Performance evaluation of the empirical method for online detection of power oscillations: a multiterminal HVDC application

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***Abstract*—This paper presents the performance evaluation of an empirical method for online detection of power and voltage oscillations electric grids and is used as a monitoring system to evaluate the grid performance. Additionally, the method is applied to a multiterminal HVDC grid. Finally, the performance is evaluated based on a database from the simulation results.**

***Index Terms*—Power oscillation, Ring-down, Prony analysis, Power system monitoring, Damping ratio.**

I. Introduction

The rising environmental awareness and the need to transfer huge amounts of power over long distances is determining an increasing number of installed HVDC transmission systems, tightly interconnected to the traditional AC grids. The availability of proper tools to analyze the dynamics of the resulting hybrid AC-DC grids is of paramount importance to ensure the stability and efficient operability of the modern power systems and avoid costly interruptions.

Besides the elaboration and use of theoretical frameworks and simulation approaches to anticipate the possible arise of critical operating conditions within the electrical grid, it seems equally important to develop accurate methods to empirically detect oscillating conditions from available measurements, before they become critical. While such methodologies have been so far proposed for oscillation detection in traditional AC systems [1], [2], similar methods have not yet been investigated for HVDC systems. The importance of correctly assess the dynamic behavior of HVDC links, especially during critical/abnormal operating conditions, has recently been deemed important by Transmission Systems Operators (TSOs) [3]. Moreover, the capability to extract relevant information on the (normal/abnormal) operating condition of an HVDC system based on its DC voltage and or DC power measurements will be a topic of increasing importance for TSOs, especially following the expected deployment of large and interconnected HVDC systems required for massive integration of renewable energy sources onshore [4] and offshore [5].

This paper proposes a contribution to address this open issue. Specifically, it investigates if a methodology proposed for the online detection of oscillations in AC systems can be adapted to HVDC systems. The HVDC grid is developed based on the CIGRE guide and assessed on a four-terminal test case[6].

The method uses AC and DC signals of the multiterminal HVDC grid for two cases. The first case presents the ideal behavior of the system. The second case presents the abnormal behavior of the multiterminal HVDC grid. Besides, a detector uses the peak to peak magnitude of the oscillation in a transient and a threshold to study this transient. The next stage uses Prony's algorithm when the transient requires the analysis and this method determines the damping ratio.

The paper is organized as follows: section II shows the oscillation of the transient event signal with a damped behavior, the method for empirical detection of the transient and the performance index to evaluate the detector method. Section III describes the multiterminal HVDC grid, section IV shows the computational results, the database used to test the detector, the performance of the detector and the damping factor calculated with the event detected signal. Finally, the conclusions are highlighted in section V.

II. Transient and oscillations

In order to give an index of the criticallity of the signal transient, this paper uses the concept of damping ratio of dynamic systems [7]. It is useful to analyze the time response of the signal in the transmission systems. However, in this case we study the behavior of a signal in a multiterminal HVDC grid. The method uses the second order system per signal (1), with $y(t)$ the signal under test (in this case the power or DC voltage of the HVDC grid), $u(t)$ can be a change in a signal reference that excites the system. This excitation usually occurs as a consequence of major system disturbances or faults. The small variations or random small amplitude excitations are not analyzed in this paper.

$$\frac{d^2y(t)}{dt^2} + 2\rho\omega_n \frac{dy(t)}{dt} + \omega_n^2 y(t) = u(t), \tag{1}$$

where the damping ratio is ρ, the natural frequency of the system is ω_n. Under-damped systems present a $\rho < 1$ and they have the characteristic behaviours studied.

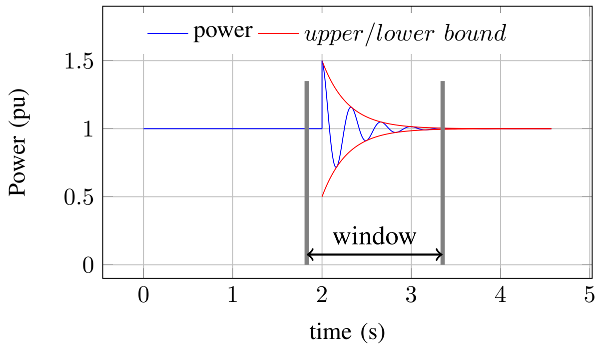

Fig. 1. Example of a ring-down signal.

