MPC based AGC for AC/DC grids with delays and voltage constraints

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***Abstract*—Multi-terminal HVDC (MTDC) grids have been cited as a means of efficiently sharing renewables over wide areas, such as the European grid. As these grids proliferate it is of interest to include these grids in frequency regulation. Here Model Predictive Control is presented as a means of using MTDC grids to aid in Automatic Generation Control (AGC) while considering delays and regulating DC voltages within bounds.**

I. Introduction

In grids worldwide, it is recognised that the sharing of electrical energy resources over wide areas can pose significant advantages. An example of this is the proposed development of the European "Supergrid" which has the potential to allow the sharing of renewable resources across the continent [1]. High Voltage Direct Current (HVDC) grids in particular are seen as an enabling technology for sharing these resources as they allow the transfer of large volumes of electricity with low losses over long distances and allow a high level of controllability over grid connections. In recent years, Multi-Terminal HVDC (MTDC) grid technology, which enables the development of meshed DC grids with bi-directional power flows, has been seen as a vital tool in the development and integration of onshore and offshore renewables in large scale AC/DC systems [2].

As MTDC grids become more prominent in power systems, they are expected to contribute to frequency regulation. This frequency regulation occurs on two time scales. Primary Frequency Control (PFC), which occurs on the ms to s time scale, is based on local measurements of frequency and is carried out in a decentralised fashion by power sources. Secondary frequency control, typically referred to as Automatic Generation Control (AGC), coordinates the actions of various power sources over the seconds to tens of seconds scale in order to eradicate longer term frequency biases. Several PFC [3], [4] and AGC approaches have been developed for aiding in frequency control in AC networks using MTDC grids [5]–[7].

Typically, AGC approaches are based on PI controllers. Model Predictive Control (MPC) is an optimisation based control technique that uses state-space predictions in order to form optimal inputs to the system. As it is a MIMO technique, it can take full advantage of system models, and it can explicitly consider delays and system constraints. It has been shown previously that there is the potential for an improvement in overall system performance in terms of frequency regulation if MPC approaches are used versus PI controllers for AGC [7], [8].

However, in the aforementioned MPC papers, delays and voltage constraints were not considered in the formulation of the MPC. Realistically, some control delay in the seconds range needs to be considered in order to account for control delays between the controller stations and the devices being controlled. As regards DC voltage constraints, when using DC grids as part of a frequency control strategy for AC grids, it is important that DC voltages are maintained in close proximity to their original setpoints such that DC power delivery setpoints do not deviate significantly from their original values. Under MPC, if these voltage constraints are implemented as regular inequality constraints, there is a danger of infeasibility of the solution, as subject to certain uncertainties the DC voltage may exceed the upper or lower DC voltage constraint. To avoid this, it is possible to reform these 'hard' inequality constraints as so-called 'soft' inequality constraints by introducing an extra slack variable which encourages the satisfaction of the inequality constraint, while maintaining feasibility when these constraints are violated [9].

Thus, in this paper a MPC formulation for AGC over MTDC grids is constructed which explicitly considers delays and DC voltage constraints using soft inequality constraints. The paper is divided as follows; Section II outlines the modelling of the AC and DC grids; in Section III MPC and its application to AGC are described, Section IV presents the simulations and results, and Section V outlines conclusions and future work.

II. Modelling

This section describes briefly the modelling of the VSCs, and the interactions between the AC and DC networks. Due to space constraints many details of the VSC are omitted here. The VSC models used in this paper were previously described in [2], [8].

The j^{th} ideal VSC is illustrated in Fig. 1, injecting power from the j^{th} DC grid node into the AC grid. The voltage dynamics at the j^{th} DC grid node are given by:

$$C_{\mathrm{dc}j}\frac{\mathrm{d}}{\mathrm{d}t}v_{\mathrm{dc}j} = \sum_{i=1}^{r_j} R^{-1}_{\mathrm{dc}j\mathcal{N}_j\{i\}}(v_{\mathrm{dc}\mathcal{N}_j\{i\}} - v_{\mathrm{dc}j}), \qquad (1)$$

where $v_{\mathrm{dc}j}$ is the DC voltage at node j, $C_{\mathrm{dc}j}$ is the DC side capacitor, $R_{\mathrm{dc}jh}$ is the resistance in the line connecting DC

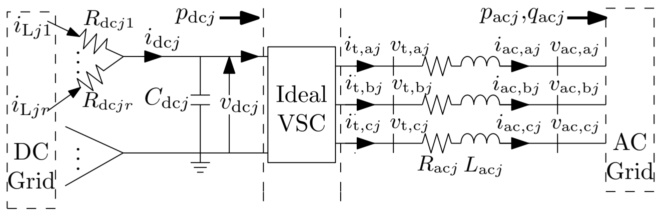

Fig. 1. The j^{th} ideal VSC between the DC and AC grids [8].

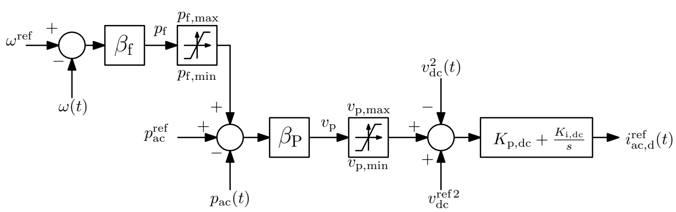

Fig. 2. The primary frequency controller of the VSC HVDC modules [2].

voltage nodes j and h, and $\mathcal{N}_j$ is the indexed set of DC nodes connected to DC node j through a DC line with cardinality r_j.

The AC voltages at the points of connection are regulated by VSCs as in [8]. The VSC primary frequency controller is given in Fig. 2. This controller trades off frequency regulation in the AC grid, maintenance of the AC power setpoint $p_{\mathrm{ac}}^{\mathrm{ref}}$, and DC voltage regulation about the DC voltage setpoint $v_{\mathrm{dc}}^{\mathrm{ref}}$.

A 6^{th} order Marconato synchronous machine is used to model the synchronous generators [10]. While the full synchronous machine equations are omitted here for compactness, they result in the following state for each synchronous machine, $\boldsymbol{x}_{\mathrm{sm}} = [\delta, \omega, e_{\mathrm{q}}^{'}, e_{\mathrm{d}}^{'}, e_{\mathrm{q}}^{''}, e_{\mathrm{d}}^{''}]^{\mathrm{T}}$, where δ, ω represent the rotational mechanical states, and $e_{\mathrm{q}}^{'}, e_{\mathrm{d}}^{'}, e_{\mathrm{q}}^{''}, e_{\mathrm{d}}^{''}$ the dynamic magnetic states. The following simplified frequency model (which is used now simply for illustrative purposes) describes how the frequency is influenced where there are ρ sources of power in the synchronous area:

$$\frac{\mathrm{d}}{\mathrm{d}t}\omega(t) = \frac{1}{M}\Big(\sum_{j=1}^{\rho} p_{\mathrm{in}j}(t) - p_{\mathrm{L}}(t) - D(\omega(t) - \omega_{\mathrm{ac}})\Big) \quad (2)$$

where M represents the inertia of the generator, $\omega(t)$ is the frequency, $p_{\mathrm{in}j}(t)$ is the j^{th} source of power in the synchronous area, $p_{\mathrm{L}}(t)$ represents the current power load in the system at time t, and D is a damping coefficient. This equation is a straightforward illustration of how the frequency in the system can be regulated by carefully controlling the various power sources entering the AC grid. This motivates the use of MPC for control of the frequency as it is capable of coordinating each of the sources optimally.

III. Model Predictive Control for AGC in MTDC networks

A. Model Predictive Control

Model Predictive Control is an optimisation based control technique that uses state-space based predictions in order to form optimal inputs to a system over a prediction horizon. While inputs are calculated over the full prediction horizon, only the input for the first sample step of the prediction horizon is applied to the system, and this process is repeated every sample step.

