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Stabilization of Structure-Preserving Power Networks with Market Dynamics ⋆

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Abstract: This paper studies the problem of maximizing the social welfare while stabilizing both the physical power network as well as the market dynamics. For the physical power grid a third-order structure-preserving model is considered involving both frequency and voltage dynamics. By applying the primal-dual gradient method to the social welfare problem, a distributed dynamic pricing algorithm in port-Hamiltonian form is obtained. After interconnection with the physical system a closed-loop port-Hamiltonian system of differential-algebraic equations is obtained, whose properties are exploited to prove local asymptotic stability of the optimal point.

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1. INTRODUCTION

The future power network needs to operate reliably in the face of fluctuations resulting from distributed energy resources and the increased variability in both supply and demand. One of the feedback mechanisms that have been identified for managing this challenge is the use of real-time dynamic pricing. This feedback mechanism encourages consumers to modify their demand when it is difficult for system operator to achieve a balance between supply and demand (Borenstein et al., 2002). In addition, real-time dynamic pricing allows to maximize the total *social welfare* by fairly sharing utilities and costs associated with the generation and consumption of energy among the different control areas (Kiani and Annaswamy, 2010).

Many of the existing dynamic pricing algorithms focus on the economic part of optimal supply-demand matching (Kiani and Annaswamy, 2010; Roozbehani et al., 2010). However, if market mechanisms are used to determine the optimal power dispatch (with near real-time updates of the dispatch commands) dynamic coupling occurs between the market update process and the physical response of the power network dynamics (Alvarado et al., 2001).

Consequently, under the assumption of market-based dispatch, it is essential to consider the stability of the coupled system incorporating both market operation and electromechanical power system dynamics simultaneously.

While on this subject a vast literature is already available, we focus on a more accurate and higher order model for the physical power network than conventionally used in the literature. In particular, a structure-preserving model for the power network with a third-order order model for the synchronous generators including voltage dynamics is used. As a result, market dynamics, frequency dynamics and voltage dynamics are considered simultaneously.

1.1 Literature review

The coupling between a high-order dynamic structure-preserving power network and market dynamics has been studied before in Alvarado et al. (2001). Here a fourth-order model of the synchronous generator is used in conjunction with turbine and exciter dynamics, which is coupled to a simple model describing the market dynamics. The results established in Alvarado et al. (2001) are based on an eigenvalue analysis of the linearized system.

It is shown in Trip et al. (2016) that the third-order (*flux-decay*) model for the synchronous generator, as used in the present paper, admits a useful passivity property that allows for a rigorous stability analysis of the interconnection with optimal power dispatch controllers, even in the presence of time-varying demand. In Trip and De Persis (2015) a structure-preserving power network model is considered with turbine dynamics where a similar internal-model controller is applied, which also has applications in microgrids, see De Persis et al. (2016).

Another commonly used approach to design optimal distributed controllers in power grids is the use of the primal-dual gradient algorithm (Arrow et al., 1958), which has

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been proven useful in network flow theory (Feijer and Paganini, 2010). The problem formulation varies throughout the literature on power systems, with the focus being on either the generation side (Li et al., 2014; Seungil and Lijun, 2014), the load side (Mallada and Low, 2014; Zhao et al., 2015; Mallada et al., 2014) or both (Zhang et al., 2015; Zhang and Papachristodoulou, 2015).

Many of these references focus on linear power system models coupled with gradient-method-based controllers (Li et al., 2014; Seungil and Lijun, 2014; Mallada and Low, 2014; Mallada et al., 2014; Zhang et al., 2015; Zhao et al., 2014). In these references the property that the linear power system dynamics can be formulated as a gradient method applied to a certain optimization problem is exploited. This is commonly referred to as *reverse-engineering* of the power system dynamics (Zhang et al., 2015; Li et al., 2014; Seungil and Lijun, 2014). However, this approach falls short in dealing with models involving nonlinear power flows.

Nevertheless, Zhang and Papachristodoulou (2015); Zhao et al. (2015) show the possibility to achieve optimal power dispatch in structure-preserving power networks with nonlinear power flows using gradient-method-based controllers. On the other hand, the controllers proposed in Zhang and Papachristodoulou (2015) have restrictions in assigning the controller parameters and in addition require that the topology of the physical network is a tree.

1.2 Main contributions

The contribution of this paper is to propose a novel energy-based approach to the problem that differs substantially from the aforementioned works. We proceed along the lines of Stegink et al. (2015, 2016), where a port-Hamiltonian approach to the design of gradient-method-based controllers in power networks is proposed. In those papers it is shown that both the power network as well as the controller designs admit a port-Hamiltonian representation which are then interconnected to obtain a closed-loop port-Hamiltonian system. In the present paper we extend some of these results to structure-preserving power networks.