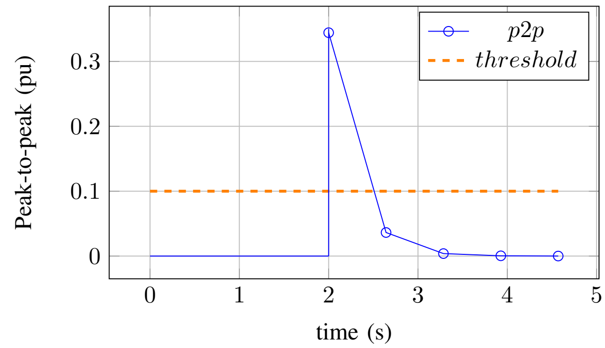

Fig. 2. Outer bounds detected oscillation magnitude.

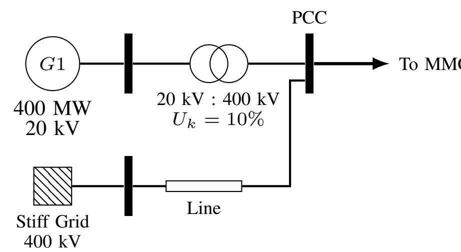

Fig. 3. Topology of ac grid at node 1.

It is known from dynamic systems that the roots of the characteristic equation (1) are the eigenvalues of the system and they can be obtained as shown in (2).

$$\begin{aligned} \lambda_{1,2} &= -\rho\omega_n \pm j\omega_n\sqrt{1-\rho^2}, \\ \lambda_{1,2} &= \alpha \pm j\omega_t, \end{aligned} \tag{2}$$

where ω_t is the oscillation frequency and is different from ω_n, $\omega_t = \omega_n\sqrt{1-\rho^2}$. The real part of λ is the attenuation, and the damping ratio can be obtained as $\rho = -\alpha/\sqrt{\alpha^2+\omega_t^2}$. If the real part of $\lambda_{1,2}$ is positive then the damping ratio is negative.

The damping coefficient and the frequency of the oscillation are computed with a basic Prony's analysis for each signal following the method in [8].

A. Outer bound detector method

The oscillation of the signal can be easily detected by the outer bound method [1]. The method has low computational cost. Moreover, the aim is to calculate the difference between the first transient peak and the next minimum of the signal as the peak to peak oscillation magnitude value. Therefore, using a measurement window, it is possible to detect the oscillation magnitude calculating the difference between the peak and the next nadir. Figure 1 illustrates the idea and shows the upper and lower bounds of the signal and the window that is used to find the transient. Figure 2 shows the peak-to-peak magnitude ($p2p$) and the threshold used for the transient detection algorithm.

1) Performance index for the detector: The *true positives rate* (tp_{rate}) is an index that measures the performance of the detector for multiple thresholds [9]. This index quantifies the number of correctly detected transient events (TP) over the number of transient events of the signal (P). Equation (3) defines the tp_{rate}.

$$tp_{rate} = \frac{TP}{P} \tag{3}$$

A $tp_{rate} = 1$ means that the detector has 100% accuracy and finds all the transients of the signals at the correct instant.

III. Multiterminal HVDC grid

The considered multiterminal HVDC grid (Fig. 4) uses two MMC stations to interconnect two offshore wind farms with the onshore grids. Additionally, the onshore grids have two MMC stations. The parameters of the systems were taken from the CIGRE guide for development of models for the converters in HVDC grids [6]. The converter at node 1 is assumed as grid forming (i.e. the converter controls the voltage of the grid at the DC side), the converters for node 2, 3 and 4 are controlled with voltage-power droop controller to regulate the power injected into the DC grid by the wind farms. The AC grid at node 2 of the HVDC system is considered as stiff. The ac grid at node 1 is modeled by a combination of a local synchronous generator and a stiff grid connected through a line as shown in Fig. 3. Parameters of the synchronous generator, $G1$, are chosen in such a way that the machine exhibits a poorly damped electromechanical mode with frequency of 1 Hz and damping of 5 %. Length of the transmission line between the stiff grid and the Point of Common Coupling (PCC) determine the strength of the grid. If the line is long, dynamics of the grid are heavily influenced by $G1$ resulting in a weak grid. The opposite is true for the case of a short line. Hence, two sets of results, with weak and strong grid conditions, generate the database for the test of the detector and damping estimation methods.

