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Robust control for voltage and transient stability of power grids relying on wind power

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ABSTRACT

Common practice in stabilization of power grids is to refer to different stability categories (transient stability, voltage stability, rotor angle stability) and to address these by designing dedicated controllers separately based on models linearized around nominal operation points. Furthermore, the controllers of a generating unit contained in the grid are usually synthesized without considering other grid nodes. This work, in contrast, proposes a scheme for unified synthesis of controllers which conjunctively address rotor angle stability and voltage stability for grids containing synchronous generators as well as wind energy conversion systems based on doubly-fed induction generators. First, a procedure is proposed to describe the generating units by linear-parameter-varying (LPV) systems, in which fluctuations imposed by the grid or the wind are mapped into time-varying model parameters. For appropriate ranges of these parameters, decentralized robust controllers can be synthesized by semidefinite-programming, such that the power grid is stabilized for the considered fluctuations and disturbances. The effectiveness of the approach is demonstrated for a multi-bus benchmark system, where the grid oscillations are well damped and the LPV-controller stabilizes the grid after permanent changes.

1. Introduction

Ensuring stability has always been a main concern of power system operation, even more so since renewable energy intensifies fluctuations. To account for different measures of convergence for power grids, specific stability categories were introduced (Kundur et al., 2004): *frequency*, *rotor angle* and *voltage stability*. This work is concerned with the latter two categories, where rotor angle stability (also called transient stability) ensures that the synchronous generators (SG) remain synchronous after grid faults and that electromechanical oscillations are damped down in a reasonable time. Voltage stability is concerned with the restoration of a certain voltage level after the occurrence of a fault or for changing operating conditions. Though the two categories are physically interdependent, the respective standard controllers of power system components are often designed separately considering only one single control objective. Thus, unsatisfactory coordination between the controllers for one grid component can lead to performance degradation, or even to system failure (Gordon & Hill, 2008). Furthermore, the controllers of different grid components are usually designed independently, while assuming that all other components maintain their nominal behavior. However, the strong coupling throughout the grid renders this assumption questionable, e.g. in the case that synchronous generators (SG) and wind energy conversion systems (WECS) coexist - the focus of this paper. Typically, the local controller design for both systems are based on linearized models around operating points and the performance can degrade significantly with changing operating points. The transition of power grids to a more decentralized energy generation leads to more fluctuations. Hence, the design methods must be reconsidered to achieve sufficiently good robustness. The following literature review first surveys existing approaches for robust control of rotor angle and voltage for SG, and then discusses techniques for control of WECS. Combined control for transient stability and voltage control based on the technique of direct feedback linearization (DFL) is proposed in Gordon and Hill (2008). One controller is designed to control the rotor angle stability during a fault phase. In the post-fault period, a global controller activates the voltage regulator. Asymptotic stability for the whole grid is not proven and permanent faults / changes of operating points are not considered with respect to steady state accuracy of the voltage. In Fusco and Russo (2011), the voltage control loop restores the pre-fault voltage value, and an additional loop ensures synchronism. However, the system performance strongly depends on proper estimation of system parameters, and stability is not discussed. In Liu, Hu, and Song (2012), excitation control based on the DFL-technique is described, and asymptotic stability is ensured based on Lyapunov functions, but criteria such as robustness are not discussed. An overview for robust

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controllers designed for power systems is given in Fan (2009); Schaab and Stursberg (2015): One promising technique to ensure robust operation of the SG is the synthesis based on linear-parameter-varying(LPV) systems. The idea behind them is to transform the nonlinearities and the system variabilities into varying parameters of the LPV-system. Stabilizing the LPV-system for all parameters implies the stabilization of the original nonlinear system.

In Liu, Vittal, and Elia (2006a,b); Qiu, Vittal, and Khammash (2004), LPV techniques are used for robust control of SG and FACTS to enhance rotor angle stability by using sets of linearized models around several operating points. The success of this method to obtain LPV-models is highly dependent on a gridding process, and the original dynamics is not represented exactly. In He et al. (2006, 2009), an exact polytopic model of the SG is derived, including the grid equations of a small example of the grid. Stability is guaranteed as long as the parameters stay in the prescribed ranges, making this concept robust against sudden, and permanent changes. An application to larger grids does not appear possible for this method, since the LPV-model includes the algebraic equations of the grid, leading to very complicated models for larger grids. This drawback was addressed in Schaab and Stursberg (2015) and Schaab and Stursberg (2015), by deriving a decentralized and exact LPV-model of the SG in order to control the rotor angle. The changes within the grid and interconnections between the SGs of the power system are mapped in parameter ranges, making the resulting controller robust against the considered grid-changes. Using this approach for all grid nodes of a system assures grid-wide stability, as shown in Schaab and Stursberg (2015). While all discussed papers on techniques using LPV-models only address transient stability, none of them discusses the control of WECS as well.

However, other methods for WECS to improve rotor angle stability in case of system disturbances and to damp electromechanical oscillations exist. Since the electrical components react significantly faster than the mechanical ones (e.g. blade system, pitch system, and drive train) (Domínguez-García, Gomis-Bellmunt, Bianchi, & Sumper, 2012), they are solely discussed here. In Hughes, Anaya-Lara, Jenkins, and Strbac (2006), the control signal is added to the active power control loop of the standard DFIG converter controller to damp system oscillations. Likewise in Miao, Fan, Osborn, and Yuvarajan (2009) and Mishra, Mishra, Tripathy, Senroy, and Dong (2009), an additive signal on the standard control loops achieves a good damping using pole-placement. In all three cases, voltage control was not explicitely considered, but is included only by standard (reactive power) control loops. It is observed as a drawback that all controllers are based on linearization around operating points, i. e. robustness is not achieved for changing operating conditions. Again, LPV-based techniques may address robustness, and have already been used in the context of WECS. Most of the literature in this regard is concerned, however, with the damping of the mechanical oscillations to minimize fatigue loads, or with aerodynamic phenomena (e.g. Mohammadpour & Scherer, 2012). Some results are discussed nevertheless, to consider the existing LPV-models of WECS and their applicability to transient stability. In Wang and Weiss (2014), an approach to robust (grid) frequency control is presented, and detailed LPV-models of the mechanical and the electrical parts are derived. Through H_∞ controller design, a robustification against grid changes is introduced using an auxiliary disturbance input. However, only the electrical part of the WECS is considered for controller design, and a unified model of the electrical and mechanical equations is not presented. Instead, a switching mechanism is introduced to prevent the rotor speed from falling too low. Similarly in Muhando, Senjyu, Uehara, and Funabashi (2011), two LPV-models for the mechanical and electrical parts are presented, and one control loop each is designed to minimize fatigue loads and to damp the electrical torque fluctuations. To the best of the authors knowledge, a unified LPV-model of the WECS consisting of the electrical and mechanical parts for robust control of power grids including WECS after grid faults and for voltage control at the same time has not been presented so far.

The main contributions of this paper are (i.) to extend the technique for transient stabilization of a grid by SG as presented in Schaab and Stursberg (2015) to voltage control; for this reason a new exact LPV-model is derived, and a multiobjective, robust and decentralized LPV controller is synthesized to achieve transient stability, and to control the voltage; (ii.) an exact LPV-model of a WECS based on DFIG is derived such that it comprises the mechanical and electrical parts; (iii.) a method to damp grid-oscillations, to control the voltage and rotor angular velocity is proposed for the WECS. Using LPV-models and controller synthesis of the same type for all these aspects, this approach is unifying for grids comprising SG and WECS.

This paper is organized as follows: First, the standard nonlinear differential algebraic equations of a power system are presented in Section 2, comprising the equations of the SG, the DFIG-based WECS, and the grid. The derivation of the affine LPV-models for the SG and the WECS are presented in Section 3, followed by the description of the robust LPV-controller synthesis in Section 4. The resulting decentralized and robust controllers are illustrated by simulation for a multi-machine benchmark system in Section 5. Finally, the paper concludes with a discussion and a view on future work in Section 6.

2. Differential-algebraic model of the power grid

In this work, the two stability categories *transient stability* and *voltage stability* according to Kundur et al., 2004 are addressed. Thus, the power system model must include the electromechanical phenomena. The related equations are standard, and are typically formulated in dq-coordinates (indicated by the indices d and q throughout this chapter) and in *per units* (Kundur, 1994). For illustrative description this paper refers in different parts to a 9-bus-system as shown in Fig. 1. This system is taken from Anderson and Fouad (2003) and will be modified later by assuming that the generators (indicated by G_h, if connected to a bus with number h) are either realized as SG or as WECS.

Each of the dynamic components is modeled by first order DAE-equations of the type

$$\dot{x}(t) = f(x(t), y(t), u(t)), \quad (1)$$

$$0 = g(x(t), y(t), u(t)), \quad (2)$$

where $x \in \mathbb{R}^{n_d}$, $y \in \mathbb{R}^{n_a}$, and $u \in \mathbb{R}^m$, are the vectors of n_d differential variables, of n_a algebraic variables, and of m inputs.[1] The grid furthermore contains transformers T_h, the loads A, B, and C, and, of course, the connecting lines of the grid. Typically, in the context of the control objectives of this work, these components are modeled as constant impedances and can be encoded, together with the grid

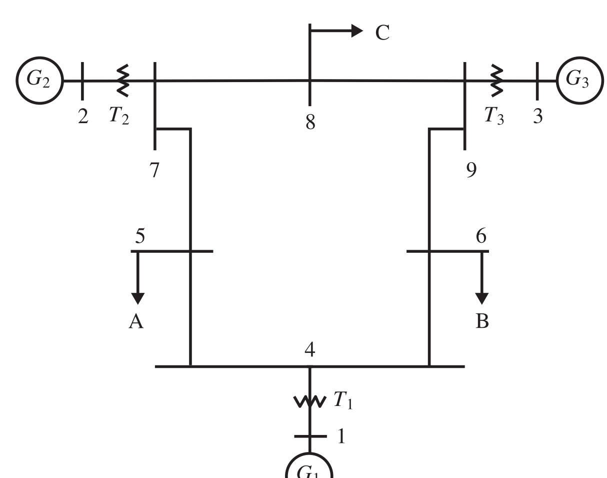

Fig. 1. Structure of the 9-bus-system.