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Fault tolerant emergency control to preserve power system stability[☆]

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ABSTRACT

This paper introduces a method for fault-masking and system reconfiguration in power transmission systems. The paper demonstrates how faults are handled by reconfiguring remaining controls through utilisation of wide-area measurement in real time. It is shown how reconfiguration can be obtained using a virtual actuator concept, which covers Lure-type systems. The paper shows the steps needed to calculate a virtual actuator, which relies on the solution of a linear matrix inequality. The solution is shown to work with existing controls by adding a compensation signal. Simulation results of a benchmark system show ability of the reconfiguration to maintain stability.

1. Introduction

Interconnected power systems often experience problems related to low-frequency electromechanical oscillations (in the 0.1–2 Hz range). These oscillations arise from the power and phase–angle relationship interacting with generators' inertia, forming an equivalent to a multi-mass–spring system. Large-scale power systems exhibit both local and inter-area eigenmodes. Local eigenmodes are related to those of a single machine against the rest of the system, inter-area modes are formed by one group of generating units working against another group. If the eigenmodes are poorly damped, this might lead to a loss of synchronism between synchronous generators and cause cascading of tripping events.

Power system stabilisers (PSSs) and Power Oscillation Dampers (PODs) (hereafter, collectively termed stabilisers) are effective tools to damp such low-frequency oscillations. Stabilisers are installed on voltage and power-flow controlling devices to compensate for oscillations in active power transmission (Kundur, 1994). On voltage regulators, the PSS superimposes auxiliary signals on the voltage regulation. The performance of a power system is usually analysed by checking the eigenproperties, and improved by adding active damping control to the electromechanical modes.

The performance of locally designed stabilisers can be improved using wide-area measurement signals and wide-area control (WAC) (see e.g. Snyder et al., 1998). With the growing use of new technologies such as phasor measurement units (PMU) and fast communication technologies, WAC has given rise to new possibilities in power system operation. This includes use of such wide-area information for improved stability and for emergency control (Begovic, Novosel, Karlsson, Henville, & Michel, 2005). Furthermore, the communication network allows the use of multiple measurements, whereby fewer devices need to be implemented in a power system to achieve proper damping. When the stabilisers in a multi-machine power system work collaboratively, a proper functionality is expected from each individual stabiliser as a fault in one stabiliser could cause unsatisfactory performance or even instability of the collective control objective. In the present systems, cascaded tripping is a concern if a power damping device is disconnected from the system. In this paper, it is shown how wide-area measurement signals can be used and design a wide-area reconfiguration block that can reconfigure the control action and stabilise the system in an event of failure which removes local stabilisers.

With the penetration of synchronised Power Measurements Unit (PMU) technology into power transmission systems, wide-

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[☆] A preliminary version of this paper Pedersen, Richter, Tabatabaeipour, Jóhannsson, and Blanke (2014) was presented at IFAC World Congress 2014, in Cape Town, South Africa.

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area control has become realistic, not only for normal operation, but in particular during emergency conditions, where reconfiguration schemes can be employed to encapsulate local failures of devices. The purpose of reconfiguring after a fault is to preserve specific properties of the closed-loop system (Blanke, Kinnaert, Lunze, & Staroswiecki, 2015). This work is focused on faults related to devices with stabilisers. Handling of actuator faults to preserve certain properties before and after a fault is referred to as model matching. Model matching design to handle actuator faults were dealt with by Yang and Blanke (2000) and Yang, Blanke, and Verhagen (2007), who suggested a robust control mixer concept, and Steffen (2005), who proposed the virtual actuator approach. Lunze and Steffen (2006) showed that control reconfiguration of a linear system after an actuator fault is equivalent to disturbance decoupling. Control reconfiguration methods using virtual actuators and sensors for piecewise affine systems and Hammerstein–Wiener systems were proposed in Richter, Heemels, van de Wouw, and Lunze (2008, 2011), Richter and Lunze (2008), and Richter (2011). AFTC for Lure systems with Lipschitz continuous nonlinearity subject to actuator fault using a virtual actuator was presented in Richter, Seron, and De Dona (2012), where it was assumed that the state of the faulty system is measurable. AFTC for a system with additive Lipschitz nonlinearity subject to actuator faults using a virtual actuator was presented in Khosrowjerdi and Barzegary (2014). Fault tolerant control of polytopic linear parameter varying (LPV) systems subject to sensor faults using virtual sensor was proposed in de Oca and Puig (2010), where the structure of the nominal controller was assumed to be known. It was further assumed that the nominal controller consists of a state feedback combined with an LPV observer. Tabatabaeipour, Stoustrup, and Bak (2012) considered the problem of control reconfiguration for continuous-time LPV systems with both sensor and actuator faults and without any assumptions about the structure of the nominal controller. In this context input-to-state stability properties of the reconfigured system were investigated. In Tabatabaeipour, Stoustrup, and Bak (2015) the control reconfiguration for discrete-time LPV systems with both sensor and actuator faults were considered and both stability and performance of the reconfiguration block were investigated. Reconfigurable control design using a reconfiguration block for input-affine nonlinear dynamical systems was investigated in Tabatabaeipour and Galeazzi (2015) . Using incremental stability properties, it was shown how to design the nonlinear virtual actuator independent of the nominal controller to achieve ISS of the reconfigured closed-loop system. The design of the nonlinear virtual actuator is achieved using backstepping control. Extension to nonlinear systems was obtained in Richter (2011). Fault accommodation for large-scale interconnected system was achieved in Panagi and Polycarpou (2011), using a distributed AFTC scheme.

