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Slow Inter-area Electro-mechanical Oscillations Revisited: Structural Property of Complex Multi-area Electric Power Systems

Hiya Akhil Gada[1] and Marija D. Ilic[2]

***Abstract*— This paper introduces a physically-intuitive notion of inter-area dynamics in systems comprising multiple interconnected energy conversion modules. The idea builds on an earlier general approach of setting their structural properties by modeling internal dynamics in stand-alone modules (components, areas) using the fundamental conservation laws between energy stored and generated, and then constraining explicitly their Tellegen's quantities (power and rate of change of power). In this paper we derive, by following the same principles, a transformed state-space model for a general nonlinear system. Using this model we show the existence of an area-level interaction variable, $intVar$, whose rate of change depends solely on the area internal power imbalance and is independent of the model complexity used for representing individual module dynamics in the area. Given these structural properties of stand-alone modules, we define in this paper for the first time an inter-area variable as the difference of power wave incident to tie-line from Area I and the power reflected into tie-lie from Area II. Notably, these power waves represent the interaction variables associated with the two respective interconnected areas. We illustrate these notions using a linearized case of two lossless inter-connected areas, and show the existence of a new inter-area mode when the areas get connected. We suggest that lessons learned in this paper open possibilities for computationally-efficient modeling and control of inter-area oscillations, and offer further the basis for modeling and control of dynamics in changing systems comprising faster energy conversion processes.**

I. Introduction

The existence of low-frequency electro-mechanical oscillations has been recognized and studied as a long-standing industry problem [1], [2], which has recently become even more pronounced. To mention a few, electric power systems have experienced these problems in the form of sub-synchronous resonance (SSR) between turbine modules and series compensated transmission lines [3]; low-frequency oscillations between different control areas during loss of large power plants [4]; and, more recently, wide-area oscillations, such as between Ukraine and Spain, and between Sweden and Spain [5]. The problem of forced oscillations has also been studied [6].

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[1] Hiya Akhil Gada hiyagada@mit.edu is a Ph.D. candidate at the Laboratory for Information and Decision Systems (LIDS) of Massachusetts Institute of Technology, Cambridge, MA, USA. hiyagada@mit.edu

[2] Marija D. Ilic is a Joint EECS Adjunct Professor and a Senior Research Scientist at Laboratory for Information and Decision Systems (LIDS), Massachusetts Institute of Technology (MIT), Cambridge, USA. She is also a Professor Emerita in the Electrical and Computer Engineering (ECE) Department of Carnegie Mellon University, Pittsburgh, PA. ilic@mit.edu

As these problems continue to emerge, it has become very difficult to identify their root causes, and to design control needed to suppress them. Most of the efforts have gone into transient stability simulations and small signal stability analyses, in particular as the slow power plants get replaced by smaller-scale Inverter Based Resources (IBRs) [5]. A particular new challenge perceived by the industry is a lack of detailed models of diverse components. Also, several renown researchers have proposed in the past modeling and analyses approaches, notably use of normal forms [7] and notions of dissipating energy flows [8]. While these methods help with locating the source of inter-area oscillations, they do not model the inter-area interactions dynamically.

The primary contribution of this paper is to meet the need to have a physically-intuitive interpretation of dynamic interactions, in terms of energy conversion, power and rate of power exchanges, between different energy conversion components and their relations to the existence of inter-area oscillations within an interconnected electric energy system. We do this by observing that each stand-alone module i (component, sub-system) can be characterized in terms of its own internal states and the shared [9] interaction variable $intVar^i$ which is a function of its own internal states only, as introduced in our earlier work [10], [11]. We then provide a notion of dynamic interaction between two areas by introducing, for the first time, an inter-area variable as the difference of the interaction variables of the respective areas.

In Section II we review a previously introduced aggregate state space model representing dynamics of energy and power within a multi-area interconnected electric power system; we review a previously-introduced structural definition of a technology-agnostic interaction variable associated with each stand-alone module i; and, define electro-mechanical inter-area oscillation as an interplay between interaction variables of neighboring modules $j \in C_i$. We stress that these concepts are general and applicable to systems comprising both conventional generation and renewable resources.

