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Robust Decentralized LPV Control for Transient Stability of Power Systems

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Abstract: In daily operation of power systems, transient stability is targeted by designing local standard controllers for narrow operating ranges of any generating node. If deviations due to disturbances or a higher share of (uncertain) renewable energy occur, exemption routines are necessary for returning to nominal operation. This paper proposes a method for synthesizing local robust multivariable controllers such that the interaction between the grid nodes is explicitly considered. It is shown that variably parametrized controllers in conjunction with linear-parameter-varying models of the grid nodes can consistently stabilize the system. Since the control architecture is nevertheless decentralized, the design effort grows moderately with the size of the power system.

Keywords: Power system, decentralized control, transient stability, robust control, scalability.

1. INTRODUCTION

Power grids constitute large distributed systems which can be represented by nonlinear differential algebraic equations (DAEs). Reliable operation is typically achieved by a separation of concerns, resulting in the three stability categories *rotor angle stability*, *frequency stability*, and *voltage stability* (Kundur et al., 2004). The category of concern in this work is the so-called *transient stability*, i.e. the subclass of rotor angle stability describing the ability of synchronous generators to stay in synchronism after a large disturbance. The standard controller to establish transient stability and to achieve a good damping of electromechanical oscillations is the so-called *power system stabilizer* (PSS). It represents a decentral controller and is typically based on modeling the synchronous generator as a linear time-invariant (LTI) system, i.e. the PSS is applicable only close to the chosen operating point. Uncertainties arising from changing operating conditions, neglected model nonlinearities, and parameter changes can deteriorate the controller performance – these uncertainties will become more important in the future due to increasing shares of renewable energies in power grids.

Different schemes to enhance robustness of PSS have been proposed, see (Fan, 2009) for an overview. The key to robustness is the handling of the DAE-system including the nonlinearities and parameter changes. In (Gordon and Hill, 2008), *direct feedback linearization* (DFL) was used to linearize the decentralized system. Robust controllers for transient stability were designed with considering the coupling to the grid by bounded ranges for the uncertain variables. Although the feedback controllers are decentralized, global stability of the considered power system is shown. The drawback of the DFL techniques is that the damping of the dynamic behavior may not be sufficient. Damping can be enhanced by pole-placement, as reported in (Rao and Paul, 2011; Rao and Sen, 2000; Werner et al., 2003; Shayeghi et al., 2010). The resulting robust controllers place the closed-loop poles such that a desired damping is achieved for the considered parameter range. In (de Oliveira et al., 2010) this is done by using a classical PSS structure and computerized tuning of the parameters for different operating points. The pole-placement is ensured by using formulations of linear matrix inequalities (LMI). In (Rao and Paul, 2011) and in (Werner et al., 2003), output feedback controllers were synthesized using LMI formulations as well. These approaches determine a single robust controller for the whole space of uncertainties. (Rao and Sen, 2000) uses similar techniques for synthesizing state feedback controllers, and shows the application for a relatively large system. Stability of the whole power system is only shown by simulation. The common drawback of the techniques in the last three papers referenced is that they are based on linearization of the DAEs, rather than using matrix polytopes in order to obtain a conservative system representation. As stated in (Rao and Sen, 2000), finding a system description in the form of a matrix polytope containing all uncertainties is usually difficult. Furthermore, finding a single controller for the whole range of uncertainties may be impossible for large ranges. An alternative approach to handle system nonlinearities and parameter variations is the use of *linear parameter varying* (LPV) techniques, in which the operating range is defined by varying parameters. The controller is no longer constant but is defined depending on the model parameters as well. The stability of the controlled system can be proven under certain conditions. In (Qiu et al., 2004), an LMI-based controller synthesis based on LPV-systems is proposed for designing a decentralized PSS, and in (Liu et al., 2006b,a) the approach is extended to the control of FACTS. The decentralized models are also derived by linearizing for a set of operating points and interpolation in between. The success of this approach depends on the choice of linearization points. An alternative approach which combines the positive aspects of LMI-based pole-placement technique and an LPV-controller

