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Adaptive Droop Control of Multi-Terminal VSC HVDC Systems With Distributed DC Voltage Control

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ABSTRACT: This article is focused on the droop-based DC voltage control design for multi-terminal VSC-HVDC grid systems, considering the AC and the DC system dynamics. The droop control design relies on detailed linearized models of the complete multi-terminal grid, including the different system dynamics, such as the DC grid, the AC grid, the AC connection filters and the converter inner controllers. Based on the derived linear models, classical and modern control techniques are applied to design the different controllers, including a multi-variable frequency analysis to design the grid voltage droop control. In combination with the droop control, a DC oscillation damping scheme is proposed, in order to improve the system performance. The control design is validated through simulations of a one terminal system. Finally, the paper discusses two possible model reductions, in line with the assumptions made in transient stability modeling. The control algorithms and VSC HVDC systems have been implemented using MatDyn, an open source MATLAB transient stability program, as well as the commercial power system simulation package MATLAB.

KEYWORDS: High voltage direct current (HVDC) transmission control, Voltage (VSC) source converter.

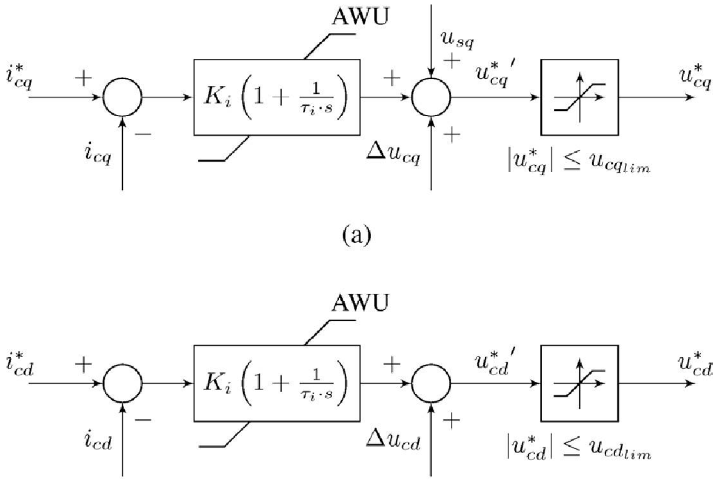
I.INTRODUCTION

The multi-terminal VSC-HVDC grid concept poses several challenges as the technology of the different elements connected to the system is still evolving in terms of power and voltage levels. Among other problems, the control of the DC voltage of multi-terminal VSC-HVDC grids has become a priority, in order to ensure the overall grid system stability. Electro Magnetic Transient Programs (EMTP) accurately represents the switching dynamics and electromagnetic transients. Averaged models and electromechanical stability models [1] have been used to study alternative outer controller structures [3]–[5], and optimized control settings [6]–[8] as well as dynamic interaction with the AC system [9], [10] and system frequency support [11], [12]. Power flow algorithms, as presented in [13], have been used to address the steady-state effects of a distributed DC voltage control [14], [15]. Significant work has already been carried out on the modeling and control of MTDC systems. With the DC system voltage being the most crucial control variable [4]-[7], most focus has been dedicated towards a distributed control of the DC voltage at different converters. The two main control methods are voltage margin control [5], [16] and DC voltage droop control [6]–[8], [10], [17]. This paper builds upon the fundamental frequency modeling approach presented in [2]. Two important extensions are added to the model. Firstly, current and voltage limits are represented in detail in the current control loop and in the outer controller. Secondly, a cascaded control structure is introduced in the outer controller which allows power controlling converters to take over the voltage control when the DC voltage controlling converter fails.

The main innovation is that this cascaded control structure for a two-terminal system, developed in the framework of this paper, is extended in a systematic way to obtain a generalized cascaded control scheme for MTDC systems. This generalized cascaded control scheme can accommodate for voltage margin control as well as for voltage droop control. The second contribution of the paper is the investigation of the effect of the detailed modeling of the current and voltage limits, by comparing the detailed model with a simplified model. In Section II, this structure is extended to resulting in a voltage margin approach and also discusses the inclusion of a voltage droop in the control structure, enabling power sharing amongst different converters in case of a converter outage. Section III shows the results derived in the paper.

