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Offshore Wind Farms and HVDC Grids Modeling as a Feedback Control System for Stability Analysis

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***Abstract*—**

The low impedance characteristics of DC transmission lines cause the voltage source converter (VSC) in HVDC networks to become electrically closer together and increase the risk of severe interactions between the converters. Such interactions, in turn, intensify the implementation of the grid control schemes and may lead the entire system to instability. Assessing the stability and adopting complex coordinated control schemes in an HVDC grid and wind farm turbines are challenging and require a precise model of the HVDC grid, wind farm, and the controllers.

In this paper, a linear multivariable feedback control system (FCS) model is proposed to represent the dynamic characteristics of HVDC grids and their controllers. The FCS model can be used for different dynamic analyses in time and frequency domains. Moreover, using the FCS model the system stability is analyzed in both open- and closed-loop forms. The standard eigenanalysis identifies the modes of only the closed-loop system and detects the pertaining state variables. The open-loop model, in the frequency domain, is a complementary tool that helps to have more intuitive insight into the system stability.

A four terminal HVDC grid with two OWPPs and two AC grids is used for simulations and verification of the proposed FCS model.

***Index Terms*—Offshore wind power plants, High voltage DC grids.**

I. Introduction

THE number of offshore wind power plants (OWPPs) is increasing and their distance from onshore ac systems is also extending to the range of hundreds of kilometers. For such remote wind power plants the HVDC transmission facilities are mostly the option to deplete the energy of the plants to the onshore ac systems. These HVDC systems are mainly based on voltage-source converter (VSC) which possess benefits such as: smaller space for installation–which is important problem in an offshore site–, the capability of independent control of active and reactive power, the ability to use of cheap and robust XLPE cables, the ability to connect to weak AC systems and a black start capability [1].

With the current trend of power electronic technology development as well as the desire for wind power technology, it is foreseen that in the near future, the number of offshore wind farms connected with VSC-HVDC will be increased. It seems reasonable to devise offshore HVDC grids interfacing a number of different terminals with different ac grids, resulting in the so-called multiterminal HVDC grid [2]. An HVDC grid increases the efficiency and reliability of transmission systems to transfer the power from OWPPs to onshore ac systems. There are several technical challenges associated to HVDC grids including control systems [3] and operation [4] issues.

Stability analysis is essential in designing control system and in operational scenarios. Comparing to conventional ac power systems, the HVDC grids inherently possess higher dynamics–too many modes with high frequency oscillations–and higher interactions between different power components such converters, turbines, transformers, generators in onshore systems and so on. Moreover, the system dynamics in HVDC grids relies too much on measured and transmitted signals which consist communication delays which restrict the controllers gain. To investigate the nature and cause of these dynamics, which can lead the entire system to instability, appropriate analytical models of HVDC grid components are required. The electro-magnetic transient programs can demonstrate instabilities but they are unable to provide the analytical insight (e.g. information about how stable the system is or what is/are the cause of instability or interaction) [5]. The conventional transient stability programs, which use phasor modeling techniques [6], do not have aforementioned problems, but they cannot directly represent the faster transients characterizing the HVDC systems [6].

In [7]–[12] a new concept, called *Jacobian Transfer Matrix* (JTM), has been used to model a VSC-connected ac grid to introduce a new control system for converter. The JTM not only can analyze the stability issues but also it regards the ac network model in a feedback loop which is ideal for VSC controller design. The stability analysis by JTM is based on monitoring the zeros of network transfer function [7], therefore, it is limited to only a Thevenin model of a power system. This model was developed further in [13] for larger power system. However, HVDC grid was not included in the model.

