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A latencies tolerant model predictive control approach to damp Inter-area oscillations in delayed power systems

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ABSTRACT

Automatic voltage regulators and power system stabilizers have been employed successfully to deal with fast dynamics associated to local oscillations phenomena. Whereas, inter-area oscillations damping in large power systems requires remote feedback controllers fed by Wide Area Monitoring Systems (WAMS). Although these improvements in the inter-area oscillations behavior have been effective, a new challenge emerges: reaching stability with a closed loop control despite latencies due to measurements taken far away from the control centre. The research was motivated by the need for modernization of power systems capable of dealing with control difficulties in centralised WAMS for damping inter-area oscillations in power systems caused by delays in the communication system. Herein, time delay and control problems are addressed separately. The time delay problem is solved by a database based time compensation solution relying on the most updated available state of the system. The control problem is solved by a Model Predictive Control (MPC) with terminal cost and constraint set to handle complexities due to nonlinearities of the power system, the large scale of the problem and the parametric variations. Both solutions work in a coordinated way with local controllers to implement a decentralised coordinated strategy that manages slow global dynamics and fast local dynamics as well. The integrated proposed approach is called Time-Delay-Tolerant Model Predictive Control (TDT-MPC). Coordinated and coherent performance of the two TDT-MPC components (Kalman compensator and MPC) is achieved thanks to unifying power system reference models for both strategies. The approach has been tested on the IEEE 39 system and validated with time domain nonlinear simulations, obtaining post-fault damped oscillations and a good tracking of new power references when tripping tie lines.

1. Introduction

Nowadays, power systems work close to their maximum level; under these conditions, problems in stability, reliability and security may take place [1]. Large power systems not only have to deal with local oscillations (present in small power systems) but also with inter-area oscillations that affect mostly power flows in tie lines [2–5]. As in the case of power systems with stressed tie lines, the emergence of inter-area phenomena would provoke cascade events and blackouts when strong disturbances occur [6–8], this has been categorized as a process control system security, making evident the need for robust self-decision making ability aiming to lay the foundations of Smart Transmission Grids [9].

Automatic Voltage Regulators (AVR's) and Power System Stabilizers (PSS's) have been employed successfully to deal with fast dynamics associated to local oscillations phenomena [6,7,10]. Whereas, inter-area oscillations damping requires remote feedback controllers fed by Wide Area Monitoring Systems (WAMS) [8,11], which in turn basically are built from Phasor Measurement Units (PMÚs) and communication schemes. Although these improvements in the inter-area oscillations behavior have been effective, a new challenge emerges: reaching stability with a closed loop control despite latencies due to measurements taken far away from the control centre [10]. Briefly, the signals travel from each possible source of measurements following the next WAMS path: PMU-PDC-SPDC-Control Centre [12,13], including the corresponding wire or wireless channels. Besides the inherent delay to the feedback procedure, additional delays are added to the transmission signal due to interruptions, re-routing and congestion in the context of cyber contingencies in communication layer [14]. Having said that, the subsequent destabilizing effects in the closed loop control derived from

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Nomenclature

ANN	Artificial Neural Networws
AVR	Automatic Voltage Regulator
HIL	Hardware in the Loop
MPC	Model Predictive Control
MUAS	Most Updated Available State
PDC	Phasor Data Concentrator
SPDC	Super Phasor Data Concentrator
SPB	Sliding Prediction Block
TDT	Time Delay Tolerant
SISO	Single Input Single Output
MISO	Multiple Input Single Output
PMU	Phasor Measurement Unit
PSS	Power System Stabilizers
ROP	Receding Optimization Problem
RFC	Remote Feedback Control
WAMS	Wide Area Monitoring System
R, **Q**, **P**	weighting factors for reference error, control efforts and terminal cost respectively
τ_d	time delay
k	discrete time
t_{PMU}	PMU time stamp
Ts	sample time
Hp	horizon of prediction
$\mathbf{u}(t)$	control signal of the power system
$\boldsymbol{x}(t)$	states of the power system
$\boldsymbol{x}(t-\tau_d)$	delayed states
$\hat{\boldsymbol{x}}(k-\tau_d)$	delayed estimated states
$\Phi_G(\sigma)$	fast dynamic problem
$\Omega_G(\sigma)$	slow dynamic problem
$W_G(\sigma)$	global stability problem
$\Gamma_G(\alpha)$	fast dynamic solution
$\Lambda_G(\sigma,\alpha)$	extended global stability problem

the aforementioned issue, are an important challenge in large scale power systems and have raised the awareness of researchers [1,2,15,16]. The research was motivated by the need for modernization of power systems capable of dealing with control difficulties in centralised WAMS for damping inter-area oscillations caused by latencies in the communication system.

