



Efficient implementation of MPC-based AGC for real-world systems with low inertia

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ABSTRACT

The paper discusses practical implementation and computational aspects of an AGC scheme based on model predictive control (MPC) for a real-world power system, namely the all-island Irish transmission system. This system is particularly interesting from the frequency regulation point of view due to the high penetration of wind power generation. This leads to a significant reduction in system inertia, which in turn impacts on the ability of the system operator to regulate the system frequency. The paper compares the performance of the MPC-based AGC with a conventional AGC based on PI controllers and draws relevant conclusions. The case study is a high-resolution simulation of a 1479-bus model of the Irish electrical grid with significant wind penetration, stochastic loads, and controller delays.

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1. Introduction

1.1. Motivation

Current implementations of primary and secondary frequency regulation of power systems rely on the inertia of synchronous machines and control characteristics of conventional power plants [1]. As renewable penetration levels increase in grids, tight frequency regulation becomes increasingly difficult [2,3]. While primary control gains are typically designed to be fixed and local in nature, secondary control algorithms are capable of using global system information to determine the control inputs to send to generators. By improving control coordination mechanisms it is possible to improve frequency regulation.

Model predictive control (MPC) appears as a promising technique to improve frequency control and has been considered in recent years in several studies [4,9–12,15–18]. However, computational and implementation issues related to MPC have often been pointed to as the most serious constraint facing its practical implementation. As a matter of fact, the current literature only considers small- and medium-size cases studies. This paper deals with an efficient and realistic implementation of an MPC-based AGC and considers a real-world power system, namely a 1479-bus model of the all-island Irish transmission grid, with a high penetration (up to 55%) of non-synchronous generation.

1.2. Literature review

Model predictive control (MPC) is a MIMO optimization based control technique that uses state-space predictions in order to formulate optimal inputs to a system. MPC is a mature technology at this stage having originally been developed in the 1980s. It is used in a widespread fashion in the process industry and is available in a number of commercial packages such as ABB's 3dMPC, AspenTech's Dynamic Matrix Control (DMC), and Pavilion Technologies Inc.'s Process Perfector products [6]. In recent years many researchers have considered power systems control in an optimal control framework [7,8]. MPC has been applied previously for centralised [4,9–13], hierarchical [14], and non-centralised [15–17,19] control in power systems for AGC and other applications. It has been shown to offer improved frequency regulation performance and robustness to uncertainty when compared to standard PI control [4,20].

When states are not measurable for use in MPC, they can be estimated using an optimal state estimator called a Kalman filter. Kalman filtering is also a mature technology at this stage having originally been developed by Kalman and Bucy in the 1960s. It is used for a wide variety of applications in industry, most famously being used by NASA as part of the Apollo project to aid the navigation of manned spacecraft going to the moon and back [21]. A range of Kalman filters have been proposed for power system state estimation [22–24].

One of the main issues with most implementations of MPC for power systems control is the scale and realism of the power system considered. Typically relatively small scale power systems with less

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than 50 buses are considered, and the power systems used for studies are usually not derived from real life grid configurations. There are a number of notable exceptions in the literature. MPC has been used to control Voltage Source Converter based devices embedded in models of the European and British grids in [11,25], respectively.

Advanced MPC control strategies were used for applying distributed voltage control and centralized AGC to the Nordic 23-generator system model in [12,9]. In [26] advanced MPC is used to penalise deviations from dispatch setpoints considering a range of constraints, and is applied to a large scale model of the Californian system. It should be noted that while [9] considers transient dynamics, only the long term thermal line dynamics are considered in [26], with the remaining variables considered at a linearised power flow level.

1.3. Open challenges with MPC for AGC

1.3.1. AGC for low-inertia systems

As synchronous machines are replaced in power systems, and there is a consequent decrease in system inertia and increase in generation uncertainty, tight frequency regulation becomes more difficult. Thus, it is of interest to investigate the performance of MPC for AGC in large-scale realistic power systems with large renewable penetrations, and low levels of system inertia. This, in turn, would provide evidence as to whether MPC could aid in allowing larger penetrations of renewable sources on grids, when compared to standard PI approaches.