An HVDC grid is basically a multi-input multi-output (MIMO) dynamic system. If the entire system can be modelled as the standard feedback control system (FCS), then the stability of the system can be analyzed with mature methods in time and frequency domains [14]. This paper introduce a step-by-step procedure to develop an FCS model for HVDC grids. It is shown how interactions between converters as well as interactions between different control variables can be quantified and qualified. Moreover, it is shown how the FCS model can be useful in instability cause detection where the

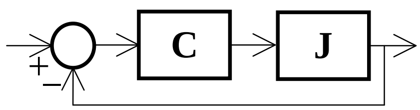

Fig. 1: FCS block diagram. $\mathbf{C}$ and $\mathbf{J}$ are respectively controller and plant blacks.

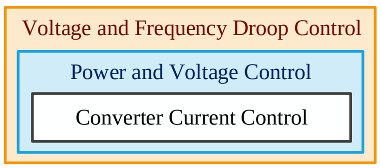

Fig. 2: Different control layers (levels) in an HVDC grid.

conventional modal analysis fails. The effect of time delay in measurement and communication system on system stability is demonstrated and shown how it can restrict the achievable control bandwidth.

II. Feedback Control System Model of an HVDC Grid

The FCS model is in fact a systematic procedure to obtain a linear representation of complex multi-terminal HVDC networks as a classical feedback control system. As shown in Fig. 1, the standard FCS model has two blocks in series; the state-space model–or transfer function–of controller(s) is placed inside the control block $\mathbf{C}$ and controlled system model inside the plant block $\mathbf{J}$.

For an HVDC grid a control hierarchy with different control levels have been defined in this paper. As shown in Fig. 2 these layers have been divided into three levels: converter current control level, power and voltage control level, and droop control level in which direct voltage and frequency droop controls are implemented . Including frequency control in onshore converter controllers depends on grid code requirements and it's not a necessity for converter operation. For each control level a particular control and plant blocks (models) are defined. For instance for a converter current controller design, the plant model can be regarded as a Thevenin model of the ac system to which the converter is connected. However, current controller block is included in plant model of power and voltage control loop which is a higher level with respect to converter current control loop. In next section more detailed explanations about modeling different control levels are provided.

The dynamic specifications of the FCS model can be analyzed either by eigenvalues of the FCS closed-loop model and/or by the frequency response of FCS open-loop model. The former method–when the FCS model is developed for highest level of control hierarchy–is similar to the one is used conventionally for small-signal stability analysis in power systems [15].

Depending on a interested study a certain level of control level which has a particular FCS model is considered. For

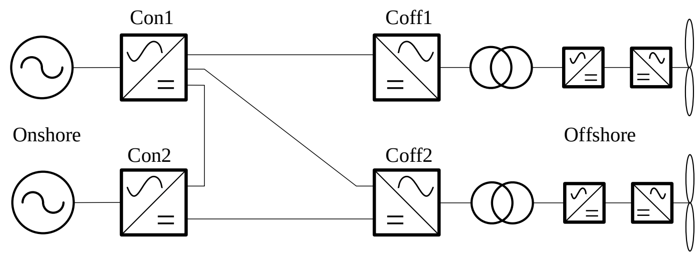

Fig. 3: Four-converter HVDC grid used for modeling and simulations.

instance when the effect of ac system weakness on system stability is interested both current control level and power/voltage control levels are studies separately with two different FCS models. Because, first it must be assured that the current controller is tuned properly for a weak system, and then power/voltage control level is investigated. By this procedure, it is convenient to detect the stability issues and their causes. In simulation sections, some case studies are provided for more clarifications.

III. FCS Model Development Procedure for an HVDC Grid

In this section step-by-step procedure of the FCS model development for an HVDC grid is regarded and connection between consecutive layers are outlined. The FCS model is generally developed for any type of HVDC connection, however, in order to provide a pictorial demonstration of model development, the HVDC grid shown in Fig. 3 is considered for modeling in this paper. The grid has two offshore converters and two onshore converters. The ac grids in onshore sides are regarded as Thevenin equivalent, however, in the frequency control level one of the Thevenin models in onshore side is replaced with a single machine equivalent model to include mechanical inertia model. It must be noticed that the dynamics of wind turbines and turbine converters in offshore sides are not considered in this paper.