The grid operates without the cable between the nodes 1-4 until 9 seconds. The integration of the cable creates a transient that is not function of a step of injected or consumed power at the converter stations.

IV. Computational results

The computational results present the database created to test the performance of the detector and the estimation of the damping ratio. Two databases are generated with the change

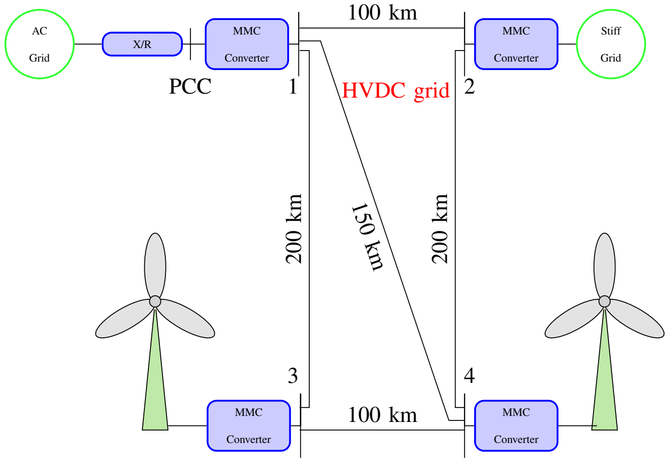

Fig. 4. Multiterminal HVDC grid.

of the X/R ratio of the AC grid equivalent at the converter of node 1. The first set of data presents the normal behavior of the power and voltage signals of the multiterminal HVDC grid with a stiff AC grid at the AC side of node 1. The second data set uses X/R=7 to create a weak AC grid. Moreover, with the second data set the aim is to recreate a similar oscillation incident reported in [3] by the ENTSO-E at the border between Spain and France which is close to the HVDC link of the two countries. Here, the oscillation is at one of the AC nodes of the multiterminal HVDC grid.

A. Normal and abnormal HVDC grid behavior

Figure 5 shows the normal behavior of the HVDC grid for an ideal behavior of the network. Besides, Fig. 6 shows the behavior of the HVDC grid for an uncommon behavior of the grid.

B. Performance of the detector

Table I presents the performance of the outer bound detector with multiple values of the threshold used to find a transient of the AC power signal at each node. There is a total of 8 transients for the AC power signals. The idea is that under normal operation just the power transients at 5.5 s and 7.7 s can be detected and the integration of the cable 1-4 at 9 s does not affect the normal behavior of the grid and the HVDC grid exhibits a damped transient. Therefore the number of positive events is $P_n = 8$. Additionally, the number of positive events for the abnormal case is $P_a = 8$ based on the sustained oscillation for more than 1 s for P_{ac1}.
With the performance analysis it is possible to conclude that the best threshold value is 0.001, this value produces a 100% of detection for both cases.
Table II presents the performance of the outer bound detector with multiple values of the threshold used to find a transient of the DC voltage signal at each node. One DC voltage signal has three transients during normal and abnormal operation. Hence, in this case the number of positive events is $P = 12$. The performance analysis with DC voltage signals shows the

