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Control strategies for automatic generation control over MTDC grids

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ABSTRACT

Increasingly in power systems, there is a trend towards the sharing of reserves and integration of markets over wide areas in order to enable increased penetration of renewable sources in interconnected power systems. In this paper, a number of simple PI and gain based Model Predictive Control algorithms are proposed for Automatic Generation Control in AC areas connected to Multi-Terminal Direct Current grids. The paper discusses how this approach improves the sharing of secondary reserves and could assist in achieving EU energy targets for 2030 and beyond.

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1. Introduction

It is recognised that a significantly higher share of renewable energy production is necessary to improve the competitiveness, security, and sustainability of energy systems across the world. Reflecting this, for example, the EU has set a goal of 27% renewable energy penetration, to be achieved collectively across Europe by 2030, which is an increase of 7% on the 2020 target (European Commission, 2014). However, stochastic, intermittent sources such as wind and solar can cause issues from a grid reliability perspective, and usually the areas most suited to the harvesting of such renewables are located far away from the location of the largest loads. By sharing these sources over a wide area, the stochasticity of the individual sources can be aggregated, improving the overall predictability and stability of the energy supply. Thus the development of suitable transmission networks is vital for the integration of these renewables (European Commission, 2014; Houghton et al., 2012). In Europe, an interconnected grid or "Supergrid" which would facilitate access to variable renewable sources across the continent, such as wind from the North of Europe and solar from the South of Europe and North Africa, has thus received widespread attention (Van Hertem & Ghandhari, 2010). In particular, the North Sea offshore grid is of note, where the combination of the large offshore wind capacity in this area and the hydro storage capacity available in Norway make it a likely candidate as a starting point for Europe's first offshore DC grid (Chaudhuri, Chaudhuri, Majumder, & Yazdani, 2014; Spro, Torres-Olguin, & Korps, 2015).

High Voltage Direct Current (HVDC) transmission facilitates the transfer of large quantities of electrical power over long distances by utilising Direct Current (DC) power transmission (Kundur, 1994). Most HVDC lines are point – to – point lines that transfer energy between only two Alternating Current (AC) areas, with a converter on each side. Modern Voltage Source Converter (VSC) based HVDC technologies allow a number of HVDC lines to be connected to a single DC grid terminal (de Courreges d'Ustou, 2012). Thus Multi – Terminal HVDC (MTDC) grids can be constructed, which consist of a radial or meshed HVDC grid with a number of connections to AC grids. Consequently, this facilitates the sharing of energy reserves over large areas and subsequently there has been much interest in developing coordinated control methods which allow power injections to and from the MTDC grid to support frequency control in connected AC areas. The world's first VSC – based MTDC grid, the Zhoushan MTDC grid in China, was put into operation in July 2014 (Tang, He, Pang, Huang, & Zhang, 2015).

A number of primary control algorithms, which operate on the milliseconds to seconds scale, and secondary control algorithms,

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Abbreviation: AC, Alternating Current; AGC, Automatic Generation Control; CMPC, Centralised MPC; DC, Direct Current; HVDC, High Voltage Direct Current; MPC, Model Predictive Control; MTDC, Multi-Terminal HVDC; (controller)-NVO, Controller with No Voltage Offsets; PFC, Primary Frequency Control; ROCOF, Rate Of Change Of Frequency; SMPC, Selfish MPC; VSC, Voltage Source Converter; (controller)-WVO, Controller With Voltage Offsets.

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which act on the seconds to minutes scale, have been developed for MTDC grids, typically for the regulation of the voltages and DC grid power transfers (Andreasson et al., 2013; Arags-Pealba, Egea-lvarez, Galceran Arellano, & Gomis-Bellmunt, 2014; Beerten & Belmans, 2013; Egea-Alvarez, Beerten, Van Hertem, & Gomis-Bellmunt, 2012, 2013; Hendriks, Paap, & Kling, 2007; Zonetti, Ortega, & Benchaib, 2014). A range of primary control algorithms exist for sharing power between areas. Techniques such as voltage margin control, droop control, ratio and priority control are used to regulate both the DC voltages and power transfers on the DC grid. In addition to these fixed controllers, adaptive droop controllers have been developed that incorporate the remaining reserves in an area into the droop gain calculation for that area, so as to adaptively change the primary reserve contributions of a particular HVDC terminal (Chaudhuri et al., 2014).

Primary Frequency Control (PFC) algorithms have also been proposed for the sharing of primary reserves over MTDC grids in order to collectively regulate the frequencies in AC connected areas (Chaudhuri, Majumder, & Chaudhuri, 2013; Dai, Phulpin, Sarlette, & Ernst, 2012; Silva, Moreira, Seca, Phulpin, & Peas Lopes, 2012; Wiget, Andersson, Andreasson, Dimarogonas, & Johansson, 2015). Communication based PFC methods can be non−robust to communication delays or failures (Dai, Phulpin, Sarlette, & Ernst, 2010) and hence a number of droop methods that do not rely on communication between areas have been proposed. These operate by manipulating the DC voltages on the grid in a decentralised fashion in order to regulate the power flows into or out of AC areas and the MTDC grid.

