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Contribution of variable-speed pump hydro storage for power system dynamic performance

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Abstract. This paper presents the study of variable-speed Pump Storage Powerplant (PSP) in the Portuguese power system. It evaluates the progressive integration in three major locations and compares the power system performance following a severe fault event with consequent disconnection of non-Fault Ride-through (FRT) compliant Wind Farms (WF). To achieve such objective, a frequency responsive model was developed in PSS/E and was further used to substitute existing fixed-speed PSP. The results allow identifying a clear enhancement on the power system performance by the presence of frequency responsive variable-speed PSP, especially for the scenario presented, with high level of renewables integration.

1. Introduction

On the last decades, European countries have been adopting renewable generation to cope the European Union ambitious targets on green-house gases reduction and on the share of renewable energy in the electricity consumption. From a chronological perspective, hydro power has been in-line with these objectives for many decades. However, the need of resource diversification and the unavailability of significant conditions for exploring hydro resources in many countries have been pushing for the integration of different technologies such as solar photovoltaic and wind energy.

In that particular field, Portugal is an interesting test-case regarding wind power integration having 4937 MW (2015 data) [1] of installed power and record-level renewable energy in the electricity consumption having supplied the entire load during 107 hours by renewable energy [2] In addition, the Portuguese power system recently accommodates the biggest variable speed pump/generators, 400 MVA units at the Venda Nova III power plant [3]. The work presented in this paper is focused in the evaluation of the Portuguese power system transient stability with the penetration of frequency-responsive variable-speed PHS. In order to achieve such fulfillment, a reduced-order model has been developed and implemented in PSS/E over the Portuguese power system in the valley hours' scenario. The analyzed cases comprise the actual scenario (comprising only fixed-speed PSP) and progressively takes into account the interconnection of new variable-speed PSP by considering firstly the aforementioned Venda Nova III and then the substitution of fixed-speed PSP for frequency-responsive variable-speed PSP. The analysis was performed for major disturbances such a fault event and the disconnection of a large conventional thermal generation unit. The results show the benefits overcoming from the extra flexibility provided by variable-speed PSP on participating in the primary frequency regulation.

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2. Modelling of variable-speed PHS for transient stability studies in large power systems

The modelling of hydro powerplant is a topic of extreme importance for the performance of transient stability studies. The accuracy on describing the parameters and defining the hydraulic time constants are crucial for obtaining representative results. The work carried out in the FP7 Hyperbole Project, consisted on the developing and evaluating the performance of reduced-order models for representing variable-speed PSP based on Doubly-fed Induction Generator (DFIG) and on Full Scale Frequency Converter (FSFC) technologies. The control flexibility provided by power converters in both technologies fully decouples machine speed and grid frequency, thus allowing fast responses with respect to active power control. In the context of Hyperbole project a deep analysis was performed between the full-order model in SIMSEN and a reduced order model in Matlab/Simulink. The major outcome from this task consisted on the identification that the reduced-order model represents the major PSP dynamics, being sufficient for transient stability studies.

2.1. The variable-speed PSP model

For the sake of the work presented in this paper, the original idea consisted on transposing the reduced-order model to PSS/E via an add-on called Graphical Model Builder (GMB) that basically should help on the transposition of the aforementioned model to PSS/E. Unfortunately, the GMB proved to be ineffective on providing support on this specific target. On alternative, the variable-speed PSP has been represented by a frequency responsive load model, an approach commonly used to represent electronically interfaced sources (the FSFC case) on transient stability studies where the objective is to study the impacts that this new generation sources will bring to the power system dynamic response.

Have stated that, the variable-speed PSP was represented by the load model illustrated in Figure 1.

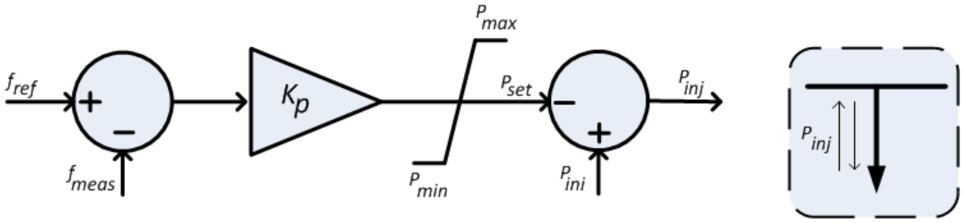

Figure 1: Power/Frequency proportional controller

Basically, the load model is composed by a proportional controller, responsible for setting the active power at the load. The Active Power/Frequency proportional controller is responsible for defining the load active power variation proportionally to the frequency deviation measured at the machine terminals, adapted by the K_p droop gain. In order to better characterize the typical variable speed PSP behaviour, a ramp rate was also included limiting fast responses, based on the outcomes from the modelling work presented on the Hyperbole Project deliverable 6.2 [4].

2.2. The Power System model

The power system base case model was kindly provided by REN (the Portuguese Transmission System Operator – TSO). Considering that the major objective of the work here presented consisted on evaluating the performance of the power system dynamics in the presence of variable-speed PSP, namely in pump mode, the scenario adopted for the elaboration of the simulations was the valley hours' scenarios which contained some hydro power plants operated in pump mode (despite being fixed-speed PSP). Due to confidentiality aspects, REN could not provide the Spanish grid-side. Thus, dynamic equivalents were developed and placed in the interconnections for enabling the provision of inertia and frequency response following disturbances. After these modifications, the final case was used as the base case that will be presented hereafter.

In order to accomplish the test-cases, the variable-speed frequency responsive PSP have been integrated in PSS/E by coding the model presented in Section 2.1. in Fortran and compiling it for PSS/E use. That way, this model can be associated to any busbar of any PSS/E simulation. For the sake of the study here presented, the model was used on different locations of the Portuguese power system as presented in Section 2.3.

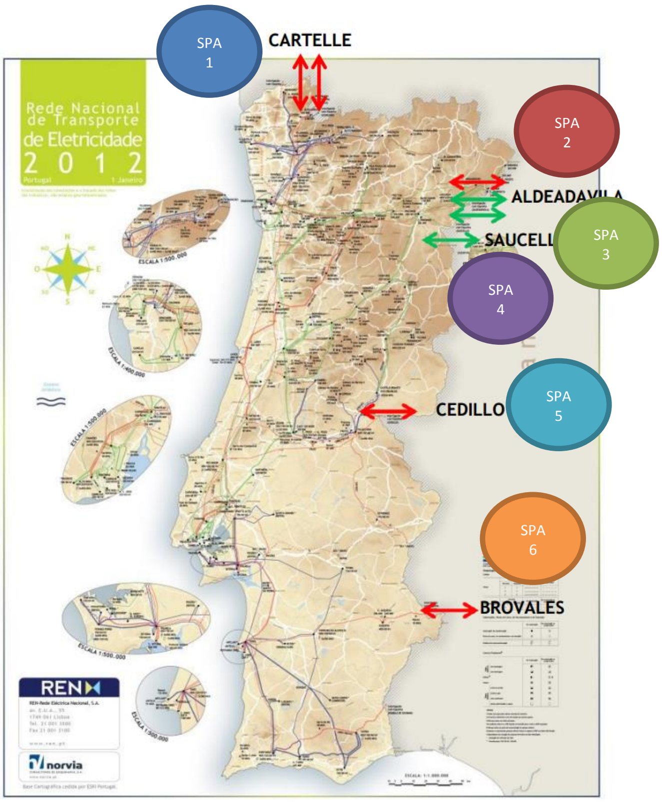

Figure 2: Portuguese power system with Spanish dynamic equivallents – adapted from [5]

2.3. Test Case definition

The test cases analysed in this paper consists on the incremental integration of the variable-speed PSP units in the Portuguese power system, by substituting fixed-speed pumping units with the previously presented variable-speed PSP frequency responsive model. The rationale consisted on creating a base-case scenario, CASE A for allowing further comparisons. Then, the approach consisted on evaluating the system performance with the first Portuguese variable-speed PSP, Venda Nova III (CASE B). Finally, CASE C and CASE D were created to allow assessing what would be the impacts of retrofitting existing fixed-speed PSP units for variable speed ones, namely Aguieira PSP (CASE C) and finally Alqueva PSP (CASE D). The cases and associated details are presented in Table 1.