A discrete-time, linear, time-invariant state-space model for a system is given by

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) \quad (3)$$

$$\boldsymbol{y}(k) = \boldsymbol{C}\boldsymbol{x}(k), \quad (4)$$

where $\boldsymbol{x}(k)$, $\boldsymbol{u}(k)$, and $\boldsymbol{y}(k)$ are the states, inputs, and outputs of the system at sample step k, respectively. Matrices $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are the relevant state-space matrices. An augmented state-space model allows these equations to be framed in terms of $\Delta\boldsymbol{u}(k)$ and the augmented state $\boldsymbol{\chi}(k)=[\Delta\boldsymbol{x}^{\mathrm{T}}(k)\ \boldsymbol{x}^{\mathrm{T}}(k)]^{\mathrm{T}}$ (for a general variable $b(k)$, $\Delta b(k)=b(k)-b(k-1)$, i.e., the Δ operator denotes the change in a variable between sample steps $k-1$ and k), which ensures integral action in the controller. This is given as follows:

$$\boldsymbol{\chi}(k+1) = \overbrace{\begin{bmatrix} \boldsymbol{A} & \boldsymbol{0} \\ \boldsymbol{A} & \boldsymbol{I} \end{bmatrix}}^{\hat{\boldsymbol{A}}} \boldsymbol{\chi}(k) + \overbrace{\begin{bmatrix} \boldsymbol{B} \\ \boldsymbol{B} \end{bmatrix}}^{\hat{\boldsymbol{B}}} \Delta\boldsymbol{u}(k) \quad (5)$$

$$\boldsymbol{y}(k+1) = \overbrace{\begin{bmatrix} \boldsymbol{0} & \boldsymbol{C} \end{bmatrix}}^{\hat{\boldsymbol{C}}} \boldsymbol{\chi}(k+1). \quad (6)$$

The predicted state $\tilde{\boldsymbol{x}}(k+1)$ and incremental predicted state $\Delta\tilde{\boldsymbol{x}}(k+1)$ can be found from these equations, where for a general vector $\boldsymbol{p}$, its prediction vector is $\tilde{\boldsymbol{p}}(k) = [\boldsymbol{p}^{\mathrm{T}}(k) \ldots \boldsymbol{p}^{\mathrm{T}}(k+H-1)]^{\mathrm{T}}$, where H is called the prediction horizon for the system [9]. This results in the following state prediction matrices:

$$\tilde{\boldsymbol{\chi}}(k+1) = \tilde{\boldsymbol{A}}\tilde{\boldsymbol{\chi}}(k) + \tilde{\boldsymbol{B}}\Delta\tilde{\boldsymbol{u}}(k). \quad (7)$$

The tilde notation is used with the matrices here to denote that they are prediction matrices.

It should be noted that once these predictions have been formulated it is straightforward to consider the case where there is control communication delays. If there is a delay of ς samples, then $\Delta\boldsymbol{u}(k), \ldots, \Delta\boldsymbol{u}(k+\varsigma-1)$ are considered constant at the values that they were calculated at in sample steps $k-\varsigma, \ldots, k-1$, and inputs variables $\Delta\boldsymbol{u}(k+\varsigma), \ldots, \Delta\boldsymbol{u}(k+H-1)$ are optimised for. Thus $\tilde{\boldsymbol{B}}$ in (7) can be separated into those elements that correspond to the constant part of the input vector and the part that corresponds to the subset of the predicted inputs that are to be optimised for.

MPC problems are constructed to fulfill control objectives for a system based on knowledge of $\boldsymbol{x}(k)$. A cost function, $J(\boldsymbol{\chi}(k), \Delta\tilde{\boldsymbol{u}}(k))$ (which will henceforth be denoted by $J(k)$), is designed so as to embody the system's objectives. Typically this cost function is quadratic in $\Delta\tilde{\boldsymbol{u}}$ and in this paper the cost function takes the following form:

$$J(k) = \tilde{\boldsymbol{e}}^{\mathrm{T}}(k+1)\boldsymbol{Q}_{\mathrm{e}}\tilde{\boldsymbol{e}}(k+1) + \Delta\tilde{\boldsymbol{u}}^{\mathrm{T}}(k)\boldsymbol{Q}_{\mathrm{u}}\Delta\tilde{\boldsymbol{u}}(k) \quad (8)$$

where the error vector, $\boldsymbol{e}(k)=\boldsymbol{y}(k)-\boldsymbol{r}(k)$, and $\boldsymbol{r}(k)$ are the setpoints of subsystem a at sample step k.

The weighting matrices $\boldsymbol{Q}_{\mathrm{e}}$ and $\boldsymbol{Q}_{\mathrm{u}}$ determine the relative importance of minimising errors and the incremental changes in inputs, respectively.

