COMPARATIVE STUDY OF FREQUENCY RESPONSE USING MTDC GRIDS

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Abstract: The paper is studying the comparison of various control strategies which provides the exchange of frequency response between AC power systems connected by a three- terminal meshed offshore HVDC grid. The paper accent the influence of such additional control loops on HVDC grid direct voltage response and on the AC systems frequency stability using instantaneous value average dynamic models. The control strategies evaluated and tested while studying the paper are- the synthetic inertia control loop using the AC system frequency derivative as input, the classical frequency droop based method and finally an integrated synthetic inertia emulation control scheme utilized as part of the direct voltage control loop. The controlling aim is the exchange of frequency reserves between the two AC systems through the HVDC grid.

IndexTerms –

R_{dc}, L_{dc}, C_{dc}	**Resistance, inductance and capacitance of the HVDC cable n- model.**
U_s, U_c	**Instantaneous value voltage at the grid connection point and at the converter station respectively.**
P_{dcj}, U_{dcj}, I_{dcj}	**DC power, direct voltage at each DC node of the MTDC and the direct current of each cable section.**
V_{ed}, V_{eq}	**d-axis, q-axis component of the converter voltage**
i_d ref, i_q ref	**d-axis, q-axis reference component of the current.**
i_d, i_q	**d-axis, q-axis component of the current at PCC.**
k_j, k_p	**Integral and proportional gain respectively of the PI controller**
f_{ref}	**Reference value of the AC system frequency**
C_{VSC}, S_{VSC}, H_{VSC}	**Capacitance, power rating and inertia constant of the VSC station.**

I. INTRODUCTION

The HVDC transmission VSC-BASED is considered as a modernized sensible solution for the grid connection of far from shore and large offshore wind power plants. In addition, HVDC transmission system technology would enable the future construction of a Pan-European HVDC transmission network, which could be used as bulk overlay DC grid operating next to AC power systems. The latter option can also facilitate the inter-connection of previously asynchronous power systems via multi-terminal DC grid [1]. Such an offshore multi-terminal DC(MTDC) grid would provide the grid connection of large amounts of offshore wind power plants while at the same time enabling the interconnection of different control areas, such as the Continental European power system to the Nordic and/or the Great Britain's system [1-2].

However, the VSC-HVDC stations forming part of the MTDC network, by their nature, would decouple the AC power system dynamics. Hence, the inertia response and/or primary frequency exchange among AC systems, if needed, would not be possible unless additional control loops are applied. Research which has been recently conducted in defining control schemes for provision of synthetic inertia and primary frequency control for both the point-to-point AC [3-5] as well as the VSC-HVDC connected wind power plants [6]. Authors in [3-6] have proposed control loops for provision of synthetic inertia response by making use of the frequency derivative measured at the grid connection. Lately, in [5], a new synthetic inertia emulator control scheme, integrated in the VSC-HVDC system direct voltage control loop, is proposed. This particular control scheme has the advantage of utilizing the frequency as given by the PLL. This paper compares different control strategies documented in the literature for the exchange of frequency support among DC interconnected power systems. The controllers tested and evaluated are namely: a classical frequency droop controller [4], [6], [7], an integrated synthetic inertia emulation controller implemented on the DC voltage control loop of the HVDC converter station [5] and finally, a classical synthetic inertia controller using the frequency derivative [1], [8], [9].

Given that the power injection by a voltage source converter can be independently controlled, the above mentioned control loops enable an artificial coupling of MTDC connected AC systems. The comparison of this control methods is done through time domain simulations on a small benchmark system observing both AC systems frequency response as well as HVDC grid direct voltage variations. The results would provide insight about possible interactions between different control modules of the MTDC grid and could be useful for the design of the grid codes related to the operation and control of MTDC grids connected to AC power systems.

II. MODEL OF THE MTDC GRID

2.1 Voltage Source Converter HVDC Model

A time-average instantaneous value model of the VSC- HVDC system has been used in this paper. The model has been developed in MATLAB/Simulink. The VSC-HVDC converter is assumed to be a two level converter. Both inner and outer control loops are represented using a SRF-PLL. The AC side of the converter has been modelled as three phase controllable voltage source, while the coupling between the AC and DC side is done by power conservation assuming a completely lossless converter station. Cascaded control layers have been used for the converter, including inner as well as outer control loops. The inner controller presents a fast dynamic response while the outer controller regulates the active and reactive power. The control of the direct voltage is a well-documented and important feature for the secure operation of the HVDC grid. For the present work, the classical direct voltage droop control is used, applied directly at the active current control loop of the onshore converter station.

III. TEST SYSTEM

The test system used is a meshed three-terminal HVDC grid which connects two asynchronous AC systems and an offshore wind power plant. The models and the test system have been developed in Matlab/Simulink.

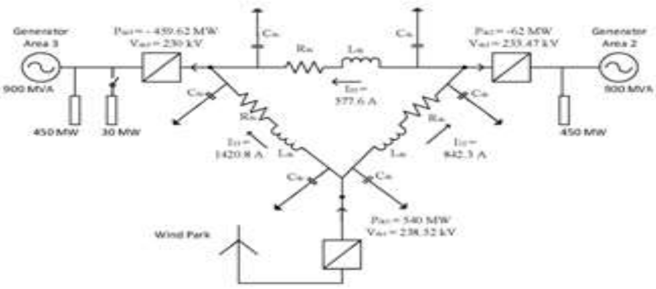


fig.1 multi-tenninal dc grid test system used in this paper analysis. this figure presents also the ac-dc system operating point used for the simulations presented in this paper.

For the present frequency stability study, each AC power system is modeled by single machine representation. The generator is equipped with a governor and an excitation system. The two AC systems have identical parameters in terms of control modules. Fig. 1 shows the test system and the power flow snapshot considered in this study. So in this case a significant share of power electronic dominated generation is considered. The inertia constant used for the generators was 6.5s. The power injected in the HVDC grid and the powers received by the AC systems can also be seen in Fig. 1. The operating point of the MTDC has been computed using the Newton-Raphson algorithm [l0], [12]. The grid side converters are rated at 900 MW. The generators have a similar rating at 900 MYA and the simulations start with a loading of 50% of the rated power.

IV. FREQUENCY CONTROL METHODS

4.1 Frequency Droop Control

In conventional power systems, the generation-load balance is regulated via the primary and the secondary frequency response [12]. In the case of the primary response, the power generation of conventional power plant units is controlled through the well understood governor's frequency droop control loop. In a similar manner, the power of VSCs forming a MTDC grid can be accordingly controlled in order to provide frequency support to the AC system. The first and most understood control scheme for such a case would be the power frequency droop [12]. This control strategy can be easily implanted at the onshore HVDC grid converters coupling two AC systems as first shown in [6], [11] and later in [7]. Fig. 2 presents the frequency droop control used in this paper. Please note that in this case, both the direct voltage droop and the frequency droop act simultaneously at the active current loop. A dead-band, between 49.9 - 50.1 Hz, has been used in order to avoid the controller triggering for normal operation frequency deviations. No dead-band is applied at the direct voltage control loop.

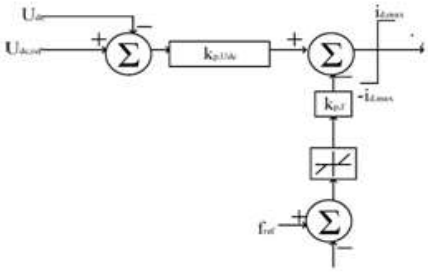


fig.2 frequency droop controller.

4.2Integrated with PLL Synthetic inertia emulation control

Another similar controller is the synthetic inertia emulation strategy, as given in [5]. This method is first applied in point- to-point VSC-HVDC links connecting offshore wind power plants. The synthetic inertia emulation controller has a different implementation than the frequency droop controller. Here the control action is applied on the voltage reference rather than directly on the d-axis (active) current reference. The control parameters have been calculated as in [5]. fig. 3 gives the block diagram of such control loop. It is important to observe that the frequency deviation is obtained from the PLL in the case of the present controller.