A. Converter Current Control Loop

The converter current control (CC) loop is the first layer in the FCS model. The input of this layer is reference current vector, and the output of the layer is converter current vector. Depending on the type of studies the model of this layer can be different. For instance, in case of frequency study the dynamics of CC layer can be neglected or approximated with a very small time constant first-order equation (typically its bandwidth frequency is in the range of thousands of radians per second). In case of high frequency studies or in case of weak ac system, the dynamics of CC layer must be considered, which requires an appropriate model. The FCS model for CC layer is presented in [16] with clear definitions of transfer functions. In this paper the model of this layer is shown in black in Fig. 4 with controller and plant blocks which are indicated with $\mathbf{C}_{\mathrm{CC}}$ and $\mathbf{J}_{\mathrm{CC}}$ respectively. For four-converter HVDC grid the plant model will be block-diagonal matrix with zero interaction as the dc transmission lines are not regarded in

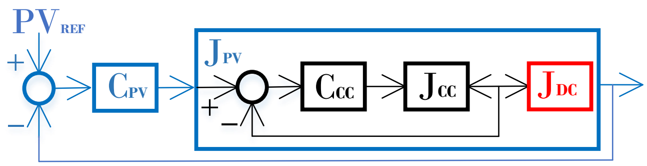

Fig. 4: Power and voltage control layer represented as FCS model.

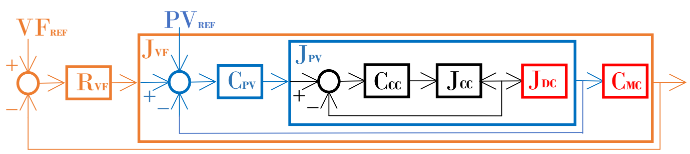

Fig. 5: FCS model for entire HVDC grid including voltage and frequency droop control.

the plant model. Disregarding the dc lines dynamic in current control loop is a sensible assumption because the converter capacitors plus offshore cable capacitors are so big that they do not interfere in CC loop's dynamics.

B. Power and Voltage Control Loop

Higher than CC level is the power and voltage (PV) control level which is shown in blue in Fig. 4. The input and output of this layer are respectively reference and measured vector of active power, reactive power, ac and dc voltage of all converters. The control block of this layer, $\mathbf{C_{PV}}$, is a block-diagonal model consists of proportional-plus-integral (PI) controllers. The plant model of this layer, $\mathbf{J_{PV}}$, includes the dynamics of ac and dc systems plus converter current controllers. The dc network model which consists cables model as well as converter capacitors are is represented by $\mathbf{J_{DC}}$. The mathematical representation of dc grid is given in [10].

C. Direct Voltage and Frequency Droop Control Loop

In an HVDC grid the direct voltage is usually controlled with more than one converter using droop controller [1], [2], [17]. Moreover, the HVDC converters feeding onshore grids need to fulfill the grid code requirements and providing frequency support is one of which [18]–[22]. In FCS format the droop control layer is shown with orange color in Fig. 5. The proportional gains used in $\mathbf{C_{VF}}$ are generally the inverse of droop gains particularly chosen for each converter. The output of $\mathbf{C_{VF}}$ block is active power ΔP_{VF} which is added to active power reference in PV control layer.

A variety of VF droop implementation methods can be found in literature [18]–[22]. In this paper, the droop control scheme shown in Fig. 6 is used for onshore converters. In this figure, V_{ref} and f_{ref} are the reference values of voltage and frequency, and V_m and f_m are the measured values of voltage and frequency. R_f and R_V are the inverse of voltage and frequency droops.

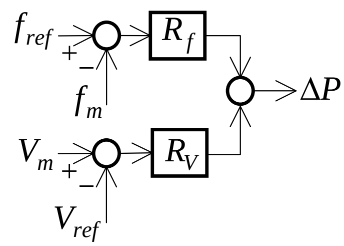

Fig. 6: Voltage and frequency droop control scheme for onshore converters.