Next, in Section III, we illustrate a particular case of linearized power-frequency energy dynamics comprising conventional power plants. This section is a short summary of the earlier work [10] which laid the foundations for claiming the existence of interaction variables in linearized models of electric power grids. An important aspect of this modeling of power dynamics is that the load power deviations from forecast can be explicitly modeled.

Section IV concerns eigenvalue analyses of states contributing to inter-area oscillations. To start with, the existence of an interaction variable associated with a stand-alone module is a direct result of its own power conservation. Importantly, the structural existence of an eigenmode in an interconnected system, not present in two disconnected subsystems, is now shown to be a direct consequence of power conservation, both mathematically and through simulations. Based on these properties, in sub-section IV-A we propose a method for quickly identifying the modules whose states contribute the most to the inter-area oscillations. This method could be potentially of major use in real-world large-scale systems for which understanding causes of inter-area oscillations becomes a major problem [5].

In Section V we describe numerical simulations to illustrate the sensitivities of inter-area oscillations with respect to the strength of tie-line flow connections and inertia of generators. For the first time the effects of grid design and energy conversion processes on physically-intuitive properties such as frequency of inter-area oscillations can be interpreted without requiring full-blown time domain simulations.

In Section VI we add an intermittent source and simulate an example to show its effect on the inter-area oscillations depending on the frequency of intermittent disturbances. We close in Section VII by stressing the structural nature of inter-area oscillations and potential for further generalization of these properties to multi-energy systems.

II. Structural property of complex multi-area electric power systems

In electric power systems, such as the one shown in Figure 1, typically single port modules, generators and loads, are interconnected via transmission lines whose real power flows are nonlinearly dependent on the nodal phase angle differences. All components, except perfect resistors, have state variables and time constants defining their natural and/or forced response given initial conditions. In today's AC electric power systems these state variables are frequency $\omega(t)$, voltage $V(t)$, real power $P(t)$ and reactive power $Q(t)$. When writing the dynamic model in terms of these variables, one quickly loses physical insights. It therefore becomes quite hard to understand root causes of dynamic problems of interest. To overcome this complexity, we take a modular approach to modeling complex interconnected electric power systems. We introduce a transformed state space which is

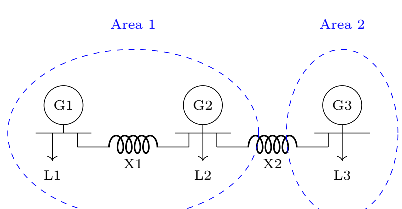

Fig. 1. An interconnected 3-bus 2-area system

derived by combining the dynamics of conventional internal state variables $\tilde{x}_{old,i}(t)$ in each module i (except the nodal phase angle δ_i) and its generated power $P_i(t)$. The structural form of this transformed state space is derived by introducing a new, transformed state variable comprising a technology-dependent $\tilde{x}_{old,i}(t)$ and the power $P_i(t) = \frac{dE_i(t)}{dt}$

$$x_{new,i}(t) = \begin{bmatrix}\tilde{x}_{old,i}(t) & P_i(t)\end{bmatrix}^\top \quad (1)$$

A. General structure of single port dynamic components

We first derive a general structure of single port components by recognizing that each one can be thought of as an energy conversion processing module which has certain structural properties resulting from fundamental conservation of energy.

$$\dot{E}_i(t) = -\frac{E_i(t)}{\tau_i} - P_i(t) + P_{in,i}(t), \quad E_i(0) = E_{i0} \quad (2)$$

Here $E_i(t)$, and $P_i(t)$ are stored energy in module i and real power generated by module i at the port/node. $P_{in,i}(t)$ is the exogenous power input into module i. The term $\frac{E_i(t)}{\tau_i}$ stands for Joule losses internal to module i, and τ_i is the time constant representing rate at which energy stored in the module dissipates, and can be interpreted as the ratio of stored and dissipated energy [12].

