Control Engineering Practice 74 (2018) 132–143

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Distributed wide-area control of power system oscillations under communication and actuation constraints

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ARTICLE INFO

Keywords:
Distributed control
Wide-area control
Predictive optimization
Oscillation damping
Participation factors

ABSTRACT

In this paper a distributed Model Predictive Control design is presented for inter-area oscillation damping in power systems under two critical cyber–physical constraints — namely, communication constraints that lead to sparsification of the underlying communication network, and actuation constraints that respect the saturation limits of generator controllers. In the current state-of-art, distributed controllers in power systems are executed over fixed communication topologies that are most often agnostic of the magnitude and location of the incoming disturbance signals. This often leads to a sub-optimal closed-loop performance. In contrast, the communication topology for the proposed controller is selected in real-time after a disturbance event based on event-specific correlations of the generator states with the dominant oscillation modes that are excited by that event. Since these correlations can differ from one event to another, so can the choice of the communication topology. These correlations are used to identify the most important sets of generators that must exchange state information for enhancing closed-loop damping of the inter-area modal frequencies. Effectiveness of this strategy is shown via simulations on the 48-machine, 140-bus model for the Northeast Power Coordinating Council.

1. Introduction

Over the past decade, significant increase in transmission expansion and renewable integration in the US power grid have forced power system operators to look beyond the traditional mindset of controlling the grid using local control methods, and transition to wide-area control (WAC) using synchronized phasor measurements available from Phasor Measurement Units (PMUs). One of the most commonly known application of WAC is to improve damping of power flow oscillations in small-signal models of power systems by employing state exchange between distant generators through a wide-area communication network. An enormous literature already exists for damping control of synchronous generators (Boukarim, Wang, Chow, Taranto, & Martins, 2000; Larsen, Sanchez-Gasca, & Chow, 1995; Noroozian, Ghandhari, Andersson, Gronquist, & Hiskens, 2001) using local output feedback via power system stabilizers (PSS) and FACTS devices. These controllers are known to damp fast oscillation modes quite satisfactorily, but they often fail to improve the damping of low-frequency inter-area oscillations (Jain, Biyik, & Chakrabortty, 2015). Recent papers such as (Chakrabortty & Khargonekar, 2013; Chaudhuri & Pal, 2004; Dörfler, Jovanovic, Chertkov, & Bullo, 2014) have shown that WAC can be a promising solution to this problem.

Ideally, WACs can be designed using standard pole placement techniques and state-feedback controllers such as linear quadratic regulators (LQR) (Zolotas, Chaudhuri, Jaimoukha, & Korba, 2007) or Model Predictive Controllers (MPC). Compared to the offline optimal control methods such as LQR, MPC exhibits more robustness to load fluctuations and parametric uncertainties in the grid model as it evaluates the control inputs based on the current state of the system at every time-step (Maciejowski, 2002). It also explicitly incorporates actuator constraints, which is important for WAC as the margin of variation for excitation voltages in supplementary controllers can be significantly limited (Kundur, 1994).

Several works in literature have proposed the use of a single MPC controller in the context of power systems. In Azad, Iravani, and Tate (2013), an MPC controller is proposed to modulate the reference point of a High Voltage Direct Current (HVDC) controller to damp inter-area oscillations. It is noted that HVDC can only be installed on a fixed transmission line, and hence might be less effective in damping oscillations originating from an electrically distant part of the grid. An adaptive version of centralized MPC is proposed in Ye and Liu (2013) which solves the problem of simultaneous control and identification of model parameters using subspace methods. Over recent years, MPC

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https://doi.org/10.1016/j.conengprac.2018.03.003
Received 24 August 2017; Received in revised form 24 February 2018; Accepted 2 March 2018

has also emerged as a popular choice for frequency regulation and load-frequency control (LFC). For example, in Ulbig, Arnold, Chatzivasileiadis, and Andersson (2011) cascaded MPCs are proposed to be deployed for multiple time-scale operations, so as to co-ordinate between the frequency control problem and the long-term power dispatch problem. This approach does not consider contingency scenarios such as faults on transmission lines, which can cause system instabilities. A constrained LFC problem is solved in Vazquez et al. (2014) with MPC, where the objective is to maintain high-frequency deviations in system frequency, caused due to load fluctuations, within acceptable limits. The effect of low-frequency oscillations is not considered. It is noted that all the above MPC methods applied to power systems are centralized methods, and hence do not consider the communication requirements for control.

Nomenclature

Section 2

i	Refers to the ith generator or the ith controller.
n, m	Number of power system states, and number of generators, respectively.
x, u, y	Vector of states, inputs and outputs, respectively.
δ, ω	Generator phase angle in radians and rotor velocity in per unit (p.u.), respectively.
$\acute{E}_q, \acute{E}_d$	q-axis and d-axis voltage behind transient reactances, respectively.
E_{fd}	Field excitation voltage in p.u.
V, I	Bus voltage and current, respectively, in p.u.
κ, M	Refers to the κ^{th} utility area and the number of utility areas, respectively.
$\mathfrak{c}, \mathfrak{p}$	Vector denoting PMU placement costs, and binary vector denoting absence/presence of PMUs.
$\mathcal{N}$	Number of buses in a given area.
$z, \tilde{z}$	Vector of generator algebraic variables, in polar and rectangular co-ordinates, respectively.
$\tilde{\chi}$	Vector of voltage and current measurements from PMU buses, in rectangular co-ordinates.
ϵ	Noise vector for PMU measurements with covariance matrix Σ.
T, k	Discrete-time sampling period and discrete time-step, respectively.

