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Mismatched disturbance attenuation control for static var compensator with uncertain parameters

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ABSTRACT

The use of a static var compensator (SVC) as a component of flexible alternating current transmission system (FACTS) devices to control power systems has been investigated for decades. Its aim is to regulate the system voltage and improve the stability and loadability of power systems. A typical assumption in such a system is that the parameters of the controlled system are known accurately, which is rarely satisfied in practice. This paper explores the development of a simple but effective controller for a single-machine infinite-bus power system with SVC subjected to both matched and mismatched disturbances where the controller derivation is based on the assumption that all parameters used in the system modeling are *unknown*, but bounded in size. The research in this paper illustrates how an indirect robust control can be incorporated with a modified disturbance observer-based feedforward term to attenuate the influence of parameter variations and disturbances from the outputs of the system. Simulation results are presented to confirm the effectiveness of the proposed scheme.

1. Introduction

The power system stability as a technically rich subject has been extensively studied over the past decades [1]. The motivation for the power system control is spawned from the consequence of the fact that the perpetuated growth of load demand has led to the overexploitation of existing transmission systems, and the power systems operate closer to their physical limits. Therefore, it is possible to face with the stability and security problems. In particular, due to diminishing fossil fuel resources, concerns about global warming and environmental pollution, the use of renewable energy resources has been rapidly increased all over the world. However, the injection of distributed renewable power sources into the grid introduces advantages, but it has posed several challenges to the power industry [2]. Voltage stability is one of these concerns. The presence of renewable sources such as wind and Solar powers, which can cause voltage magnitude to increase or decrease, has made the power system stability a challenging problem [2].

In such situations, a single generator excitation control cannot directly and promptly provide the prerequisite of power system stability, and the power industry requires more efficient control means for this purpose [3]. Improving the stability and performance of power systems can be fulfilled by employing flexible alternating current transmission system (FACTS) devices [1]. The static var compensator (SVC) is one of the most preferred members of FACTS family and has become a significantly effective tool to regulate bus voltage and reactive power in a cost-effective manner [3–5].

Controlling power systems with SVC is, in general, not a simple problem as plant uncertainties, unmodelled perturbations, system fault, loss of generation, or circuit contingencies, and external disturbances affect the overall performance of the system. To tackle such a challenge, various kinds of control strategies have been proposed, including proportional-integral-derivative (PID) controllers [6–8], backstepping control method [9], immersion and invariance adaptive based controllers [3,10], variable structure control scheme [11], and fuzzy logic and neural network controllers (e.g., [12–15]).

Although each of the mentioned contributions is able to achieve a certain performance, resultant algorithms typically either rely on using approximately linearized model without taking nonlinear features into consideration, or on the perfect knowledge of the system parameters. Therefore, the resulting controllers cannot often achieve robustness to uncertainties and parameter variations of the control system [9]. Furthermore, a majority of the robust methods are complex and difficult to be implemented, and the robustness and disturbance rejection properties of these controllers are established at the price of sacrificing the nominal control

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Nomenclature

δ	power angle of the generator (rad)
ω	synchronous speed of the generator (rad/s)
D	damping coefficient (pu)
ω_0	the initial stable value of ω (rad/s)
H	inertia constant (s)
P_m	mechanical input power (pu)
E'_q	inner generator voltage (pu)
V_s	infinite bus voltage (pu)
T_{svc}	time constant of SVC regulator (s)
y_{SVC}	susceptance of the overall system (pu)
X'_d	direct axis transient reactance of the generator (pu)
X_T	reactance of the transformer (pu)
X_L	line reactance (pu)
B_L	susceptance of the inductor in the SVC (pu)
B_C	susceptance of the capacitor in SVC (pu)
u	equivalence input of SVC regulator (pu)
d_i	unknown disturbance function, $i = 1, 2, 3$

performance [11]. These approaches cannot maintain steady voltages and even become unstable when subjected to large disturbances. A notable exception includes the one discussed in [11] where the authors investigated a composite controller for a single-machine infinite-bus (SMIB) power system with SVC. The composite controller is developed by using a finite time control technique and a finite time disturbance observer. The developed control provides a satisfactory performance and finite time stability, but since both the controller and observer are obtained via the high order sliding mode technique, the resulting composite controller is a high order controller, leading to a large number of terms in the control law and increased computation time.