We also recall that the rate of change of energy conversion within each module $\dot{E}_i(t)$ is technology-specific and can be expressed in terms of derivatives of its own local state variables $\dot{\tilde{x}}_{old,i}(t)$. It then follows from the basic conservation law in (4) when combined with energy conversion (2) that the dynamics of the local variables $\tilde{x}_{old,i}(t)$ can be expressed structurally in terms of its own states and its rate of change of energy, namely power.

$$\dot{\tilde{x}}_{old,i}(t) = \tilde{f}_i(\tilde{x}_{old,i}(t), P_i(t), u_i(t), m_i(t)) \quad (3)$$

where $u_i(t)$ and $m_i(t)$ are the local control and exogenous inputs, respectively. The key observation when interconnecting modules of diverse energy conversion components is that power and rate of change of power are Tellegen's quantities, as a direct consequence of power conservation [13]. This means that power output from module i must equal power injected into modules $j \in C_i$, where C_i is the set of i's neighbouring modules. For the example of electric power grid, power produced by the generator equals the sum of power taken out by the components j directly connected to it, namely transmission lines.

$$P_i(t) = \sum_{j \in C_i} P_{ij}(t) \quad (4)$$

where $P_{ij}(t)$ is the real power flow from module i to j. For purposes of capturing rates of interactions between modules, we observe that rates of change of power $\dot{P}_i(t)$ must balance with the rates of change of power, say $\dot{P}_{ij}(t)$, taken out by the other components, $j \in C_i$,

$$\dot{P}_i(t) = \sum_{j \in C_i} \dot{P}_{ij}(t) \quad (5)$$

The dynamics of $x_{new,i}$ takes on the form,

$$\dot{x}_{new,i}(t) = \begin{bmatrix}\dot{\tilde{x}}_{old,i}(t) \\ \dot{P}_i(t)\end{bmatrix} = \begin{bmatrix}\tilde{f}_i(\tilde{x}_{old,i}(t), P_i(t), u_i(t), m_i(t)) \\ h_i(\tilde{x}_{old,i}(t), \dot{P}_j, j \in C_i)\end{bmatrix} \quad (6)$$

B. Existence of interaction variable at component level

Consider a component's interaction variable as the power generated by the component P_i [10], [11]. By re-writing (2) as

$$P_i(t) = P_{in,i}(t) - \dot{E}_i(t) - \frac{E_i(t)}{\tau_i} \tag{7}$$

it follows that a disconnected component has $P_i(t) = 0$ and that it is a function only of its internal inputs and state variables.

C. Simplified model of two-port components

Similarly, the basic conservation of power for two-port transmission lines interconnecting its sending end i and receiving end j is

$$\frac{dE_{ij}(t)}{dt} = P_i(t) + P_j(t) - \frac{E_{ij}}{\tau_{ij}} \tag{8}$$

where $\frac{E_{ij}}{\tau_{ij}}$ represents Joule losses in the transmission line, and, assuming negligible resistance it is approximately zero. When studying slow electro-mechanical oscillations $\frac{dE_{ij}(t)}{dt} \approx 0$ because the time constants of its LC parameters are near zero relative to the time constants of electrical machines. Consequently, the line is modeled as having inductance parameter X_{ij}. It follows from (8) that

$$P_i(t) + P_j(t) = 0 \tag{9}$$

D. Interaction variable of stand-alone area i

To review a general structural notion of an interaction variable $intVar^1$ of Area 1 proposed in [10], [11], we re-state constraint given in (4) for each network node within the area by stating a conservation of rate of change of power for the two modules (generator-load pairs are taken as one module) in $Area\ 1$

$$P_i = \sum_{j \in C_i} P_{ij}(t) \tag{10}$$

For all $i \in Area\ 1$ in the network shown in Figure 1 power generated by the two modules at the two nodes are $P_1^1(t) = P_{G1}^1(t) - P_{L1}(t)$, and $P_2^1(t) = P_{G2}^1(t) - P_{L2}(t)$, respectively. Further, when applying constraint given in (4) we get,

$$intVar^1(t) = P_1^1(t) + P_2^1(t) = F_{1-2} \tag{11}$$

where F_{1-2} is the power flow from Area 1 to Area 2 through the tie-line. We can infer that, for a disconnected area, $F_{1-2}(t) = constant$ and $\dot{F}_{1-2}(t) = 0$, i.e. net power out of disconnected area must remain constant and its derivative is zero. This linear combination of net power generated by all modules within a given Area 1 is defined as the $intVar^1(t)$ of Area 1 with the rest of the system [10], [11].