Section 3

$\mathbf{x}, \mathbf{u}, \mathbf{y}$	Vector of linearized states, control inputs and outputs, respectively.
A, B, C	State, control and output matrices for the linearized power system, respectively.
$\mathbf{x}_0$	Vector of post-disturbance linearized states.
$\mathcal{U}$	Linear constraint set for u.
λ, ρ	Eigenvalues and right eigenvectors of A, respectively.
$\bar{\rho}, \bar{\boldsymbol{\rho}}$	Eigenvalue (modal) residues and dominant modal residues, respectively.
$\mathcal{M}$	Modal matrix (matrix of eigenvectors) for A.
G	Represents a single generator node.

Section 4

N	DFT horizon as well as MPC prediction horizon.
$\bar{\mathcal{Y}}, \tilde{k}$	DFT vector with elements $\mathcal{Y}$, and frequency index, respectively.
W_N	DFT matrix with size $(N \times N)$.
Q	SDFT weighting matrix.
β^l, β^r	Left and right edges (in Hz) of the SDFT window, respectively.

Section 5

$\mathbb{P}(X)$	Power set of X, i.e. set of all subsets of X.
$\boldsymbol{\mathcal{A}}$	Represents the set of modal areas $\{\mathcal{A}\}$.
$\mathcal{C}$	Represents a single dMPC controller.
$\mathcal{C}^d, \mathcal{C}^u$	Set of downstream and upstream generators for $\mathcal{C}$, respectively.
p, r	Number of modal areas and number of designed distributed controllers, respectively.
m_d, m_u	Number of generators in $\mathcal{C}^d$ and $\mathcal{C}^u$, respectively.
$X \setminus Y$	Represents a set of elements which belong to set X but not to set Y.

Section 6

$\mathbf{z}, \mathbf{v}, \boldsymbol{\eta}$	Vectors for dMPC states, control inputs and outputs, respectively.
$\mathbf{w}$	Vector of communicated control inputs computed at the previous time-step.
T_z, T_v, T_w, T_η	Binary matrices for selection of $\mathbf{z}, \mathbf{v}, \mathbf{w}, \boldsymbol{\eta}$, respectively.
N_c	dMPC control horizon.
J	dMPC cost function to be minimized.
$\mathbb{Q}, \mathbb{R}, \mathbb{S}$	dMPC cost weighting matrices.
Δ	Operator for taking the difference between values at the current and previous time-steps.

Distributed MPC (dMPC), where multiple spatially distributed MPC controllers are used to satisfy a control objective, has also been proposed recently in literature for designing power system controllers. In various works (Camponogara, Jia, Krogh, & Talukdar, 2002; Franze & Tedesco, 2011; Mc Namara, Negenborn, De Schutter, & Lightbody, 2013; Mohamed, Bevrani, Hassan, & Hiyama, 2011; Negenborn, 2007; Venkat, Hiskens, Rawlings, & Wright, 2008), the LFC problem is solved in a distributed/decentralized manner using dMPC. Constraints are usually imposed on the output system frequency for tight regulation. However, these methods are not directly extendable to the WAC problem due to severe computational requirements for large-scale systems and inability to specifically target the inter-area oscillation modes. For instance, in Venkat et al. (2008) the authors propose multiple iterations for state-feedback communication within a single time-step, whereas in Mc Namara et al. (2013) a particle-swarm optimization method is proposed to reach a global solution with adaptive tuning of weights. Both these approaches will be prohibitive when applying these controllers to a WAC problem because of long communication delays and severe computational requirements. In contrast, the dMPC design proposed in this paper promotes communication sparsity for control while also successfully damping inter-area oscillations. A general review of dMPC designs can be found in Christofides, Scattolini, de la Pena, and Liu (2013).

To highlight the novelty of the proposed approach in this paper, it is noted that all of the above mentioned control schemes also suffer from either one or both of the following two additional drawbacks. First, they lead to a dense all-to-all communication topology between the generators amounting to a centralized implementation, and second, they are designed offline based on nominal models of the power system that are most often agnostic of where a disturbance may occur, or how this disturbance may impact the inter-area oscillations. In a recent paper (Jain, Chakrabortty, & Biyik, 2017) a sparse LQR controller was designed to counteract both of these drawbacks. In this paper that design is extended to a completely online MPC strategy that accommodates additional constraints on actuation. The oscillation damping problem is posed in terms of minimizing a quadratic objective function of the generator frequencies over a chosen time-horizon. A sparse state-feedback controller is developed to minimize this function following a disturbance in the grid with the sparsity pattern of the underlying communication