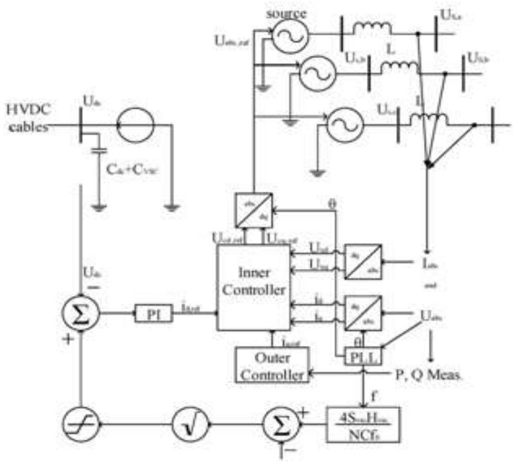


fig. 3 synthetic inertia emulation controller loop

$$K2 = \frac{4HvscSvsc}{NC} - U2dco$$

$$U2dc = \sqrt{\frac{4HvscSvsc}{NCfo} f - K2}$$

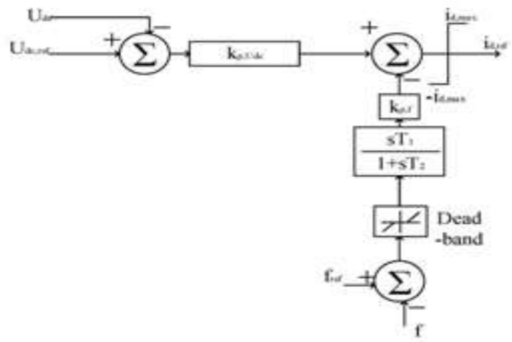
$$Hvsc = \frac{\frac{NCdcU2dco}{2Svsc}\left[\left(\frac{\Delta Udc}{Udco} + 1\right)_2 - 1\right]}{2\frac{\Delta f}{fo}}$$

$$H_{VSC} = \frac{\frac{NC_{dc}U_{dco}^2}{2S_{VSC}}\left[\left(\frac{\Delta U_{dc}}{U_{dco}}+1\right)^2-1\right]}{2\frac{\Delta f}{f_0}}$$

4.3Classical synthetic inertia control based on the frequency derivative

Finally, the third controller found in the literature is the classical method for provision of synthetic inertia response known as synthetic inertia controller using the frequency derivative, *dj/dt*, [1], [8]. Following the same approach, we have implemented this controller shown in Fig. 4 in the MTDC study grid. The synthetic inertia method using the frequency derivative can be applied at any onshore VSC-HVDC station, enabling the HVDC grid to contribute with an inertial response during generation outages or disturbances [3], [4], [8]. The active power is changed by modifying the reference value of the d-axis current in the outer controller of the converter station.

The same type of dead-band as for the previous controller is used; such that the frequency's normal operating oscillations are not considered. The derivative has been implemented using a washout filter.



V. SIMULATION RESULTS

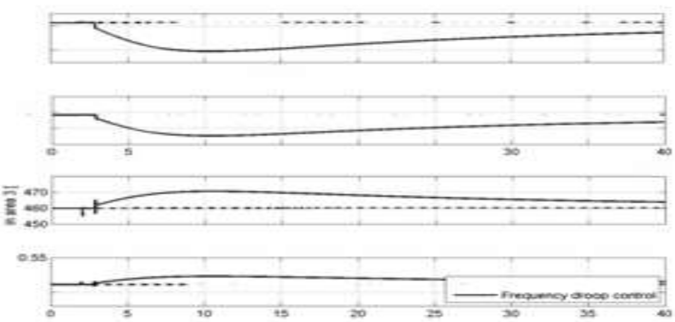
For the three given control strategies, the AC-DC system response will be presented. The base case is the 'no frequency control' case, where the converters are not equipped with any kind of frequency control loop. Therefore, the frequency disturbance is isolated and concerns only the area where the power imbalance occurs.