E. Inter-area dynamics: Definition in terms of interaction variables of stand alone areas

We propose, given the above fundamental relations for energy conversion, and the notion of stand-alone of interaction variable $intVar^I(t)$, for each area I that when interconnecting the two areas shown in Figure 1 via transmission line, whose parameter is X_2, general Tellegen's Theorem in (4) implies:

- Incident power into transmission line from Area 1 must be the same as the power generated by the Area 1, given in (7), $I = 1$.
- Reflected power into transmission line from Area 2 is given by the same (7), $I = 2$
- **Definition: Inter-area variable I-II** is the difference between incident and reflected powers into the tie line interconnecting them.

It can be seen from (7) that the incident power is mainly contributed by some internal power injected into Area 1 reduced by the Joule losses inside the area and the rate for change of energy consumed by the area. These definitions of incident and reflected power are degenerate since the travelling waves of tie-line are not modeled when capturing slow electro-mechanical inter-area dynamics which is mainly created by the difference in powers injected from the areas.

III. Linearized modeling of power dynamics

In this section we suggest that the linearized modeling of power dynamics introduced earlier in [10] follows from the more general derivations in Section II which do not require linearization and are technology-agnostic. For completeness, we briefly summarize this early derivation. To do so, we consider the same two-area interconnected system shown in Figure 1, which comprises a mix of conventional generators and loads interconnected via lossless transmission lines.

A. Dynamics of a single generator

The linearised model of a single governor-turbine-generator (G-T-G) set includes the rotor swing equation, the turbine dynamics and the local governor feedback proportional control. The standard state space form of a governor-turbine-generator (G-T-G) (12) has the generator state ω_G, the turbine state P_t and the governor state a, all being the deviations from their nominal value.

$$\begin{aligned} \dot{x}_{LC} = \begin{bmatrix} \dot{\omega}_G \\ \dot{P}_t \\ \dot{a} \end{bmatrix} &= \begin{bmatrix} \frac{-D}{M} & \frac{1}{M} & 0 \\ 0 & \frac{-1}{T_t} & \frac{K_t}{T_t} \\ \frac{-1}{T_g} & 0 & \frac{-1}{rT_g} \end{bmatrix} \begin{bmatrix} \omega_G \\ P_t \\ a \end{bmatrix} + \begin{bmatrix} \frac{-1}{M} \\ 0 \\ 0 \end{bmatrix} P_G, \\ &= A_{LC} x_{LC} + c_M P_G, \end{aligned} \tag{12}$$

where M, D, T_t, T_g are moment of inertia of the combined G-T-G set, its damping coefficient, and the time constants of the turbine and governor, respectively. ω_G, P_G, P_t, a are the rotor frequency of the generator, its real power output, power produced by the turbine, and the valve opening, respectively. K_T and r are the local control gains in the turbine and governor respectively. This model is effectively a particular case of the general nonlinear dynamics of a generator (6) in transformed state space.

B. Network constraints

Real power flow into a node is a function of the nodal voltage magnitudes and phase angles of the network, $P^N = P^N(\delta, V)$. Linearizing power flow into a generator bus and a load bus under the decoupling assumption ($\partial P^N/\partial V = 0$) gives us,

$$P_G + F_G = J_{GG}\delta_G + J_{GL}\delta_L \tag{13}$$
$$F_L - P_L = J_{LG}\delta_G + J_{LL}\delta_L \tag{14}$$

where the network has n generators and m loads. δ_G and δ_L correspond to the vector of phase angles, and F_G and F_L correspond to the real power flow from neighbouring modules at the generator and load bus respectively. The network constraints given in (13) and (14) are well-known linearized power flow equations, and represent a particular case of a more general power balance given as (4) earlier. The main step in deriving a transformed state space requires applying general constraints on rate of change of power shown in (5) introduced earlier, implying that differentiation of power balance equations is a valid step. In today's power systems problems P_L is predicted and dynamical system response to its deviations $\dot{P}_L$ is of direct interest. This is obtained by expressing ω_L as a disturbance caused by the load power deviations $\dot{P}_L$ and replacing it in the network constraints imposed on the rate of change of power generation $\dot{P}_G$ In short, define

$$K_P = J_{GG} - J_{GL}J_{LL}^{-1}J_{LG}, \;\; D_P = J_{GG}J_{LL}^{-1} \tag{15}$$

Differentiate and rearrange (13) and (14), to obtain

$$\dot{P}_G = K_P\omega_G + \dot{F}_e - D_P\dot{P}_L \tag{16}$$

Here $F_e = J_{GG}J_{LL}^{-1}F_L - F_G$ represents the effective flow from neighbouring areas as seen by each generator. Equations (12) represent linearized model of G-T-G components in the entire system and when subject to Tellegen's constraints on their rate of change power in the interconnected system, given as (16), jointly result in a particular case of transformed state space model introduced earlier in (6).