To provide the frequency support to onshore ac systems, the mechanical dynamics of the system must be included in the FCS model. The mechanical model which is represented by $\mathbf{C_{MC}}$ is the second order motion equation with active power as an input and frequency deviation as an output. For the frequency control in an HVDC grid at least one of the offshore converters must be responded and provide the requested power. The power request from offshore converter can be implemented either by communication system or by sensing the direct voltage magnitude in offshore side and forcing the offshore converter to compensate the voltage. In the latter method, which is referred as communication-less frequency control, the operation of other onshore converters, which contribute to direct voltage control will be affected as consequence of direct voltage change. The communication-based frequency control prevents the aforementioned problem, however, it suffers from the time delay that communication system causes. This time delay can degrade the fast frequency support; this is shown in simulation section.

IV. Numerical Analysis of FCS Model Developed for an HVDC Grid

In this section simulation results for different layers of the FCS model are presented. First, the step response of the the current of converter C1 in dq framework is shown in Fig. 7 where the plant (left) and closed loop (right) step responses are both presented. The time delay seen in this figure is caused by measurement, communication and PWM process. This time delay is a limiting factor for the highest achievable control bandwidth. considering this time delay, the proportional gain of converter one current controller is increased and the entire system becomes unstable. The cause of instability can be detected by the frequency response of the open loop system model as shown in Fig. 8.

In order to show the FCS capability in tuning of control parameters, the step responses of plant model of PV control layer is regarded, shown in Fig. 9. As seen, there are some sever overshoots in open-loop response which are not acceptable to be present in closed-loop response. The controller, $\mathbf{C_{PV}}$, is so design that removes these overshoots and maintain the required bandwidth, see right-hand-side of Fig. 9. To design and tune such controller, first the frequency response of the plant $\mathbf{J_{PV}}$, shown in Fig. 10, is investigated. As seen from the figure, the plant has higher gain in higher frequency which

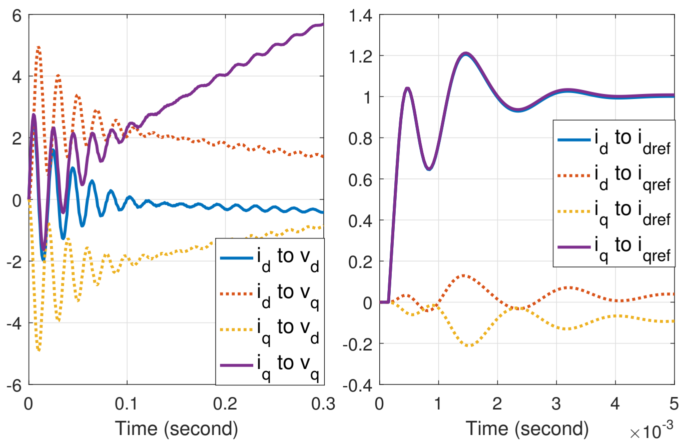

Fig. 7: Step response of $\mathbf{J_{CC}}$ (left) and closed-loop model of CC (right) for converter one. The magnitudes are given in per unit.

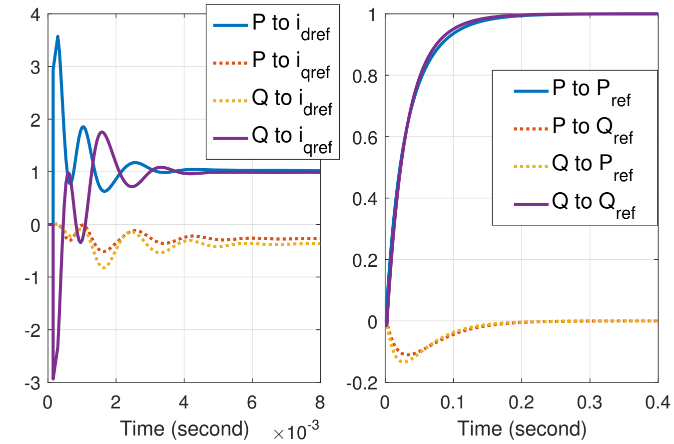

Fig. 9: Step responses of $\mathbf{J_{PV}}$ (left) and closed-loop model of PV (right) for converter one. The magnitudes are given in per unit.