5.1 Combined AC-DC system dynamic response with frequency droop control loop

First, we assume a case where only the grid-side converter of AC area 3 is equipped with a frequency droop control loop. No frequency control loop is applied at area 2 converter station. Both onshore converters are in direct voltage control strategy applying direct voltage droop control loop.

Fig. 5 presents the active power response of the two onshore converters stations, while Fig. 6 presents the frequency response in the two AC systems connected through the DC grid. As it can be observed, the engagement of the onshore converter station of system 3 in the primary response by the frequency control loop, improves the frequency stability of the AC system 3 at the cost of disturbance induced in the remotely DC connected system 2. The power needed for the primary response in area 3 is provided from area 2 by means of the power balance mechanism of the DC grid. No communication is needed in this case.

Furthermore, the impact of the dead-band selected is presented in Fig. 7. As it can be observed, the presence of the dead-band has created non-linearity in the response of the onshore converter station which creates oscillations. Finally, Fig. 8 shows the influence, on the frequency response of the AC systems, of the instantaneous application of frequency droop control on both the onshore converter station.



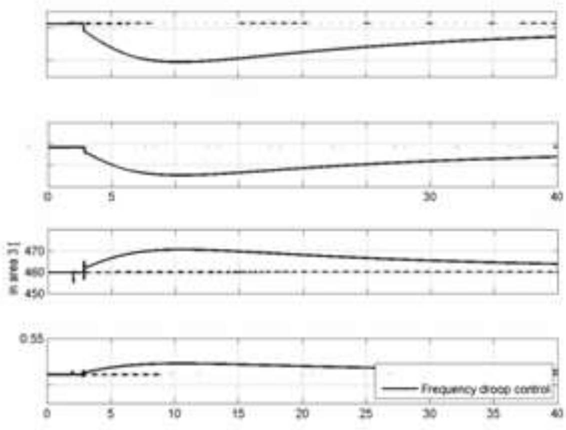


fig. 5 comparison between the no frequency control case and frequency droop controller used at the gsvsc of area 3

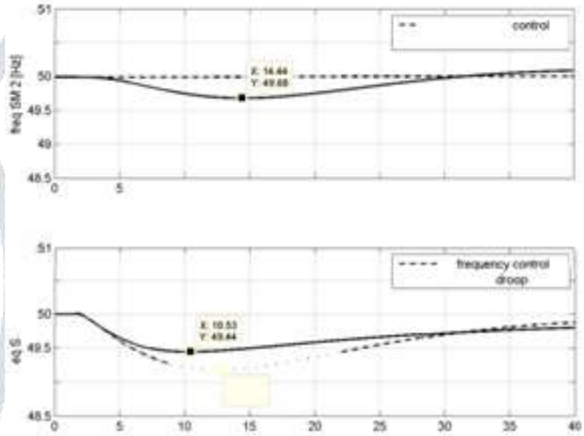


fig. 6 frequency nadir values for areas 2 and 3 in the case of no frequency controller and in the case of frequency droop control in area 3

As observed in Fig. 6, the participation of the converter station in area 3, in the frequency response, creates a frequency deviation in area 2. If the converter in area 2 is equipped as well with a frequency droop control loop, then this converter will react and in a way cancel the power transferred between the two systems. The influence of this interaction is presented in Fig. 8 where the maximum frequency deviation or NADIR is shown for the cases where one or both onshore converters are equipped with frequency droop control.

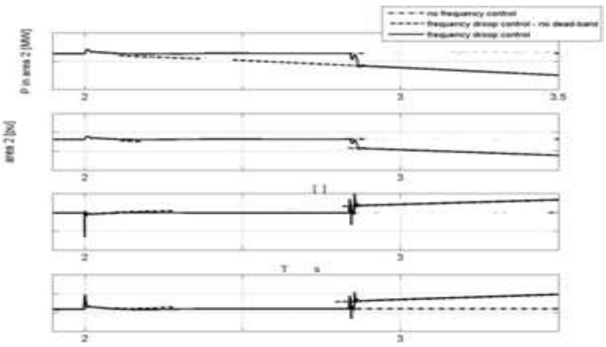


fig. 7 comparison between the case with dead·band and the case without a dead·band in the frequency controller for frequency droop