C. Interconnected system dynamics in transformed state space

It was shown in [10], [11] that when using the vector and diagonal matrix notation for a general power system, and combining the local generator dynamics and the network constraints, one obtains without loss of generality transformed state-space model of the system [10], [11]

$$\begin{bmatrix}\dot{x}_{LC}\\ \dot{P}_G\end{bmatrix} = \begin{bmatrix}A_{LC} & C_M\\ K_PE & 0\end{bmatrix}\begin{bmatrix}x_{LC}\\ P_G\end{bmatrix} + \begin{bmatrix}0\\ \dot{F}_e\end{bmatrix} + \begin{bmatrix}0\\ -D_P\dot{P}_L\end{bmatrix} \tag{17}$$

The system matrix of the augmented state space takes on the form

$$A = \begin{bmatrix}A_{LC} & C_M\\ K_PE & 0\end{bmatrix} \tag{18}$$

This model is basically a linearized model of a more general nonlinear model derived earlier in (17).

IV. Eigen-mode Analysis of Inter-area Dynamics

In this section, we make use of the transformed state space model shown above and its system matrix given in (18) to carry our eigen-mode analysis. In particular, given structural properties of this model and its system matrix, we wish to assess relations between the eigen-modes in disconnected control areas as well as in the interconnected system. We expect that each disconnected area itself has a zero eigen-mode reflecting structural constraint on its Tellegen's quantities, power and/or rate of change of power. These modes are naturally contributed by the states internal to the areas. We also anticipated that an additional eigen-mode appears when the areas are interconnected and that the state contributing to this eigen-mode are from both areas. The inter-area oscillations (IAO) are then contributed by these states. Using participation factor analysis we identify the state variables of the components that contribute the most to the IAO eigen-mode. Most importantly, we illustrate how the transformed state space makes it convenient to identify causes of oscillations.

A. Methodology to identify the interconnection eigen-mode

To understand which states contribute the most to the inter-area oscillations, we first need to identify which eigen-modes of the system arise due to the interconnection of the areas. A general method to identify the interconnection eigen-mode is explained below, followed by a simulated example.

For our analysis, consider an undamped single isolated system ($F_e = 0$) with constant power load ($\dot{P}_L = 0$). Its state space formulation reduces to,

$$\dot{x} = Ax \tag{19}$$

We simulate two cases,

- **Connected Isolated System (CIS):** The original system of interest, like in Figure 1
- **Disconnected Isolated System (DIS):** The same system in Figure 1 but with a disconnected inter-area tie line

The structure of the eigen-values of A [10], [11] for DIS is,

$$\lambda(A_{DIS}) = \begin{bmatrix}0\\ \vdots\\ 0\\ \vdots\\ \pm\Omega_1 j\end{bmatrix} \tag{20}$$

where $\pm\Omega_1 j$ corresponds to the local eigen-values of the two areas. The zero eigen-values are due the conservation of power/rate of change of power in each of the areas. The structure of the eigen-values of A [10], [11] for CIS is,

$$\lambda(A_{CIS}) = \begin{bmatrix}0\\ \vdots\\ \pm\omega j\\ \vdots\\ \pm\Omega_2 j\end{bmatrix} \tag{21}$$

where, like in DIS, $\pm\Omega_2 j$ corresponds to the local eigen-values of the two disconnected areas. We have an additional non-zero eigen-value $\pm\omega j$ which arises due to the interconnection of the two areas and is responsible for the IAO. To identify the eigen-value that corresponds to the interconnection, one can compare λ_{DIS} and λ_{CIS} and find the additional non-zero interconnection eigen-value $\pm\omega j$. In most cases, the interconnection eigen-mode will be of a lower frequency than the local eigen-modes. A simple participation factor analysis can then be done to find the state variables contributing to $\pm\omega j$.

