. The main reason is that, when applying reduction on the closed-loop dynamics, the algorithm has the flexibility to choose the corresponding values of inertia and damping to be different from the aggregate ones in order to better approximate the response. More precisely, from the reduced

³For reduced-order models obtained via frequency weighted balanced truncation, there exists an extremely small but non-zero DC gain mismatch that makes the \mathcal{L}_2 -norm unbounded. We resolve this issue by simply scaling our reduced-order models to have exactly the same DC gain as $\hat{g}(s)$.

model we obtain

$$\tilde{g}_2^{cl}(s) = \frac{4.9733s + 1}{(0.06715s + 0.01464)(4.9733s + 1) + 0.1118},$$

from which we can get the equivalent swing and turbine models as:

$$\text{swing model: } \frac{1}{0.06715s + 0.01464}, \quad \text{turbine: } \frac{0.1118}{4.9733s + 1}.$$

The equivalent inertia and damping are $\tilde{m} = 0.06715$ and $\tilde{d} = 0.01464$, which are different from the aggregate values \hat{m}, \hat{d} . Therefore, when compared to reduction on turbine dynamics, reduction on closed-loop dynamics is less constrained on the parameter space, thus achieving smaller approximation errors.

C. Comparison with Existing Methods

Lastly, we compare reduced-order models via balanced truncation on the closed-loop dynamics, $\tilde{g}_2^{cl}(s)$, $\tilde{g}_3^{cl}(s)$, with the solutions proposed in [9], [10]. The step responses and the approximation errors are shown in Fig. 5 and Table. II.

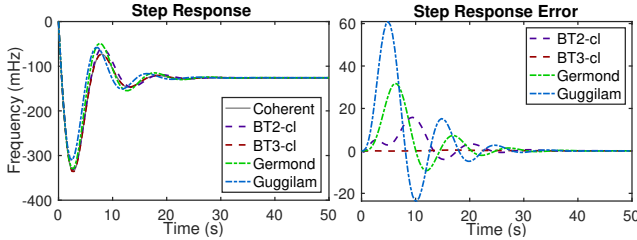


Fig. 5. Comparison with existing reduced-order models

In the comparison, $\tilde{g}_3^{cl}(s)$ outperforms all other reduced-order models and is the most accurate reduced-order model of $\hat{g}(s)$. It is also worth noting that $\tilde{g}_2^{cl}(s)$ has the least approximation error among all 2nd order models. In general, our results suggest that to improve the accuracy of reduced-order models of the coherent dynamics of generators $\hat{g}(s)$, we should consider: 1) increasing the complexity (order) of the reduced model; 2) reduction on the closed-loop dynamics instead of the turbine dynamics.

V. CONCLUSION

This paper concerns tractable models for frequency dynamics in a power grid, starting with the characterization $\hat{g}(s) = (\sum_{i=1}^n g_i^{-1}(s))^{-1}$ for the coherent response, which is shown to be asymptotically accurate as the coupling between generators (characterized via $\lambda_2(L)$) increases. Our characterization justifies existing aggregation approaches and also explains the difficulties of aggregating generators with heterogeneous turbine time constants. We leverage model reduction tools from control theory to find accurate reduced-order approximations to $\hat{g}(s)$. For $\{g_i(s)\}_{i=1}^n$ given by the 2nd order generator models, the numerical study shows that 3rd order models based on frequency weighted balanced truncation on closed-loop dynamics are sufficient to accurately represent $\hat{g}(s)$.

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