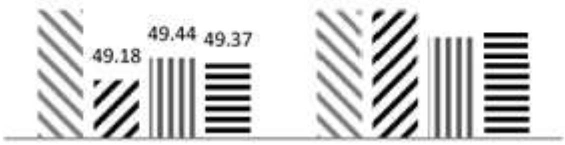


fig. 8 frequency nadir comparison for the frequency droop controller used in no gsvsc, in gsvsc 3 and in both gsvsc 2 and 3

5.2 AC-DC system response with integrated inertia emulation control scheme

Next the synthetic inertia emulation control is integrated at the direct voltage control loop will be examined. The dynamic response of the AC-DC system is shown in Fig. 9 and Fig.10, while figure Fig. 11 presents the sensitivity of the inertia emulation constant Hvsc.

From the simulation results it is clear that the frequency control loop is capable of facilitating the exchange of primary frequency reserves between the two systems. The response of the system is very similar to frequency droop control loop. Even though, the name suggests inertia response, the behavior is rather similar to primary frequency response and less to the inertia response. Normally, a classical synthetic inertia controller provides fast active power response in the first seconds of the power imbalance in order to improve the frequency ROCOF.

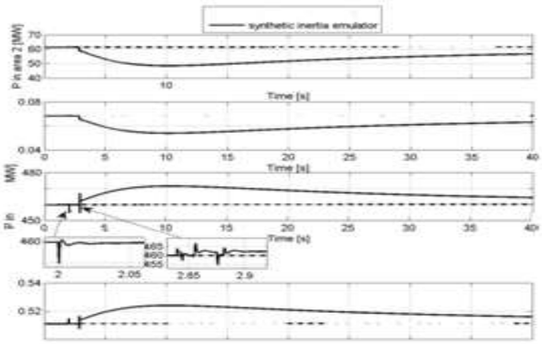


fig. 9 comparison between the no frequency control case and synthetic inertia emulation control used at the gsvsc of area 3

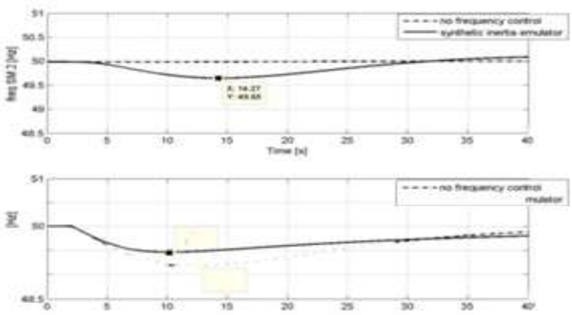


fig.10 frequency nadir values for area 2 and 3 in the case of number of frequency controller and in the case of synthetic inertia emulation control in area 3

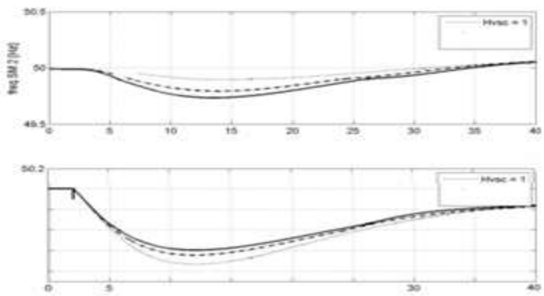


fig. 11 sensitivity study for inertia constant for the synthetic inertia emulation control used in gsvsc of area 3

One such example is shown in [4] and [8]. The name of the present controller is given because of the capability to assign an inertia constant, rather than the behavior of the frequency response strategy [5]. The inertia constant assigned to the grid side converter will influence the behavior of the grid-side converter in the same manner as that of a synchronous machine. This sensitivity can be observed in Fig. 11. In the case of implementing a synthetic inertia emulation control at area 3, the increase of the inertia constant improves the frequency response of this area, at a higher risk to area 2.