V. Sensitivity of inter-area oscillations with respect to system parameters

We simulate an example to better understand the effect of weak inter-area tie lines and low inertia generators on inter-area oscillations (IAO). Consider the three-bus two-area system in Figure 1. The system is undamped, isolated and is subjected to constant power loads L_1, L_2, and L_3. The lines are taken as purely inductive with reactances X_1 and X_2. A similar analysis can be done for a damped system, but the idea remains the same.

A. Effect of tie-line strength

We demonstrate the effect of the strength of the inter-area tie-line on the interconnection eigen-mode and IAO by considering three cases.

1) Case 1: We keep the reactance of tie-line relatively small and comparable to the local line strengths.

$$X_2 = X_1$$

2) Case 2: We keep the reactance of tie-line relatively bigger than the local line strengths.

$$X_2 = 10X_1$$

3) Case 3: This is the DIS case, in Figure 1, where the tie-line is very weak and almost non-existent.

$$X_2 >> X_1$$

In our eigen-mode and participation factor analysis for case 1, we identify the following non-zero eigenvalues and their primary contributing state variables.

$$\Omega^1 = \pm 3.7499j \longrightarrow \omega_G^2, P_G^2$$
$$\omega^1 = \pm 2.1650j \longrightarrow \omega_G^1, P_G^1, \omega_G^3, P_G^3$$

Similarly for case 2,

$$\Omega^2 = \pm 3.1028j \longrightarrow \omega_G^1, P_G^1, \omega_G^2, P_G^2$$
$$\omega^2 = \pm 0.8274j \longrightarrow \omega_G^1, P_G^1, \omega_G^3, P_G^3$$

And for case 3,

$$\Omega^3 = \pm 3.0618j \longrightarrow \omega_G^1, P_G^1, \omega_G^2, P_G^2$$

It is straightforward to identify the interconnection eigen-mode for case 1 and case 2 as ω^1 and ω^2 respectively. The states of generator G_1 and G_3 contribute to the interconnection eigen-mode, the mode that disappears in the DIS

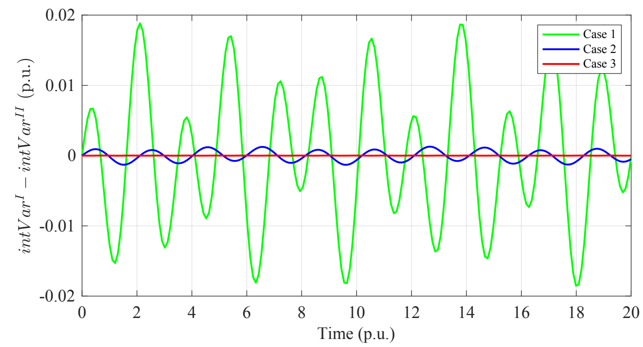

Fig. 2. Inter-area oscillation as a difference of the rate of change interaction variables in the two areas for varying tie-line strength

case 3. We also note that the local eigen-modes, $\Omega^1, \Omega^2, \Omega^3$, are primarily dependent on the states of generators in their respective area.

As defined in Section II, inter-area oscillations are expressed as the difference between the rate of change of interaction variables of two disconnected areas. We plot this for the three cases in Figure 2. The weaker the line gets, the slower is the oscillation of the power flowing through it, with the oscillation going to 0 for DIS. This can also be seen in the eigenvalues obtained for each case.

B. Effect of inertia of generator

We now demonstrate the effect of generator inertia on the interconnection eigen-mode and IAO. Again, consider the isolated system in Figure 1 and take two cases.

1) Case 1: The inertia of all generators is equal

$$M_{G1} = M_{G2} = M_{G3}$$

2) Case 2: The inertia of generator in area 2 is taken to be relatively bigger than the other generators

$$M_{G1} = M_{G2} < M_{G3}$$

We take $X_1 = X_2$ for this particular experiment. The parameters chosen for our simulation are given in the appendix. On doing eigen-mode analysis and participation factor analysis for case 1 we get,

$$\Omega^1 = \pm 3.7499j \longrightarrow \omega_G^2, P_G^2$$
$$\omega^1 = \pm 2.1650j \longrightarrow \omega_G^1, P_G^1, \omega_G^3, P_G^3$$

Similarly for case 2,

$$\Omega^2 = \pm 3.5221j \longrightarrow \omega_G^1, P_G^1, \omega_G^2, P_G^2$$
$$\omega^2 = \pm 1.4578j \longrightarrow \omega_G^1, P_G^1, \omega_G^2, P_G^2, \omega_G^3, P_G^3$$

When G_3 has a large inertia, the interconnection eigen-mode (ω^2) gets slower and G_3 states start contributing more to it. As is expected, generators with large inertia have a slower response and can be seen in the Figure 3 which plots the inter-area oscillation for the two cases.