As with the case of decentralised PFC in AC areas, it is necessary to provide secondary frequency control, usually referred to as Automatic Generation Control (AGC) so as to satisfy long−term frequency regulation goals across areas connected to MTDC grids. A number of decentralised PI−based AGC strategies have been proposed previously for MTDC systems in Dai (2011) and Chaudhuri et al. (2014), while a centrally optimised PID−based method was proposed in de Courreges d'Ustou (2012).

Model Predictive Control (MPC) (Maciejowski, 2002) algorithms enable the optimal control of a system based on the use of state−space predictions. MPC has been used previously for the control of HVDC systems (Azad, Iravani, & Tate, 2013; Fuchs, Imhof, Demiray, & Morari, 2014; Mariethoz, Fuchs, & Morari, 2014) and has also been applied to power systems for AGC (Ersdal, Imsland, & Uhlen, 2016; Ersdal, Imsland, Uhlen, Fabozzi, & Thornhill, 2016; Ma, Chen, Liu, & Allgöwer, 2014; Mohamed, Morel, Bevrani, & Hiyama, 2012; Shiroei & Ranjbar, 2014; Shiroei, Toulabi, & Ranjbar, 2013; Wang, Glavic, & Wehenkel, 2014). There are a number of advantages to the use of MPC versus PI controllers. MPC offers a systematic methodology for handling the control of MIMO systems. Control is implemented via the minimisation of a weighted sum of different cost functions which represent the various control goals of the system. As a result the tuning of MPC controllers is highly intuitive as users have only to change the weights assigned to each of these goals to achieve the desired performance. As MPC is based on optimisation, constraints can be systematically included in the control formulation. While MPC can be susceptible to problems such as model uncertainty and noise, it typically offers improved robustness in comparison to PI controllers. Finally, once an MPC framework has been derived for the control of a system, it is possible then to combine a vast range of techniques from both the control and optimisation literature in order to control the system as desired.

Given the widespread use of linear analysis in power systems, it is desirable to develop linear MPC algorithms for use in power systems. Thus in this paper, a number of simplified linear gain based MPC controllers are proposed for use with AGC for MTDC grids. Also, by keeping these algorithms as simple as possible it encourages their adoption by industry based practitioners.

The use of additional secondary voltage offsets is also investigated in this paper. These act as a means of improving the control of DC voltages on a long−term basis, thus giving TSOs increased flexibility in terms of how secondary reserves may be shared between AC areas, with the aim of improving the efficiency with which secondary reserves are used over the entire electrical grid.

Thus the following controllers are proposed for the control of the MTDC system:

- Firstly, decentralised PI controllers With Voltage Offsets (PI−WVO) and decentralised PI controllers with No Voltage Offsets (PI−NVO) are considered (hereafter WVO and NVO will be used to denote controllers with and without voltage offsets, respectively).
- Then, two Centralised MPC (CMPC) controllers, CMPC−WVO and CMPC−NVO, are designed.
- Finally, based on the centralised MPC design two decentralised Selfish MPC (SMPC) controllers, SMPC−WVO and SMPC−NVO, are derived.

The proposed MPC design approaches for AC frequency control of areas connected to the DC grid are, to the authors' best knowledge, novel.

The remainder of the paper is organised as follows; the modelling and PFC of the MTDC grid is presented in Section 2, and the PI based strategies for AGC are introduced in Section 3. The centralised and decentralised MPC approaches are introduced in Sections 4 and 5, respectively. Section 6 then shows how AGC can be achieved using MPC. Results of a simulation study are given in Section 8 and, finally, conclusions are presented in Section 9.

2. Modelling and primary frequency control for multi-terminal HVDC grids

A MTDC grid is composed of a DC grid and N AC areas, each with a converter which serves as an interface for transferring power to and from the DC grid, as in Fig. 1 (Sarlette, Dai, Phulpin, & Ernst, 2012). Each AC area i, for $i = 1, 2, \ldots, N$, has a state vector

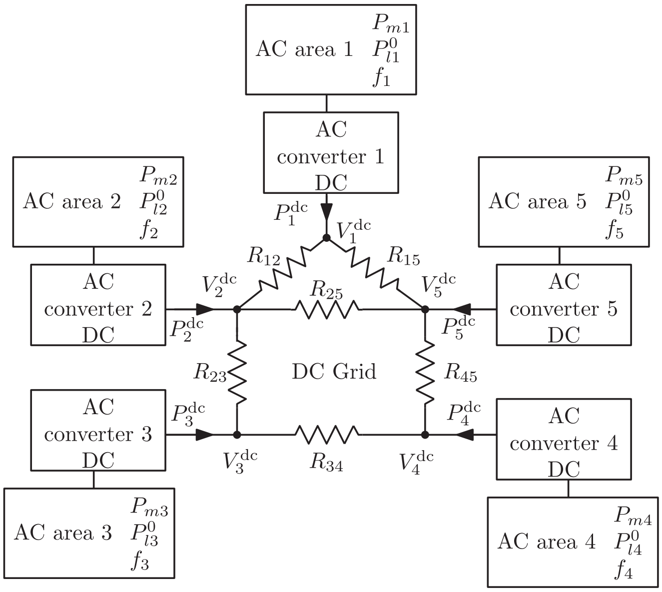

Fig. 1. A multi-terminal DC grid connecting $N=5$ AC areas via converters (Sarlette et al., 2012).

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