First it is shown that the dynamical model describing the power network as well as the market dynamics admit a port-Hamiltonian representation. Then, following Stegink et al. (2015, 2016), it is proven that all the trajectories of the coupled system converge to the desired synchronous solution and to optimal power dispatch.

Since our approach is based on passivity and does not require to reverse-engineer the power system dynamics as a primal-dual gradient dynamics, it allows to deal with more complex nonlinear models of the power network. More specifically, the physical model for describing the power network in this paper admits nonlinear power flows and time-varying voltages, and is more accurate and reliable than the classical second-order model (Machowski et al., 2008; Kundur, 1993; Sauer and Pai, 1998; Bergen and Hill, 1981). In addition, a distinction is made between generator nodes and loads nodes, resulting in a system of differential-algebraic equations.

The results that are established in the present paper are valid for the case of nonlinear power flows and cyclic networks, in contrast to Zhang et al. (2015); Li et al. (2014); Seungil and Lijun (2014); Zhao et al. (2014), where the power flows are linearized and Zhang and Papachristodoulou (2015) where the physical network topology is a tree. Moreover, in the aforementioned references the voltages are assumed to be constant.

While the third-order model for the synchronous generators has been studied before using passivity based techniques (Trip et al., 2016; Stegink et al., 2016), the combination of gradient method based controllers with structure-preserving power network models is novel. In addition, the stability analysis does not rely on linearization and is based on energy functions which allow us to establish rigorous stability results. Moreover, we do not impose any restrictive condition on controller design parameters for guaranteeing asymptotic stability, contrary to Zhang and Papachristodoulou (2015).

The remainder of this paper is organized as follows. In Section 2 the preliminaries are stated. Thereafter, the power system dynamics is introduced in Section 3 and a port-Hamiltonian representation of the system of differential-algebraic equations is given as well in this section. Then the dynamic pricing algorithm in port-Hamiltonian form is presented in Section 4. The closed-loop system is analyzed in Section 5 and local asymptotic stability of the optimal points is proven. Finally, the conclusions and the future research directions are discussed in Section 6.

2. PRELIMINARIES

2.1 Notation

Given a symmetric matrix $A \in \mathbb{R}^{n\times n}$, we write $A > 0$ ($A \geq 0$) to indicate that A is a positive (semi-)definite matrix. The set of positive real numbers is denoted by $\mathbb{R}_{>0}$ and likewise the set of nonnegative real numbers is denoted by $\mathbb{R}_{\geq 0}$. The notation $\mathbb{1}_n \in \mathbb{R}^n$ is used for the vector whose elements are equal to 1. The $n \times n$ identity matrix is denoted by I_n. Given an ordered set $\mathcal{I} = \{i_1, i_2, \ldots, i_k\}$ and a vector $v \in \mathbb{R}^n, k \leq n$, then $\mathrm{col}_{i\in\mathcal{I}}\{v_i\}, \mathrm{diag}_{i\in\mathcal{I}}\{v_i\}$ denotes the k-column vector, respectively $k \times k$ diagonal matrix whose entries are given by $v_{i_1}, v_{i_2}, \ldots, v_{i_k}$. Likewise, given vectors v_1, v_2 then $\mathrm{col}(v_1, v_2) := \left[\begin{smallmatrix} v_1 \\ v_2 \end{smallmatrix}\right]$. Let $f(x, y)$ be a differentiable function of $x \in \mathbb{R}^n, y \in \mathbb{R}^m$, then $\nabla f := \mathrm{col}(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y})$ and $\nabla_x f := \frac{\partial f}{\partial x}$ denotes the gradient of f with respect to x. Given a twice-differentiable function $f : \mathbb{R}^n \to \mathbb{R}^n$ then the Hessian of f evaluated at x is denoted by $\nabla^2 f(x)$.

2.2 Differential algebraic equations

Let us consider a system of differential-algebraic equations (DAE's) of the form

$$\dot{x} = f(x, y), \tag{1a}$$

$$0 = g(x, y), \tag{1b}$$

where $x \in \mathbb{R}^n$ and $y \in \mathbb{R}^m$.

Definition 1. (De Persis et al. (2016)). Let $\mathcal{D} \subset \mathbb{R}^n \times \mathbb{R}^m$ be an open connected set. The algebraic equation $0 = g(x, y)$ is *regular* if the Jacobian of g w.r.t. y has constant full rank on $\mathcal{D}$, that is,

$$\mathrm{rank}(\nabla_y g(x, y)) = m \qquad \forall (x, y) \in \mathcal{D}.$$

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