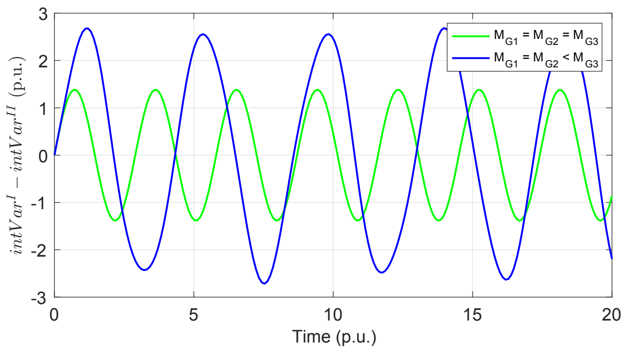

Fig. 3. Inter-area oscillation as a difference of rate of change of interaction variables from two areas for varying generator inertia

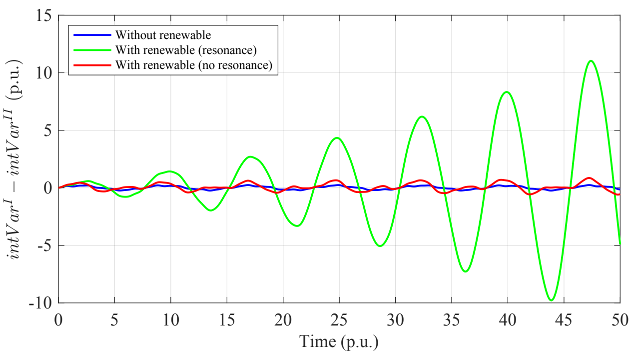

Fig. 4. Inter-area oscillation expressed as a difference of rate of change interaction variable of the two areas with and without a varying renewable source

VI. Impact of Intermittent Resources on IAO

The transformed state space has another advantage; it allows us to express load disturbances in the form of $\dot{P}_L$ (17). Specifically, renewable sources are intermittent and can be characterised as a varying negative load. Consider the network in Figure 1, with and without a renewable source in the place of L_1. When the damping is insufficient and the renewable power output deviations include the interconnection mode ($\dot{P}_L = A_\circ \sin(\omega t)$, ω is the interconnection eigenvalue), it resonates with the IAO and makes it unstable as can be seen in Figure 4.

VII. Concluding remarks

The notion of $intVar$ used in this paper has two unique properties: when the area is disconnected $intVar$ remains constant, and, its rate of power exchange with other areas is zero. Given these properties, we claim that the energy dynamics interpretation of interactions within a multi-area system is structural, i.e., they depend only on the basic conservation laws and Tellegen's theorem and are agnostic to technology of the internal energy conversion dynamics of modules. This means that the inter-area dynamics only depend on the range of interface specifications, an essential property for distributed modeling, sensing, computing and control. An example of aggregate mathematical model is shown on a small electric power system comprising two areas to illustrate these structural properties. Future work include, incorporating real-reactive power coupling and losses in the modeling, analysing practical examples and studying the relationship between feedback linearizing control and the structural inter-area property for suppressing slow inter-area oscillations between New York and New England areas [4] and for eliminating sub-synchronous resonance [14].

Appendix

For Section V-A, all generators are taken to be identical, i.e., their A_{LC} matrix is the same. The generator inertias are $M = 3.2$ p.u. and line reactance $X_1 = 6.67 \cdot 10^{-2}$ p.u.. For Section V-B, $X_1 = X_2 = 6.67 \cdot 10^{-2}$ p.u.. For case 1, generator inertias are $M_{G1} = M_{G2} = M_{G3} = 3.2$ p.u. and for case 2, $M_{G3} = 32$ p.u.. All simulations show deviations of the quantities around equilibrium. As both the examples consider an undamped system, $D = 0$ and the time constants T_t, T_g are very large numbers.

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