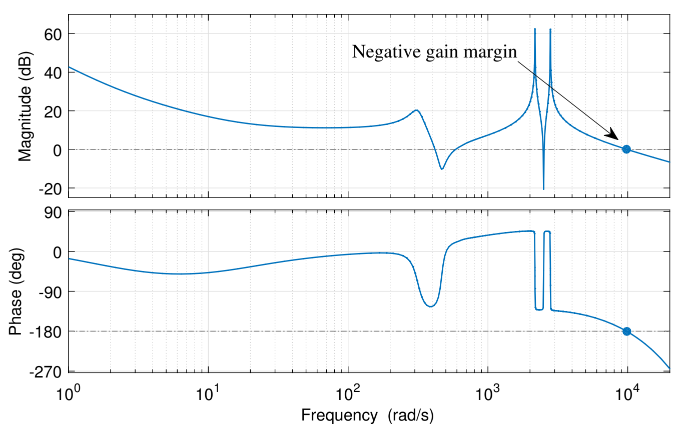

Fig. 8: Frequency response of open-loop model of CC for converter one. The negative gain margin in Bode plot indicated system instability.

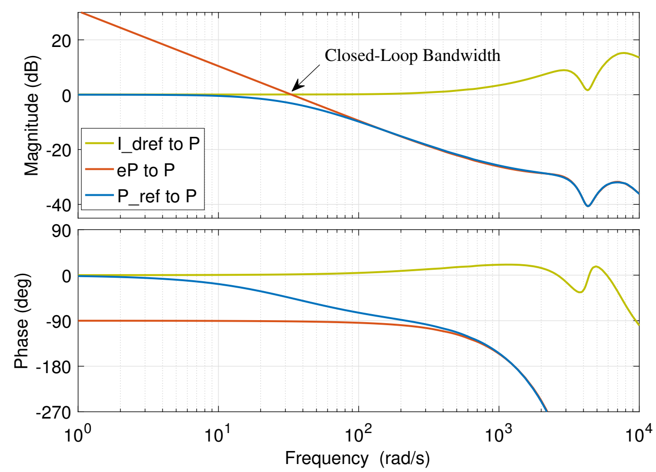

Fig. 10: Frequency responses of $\mathbf{J_{PV}}$, open-loop, and closed-loop model of PV layer for converter one.

must be attenuated by the controller. The proportional gain boosts this gain and it is not a right option. The integrating controller boosts the gain in low frequency and weakens at high frequency, and therefore is a right option. The open- and closed-loop responses shown in Fig. 10 demonstrate how the desired bandwidth is achieved with only integrating type of controller.

It is supposed that the onshore converters, i.e. converter one and two, control the direct voltage by equal droop gains. The plant as well as the closed loop response of FV control layer are shown in Fig. 11.

The frequency of the ac system behind converter one is supported by the OWPP one–it's converter No. is three–and control process is implemented through a communication link which has a delay of 100 ms. The step responses of the plant $\mathbf{J_{FV}}$ and closed-loop model with and without communication time delay are shown in Fig. 12. In the latter case, with communication delay, there exist a high overshoot in the step response. In order to understand how the time delay causes such overshoot, the frequency response of FV loop is considered in Fig. 13. In this figure the open-loop frequency responses with and without communication time delay are