The optimal choice of controls can be found by solving the following optimisation problem:

$$\begin{aligned} \Delta\tilde{\boldsymbol{u}}^*(k) &= \min_{\Delta\tilde{\boldsymbol{u}}(k)} J(k), \\ \text{s.t.} \qquad \boldsymbol{A}\Delta\tilde{\boldsymbol{u}}(k) &\leq \boldsymbol{b}, \end{aligned} \tag{9}$$

where a superscripted * denotes the optimum value of a variable, and $\boldsymbol{A}$ and $\boldsymbol{b}$ represent inequality constraints in the control problem.

In cases where there may be feasibility issues associated with the inequality constraints, due to model uncertainties, it is possible to reframe the inequality constraints as 'soft' constraints by minimising the infinite norm of an additional slack variable, ϵ. Feasibility is thus maintained by seeking to minimise the value of ϵ in order to maintain the desired inequality constraint. The following formulation of the problem achieves this objective [9]:

$$\begin{aligned} \Delta\tilde{\boldsymbol{u}}^*(k) &= \min_{\Delta\tilde{\boldsymbol{u}}(k),\epsilon} J(k) + \rho\epsilon, \\ \text{s.t.} \quad \boldsymbol{A}\Delta\tilde{\boldsymbol{u}}(k) &\leq \boldsymbol{b} + \mathbf{1}\epsilon, \\ \epsilon &\geq 0. \end{aligned} \tag{10}$$

Once the predicted inputs from MPC have been computed, the input at the start of the horizon $\boldsymbol{u}(k)$ is applied to the system and this process is repeated each sample step.

B. Application of MPC to AGC

In the following it will be described how MPC is applied for AGC in AC/MTDC systems in this paper. This process has been automated in the Dome power systems simulation package [11].

- A continuous-time state-space model is derived for the system by linearising the system about its nominal operating point, as derived from the load flow for the system. In this work, the $\boldsymbol{A}$ and $\boldsymbol{B}$ matrices in (3) are derived from a continuous state-space model taken from the system model. Several dynamics of the synchronous machines and VSC, that occur on time scale significantly faster than those considered for AGC, are zeroed (time constants are set to 0) in order to improve the state-space discretisation for the time scales of interest. Once these are zeroed they are incorporated into the remaining dynamic equations through simple matrix manipulation. Thus the synchronous machines, the dynamic magnetic and Automatic Voltage Regulator equations were zeroed. With regard to the VSCs, the Phase Locked Loop and fast internal VSC control dynamics were zeroed. The discretisation is performed using the Zero Order Hold method. The inputs $\boldsymbol{u}$=$[p^{\mathrm{ref}}_{\mathrm{m,mpc1}}, \ldots, p^{\mathrm{ref}}_{\mathrm{m,mpcn_g}}, p^{\mathrm{ref}}_{\mathrm{dc,mpc1}}, \ldots, p^{\mathrm{ref}}_{\mathrm{dc,mpcn_{vsc}}}]^{\mathrm{T}}$, where $p^{\mathrm{ref}}_{\mathrm{m,mpc}j}$ is the j^{th} generator setpoint controlled by MPC, where there are n_g generator setpoints controlled by MPC, and $p^{\mathrm{ref}}_{\mathrm{dc,mpc}j}$ is the j^{th} VSC power setpoint that is controlled by MPC, where there are n_{vsc} VSC power setpoints controlled by MPC. The outputs $\boldsymbol{y}(t) = [\omega_{\mathrm{mpc1}}, \ldots, \omega_{\mathrm{mpcn_g}}]^{\mathrm{T}}$, where $\omega_{\mathrm{mpc}j}$ is the frequency of the j^{th} generator controlled by MPC, where there are n_g generators controlled by MPC.
- Delays and soft constraints are dealt with as discussed previously in this section. The delays here are associated with the number of samples needed to calculate the control and transmit the control actions to the relevant generators. The application of hard constraints to the DC voltages is not desirable as certain faults may result in infeasibility of the optimisation problem. Thus the DC voltage constraints $v^{\min}_{\mathrm{dc}i} \leq v_{\mathrm{dc}i} \leq v^{\max}_{\mathrm{dc}i}$, for $i = 1, \ldots, n_{\mathrm{vsc}}$ are implemented using soft constraints.
- Then MPC can be used to calculate $\boldsymbol{u}(k)$ at each sample step using (10). In this paper the $\boldsymbol{Q}_{\mathrm{e}}$ and $\boldsymbol{Q}_{\mathrm{u}}$ matrices, and ρ are used to trade off the system objectives of minimising the frequency deviations of each generator and the control effort used to minimise these deviations, while seeking to satisfy the inequality constraints. The effect of the feedback is used to counteract the unknown system disturbances and nonlinearities.

IV. Simulation And Results

In order to illustrate the application of MPC for AGC in MTDC connected AC grids grids a simulation was constructed. The simulation setup and results are described in this section.

A. Simulation setup

The same testbed that was used in [2], [8] involving 3 asynchronous AC areas connected by an MTDC grid was used here, as in Fig. 3. The simulation was built using the Dome software package [11]. Due to space constraints parameters are not given here but can be found in [8].

The MPC controller is used to control the power setpoints in all VSCs and generators. A sample time of $T_{\mathrm{s}} = 0.1$ s was used for the MPC controller with $H = 25$. The weighting matrices are given by $\boldsymbol{Q}_{\mathrm{e}}$=diag(10,. . .,10) and $\boldsymbol{Q}_{\mathrm{u}}$=diag(0.1,. . .,0.1), and $\rho = 100$.

B. Results

Simulations were run for 70 s, considering 3 different control delays of 0.1 s, 3 s, and 5 s after the loss of the load connected to bus 8. For each control delay 3 different controllers were considered. The first is a PI-based AGC control system, where decentralised PI controllers are used to control both the synchronous generator and VSC power setpoints. In the second case, a MPC is applied such that it regulates the frequencies in each area, but does not attempt DC voltage regulation within the specified upper and lower bounds. Finally, in the third case, the MPC regulates voltages in each area, and the DC voltages are regulated using soft inequality constraints. The frequency and DC voltage reactions for the center of inertia frequency in AC area 1, ω_{coi1}, and the DC voltage at DC node 2, v_{dc2}, for each of the delays are given in Figs. 4-9.

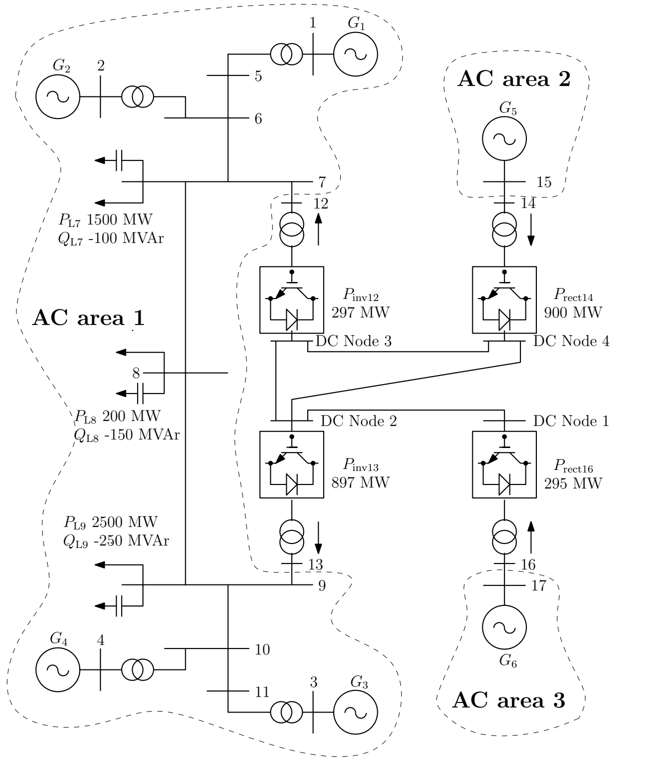

Fig. 3. Testbed with 3 asynchronous areas separated by a DC grid [2].

Firstly, considering the 0.1 s delay scenario, it can be seen in Fig. 4 that both MPC controllers provide an improvement in terms of frequency regulation in comparison to the PI controller. In Fig. 7 it can also be seen that the MPC using the slack inequality constraints is capable of maintaining the DC voltage within the desired bounds.

For the 3 s communication delay case, the MPC and PI controllers give similar frequency regulation performance, as can be seen in Fig. 5. The slack MPC controller still provides regulation of the DC voltage within the desired bounds in this case, as can be seen in Fig. 8. However, with a 5 s control delay, while the regular MPC and PI frequency regulation result in similar performance, the MPC with the slack DC voltage regulation begins to become unstable, as in Figs. 6 and 9.

The performance degradation may arise as a result of a number of factors. The accuracy of MPC predictions over longer time horizons is likely to be one source of this performance degradation. Due to system nonlinearities the system response deviates from the linear system response and so these differences may result in inaccurate prediction for longer prediction horizons. Also, in this paper a simple slack control is used where only 1 slack variables is used for all the DC voltages. By allocating 1 slack variable to each of the DC voltages individually, or by implementing a 2 norm minimisation of the slack, as in [9], it might be possible to avoid the instabilities in the response, as noted in the 5 s control delay case.

V. Conclusion

In this paper, a Multi-Terminal HVDC (MTDC) aided Automatic Generation Control (AGC) system was developed. Model Predictive Control (MPC) was proposed for this purpose, and the control system was designed in order to explicitly consider communication delays and DC voltage constraints. This controller was found to perform well for small control delays. However, the performance of this controller degraded in comparison to other controllers that did not consider voltage constraints for longer control delays. Thus it can be concluded that a fast communication system would be desirable for use with this controller, to take advantage of its potential performance enhancements. In this work just one slack variable was introduced. In future work further slack variable formulations will be investigated in order to compare their performance. Additionally, there could be much potential in the use of nonlinear MPC in the scenario envisaged in this paper, to investigate if nonlinear prediction can alleviate some of the prediction issues associated with longer time horizons.

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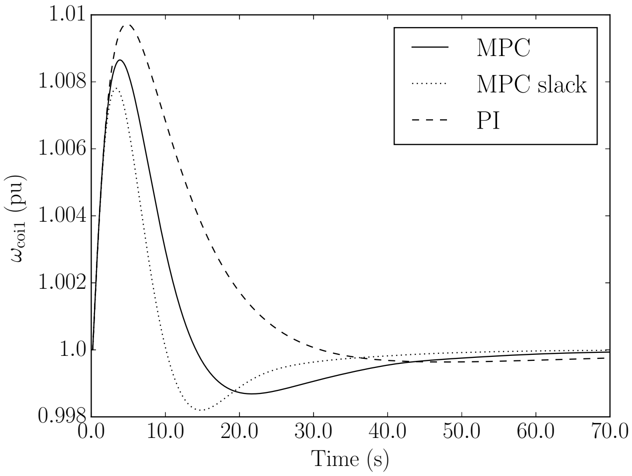

Fig. 4. Frequency response for a 0.1 s control delay.

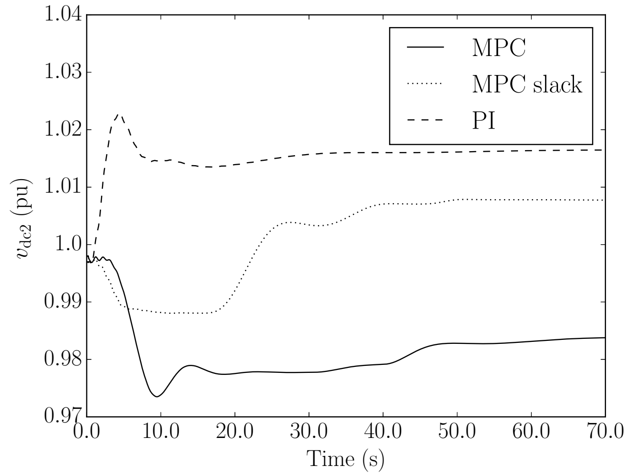

Fig. 7. DC voltage response for a 0.1 s control delay.