The idea of a virtual actuator is to keep the nominal controller in the loop and transform the input signals designed for the nominal plant to signals appropriate for the remaining healthy actuators. The reconfiguration method is applied to power systems with power oscillation damping controllers. When a damping device fails or is separated from the system, a wide-area virtual actuator is designed that restructures the nominal control loop by using the remaining healthy devices to compensate for the active damping that is missing due to the fault. The advantage of this approach is the separation of fault-tolerant control design from nominal control design. Nominal design and tuning can be used for the remaining stabilisers, fault-tolerance is obtained through a reconfiguration block. Furthermore, as the nominal controllers are still in the reconfigured loop, the implicit knowledge from the stabilisers about the closed-loop performance is preserved.

To our knowledge, no previous attempt of wide-area fault compensation in stabilisers has been done before (Pedersen et al., 2014). Design of wide-area stabilisers was pursued in Snyder et al. (1998), where locale controls were extended with remote measurements to improve observability of inter-area modes. In Kamwa, Grondin, and Hebert (2001), wide-area information was used in a hierarchical control scheme. A level of fault tolerance was obtained in Chen, Guo, and Bai (2006) and Chen and Guo (2005) where a robust wide-area controller used mixed $\mathcal{H}_2/\mathcal{H}_\infty$ output-feedback control. Adaptive stabilisers using wide-area information were designed in Zhang, Chen, Malik, and Hope (1993) and Ni, Heydt, and Farmer (2000). Compensation for the effect of wide-area control delays was considered in Chaudhuri, Majumder, and Pal (2004), where a predictor was implemented in the control loop. Using flexible AC transmission systems (FACTS) devices in a wide-area control network for power oscillation damping was considered in Yao, Jiang, Wen, Wu, and Cheng (2014), where a delay margin for the controllers is introduced. In Dotta, Silva, and Decker (2008) a two-level stabiliser design is shown for the Brazilian 7-bus southern equivalent with time delay. This test system will also be the basis for the case study in this paper.

The contributions of this work are the following: A wide-area fault-tolerant virtual actuator is designed for the power system, which stabilises the system after a fault removes or separates local stabilising devices. The proposed method does not require changes in local controllers but accommodates faults by adding signals to their output. This paper also extends the work done in Pedersen et al. (2014) by finding a reconfiguration that minimises damping degradation during fault, and also accounts for transmission delays in a wide-area communication system.

The paper is organised as follows. The background of stabilisers and fault-tolerant control is described in Section 2, in which the nonlinear nature of the emergency dynamics is also discussed and a Lure form is introduced to enable generic analysis. Section 3 then discusses reconfiguration based on a virtual actuator approach for nonlinear systems and extends virtual actuator-based theory to cope easily with the problem at hand. Section 4 presents a benchmark test system that develops instability when a line with a series-compensating device is tripped and simulations are performed showing successful reconfiguration and recovery of stability using the new approach.

2. Background

2.1. Power system damping control

Power systems can obtain oscillatory behaviour under certain circumstances related to the transmission line properties between machines, the level of power transmitted, and the control system parameters. Oscillatory behaviour is encountered under conditions of high reactance of the system (transmission and consumers) and high generator outputs. High synchronizing torque is then needed for generators, but the associated high gain in automatic voltage regulation loops causes deteriorated system damping (Kundur, 1994). Additional damping is provided by an auxiliary control loop, which measures signals related to the oscillation of active power, usually the rotor speed deviation. Power damping can also be achieved by the use of other static power-flow control and voltage control devices (FACTS).

Ideally a stabiliser is installed where the dominant electromechanical modes have highest controllability. Stabilisers can also use several inputs to damp multiple swing modes. When a stabilizing device is separated by a fault, the modes they are intended to control will become less damped. Faults that affect the oscillatory behaviour of a power system include faults on synchronous generators and synchronous condensers; faults on damping FACTS devices; transmission line faults that separate control devices. In