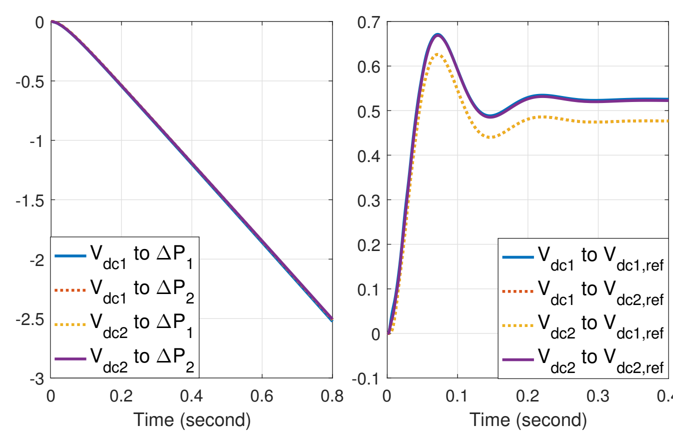

Fig. 11: Step responses of $\mathbf{J_{FV}}$ (left) and closed-loop model of FV (right) for converter one and two. The magnitudes are given in per unit.

shown. As seen, it is only the phase of the response which has been affected by the time delay and causes the poor performance of the system.

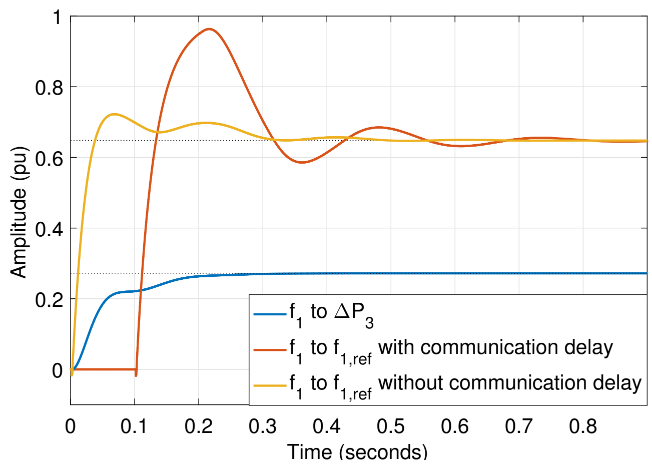

Fig. 12: Step responses of the plant $\mathbf{J_{FV}}$ (blue), and closed-loop system of the FV layer with (red) and without (yellow) communication time delay.

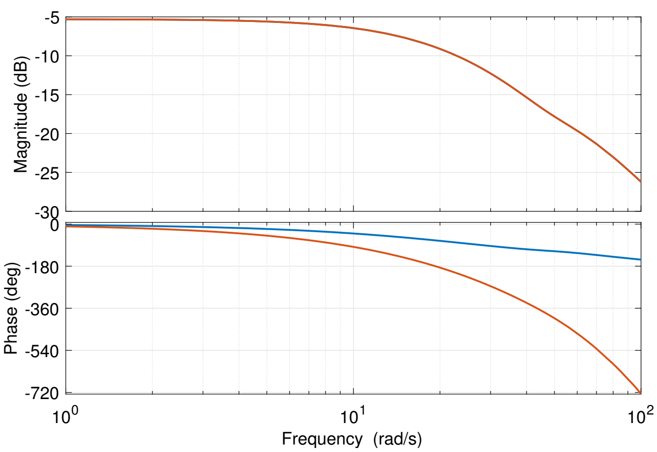

Fig. 13: Frequency response of the FV control layer with (red) and without (blue) communication time delay.

V. Conclusion

The procedure of the FCS model development for an HVDC grid was outlined in this paper. It was shown the model can be used for different levels of modeling depending on desired studies. The dynamics of converter current control loops, power and voltage control, and droop control of direct voltage and ac system frequency were considered by the FCS model and it was shown how the model assists to investigate the system dynamically and detect the cause weak performance, and also help to design and tune appropriate control for different control levels. It was shown how the time delay in control loops, which leads to oscillatory response–in some case to instability–, can be analyzed by the FCS model while the modal analysis fails in this regard.

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