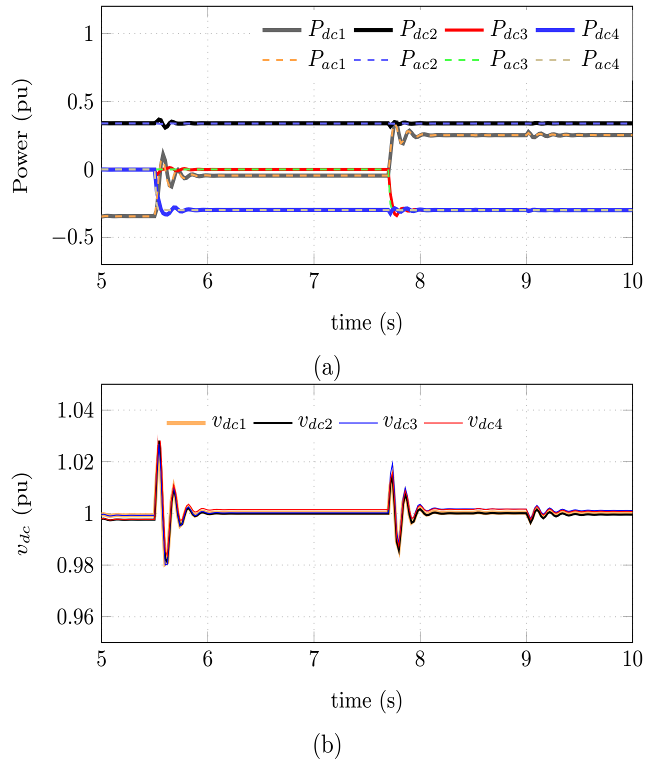

Fig. 5. Normal HVDC grid behavior, (a) power signals and (b) voltage signals at each node.

TABLE I
PERFORMANCE OF THE OUTER BOUND DETECTOR FOR THE AC POWER.

Threshold (pu)	tp_{rate}	
	normal	abnormal
0.0009	1.000	1.000
0.0010	1.000	1.000
0.0012	0.750	1.000
0.0020	0.625	0.750
0.0500	0.500	0.500
0.1000	0.500	0.500
0.1800	0.250	0.250

threshold 0.0012 as the most accurate value.
Once the threshold has been selected for each case, the test of damping ratio estimation is applied. Therefore, this paper presents the damping ratio of the AC power and the DC voltage. The damping ratio for the case of AC power of a normal behavior of the multiterminal HVDC grid is shown in Fig. 7. It is important to remark that the analysis is applied

TABLE II
PERFORMANCE OF THE OUTER BOUND DETECTOR FOR THE DC VOLTAGE.

Threshold (pu)	tp_{rate}	
	normal	abnormal
0.0009	1.000	1.000
0.0010	1.000	1.000
0.0012	1.000	1.000
0.0020	1.000	0.917
0.0040	0.667	0.667
0.0500	0.000	0.000

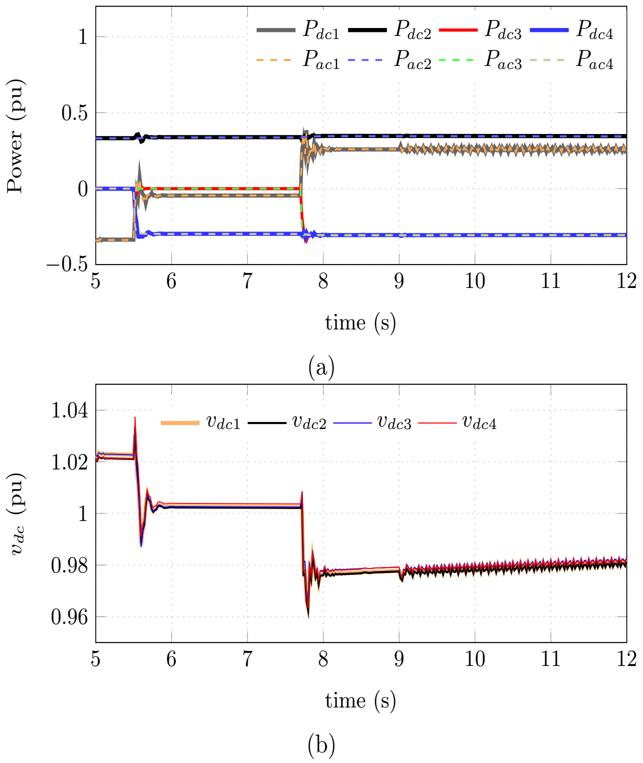

Fig. 6. Abnormal HVDC grid behavior, (a) power signals and (b) voltage signals at each node.

on each signal. The detection events in Fig. 7 are d_i with $i \in \{1, 2, 3\}$. It is important to remark that the signal P_{ac1} has three events to detect. However, the damping ratio of P_{ac1} is above the risk limit 5%. Only, P_{ac2} and P_{ac4} present a damping ratio below 5% (Fig. 6).