Table 1: Cases description according with the PSP integration

CASE #	Variable-speed PSP	Pump mode Active Power
CASE A	None	BASE CASE
CASE B	Venda Nova III	1 x 400 MW
CASE C	Venda Nova III Aguieira	1 x 400 MW 3 x 91 MW
CASE D	Venda Nova III Aguieira Alqueva	1 x 400 MW 3 x 91 MW 4 x 110 MW

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In order to analyse the effects of the primary frequency support provided by the variable-speed PSP, a fault event located at Lavos substation 400 kV busbar with a duration of 500ms was considered. The fault event in this specific location should lead to the tripping of wind farms without Fault-ride through capability, which is a severe situation for the power system operation in terms of generation loss and thus, frequency disturbance. Simultaneously, during the simulation an algorithm will monitor the Portuguese WF generation in order to determine the amount of WF disconnected following the fault event.

3. Simulation Results

As previously presented, the Portuguese power system performance was analysed for several cases, under the same disturbance, differing in the frequency-responsive variable-speed PSP integration level as described in Table 1. The disturbance considered for the sake of analysis consisted on a three-phase fault at Lavos 400kV busbar. The major results are illustrated in Figure 3 to Figure 7. The results allowed observing that during the fault event, severe voltage sag occurred and, in the aftermath, the voltage was able to recover to pre-fault level as illustrated in Figure 3.