Several promising nonlinear techniques have stablished the path for power systems control [17]. For instance; backstepping has been used to track power reference changes [18,19], feedback linearization allowed the design of closed loop controllers to manage high non-linearity [20,21], and passivity and sliding modes have shown capabilities of rejecting disturbances [22]. Furthermore, a recent work proposes dynamic state feedback controllers adjusting their models by means of significant math efforts to consider nonlinearities due to saturations [23].

In order to handle latencies on power systems, two major approaches have been proposed: latencies managing exclusively with robust controllers, or a combination of controllers with time delay compensators [24]. Robust controllers are usually based on Linear Matrix Inequalities (LMI), H_{inf} norms, ANN as in [16,25–27]; with good results reflected on hardware-in-the-loop (HIL) real-time simulations achieving stability enhancement in power systems with latencies close to *350 ms* [28]. On the other hand, some researchers have proposed compensation based on fuzzy logic, Artificial Neural Networks (ANN), mathematical calculations and Smith predictor. These strategies have shown modest results when the time delay is shorter than *100 ms* [29–32]. Since progress has been reported for the aforementioned values of latencies, efforts should focus on scalability issues and the management of changing operation points [11].

Model Predictive Control (MPC) is a control methodology widely and successfully used in industry applications [33,34]. Thanks to a closed loop feature and permanent update of control law, MPC shows a capability hard to find in the aforementioned traditional linear and nonlinear controllers: the management of both parametric variations related to changing operation points and uncertainties due to limitations of modelling. Hence, MPC is able to fulfil its tasks even if decisions are based on raw models with errors. Given this rare advantage, we made an effort to follow the direction outlined in [35,36,25,37,38,14] for MPC adaptations to power systems control.

This paper proposes a hybrid methodology which splits the main problem in two related but independent blocks: firstly, the control problem (overlooked when applied time compensators), and secondly the time delay problem in closed loop (perfunctorily analyzed when implemented robust schemes). The proposal integrates a robust MPC scheme and a database based time compensation strategy.

The MPC (as the global controller) works in a hierarchical control structure coordinating other decentralised local solutions in order to tackle the nonlinearities, uncertainties, parameter variations, scalability and the multi-time-scale problems. The latter are usually referred to as problems of interaction between local and wide-area controllers [1].

Additionally, the time compensation strategy herein proposed consists in a Kalman based compensator fed by a database which gives access to the Most Updated Available State (MUAS) of the system. Our Kalman compensation strategy obtains the time delay value by computing the difference between the arrival time and the time stamp of the signal. Unlike Smith Predictors, this time compensator does not add instabilities. Our compensation strategy is easy to implement in large scale systems, and its convergence can be guaranteed for a limited set of uncertainties in the model [39,40].

This integrated approach is called Time-Delay-Tolerant Model Predictive Control (TDT-MPC). Coordinated and coherent performance of the two TDT-MPC components (Kalman compensator and MPC) is achieved thanks to unifying power system models for both strategies, as it will be illustrated along the paper.

The paper is organized as follows. Section 2 introduces the model of the problem in general way discussing the complexities and particularities of large power system. Section 3 explains the approach and some of the underlying basis, while Section 4 introduces the results of the implementation in the IEEE 39 nodes test case. Finally, Section 5 presents the conclusions and the main contributions of this paper.

2. Formulation of delayed power system problem

An effective model that allows a better understanding of the delayed power systems should include the latencies in communications, nonlinearity complexities and the interaction problems between local controllers and wide-area controllers [1,2,36]. Our respective math representation begins with the formulation of a basic nonlinear model; once this model is stablished, the subsections proceed to the gradual introduction of the uncertainties, multi-time-scale problem, and the time delay.

2.1. The power system nonlinear model with uncertainties

Eq. (1) presents a compact nonlinear open loop model of a power system, considering the complex nature and the large amount of the devices, as well as the multiple interactions among them [7]. Its outputs are relevant variables such as tie line power flow, frequency or angular deviation. Its inputs can be supplementary signals in some relevant generators. This model also involves large number of state variables [41]: