Effective Damping Support through VSC-HVDC Links with Short-Term Overload Capability

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Abstract—Damping service provision through VSC-based HVDC links has been extensively covered in the literature. However, little or no attention has been paid to the available range of active and reactive power modulation when the HVDC link is already operating at rated capacity. In these conditions some overload capability is usually assumed, ignoring the physical constraints imposed by the safe operating area of the IGBT modules in the converter. This paper presents, in a unified framework, the provision of damping support from VSC-based HVDC links equipped with additional control for short-term overload capability. The performance of a Model Predictive Control (MPC) damping controller that accounts for the extended $P/Q$ operating area of the converter is analysed. Case studies are presented to show that the extracted short-term overload capability can significantly improve the damping support from VSC-HVDC links. Simulation results also include the impact of damping control action on the junction temperatures of the IGBT modules of the converters, quantifying the effect of this service on the semiconductor temperature dynamics.

Index Terms—Model Predictive Control (MPC), Power Oscillation Damping (POD), Power System Dynamics, VSC-HVDC, VSC Overload.

I. INTRODUCTION

As power systems are evolving towards low inertia scenarios with significant presence of voltage source converter (VSC)-HVDC systems (in the form of offshore wind farms connections, embedded links and interconnectors), overload of VSC-HVDC systems to provide ancillary services would become a critical requirement in future. This overload capability could enable numerous applications such as frequency reserve sharing, emergency power re-routing and power oscillation damping [1]. However, unlike current source converter (CSC)-HVDC connections for which overload capability is commercially available [2], for VSC-HVDC this is currently not an option from manufacturers.

In this context, VSC overload for ancillary service provision has attracted little attention to date with only a handful of papers published in the area. The use of different techniques (circulating currents and zero sequence voltages) to increase the $P/Q$ capability of VSCs was demonstrated in [3], [4], allowing up to 30% extra capacity. In [5] the use of these techniques was proposed to provide grid support in a short-term during emergency conditions (frequency response in particular), analysing the impact on the converter temperature dynamics. Reference [6] considered VSC-HVDC overload to improve system performance during fault ride through contingencies, although neglecting the converter temperature dynamics. Therefore, the potential benefits at a system level of using VSC-HVDC overload needs further discussion. In this work we focus on damping support provision.

Although use of VSC-HVDC links for damping support has been extensively covered in the literature, it is often assumed that the converter is operating de-loaded [7], [8] (which can be economically expensive) or that some overload is available without addressing the converter physical limitations [9], [10]. In order to explicitly account for the converter overload constraints in the controller design in this work we use model predictive control (MPC) theory [11]. Application of MPC-based damping controllers for HVDC connections has, for instance, been covered in [12] for CSC-HVDC systems and in [13], [8] for VSC-HVDC links. Again, in [13], [8] VSC overload was not considered.

The contribution of this work is to present, in an unified framework, the application of VSC-HVDC short-term overload capability applied to damping support provision. In addition, the influence of the proposed scheme on the converter temperature dynamics is also analysed, confirming the feasibility of the proposed controller for system support.

The structure of this paper is as follows. Section II describes the employed VSC short-term overload technique. Then, the MPC-based damping controller design is illustrated in Section III and the test system in which the controller is tested is introduced in Section IV. Section V discusses the simulation results that demonstrate the effectiveness of the support through the short-term overload feature, including the impact on the temperature dynamics of the converter. Finally Section VI offers some conclusions.

II. VSC SHORT-TERM OVERLOAD CAPABILITY

In order to provide damping support when already operating at rated capacity, a VSC\(^1\) converter must be able to operate outside its normal $P/Q$ region\(^2\). Current handling capability and AC output voltage are the two main factors that limit this area [3]. Overload capability can be achieved by oversizing the converter components, which would increase the capital cost.

\(^1\)Note that throughout this paper when the term VSC is used we are referring to standard modular multilevel converter (MMC) topologies.

\(^2\)We assume the converters are the elements more sensitive to overload in a HVDC system. In practise, limitations of other components, like transformers and cables would also need to be considered.
cost and size. Instead, in order to expand the $P/Q$ curve as shown in Fig. 1, in this work we consider use of harmonic circulating currents (second and fourth order), following [3] and [5]. This would reduce the peak of the arm currents within the converter for a given set-point, directly influencing its active power capability. In this way overload is achieved without significantly oversizing the semiconductor devices but sacrificing the converter efficiency for a short time. As damping support is provided over a relatively short time frame (tens of seconds) such compromise in efficiency to derive short-term overload is not a concern. Note that, in a similar fashion, other techniques could have been used to further expand the reactive capability of the converter (see [3]) for damping support. However, for the sake of simplicity and given the higher controllability of the active power control input over the reactive power ones in the test HVDC system, this option is neglected here (see Section IV).

Fig. 1. $P/Q$ specification for normal operation and emergency overload [5].

The harmonic currents that minimise the circulating currents within the converter are defined as follows:

\[
I_{h_a} = I_2 \sin(2(wt + \theta) + \pi/2) + I_4 \sin(4(wt + \theta) + \pi/2) \\
I_{h_b} = I_2 \sin(2(wt + \theta) + \pi/6) + I_4 \sin(4(wt + \theta) + \pi/6) \\
I_{h_c} = I_2 \sin(2(wt + \theta) + 7\pi/6) + I_4 \sin(4(wt + \theta) + 7\pi/6)
\]

where \( \theta = \tan^{-1}(Q'/P') \), \( I_2 = 0.3947 \cdot k(i_{dc}, I') \) and \( I_4 = 0.0603 \cdot k(i_{dc}, I') \) with \(|I'|\), the current reference to be tracked, being equal to \(((P')^2 + (Q')^2)^{1/2}/(\sqrt{3}v_{grid})\). Note that \( P' \) and \( Q' \) are the converter power references. The currents \( I_2 \) and \( I_4 \) are such to obtain the desired peak shaving (i.e. their coefficients have been optimised) and would allow an additional 30% short-term overload of the converter. It is important to mention that the presented short-term overload technique for damping support is only intended to be used in abnormal conditions and not during normal operation since it will cause increased losses within the converter. Therefore, these currents will only circulate when the power reference to be tracked during damping support goes above the rated capacity of the VSC and into the emergency support region.

The unified framework for VSC damping provision through short-term overload capability is represented in Fig. 2. For a point-to-point HVDC configuration, an analogous overload control block would be present at the inverter end. Following the previous discussion, in our analysis the damping controller is exercised through the active power channel and therefore placed at the rectifier end.

III. POD DESIGN

A. System Identification

The design of damping controllers for a large power system is usually based on a state-space representation of the network. We employ here a subspace identification procedure (so-called N4SID) to obtain this representation (matrices $A$, $B$, $C$, $D$), following [14]. The identified model is also validated against the response of the actual network to step pulses.

Note that the simulation platform used in this work (DIgSILENT PowerFactory) does not provide full linearised state-space models.

B. MPC-based POD

Amongst different options, model predictive control (MPC) is considered to formulate the damping controller for the HVDC link because it can explicitly handle control constraints, which are of particular importance given the limited overload capability of the converters. MPC follows a discrete-time setting, using a receding horizon approach [11]. At each time step $k$, the quadratic programming (QP) problem in (2) is solved by the MPC controller. From this solution, only the first action is applied to the system at time $k$ and, at the next step $k+1$, the same procedure is repeated.

\[
\begin{align*}
\min & \quad \sum_{i=0}^{N_p-1} (y_{err}(k+i+1))^TQ(y_{err}(k+i+1)) + \ldots + \hat{u}^T(k+i)R\hat{u}(k+i) \\
\text{s.t.} & \quad \hat{x}(k+1) = A\hat{x}(k) + Bu(k) \\
& \quad \hat{y}(k) = C\hat{x}(k) + Du(k) \\
& \quad \hat{x}(0) = 0 \\
& \quad u_L \leq \hat{u}(k) + u_0 \leq u_H \quad k = 0, \ldots, N_p - 1
\end{align*}
\]
with \( y_{\text{err}}(k) = y(k) - y_{\text{ref}}(k) \), \( \ddot{x}(k) = x(k) - x_0 \), \( \ddot{u}(k) = u(k) - u_0 \), \( \ddot{y}(k) = y(k) - y_0 \) for the initial operating point \((x_0, u_0, y_0)\).

Note that in (2) \( x \in \mathbb{R}^n \) denotes the system state variables, \( u \in \mathbb{R}^{n_u} \) the system inputs (active power at the rectifier end \( P_{\text{rec}} \) of the VSC-HVDC link) and \( y \in \mathbb{R}^{n_y} \) the system outputs (generator rotor speeds \( \omega \)). The predicted power system dynamics are described by the linearised model in (2b)-(2d), obtained through the (off-line) identification procedure mentioned in Section III-A. The cost function (2a) minimises both the deviation of the predicted outputs from a defined reference (over a prediction horizon \( N_p \)) and the control effort from the initial operating point (over a control horizon \( N_c \), with \( N_c \leq N_p \)). We consider as reference trajectory the average of the generator rotor speeds \( y_{\text{ref}}(k) = \sum H_i w_i(k) / \sum H_i \), where \( H_i \) is the inertia constant of each monitored generator. The deviation of the generator rotor speeds from this value (relative frequency error) was found to provide good performance.

For the simulation results presented next, we have considered a 20 ms time step, \( N_p = 25 \), \( N_c = 25 \) and the control weights \( Q = I \cdot [15 15 15] \cdot 10^3 \text{pu/Hz}^2 \), \( R = 1 \text{pu} \).

IV. TEST SYSTEM

The damping controller using short-term overload capability is tested in the well-known two area test system (with parameters as in page 813 of [15]) shown in Fig. 3. We have chosen a simple yet representative test system to carry out EMT (Electromagnetic Transient) simulations with low step size (50 \( \mu \text{s} \)) within a reasonable time. The presented methodology is generic and could be applied to large practical systems.

The synchronous generators in the test system are equipped with excitation (IEEE DC1A [16]) and governor control (IEEE IEEE
go
go

Fig. 3. 4-machine, 2-area test system with embedded VSC-HVDC link.

The synchronous generator speed \( \omega \) has the dynamics:

\[
\dot{\omega} = \frac{1}{J} \left( P - P_{\text{rec}} - P_{\text{inv}} \right)
\]

with \( P = P_{\text{pod}} \) and \( P_{\text{inv}} \) being the converter steady-state power reference. \( P_{\text{pod}} \) is the power provided by the damping controller when the converter short-term overload available is limited. Without damping support, the converter short-term overload capability is shown to mitigate the oscillatory instability problems in the test system. Then, the harmonic current curves that extract the converter short-term overload are presented. Finally, the impact of providing damping support on the converter thermal response is also discussed.

A. VSC Short-Term Overload for Damping Support

Fig. 4 shows the system response to the outage of Line 89b, which is cleared 83 ms after the fault by tripping the line, for three different scenarios. Without the damping controller (red traces), the system presents a highly oscillatory response, according to the identified inter-area mode. This response can be significantly improved with the inclusion of a damping controller in the embedded HVDC link. We initially consider that the power handling capability of the converter has not been increased by the use of circulating current injection technique. Therefore, the short-term overload available is very limited (almost non existent) and set at 1%. With the damping controller under this limitation, the system response is anyhow improved with the oscillations settling down within 12 s after the fault (green traces in Fig. 4). Alternatively, using the damping controller together with the converter short-term overload fully enabled up to 30%, the oscillations are immediately arrested after the outage, greatly smoothing the grid transient behaviour (black traces in Fig. 4).

The HVDC power variations associated to the damping controller with different short-term overload capacities are presented in Fig. 5 for the case of 1% short-term overload and in Fig. 6 for the 30% short-term overload one. Subplots (a) present the converter power references \( P_{\text{pod}} \) manipulated by the damping controller, whereas the actual active power transfers are shown in subplots (b). Note that some instantaneous power violations are observed during the reference tracking (Fig. 5 (b) and Fig. 6 (b)) and can be attributed to the PLL dynamics and the inner current controllers of the converter, despite the constraints on \( P_{\text{pod}} \) in eq. (2e).

Note that \( P_{\text{pod}} = P' - P^* \) with \( P^* \) being the converter steady-state reference power, as defined in Fig. 2.

In steady-state, around 667 MW is being transferred from Area 1 to Area 2 in the system, with the VSC-HDC link operating at rated capacity. For this scenario, the identified linear state-space model is of 14th order. Small-signal analysis revealed a dominant inter-area mode with damping ratio equal to \( \xi = 7.7\% \) and frequency \( f = 0.65 \text{Hz} \). Controllability results determined that the most appropriate input signal (from the three options available in the HVDC system: \( P_{\text{rec}}^*, Q_{\text{rec}}^*, Q_{\text{inv}}^* \)) to control this mode is the active power at the rectifier end \( P_{\text{rec}}^* \), in concordance with the short-term overload technique presented in Section II.

V. SIMULATION RESULTS

Simulation results are presented in three subsections. First, use of the MPC damping controller for VSCs with short-term overload capability is shown to mitigate the oscillatory instability problems in the test system. Then, the harmonic current curves that extract the converter short-term overload are presented. Finally, the impact of providing damping support on the converter thermal response is also discussed.
Fig. 4. AC system dynamic response to Line 89b outage: without additional damping controller (red), damping controller with 1% short-term overload available (green), damping controller with 30% short-term overload available (black).

Fig. 5. HVDC system dynamic response to Line 89b outage - 1% short-term overload.

Fig. 6. HVDC system dynamic response to Line 89b outage - 30% short-term overload.
In both cases, these responses managed to stabilise the system after the fault, if well use of the short-term overload capability of the converter was proven to be much more effective in performing this task. In post-fault steady-state, the damping controller with 1% short-term overload is using all the headroom available while the one with 30% short-term overload returns to transfer the rated capacity.

B. Harmonic Current Injections during Short-Term Overload

The current waveforms for the rectifier converter during damping support using emergency overload (i.e. controller with 30% short-term overload available) are seen in Fig. 7. We focus on a narrow time interval after the fault (1.6-1.8 s) in which the converter goes above its rated capacity to provide support. We can see the increased transfer in the larger phase currents (Fig. 7 (b)) and DC current (Fig. 7 (c)). Under these conditions, the harmonic currents would start to circulate to shave the peak of the currents within the converter to the same level seen during rated (pre-fault) operation, as shown for phase a in Fig. 7 (a).

Fig. 7. Current waveforms during damping support in overloaded operation.

C. Effect on the IGBT Modules Junction Temperatures

In parallel to the previous results, the power range available during short-term overload conditions would ultimately be limited by the junction temperatures of the IGBT modules in the converter. However, given the short time frame in which damping support is provided, this temperature variation is not expected to limit the provision of this service. In order to verify this, simulations are conducted using a thermal model of the converter to determine the junction temperatures of the IGBT modules when considering this service.

Following results from [19] and [5], we characterise the converter thermal response using power loss tables and thermal impedances, which were derived using detailed switching models and ANSYS FEM analysis. This thermal model is described in Fig. 8 and uses the data in [5] to derive the average diode junction temperature \( T_{j,\text{diode}} \) and the IGBT junction temperature \( T_{j,\text{IGBT}} \).

Fig. 8. VSC converter power losses and thermal model as in [5].

It can be observed that, in general, the cases without damping controller (red traces) and with damping controller using 4% it was demonstrated in [19] that the lower IGBT module of each sub-module in the converter is under significant more stress than the upper IGBT module. Because of this, only the junction temperatures of the lower IGBT module are considered in the model.

Fig. 9 and 10 show, respectively, the binding junction temperatures at the rectifier and inverter ends for the considered short-term overload scenarios with damping control. In steady state, \( T_{j,\text{diode}} \) at 97.0°C is the binding temperature for the rectifier converter, whereas \( T_{j,\text{IGBT}} \) at 93.3°C is the one for the inverter case.

Fig. 9. VSC rectifier converter: diode junction temperature variation: without additional damping controller (red), damping controller with 1% short-term overload available (green), damping controller with 30% short-term overload available (black).

![Diagram](image-url)
1% short-term overload (green traces) do not cause significant increase in the junction temperatures. The case with damping controller using 30% short-term overload is the one that leads to larger temperature variations (black traces) as the payback for the more effective damping support. However, these variations are relatively small and in the range of 5°C for a few seconds, which are considered acceptable and do not pose a high risk. The maximum specified operating temperature for the IGBT modules in the converter is usually 125°C [19] which makes the proposed damping support scheme through short-term overload feasible.

VI. CONCLUSIONS

This work demonstrates damping support provision through VSC-HVDC systems by extracting the short-term overload capability of the converter. The damping control problem is formulated in the MPC framework which can explicitly account for the converter constraints. The effectiveness of this control in improving an AC system oscillatory response has been demonstrated. It is shown that provision of damping support does not have a major impact on the IGBTs junction temperatures, with maximum transient variations in the order of 5°C. Effective damping support through VSC-HVDC links with short-term overload capability will allow higher pre-fault loading of the host AC systems and hence, better utilisation of the AC transmission assets without compromising security.

Our current work is focused on the application of the proposed controller to meshed DC grids and the inclusion of the converter junction temperature constraints in the proposed MPC formulation when considering other types of ancillary services from VSC-HVDC links.

REFERENCES