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was introduced in (He et al., 2006, 2009). In contrast to the other methods, an exact polytopic representation for the *single machine infinite bus system* (SMIB) was derived, and sufficient conditions for stability are not violated, as long as the parameters (and thus the uncertainties) stay in the range considered in synthesis. To the best of our knowledge, these are the only papers of other authors so far which use an exact LPV-model of synchronous generators. A characteristic of this approach is that the algebraic equations describing the grid are inserted into the LPV model. While this seems appropriate for the SMIB system, the extension of this principle to larger power systems with multiple generators is not possible since the grid usually has a large and complicated structure. However, stability of the whole power system must be considered and among the discussed contributions global stability was only shown in (Gordon and Hill, 2008).

In contrast, the contribution of this paper is to propose a method for designing LPV-controllers for a power system representation in which any generating node is modeled by an exact LPV model while the algebraic equations for modeling the physical coupling of the nodes and the grid are not included in the LPV model directly. Only the parameters couple the considered subsystem to the grid. The algebraic equations are used to formulate consistent parameter ranges for the node models. The synthesis of the LPV-controller for any node considers these ranges in order to guarantee transient stability as well as sufficient damping of the dynamic behavior for any permissible parameter value. In contrast to the results presented already in Schaab and Stursberg (2015), stability of the whole power system is shown. As further extension of Schaab and Stursberg (2015), the effectiveness of the approach is demonstrated on a 9-bus system.

2. POWER SYSTEMS MODEL

2.1 Differential-Algebraic Model of the Power System

Since the focus of this work is transient stability, the power system model must include the electromechanical phenomena of generators and buses as described in many standard texts, see e.g. (Milano, 2010) or (Kundur, 1994). The following description is dq-transformed and most physical values are given in per-units. A power system typically consists of many (hundreds) synchronous generators (which are the driving force for stabilizing the power system), transmission lines, and loads. The modeling equations can be separated into the differential equations of the generators (machines), the algebraic equations of the machine, and the algebraic equations of the grid and loads.

The following formulation of the generator equations does not involve any elimination of algebraic variables. The differential equations of a generator with index h comprises one ODE each for the rotor angle δ_h, the angular velocity ω_h, and the transient voltage $e'_{q,h}$ (d-axis):

$$\begin{aligned}
\dot{\delta}_h &= \Omega_{b,h}(\omega_h - \omega_{b,h}) \\
\dot{\omega}_h &= \frac{1}{2H_h}\Big(\tau_{m,h} - \tau_{e,h} - D_h(\omega_h - \omega_{b,h})\Big) \\
\dot{e}'_{q,h} &= \frac{1}{T'_{dO,h}}\Big(-e'_{q,h} - (x_{d,h} - x'_{d,h})i_{d,h} + v_{f,h}\Big)
\end{aligned} \tag{1}$$

The mechanical torque $\tau_{m,h}$ and the field voltage $v_{f,h}$ are the two inputs of the machine. The set of machine parameters include the base synchronous frequency $\Omega_{b,h}$, the reference frequency $\omega_{b,h}$, the damping coefficient D_h, the inertia constant H_h, the armature resistance $r_{a,h}$, the d-axis synchronous reactance $x_{d,h}$, the d-axis transient reactance $x'_{d,h}$, and the d-axis open circuit transient time constant $T'_{dO,h}$. In addition, the algebraic variables of the machine with index h comprise the electrical torque $\tau_{e,h}$, the machine voltages (dq-transformed) $v_{q,h}$ and $v_{d,h}$, the machine currents $i_{q,h}$ and $i_{d,h}$ as well as the injected active and reactive powers p_h and q_h. These quantities are determined by the following algebraic equations:

$$\begin{aligned}
0 &= \tau_{e,h} - (v_{d,h} + r_{a,h}i_{d,h})i_{d,h} - (v_{q,h} + r_{a,h}i_{q,h})i_{q,h} \\
0 &= v_{q,h} + r_{a,h}i_{q,h} - e'_{q,h} + x'_{d,h}i_{d,h} \\
0 &= v_{d,h} + r_{a,h}i_{d,h} - x_{q,h}i_{q,h} \\
0 &= v_{d,h} - v_h\sin(\delta_h - \Theta_h) \\
0 &= v_{q,h} - v_h\cos(\delta_h - \Theta_h) \\
0 &= p_h - v_{d,h}i_{d,h} - v_{q,h}i_{q,h} \\
0 &= q_h - v_{q,h}i_{d,h} + v_{d,h}i_{q,h}
\end{aligned} \tag{2}$$

The voltage v_h and its phasor Θ_h can be calculated using the grid algebraic equations in matrix notation [1]:

$$\underbrace{\begin{bmatrix}\bar{s}_1\\ \bar{s}_2\\ \vdots\\ \bar{s}_r\end{bmatrix}}_{\bar{s}} = \underbrace{\begin{bmatrix}\bar{v}_1 & 0 & \dots & 0\\ 0 & \bar{v}_2 & \dots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \dots & \bar{v}_r\end{bmatrix}}_{\bar{V}} \underbrace{\begin{bmatrix}\bar{y}^*_{11} & \bar{y}^*_{12} & \dots & \bar{y}^*_{1r}\\ \bar{y}^*_{21} & \bar{y}^*_{22} & \dots & \bar{y}^*_{2r}\\ \vdots & \vdots & \ddots & \vdots\\ \bar{y}^*_{r1} & \bar{y}^*_{r2} & \dots & \bar{y}^*_{rr}\end{bmatrix}}_{\bar{Y}^*} \underbrace{\begin{bmatrix}\bar{v}^*_1\\ \bar{v}^*_2\\ \vdots\\ \bar{v}^*_r\end{bmatrix}}_{\bar{v}^*} \tag{3}$$

The connections between the buses are mapped into the *admittance matrix* $\bar{Y}$, in which a diagonal element y_{hh} is the sum of all shunt and line admittances connected to the line. The non-diagonal elements $y_{hk} = y_{kh}$ are the negative values of the sum of the admittances connecting the buses h and k, and they equal to zero if no connection exists. Thus, the admittance matrix is symmetric. One can also see that the resulting complex power $\bar{s}_h$ at the bus h is equal to the sum of all powers of lines ending at the bus. The complex value $\bar{s}_h$ can be separated in active and reactive power $\bar{s}_h = p_h + jq_h$. Loads and transformers are modeled as constant impedances.

The overall set of equations constitutes a decentralized model in which $h \in \{1, \dots, r\}$ numbers the buses contained in the grid, and (3) is specified for any bus. A subset of the buses (and thus of $\{1, \dots, r\}$) is associated with synchronous generators, and a set of equations according to (1), (2) for any generator is part of the model.

2.2 LPV-Model of a Synchronous Generator

As mentioned above, the dynamics of each generator is transformed into an LPV-model for subsequent controller synthesis. With vectors of states $x_h \in \mathbb{R}^{n_{x,h}}$, outputs $y_h \in \mathbb{R}^{n_{y,h}}$, inputs $u_h \in \mathbb{R}^{n_{u,h}}$ and parameters $\theta_h \in \mathbb{R}^{p_h}$, the general form the LPV-model is:

$$\dot{x}_h(t) = A_h(\theta_h(t))x_h(t) + B_h(\theta_h(t))u_h(t) \tag{4}$$

$$y_h(t) = C_h(\theta_h(t))x_h(t) + D_h(\theta_h(t))u_h(t) \tag{5}$$

Since the controller synthesis in the following section uses a state-feedback scheme, (5) can be omitted in the sequel.

[1] A bar $\bar{\bullet}$ indicates a phasor and an asterisk $\bullet^*$ the conjugate complex of the respective variable.