Figure 8 shows the damping ratio for each event on the power signals when the abnormal behavior is studied. Based on the results of abnormal operation, the third event of P_{ac1} does not have stable behavior during the window detected. Additionally, this event generates an alarm due to its $\rho = -0.02\%$. This negative damping ratio is the result of the rising part of the transient at 9s.

Figure 9 shows the damping ratio for each event on the DC voltage signals when the abnormal behavior is studied. A set of transients present the damping ratio above 5%. The third detected transient at each voltage signal presents a very low damping ratio i.e. a value below 1%.

Finally, the damping estimation of DC power is shown in Fig. 10 for a abnormal behavior. P_{dc1} has a low damped oscillation at the third event (9 s) which activates the alarms of abnormal behavior. There is a set of low damped oscillations detected at the node 2. Moreover, the oscillations present a main component with frequency of 162 Hz estimated with the Prony method.

V. Conclusions

The paper presented the performance of the empirical detector of transients and oscillations for applications on

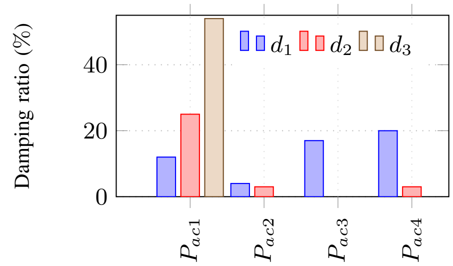

Fig. 7. Damping ratio of the oscillations detected with the normal behavior.

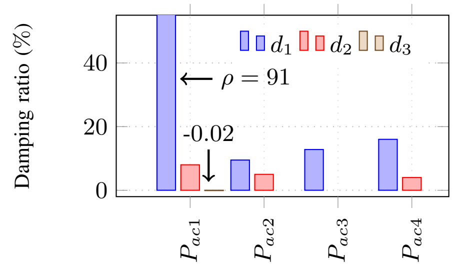

Fig. 8. Damping ratio of the oscillations detected with the abnormal behavior.

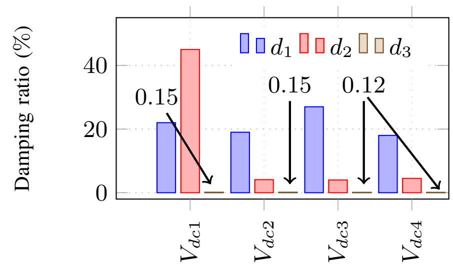

Fig. 9. Damping ratio of the oscillations detected with the abnormal behavior for the DC voltage.

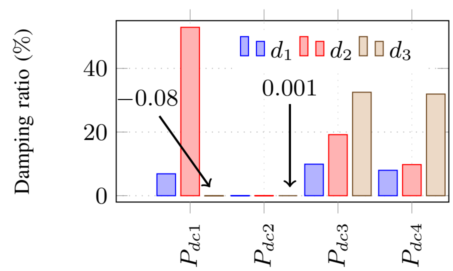

Fig. 10. Damping ratio of the oscillations detected with the abnormal behavior for the DC power.

a multiterminal HVDC grid. The study of oscillations and online monitoring of this type of events is well known from AC transmission system operators. However, the approach of this paper shows the performance of the method on the HVDC grids.

There is a trade-off for the selection of the threshold of the outer bound detector. A very low threshold generates over detected events whose analysis is not necessary. Moreover, a very high threshold value does not detect important power or DC voltage transients.

Finally the paper shows the calculations with the DC voltage and power signals to support multiterminal HVDC analysis. The use of DC power leads to a similar conclusion as the use of AC power under abnormal operation.

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