II. MULTI-TERMINAL VSC HVDC CONTROL

When the redundant control structure is used in a multi-terminal configuration, it operates as a so called voltage margin control [5] scheme, providing a backup DC slack converter in case the main slack converter (or DC voltage controlling converter) fails. Consequently, the actual value depends on the voltage at the AC bus and the ratio. The voltage margin at different converters can be determined such that different converters can take over the DC voltage control, given that only one converter at a time can control the DC voltage. Contrary to the two-terminal system, it is still possible to transfer power in case the DC slack converter fails or blocks. A modified Euler ODE solver was used with a step size of 2e-4 s. The initial power flow solution with the DC slack converter at bus 2, has been obtained using MATACDC, an open-source MATLAB-based AC/DC power flow program. The power flow has been initialized such that the average voltage is equal to unity. After the outage of the DC voltage controlling converter 2, converter 3 initially tries to control the converter voltage when its converter upper voltage limit is reached. Since its current limit is hit, converter 3 is unable to control the converter voltage further, resulting in a further increase of the DC system voltage, after which converter 1 takes over the voltage control. The power in converter 4 remains unchanged because the influence of the changing DC voltage is not fed back to the power controlling converters as long as the voltage limits are not hit.



(a)

(b)

Fig. 1. Decoupled inner current controllers. (a) I_{cq} current controller. (b) I_{cd} current controller.

A . Voltage Droop Control

Alternatively, the voltage control can be distributed amongst different converters by implementing a voltage droop control. Contrary to standard droop control schemes presented in literature, which do not contain an inner DC voltage control loop, cascading the droop control as done in this paper has the advantage that upper and lower DC voltage limits can still be included as for 2-terminal schemes, ensuring that the DC voltage can still be controlled in case a converter is operating in islanding mode, e.g., as a result of DC breaker actions. The droop design should be carried out considering all the dynamics of the multi-terminal system, as these affect the performance of the controller. For this reason, the control analysis should employ the linear model of the multi-terminal grid explained above, which includes the different systems involved in the droop operation. The complete dynamic system of the multi-terminal grid is depicted in Fig. 2, where the different control stages of the converter can be identified.

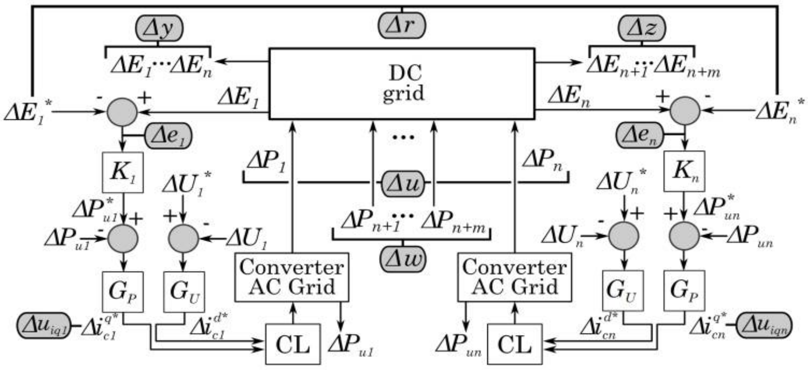


Fig. 2. HVDC grid control scheme.