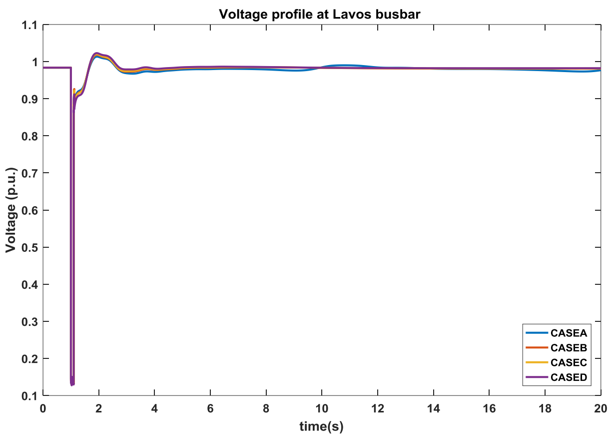

Figure 3 : Voltage profile at Lavos 400kV busbar

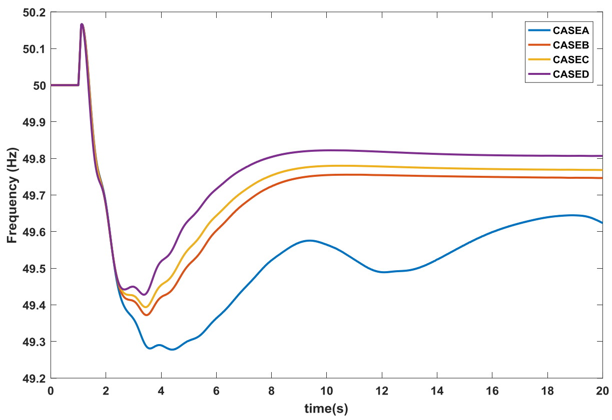

Figure 4 : Portuguese Power System frequency

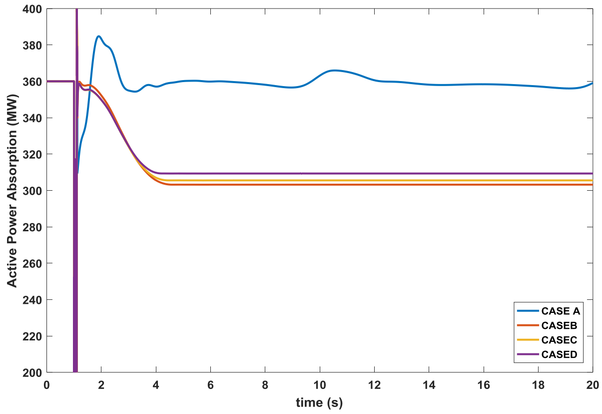

Figure 5 : Venda Nova III PSP Active Power consumption

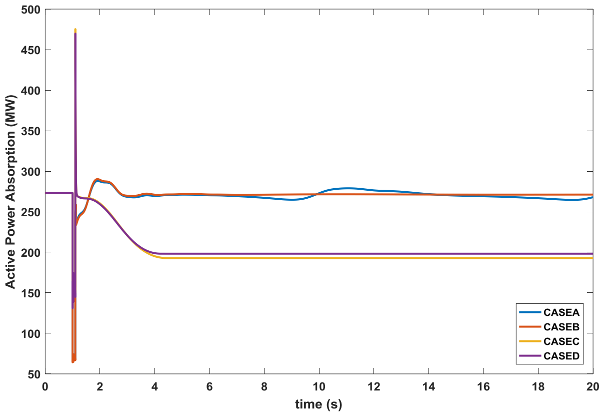

Figure 6: Aguieira PSP Active Power consumption

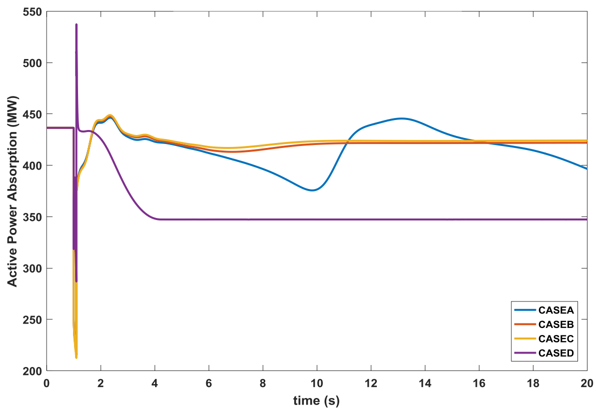

Figure 7 : Alqueva PSP Active Power consumption

In terms of frequency, the fault event and the consequent disconnection of wind power led to under-frequency deviation with large excursion as illustrated in Figure 4. For the case where no variable-speed PSP contribution was taken in consideration (CASE A), large oscillations can be observed. The integration of variable-speed PSP mitigates the oscillatory behaviour helping the power system stabilization. Furthermore, the progressive increase on the variable-speed PSP integration level reduces the frequency deviation, as depicted in Figure 4.

Regarding the active power response, the results for each power plant are illustrated in Figure 5, Figure 6 and Figure 7. For the CASE A, there is no variable-speed PSP on the grid thus, the generation units that have been monitored do not respond to frequency deviation. However, an oscillatory behaviour is observed on every power plant monitored. This behaviour is related with voltage fluctuation and with frequency disturbance, which affects the active power consumption. The inclusion of variable-speed PSP mitigate these effects thus, the active power response is smoother. It is also possible to verify that the generation units are able to provide primary frequency support by reducing the absorbed power while operating as pump. The observed active power reductions in the simulation results have a permanent characteristic. This fact is related with the inexistence of secondary control implemented in PSS/E Portuguese grid model. As a matter of fact, this is also observable in the frequency response (see Figure 4) which do not recovers back to the 50Hz but stabilizes in a value below. The aforementioned results are common for all variable-speed PSP as can be observed in Figure 5, Figure 6, Figure 7, for each analysed case.

4. Conclusions

The work presented in this paper consisted on evaluating the performance of the Portuguese Power system facing the progressive integration of frequency responsive variable-speed PSP in key locations, substituting fixed-speed PSP. A frequency responsive load model was developed in PSS/E, and parameterized for allowing the representation variable-speed PSP major grid-side dynamics. A severe disturbance consisting on a fault event that led to the disconnection of a significant amount of non-FRT compliant WF. This fault event led to load-generation imbalance, affecting the frequency, which decayed. The progressive integration of frequency-responsive variable-speed PSP showed to be beneficial regarding the provision of frequency support. The results show that the higher integration level, the lower frequency decay. In addition, the presence of variable-speed PSP helped on smoothing the power system frequency on what regards to oscillations. The effective active power contribution was achieved by the proportional active power consumption reduction at the variable-speed PSP, depending on the cases. It is also important to stress that no problems at the power system level were observed from the integration level performed. For the future, it would be important to analyze the complete Iberian power system, namely in scenarios with high share of renewable and variable-speed PSP operating in pump mode in order to assess the power system stability namely in what regards the reduced inertia levels'.

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