The development in this paper is motivated by the desire to consider the nonlinear features in the control design as a means to improve the performance and also to achieve a robust control with a less computational complexity. Specifically, for a SMIB power system with SVC, we illustrate how a simple state feedback control in conjunction with the disturbance observer yields an effective robust controller. In particular, the variations of the power system parameters are very common in practice. The electronic components have uncertain variations around their nominal values because of heating or a fault occurring in power systems. Characteristics of elements may vary when the system has been operated for a long time. The equivalent external reactances and the infinite bus voltage, which are system parameters external to the generating station, may be different under varied load conditions. Doubtlessly, these variations have significant impact on the stability of power systems. In this regard, we assume that all parameters used in the power system modeling are unknown and vary in specific intervals, leading us to a plant with matched and mismatched uncertainties. Hence, the control problem boils down to the parametric robust control area, and the stabilization of the perturbed platform becomes a primary concern in the controller development.

Loosely speaking, in such control problems, the scheme is generally employed to synthesize a stabilizing control for the entire plant family. Such a method is not preferred because of at least three reasons. First, controllers are typically of very high order. Consequently, the controller implementation is complicated and such a design may suffer from extreme fragility in the coefficients of the controller. Second, due to the pole-zero cancellation phenomenon associated with this method, the damping of the resulting closed-loop poles directly rely on the open loop system. And finally, when the nominal stable plant is subjected to disturbances and becomes unstable, the uncertainties cannot treat in such circumstances [16].

In this paper, the robust control design is recast into an equivalent optimal control problem. Indeed, we explore an indirect robust control approach such that both stability and optimality can be provided. The spirit of this approach stems from the fact that the Lyapunov function, which ascertains closed-loop stability of the uncertain dynamic system, is a solution to the steady-state Hamilton-Jacobi-Bellman (HJB) equation for the optimal-controlled nominal system with a properly defined cost function that reflects the uncertainty bounds [17]. The choice of the indirect method in lieu of direct robust control schemes has several advantages that motivate this investigation including: being conceptually simple, in that, solving the optimal control problem only involves solving an algebraic Riccati equation which is easier than tackling the robust control problem directly; flexibility, i.e., the compromise between small control input and fast response time is possible by adjusting the relative weights of states and control inputs in the cost function.

While the proposed optimal controller offers satisfactory performance in the presence of parameter uncertainties, it suffers from a certain drawback when it is put into practice. It offers an asymptotically stable closed-loop system only when disturbances are neglected. In reality, the disturbances can have adverse effects on the system performance. Therefore, the aforesaid issue in the investigated controller requires some remedies to preserve the nominal performance of the baseline optimal controller to the best.

In this paper, the disturbance observer proposed in [18] is adopted to counteract the disturbances. Although the considered observer has obtained successful achievements in many practical systems, it must be noticed that it originally is only applicable to disturbances satisfying matching condition,[1] which is not the case many practical systems may not satisfy the so-called matching condition. In the literature, the disturbance observer control is combined with some traditional robust control methods to deal with mismatched disturbances. For example in [19–21], a DOBC is employed to attenuate the matched disturbances, whereas the mismatched disturbances are compensated via H_∞ scheme [19] or sliding mode control [20,21]. However, the mismatched disturbances considered therein must satisfy the H_2 norm bound constraint.

This paper presents results of designing a disturbance compensation gain to assure that the matched and mismatched disturbances can be attenuated from the system outputs and that how the amalgamation of the modified disturbance observer-based feedforward controller with the optimal control law can be used to improve the closed-loop performance.

Throughout the paper, $\mathbb{R}^{n\times m}$ denotes the space of $n \times m$ real matrices, and $\boldsymbol{I}_m$ denotes an $m \times m$ identity matrix. For matrices $\boldsymbol{A}$ and $\boldsymbol{B}, \boldsymbol{A} \geqslant 0$ ($\boldsymbol{A} > 0$) indicates that $\boldsymbol{A}$ is non-negative (positive) definite, and $\boldsymbol{A} \geqslant \boldsymbol{B}$ ($\boldsymbol{A} > \boldsymbol{B}$) denotes the fact that $\boldsymbol{A} - \boldsymbol{B} \geqslant 0$ ($\boldsymbol{A} - \boldsymbol{B} > 0$). The notation diag($\boldsymbol{v}$) represents a square diagonal matrix with the elements of vector $\boldsymbol{v}$ on the main diagonal. Furthermore, for the sake of simplicity, the argument of the functions (functionals) will be omitted whenever no confusion can arise from the context.

[1] Here "matching" refers to the disturbances acting on the system via the same channels as control inputs.