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Comparison of centralized, distributed and hierarchical model predictive control schemes for electromechanical oscillations damping in large-scale power systems

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ABSTRACT

The paper investigates the feasibility of applying Model Predictive Control (MPC) as a viable strategy to damp wide-area electromechanical oscillations in large-scale power systems. First a fully centralized MPC scheme is considered, and its performances are evaluated first in ideal conditions and then by considering state estimation errors and communication delays. This scheme is further extended into a distributed scheme with the aim of making it more viable for very large-scale or multi-area systems. Finally, a robust hierarchical multi-area MPC scheme is proposed, introducing a second layer of MPC based controllers at the level of individual power plants and transmission lines. Simulations are carried out using a 70-bus test system. The results reveal all three MPC schemes as viable solutions to supplement existing controllers in order to improve the system performance in terms of damping. The hierarchical scheme is the one combining the best performances in nominal conditions and the best robustness with respect to partial component failures and various modeling and measurement errors.

1. Introduction

Some characteristics of modern large-scale electric power systems, such as long transmission distances over weak grids, highly variable generation patterns and heavy loading, tend to increase the probability of appearance of sustained wide-area electromechanical oscillations. The term "wide-area" is used here to emphasize the possible co-existence of local and inter-area oscillation modes of different frequencies that might appear simultaneously in different parts of large-scale systems. Such oscillations threaten the secure operation of power systems and if not controlled efficiently can lead to generator outages, line tripping and large-scale blackouts [1–3]. Current automatic control systems, designed to address low-frequency oscillations, are mostly based on very local control strategies realized through Power System Stabilizers (PSSs) and FACTS devices.

The emergence of new technological solutions such as synchronized phasor measurement devices and improved communication infrastructures enable the development of Wide Area Measurement Systems (WAMS) [4] and the design of new types of controllers [5]. Such controllers may be designed from the perspective of the whole system, focus on a wider spectrum of oscillation modes and offer improvements with respect to current local control strategies.

In this paper, such controllers to damp power system electromechanical oscillations are proposed, based on the following observations:

- The control rules and parameters of current automatic control systems are usually fixed and determined in off-line studies using time-domain simulations, Prony or eigenanalysis [1,3], and are based on local voltages, generator speeds or line powers as inputs. Increasing uncertainties brought by renewable generation, and the growing complexity resulting from new power flow control devices, make the robustness of these designs become questionable, yielding the need for more efficient, adaptive, and more widely coordinated control schemes.
- A promising option would be a control strategy able to automatically adjust its control actions to the changing nature of the system. Since power system dynamics can be quite accurately modeled [4], and given the recent progresses in large-scale optimization, a natural idea is to apply MPC [6] to design such control strategies.
- MPC is a proven technique with numerous real-life applications in different engineering fields [7] and it may be designed in different ways: centralized [6], distributed [8,9] and hierarchical [9].
- Among existing MPC formulations [6,7], those proven in other fields [7], i.e. linear MPC formulation, should be considered first.

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In this work, a series of MPC controllers is considered, which can be activated by faults or special local states, or run all the time. These MPC controllers collect system states at a given time interval, compute supplementary control inputs for existing damping controllers, like PSS and Thyristor Controlled Series Compensator (TCSC), and superimpose these supplementary inputs on these devices' own inputs in order to optimize and coordinate their control effects. Three different MPC schemes are considered (centralized, distributed, and hierarchical), and their performances are compared on a medium sized power system.

The rest of the paper is organized as follows. After a synthetic review of previous works in Section 2, Section 3 describes the linear MPC formulation that we use, and Section 4 proposes three different control architectures. The used test system and simulation parameters are given in Section 5, while results are discussed in Section 6. Section 7 offers some conclusions.

2. Related works

MPC considerations in power systems include security constrained optimal power flow [10], coordinated secondary voltage control [11], thermal overload alleviation [12,13], voltage control [14–16], transient stability [17], oscillations [18–24], and automatic generation control [25,26]. The works dealing with MPC applications to control electromechanical oscillations of power systems can be broadly classified into the three categories discussed below.

MPC to control a single device. One of the earliest applications is presented in [20] where generalized predictive control [6] is used to switch capacitors for damping power system oscillations. The control is computed by minimizing a quadratic cost function combining local system outputs and rates-of-change of control over the prediction horizon. An MPC for step-wise series reactance modulation of a TCSC to stabilize electromechanical oscillations is presented in [21], where a reduced two-machine model of the power system is used and updated using local measurements. Defining deviations of the predicted outputs from references and control input increments as an objective function, Ref. [22] proposed a model predictive adaptive controller based on an equivalent model to damp inter-area oscillations in a four-generator system.

Centralized system-wide MPC. Refs. [18,19] present a wide-area MPC to control low-frequency oscillations. A bank of linearized system models is used with the assumption that the actual system response can be represented by a suitable combination of a finite number of linearized models. For each model in the bank an observer-based state feedback controller is designed a priori and MPC is formulated to optimize the weights for individual controllers in the bank. An MPC scheme introduced in [23] coordinates local control devices (PSS, TCSC, and static var compensators (SVC)) to damp wide-area electromechanical oscillations. The MPC scheme is based on a linearized discrete-time state space model of the power system combined with a quadratic objective function.

Distributed multi-area MPC. Distributed MPC for electromechanical oscillations damping is considered in [24]. The problem is formulated using a context-driven decomposition of control areas. An MPC controller is assigned to each control area and three coordination schemes are considered: an implicit scheme where the overall system stability emerges from individual MPC controllers, and two explicitly coordinated ones.

The approaches considered in this paper put their emphasis on the need to coordinate existing damping controllers in the least intrusive way and propose the MPC approach as a paradigm for coordination. This work extends previous ones of the same authors [23,24] by introducing a hierarchical MPC control scheme and showing its superior performances through comparison with two other MPC based schemes and by considering the centralized MPC as the benchmark.

3. Generic MPC framework formulation

The principle of MPC can be shortly summarized as follows. At any time, the MPC algorithm uses the collected measurements, a model of the system and a specification of the control objective to compute an optimal open-loop control sequence over a specified time horizon. The first-stage controls are applied to the system. At the next time step, as soon as measurements (or model) updates are available, the entire procedure is repeated by solving a new optimization problem with the time horizon shifted one step forward [6]. In this section, MPC formulation is first provided in terms of the model (prediction equations) and optimal control problem (objective function and constraints). Then a way to take into account data acquisition errors and time delays due to computation and communication resources, is proposed.

3.1. Discrete time linearized dynamic system model

MPC algorithms, considered in this work, are based on a state-space model of a multi-machine power system in the form of the following linearized continuous time model:

$$\begin{cases} \dot{x} = A_c x + B_c u \\ y = C_c x \end{cases} \tag{1}$$

where $x \in R^{m_x}$ is a vector of state variables modeling also the already existing controllers, $u \in R^{m_u}$ is a vector of supplementary MPC inputs, and $y \in R^{m_y}$ is a vector of performance measurements used by MPC (outputs).

Next, from Eq. (1) the transition at time t for a small step of δ seconds is inferred by [6]:

$$\begin{cases} x(t+\delta) = (\delta A_c + I)x(t) + \delta B u(t) \\ y(t) = Cx(t) \end{cases} \tag{2}$$

yielding a discrete-time dynamic (for time steps $t + i\delta$) given by:

$$\begin{aligned} & x[i+1] = Ax[i] + Bu[i]; \\ & y[i] = Cx[i]. \\ & \text{with}: A = \delta A_c + I; B = \delta B_c; C = C_c. \end{aligned} \tag{3}$$

3.2. MPC formulation as a quadratic programming problem

At time $t = k\Delta t$ (system states are collected every Δt seconds), based on the estimation $\hat{x}(k\Delta t) = \hat{x}[k|k]$ of the current system states and on the system model, the predicted output $\hat{y}(k\Delta t + i\delta) = \hat{y}[k+i|k]$ over the next horizon $N_i\delta$ is obtained by iterating Eq. (3) i times, $i = 0, 1, 2, \ldots N_i - 1$.

$$\begin{bmatrix} \hat{y}[k+1|k] \\ \hat{y}[k+2|k] \\ \vdots \\ \hat{y}[k+N_i|k] \end{bmatrix} = P_x \hat{x}[k|k] + P_u \begin{bmatrix} u[k|k] \\ u[k+1|k] \\ \vdots \\ u[k+N_i-1|k] \end{bmatrix} \tag{4}$$

where P_x and P_u are given by

$$P_x = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_i} \end{bmatrix}, \quad P_u = \begin{bmatrix} CB & 0 & \ldots & 0 \\ CAB & CB & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{N_i}B & CA^{N_i-2}B & \ldots & CB \end{bmatrix}$$

Using these equations, the following quadratic optimization problem is solved at every time step [6]: