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Distributed MPC for frequency regulation in multi-terminal HVDC grids

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ABSTRACT

Multi-Terminal high voltage Direct Current (MTDC) transmission lines enable radial or meshed DC grid configurations to be used in electrical power networks, and in turn allow for significant flexibility in the development of future DC power networks. In this paper distributed MPC is proposed for providing Automatic Generation Control (AGC) in Alternating Current (AC) areas connected to MTDC grids. Additionally, a novel modal analysis technique is derived for the distributed MPC algorithm, which in turn can be used to determine the convergence and stability properties of the closed-loop system.

1. Introduction

High Voltage Direct Current (HVDC) links provide significant advantages over Alternating Current (AC) links for transferring electrical energy over large distances (Kundur, 1994). Traditionally HVDC systems have consisted of point to point links that connect two individual AC areas. HVDC links based on Line Commutated Converter (LCC) technology enabled the construction of HVDC grids where a number of individual HVDC lines are connected to an individual HVDC terminal, thus enabling the construction of Multi-Terminal HVDC (MTDC) grids. However, with HVDC LCC power flows in the lines are unidirectional, which limits the flexibility of LCC based MTDC grids. Voltage Source Converter (VSC) technology, on the other hand, allows for the construction of MTDC grids that support bidirectional power flows (Chaudhuri, Chaudhuri, Majumder, and Yazdani, 2014). In turn VSC HVDC based MTDC grids enable the construction of large meshed or radial DC grids such as the planned European “Supergrid”, which will be capable of integrating large quantities of renewable energies over vast geographical distances (Van Hertem and Ghandhari, 2010). These grids will be capable of providing a range of ancillary services to AC networks.

As DC connections to AC grids increase there is a consequential loss in inertial response in the AC systems. To counter this, it is therefore of interest to employ frequency control to make DC connections react to frequency imbalances in a similar fashion to AC systems (Chaudhuri et al., 2014). Furthermore, allowing the DC system to react to frequency imbalances in this way decreases the necessity for additional primary and secondary frequency control reserves in AC areas connected to DC grids, as it is possible to share reserves over large distances via the DC grid (Dai, 2011). The provision of frequency control to AC areas is therefore of particular interest.

Thus far in the literature a number of different primary frequency control algorithms, which act on the milliseconds scale to counteract disturbances, have been developed (Chaudhuri,

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Majumder, and Chaudhuri, 2013; Dai, Phulpin, Sarlette, and Ernst, 2012; Egea-Alvarez, Bianchi, Junyent-Ferre, Gross, and Gomis-Bellmunt, 2013; Silva, Moreira, Seca, Phulpin, and Peas Lopes, 2012). By necessity these algorithms act using local information only, in a decentralised fashion, so as to be less susceptible to the effects of communication delays, as communication delays can result in instability in the primary control loop (Andreasson et al., 2013; Dai, Phulpin, Sarlette, and Ernst, 2010). Typically, these methods act by manipulating the DC voltage or current in response to the local frequency error signal.

While these primary control techniques counteract the initial effects of disturbances, it is necessary to employ some form of integral action in order to provide long term frequency regulation. Traditionally, in AC networks this has been conducted using Automatic Generation Control (AGC), which acts on the seconds to minutes scale in order to regulate frequencies. Decentralised PI based methods have been proposed recently for this purpose (Chaudhuri et al., 2014; Dai, 2011; Egea-Alvarez et al., 2015) and an optimised PID method was proposed in de Courreges d'Ustou (2012).

Transmission System Operators (TSOs) are responsible for the balancing of the electricity supply to match demand across power grids. Different sections of large power systems, such as the European grid, are controlled by separate TSOs. These TSOs conduct AGC across the interconnected grid in a decentralised fashion without using inter-TSO communication (ENTSO-E, 2004; Kundur, 1994). Two issues arise from the perspective of control design here. First of all, the poor performance of traditional decentralised PI based methods for AGC in modern power systems has been noted. The Nordic grid provides an illustrative example, where with increased penetration of renewable sources, and under traditional PI frequency control, there has been a noticeable increase in frequency violations in recent years (Ersdal, Imsland, and Uhlen, 2015). Secondly, it is well known that in highly interconnected networks decentralised control can result in highly sub-optimal performance and can potentially be a source of instability (Venkat, 2006). This decrease in performance arises as a result of ignoring the effects of interactions between interconnected areas when formulating control actions. Thus, when designing AGC for MTDC grids, optimal controllers are of interest, as well as those capable of considering the interactions between different subsystems when formulating control inputs, as a means of improving control performance.

Model Predictive Control (MPC) (Maciejowski et al., 2002) algorithms enable the optimal control of a system based on the use of state-space predictions. In recent years, there has been extensive research in the field of distributed MPC (Maestre and Negenborn, 2014). Here a number of controllers, called control agents, are responsible for the control of separate interconnected subsystems in a system, and through inter-agent communication, it is possible for them to collectively achieve a performance that approximates that of a centralised MPC controller. Additionally, in certain cases distributed MPC controllers can be shown to provide stable control in situations where equivalent communication free decentralised control causes system instability due to the presence of large interconnection coefficients between interconnected subsystems (Venkat, 2006). Distributed MPC methods have been shown to improve controller performance for AGC performance in AC networks (Kennel, Gorges, and Liu, 2013), and also in many other power systems applications (Arnold, Negenborn, Andersson, and De Schutter, 2009; Hermans et al., 2012; Ma, Chen, Liu, and Allgöwer, 2014; Moradzadeh, Boel, and Vandevelde, 2013). Previously a framework for the use of MPC for the control of MTDC grids was proposed in Mc Namara, Meere, O'Donnell, and McLoone (2015), where Centralised MPC (CMPC) and communication free decentralised Selfish MPC (SMPC) were proposed for the control of MTDC grids. Given distributed control algorithms can outperform decentralised communication free approaches, it is of interest to investigate distributed MPC for AGC in MTDC grids.

Many different schemes have been proposed for implementing distributed MPC (Maestre and Negenborn, 2014). Non-iterative schemes, where agents exchange information only once per sample step, were presented in Camponogara, Jia, Krogh, and Talukdar (2002), Liu, Chen, Muñoz de la Peña, and Christofides (2010), and Hermans, Lazar, and Jokic (2010). There are also many iterative distributed MPC methods that have been developed based on game-theoretic approaches that search for optimal equilibria (Sanchez, Giovanini, Murillo, and Limache, 2011, chap. 4; Li, Zhang, and Zhu, 2005; Zhang and Li, 2007). Other decomposition-coordination based iterative methods decompose the original control problem into several smaller optimisation problems and use communication between agents to coordinate their solutions. Examples of decomposition methods include Jacobian decomposition (Venkat, 2006), Bender's decomposition (Andan, Bourdais, Dumur, and Buisson, 2010), and the Alternating Direction Method of Multipliers (ADMOM) (Farokhi, Shames, and Johansson, 2014; Negenborn, De Schutter, and Hellendoorn, 2008).

A number of distributed MPC algorithms are based on the decomposition of a centralised augmented Lagrangian MPC formulation into subproblems which are coordinated via the updating of the dual variables (Farokhi et al., 2014; Giselsson et al., 2013; Negenborn et al., 2008). The Auxiliary Problem Principle (APP) can be used to decompose a centralised augmented Lagrangian problem such that it can be solved in parallel via a number of subproblems in an iterative fashion (Royo, 2001). In Negenborn et al. (2008) a parallel distributed MPC method was proposed based on the APP.

Typically in power systems, for applications such as AGC, state and input constraints are not explicitly considered in control calculations. Usually an unconstrained control law is used for control, and approaches such as input saturation are used to maintain constraints (Kundur, 1994). The use of fixed feedback gains in turn allows the eigenvalues of the system to be determined, which can be used to find the system's modes of oscillation and their relationship with the various system states (assuming inputs and states are not subject to inequality constraints). It is therefore important that eigenvalue analysis techniques are developed for distributed MPC, in order to encourage their adoption in the power systems industry.

While a non-centralised control structure may be preferable for real-time control of power systems, in practice it is still typical for there to be a coordinating control layer that analyses the oscillatory modes in the system and that caters for issues such as stability and tuning. For instance, the European Network of Transmission System Operators for Electricity (ENTSO-E) is the body responsible for coordinating the actions of the various interconnected TSOs on the European electricity grid. Additionally, while control is usually conducted over short times scales, i.e. seconds to minutes, the tuning of controllers can be carried out over significantly longer periods such as hours or days. Therefore, it is reasonable to expect that modal analysis of the closed-loop system could be carried out at a central hub.

Unconstrained methods for modal analysis of distributed MPC have been developed previously (Li et al., 2005; Vaccarini et al., 2009; Zhang and Li, 2007; Zheng et al., 2013). Typically, while these techniques invoke the use of constant feedback gains coupled with centralised eigenvalue analysis, the derivation of the controllers relies on game theory or other non-Lagrangian optimisation formulations. There are several advantages to using decomposed Lagrangian techniques for distributed control. Many control practitioners are already familiar with Lagrangian optimisation theory and so would already be familiar with the theory