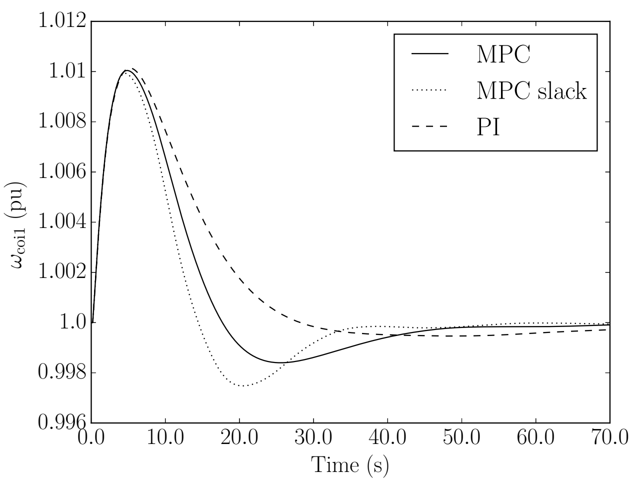

Fig. 5. Frequency response for a 3.0 s control delay.

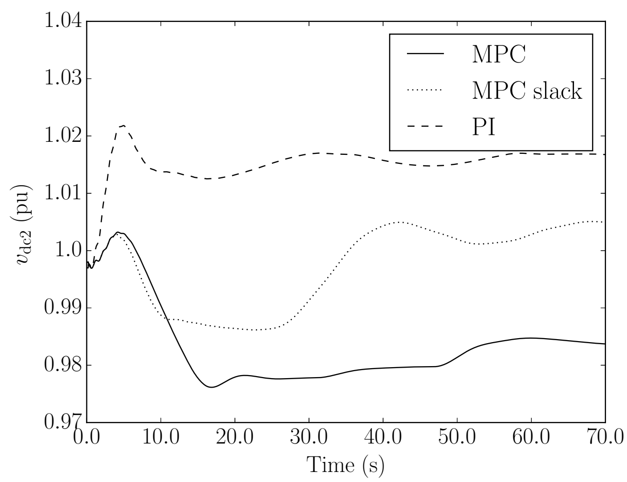

Fig. 8. DC voltage response for a 3.0 s control delay.

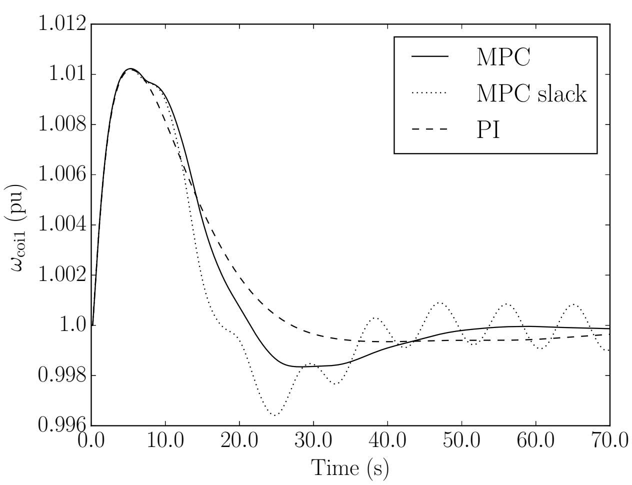

Fig. 6. Frequency response for a 5.0 s control delay.

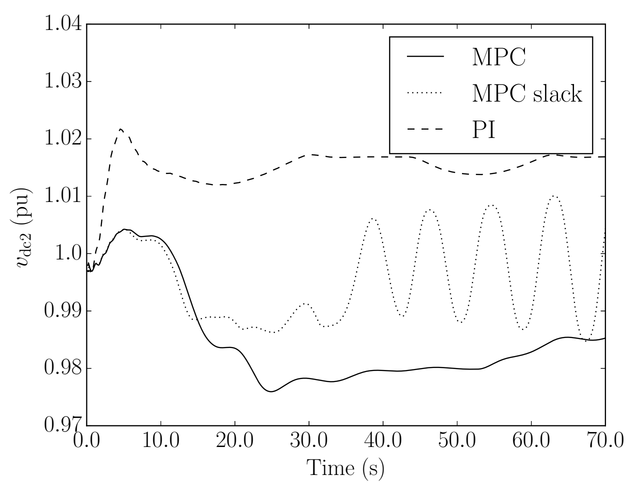

Fig. 9. DC voltage response for a 5.0 s control delay.