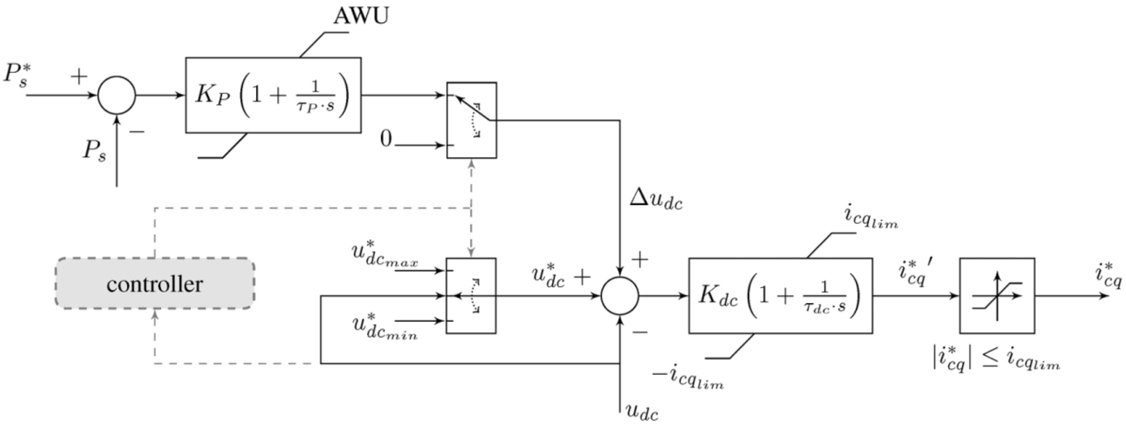


Fig. 3. Combined active power and DC voltage controller.

B. Converter Control Reduction

The converter dynamics can be easily neglected by eliminating the first order system representing the converter switching from Fig. 3. The possibilities to reduce the order of the converter and controller model further is somewhat limited by the presence of the current and voltage limits. Although these converter limits can be disregarded when undertaking small signal stability studies, they are crucial with respect to the dynamic response and steady-state working conditions of the system. This can be illustrated by observing the dynamics incorporated by the voltage limits. When approximating the current controller by an equivalent first-order system, these voltage limits are no longer taken into account. A way of dealing with this is limiting the reactive power reference, which can be written in function of the voltage limits. While this should give correct results for the steady-state values, the dynamics could be different: one would expect a slower response when the voltage limit is activated.

C. DC oscillation damping loop

The power and voltage loops are tuned in the range of tens of milliseconds in order not to interact with the lower level current controllers, designed to respond within a few milliseconds. Considering the presented control structure (Fig. 2), as the droop controller output is connected to the power loop input, certain fast power transients could cause variations of the voltage due to the grid behavior, that could not be properly damped, considering the limited bandwidth of the power loop.

A modification of the presented control scheme is shown in Fig. 4. A compensator between the voltage error and the active current reference is included to damp fast voltage variations of the system, as the current loop has a higher bandwidth compared to the power loop. The suggested compensator is based on a band-pass filter, which does not modify the power sharing in steady state established by the droop control. It should be tuned to act within the frequency range between power regulator and the current regulator bandwidth. The filter can be designed as:

$$G_{bp} = K_{bp}\frac{t_1 s}{t_1 s + 1}\frac{1}{t_2 s + 1} = K_{bp}G_f \quad (1)$$

where K_{bp} is the gain of the band-pass filter and t_1 and t_2 are the time response constants of the high-pass and lowpass filters respectively, compounding the band-pass. If t_1 $_{and}$ t_2 are selected to be the time constant of the power loop and the current loop respectively, the band pass-filter will not interfere in the operation of the mentioned controllers.

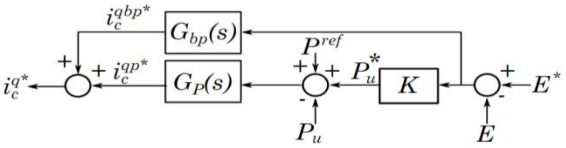


Fig. 4. Droop and power loop combined with the DC oscillation damping.

III. RESULT & DISCUSSION

The analyzed HVDC system consists of a single node multi-terminal VSC-HVDC scheme (Fig 5). Power converters are connected to the AC grid and the other is connected to output load. The proposed system is analyzed assuming that droop voltage control is carried out by GSCs supposed to inject all the generated power from the wind power plant. It is considered that both GSCs are connected to two different grids under equivalent conditions. The different controllers involved in the system are designed following the methodology described.