5.3 AC-DC system response with classical synthetic inertia control loop

Finally, the classical synthetic inertia control loop of Fig. 4 is applied at the onshore converter station. This control loop, which utilizes the frequency derivative as control input, is capable of providing a fast active power response during the first seconds of the imbalance.

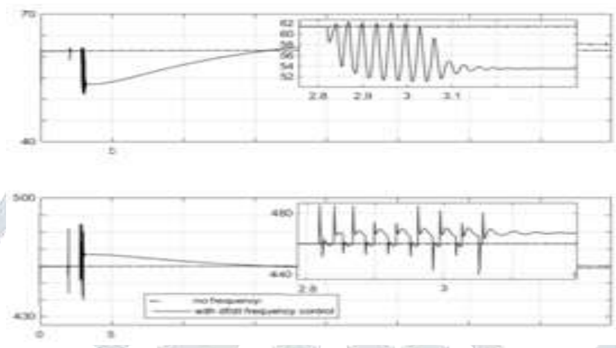


fig.12 active power of the onshore converter stations when providing inertia response using the control loop of figure 4.

As seen in Fig. 12, the utilization of the frequency derivative is creating a fast active power oscillation at the converter station. It is due to an interaction between the synthetic inertia control loop and the inner loop of the converter station. In general, such oscillation can be avoided by proper tuning of the inner loop and is not the focus of this paper. Regardless of the oscillations, this result demonstrates that the participation of MTDC grids in ancillary services may create interactions and influence the dynamic performance of the converter station and should be carefully assessed and more detailed studies are needed.

VI. DISCUSSION

The implementation of a frequency control loop at the onshore converter station of a multi-terminal HVDC grid would support the frequency stability of the relevant control area by sharing active power reserves between the AC systems connected via an MTDC. The power transferred is provided by the mechanism of the direct voltage control and requires no communication.

Given the test system and the results presented in this paper (evaluated in Fig. 13), the frequency droop control loops and the synthetic inertia emulation controller integrated in the direct voltage loop provided improvement in the system frequency stability performance. Looking at the classical inertia control using the derivative of the frequency, even if it demonstrated good performance in the ROCOF, it created a sustained frequency deviation compared to the other two methods. Furthermore, interactions with the VSC inner loop are observed. The proposed frequency controllers have demonstrated nonlinearities and oscillations when a dead-band is employed. The droop frequency controller and the integrated inertia emulator have also introduced steady state deviations in the direct voltage after the frequency disturbance has been recovered. In general the application of fast acting frequency support loops should be performed followed by extensive studies which would ensure that no interactions would occur between the inner-outer loops of the VSC and the frequency support control loops.

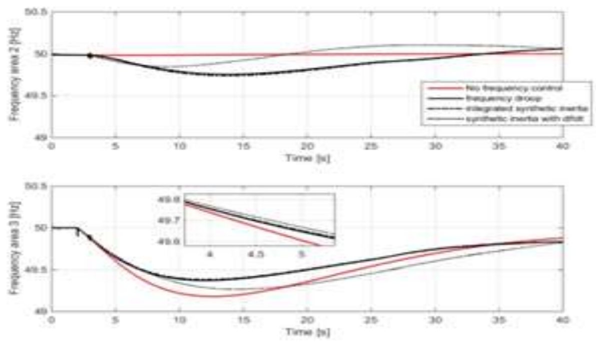


fig. 13 frequency response in the two ac systems for the three methods

VII. CONCLUSION

This paper is related with the comparison of common frequency control methods found in the literature applied to a multi-terminal VSC- HVDC grid. Its aim is to provide the exchange of power reserves by artificially coupling the AC systems. The later would boost the capability of the AC systems to overcome frequency deviations after severe contingencies. The three frequency controllers investigated are namely: the frequency droop control method, an inertia emulation control method integrated with the direct voltage control and the synthetic inertia control method using the frequency derivative. The simulation results proved the hypothesis that additional frequency control loops could engage onshore converter stations in frequency response provided to the relevant AC area. The paper also interacts and provide recommendations about the usability and applicability of all individual strategy.

VIII. REFERENCES

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