1.3.2. Practical implementation of MPC-based AGC

While [9] illustrates the application of state-of-the-art control techniques for AGC, the authors are skeptical as to how such state-of-the-art techniques would be accepted in industry. Given the conservativeness of practitioners in the power systems industry, if MPC were to be used in industry, it is hard to imagine that such complex versions of MPC would be initially embraced, given that simple PI or manual control is used in practice for AGC in most power systems today. It is also desirable in lower inertia grids with small time constants that the control would be computed efficiently. Simple, linear MPC using Kalman filtering for state estimation can be computed in a highly efficient manner and so it is of interest to see how well these algorithms perform in achieving control of the system.

1.3.3. Fast prototyping of MPC-based control schemes

Another barrier to practitioners as regards evaluating the performance of MPC for power systems control is that, to the best of the authors' knowledge, there is no power systems simulation package currently available that provides an integrated MPC toolbox. Given the recent popularity of MPC for use in power systems, and that the setup of MPC controllers involves significantly more effort than that associated with PI controllers, it is desirable that integrated MPC functionality would be incorporated into power systems simulation packages. In turn this could significantly improve the efficiency with which MPC can be set up for evaluating the application of MPC for power systems control.

1.4. Contributions

The paper deals with the three challenges discussed above. The main contributions of the paper are as follows.

- A discussion on an efficient implementation of MPC for real-world grids with low levels of inertia and a large stochastic renewables penetration. With this aim, a 1479-bus model of the Irish transmission system is utilised in the case study.
- A discussion on practical implementation aspects of the MPC-based AGC scheme, including an efficient Kalman filtering

approach for state estimation. The Kalman filter is based on measurements of the individual generator frequency and rotor position. Using modern PMUs and communication systems, it is increasingly possible for TSOs to attain such measurements. A comparison of the performance of MPC-based and conventional PI-based AGC schemes is also provided.

- An MPC software implementation based exclusively on state-of-art mathematical libraries, such as Gurobi and SuiteSparse. The MPC toolbox is then integrated in the Dome simulation package [27]. The authors believe that the developed software tool can greatly help with the fast prototyping of MPC-based control techniques for power systems applications and are happy to share the code with the interested readers.

1.5. Organization

The rest of the paper is constructed as follows: Section 2 outlines the power system modelling, focusing in particular on the synchronous generators that are used for AGC. In Section 3, the MPC and Kalman filtering approaches used in this paper are explained. Then, in Section 4, the way in which MPC is applied for AGC is given. The results of the simulations comparing the PI and MPC approaches when used for AGC on the Irish grid are given in Section 5. Finally, in Section 6 conclusions are drawn based on the results of the paper.

2. Power system modelling for simulation

Various load, synchronous generator, turbine, wind turbine models, etc., are used in this paper. Full details of the dynamics of all these models can be found in [28]. Due to space constraints in depth details of all of these models are not documented here.

Wind turbines provide the source of stochastic power production in this paper. Wind speeds are modelled using a Weibull distribution, where a Rayleigh distribution is used to model time variations in wind speed. The test case considered in this paper is the Irish grid. The Weibull distribution is used here based on the accuracy with which Irish wind speeds were described previously using this distribution [29]. However, care should be taken to ensure that suitable wind distributions are applied to different grids. For example, wind power variability was found to have a Laplacian distribution in some North American power systems in [30]. Two types of wind turbines models are used: Constant Speed and Doubly Fed Induction Generator Wind Turbines (CSWT and DFIG, respectively). The CSWT is described by a 5th-order squirrel-cage induction generator model, a turbine model without pitch control, a single-mass shaft model with tower-shadow effect, and a static capacitor bank. The DFIG is a variable-speed wind turbine described by a 5th-order doubly-fed induction generator model, a double-mass elastic shaft model with tower-shadow effect, a turbine model with continuous pitch control, a cubic maximum power point tracking approximation, a first-order Automatic Voltage Regulator (AVR) model, and a converter active power controller. When loads are deterministic, constant PQ models are used in simulations. For the cases involving stochastic PQ loads, Ornstein–Uhlenbeck processes are then used to model the loads [31].

The synchronous generator model is documented in detail in the following, as the controllers in this paper are used to control synchronous generators and so it is directly relevant to the design of the control system. A 6th order dynamic model is used to capture the relevant dynamics of the synchronous generator for simulation purposes as follows:

$$\dot{\delta} = \Omega_b(\omega - \omega_s), \quad (1)$$

$$2H\dot{\omega} = (\tau_m - \tau_e - D(\omega - \omega_s)), \quad (2)$$

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