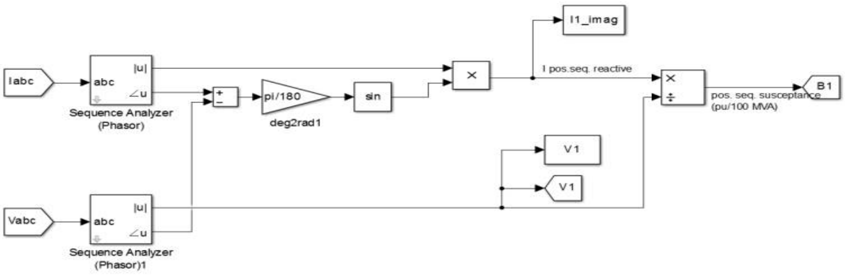
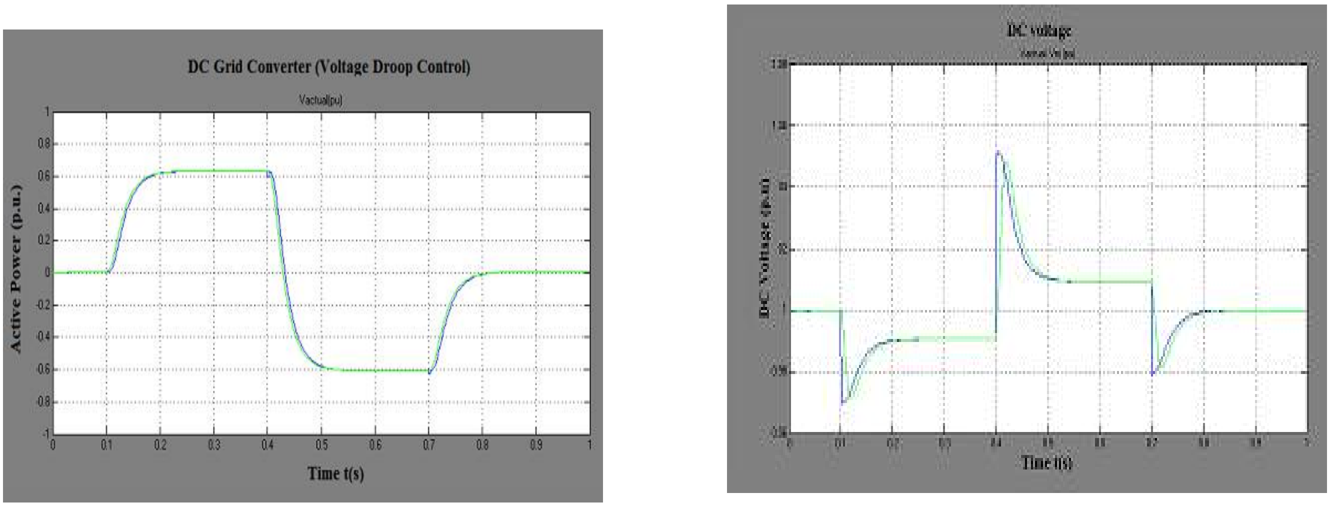


Fig. 5. Proposed Votage stability control.



(a) (b)

Fig. 6. Design output of the voltage and power loops of the converter. (a) Bode representation of the closed loop transfer functions with active power in pu. (b) DC voltage waveform for a power step change in a multi-terminal system with a voltage droop control.

IV.CONCLUSION

In this paper, a general electromechanical multi-terminal VSC HVDC model has been presented. The salient features of the model are that it has a generalized cascaded control scheme for MTDC systems that allows for voltage margin and voltage droop control and that current and voltage limits are represented in detail. A strategy to cope with a loss of the voltage controlling converter in a two-terminal system is generalized to voltage margin control for multi-terminal system and the model has been extended to include distributed DC voltage control. It is shown by simulations how the limits influence the dynamics and what the effects are of neglecting converter limits. The results indicate that reduced order models approximate the detailed model well. The model has been implemented in the open-source, MATLAB-based shell, MatDyn, as well as in a commercial power system simulation software, MATLAB, and has been tested on a four-terminal VSC HVDC system.

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