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Off-stream Pumped Storage Hydropower plant to increase renewable energy penetration in Santiago Island, Cape Verde

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Abstract. In order to reduce the high dependence on imported fuels and to meet the ongoing growth of electricity demand, Cape Verde government set the goal to increase renewable energy penetration in Santiago Island until 2020. To help maximize renewable energy penetration, an off-stream Pumped Storage Hydropower (PSH) plant will be installed in Santiago, in one of the following locations: Chã Gonçalves, Mato Sancho and Ribeira dos Picos. This paper summarizes the studies carried out to find the optimal location and connection point of the PSH plant in Santiago's electricity network. This goal was achieved by assessing the impact of the PSH plant, in each location, on power system stability. The simulation tool PSS/E of Siemens was used to study the steady-state and dynamic behavior of the future (2020) Santiago MV grid. Different scenarios of demand and renewable resources were created. Each hydro unit of the PSH plant was modeled as an adjustable speed reversible turbine employing a DFIM. The results show that Santiago's grid with the PSH plant in Chã Gonçalves is the one that has the best performance.

1. Introduction

The high dependence on fossil fuels is a matter of concern to any country. In 2009, more than 95% of electricity produced in Cape Verde was fossil fuel-based, and the high costs of this resource represent a significant expenditure in Electra (company responsible for the electricity sector) budget. Moreover, electricity consumption is expected to double in Cape Verde until 2020, which will lead to a higher production based on fossil fuels if there is no investment in other types of generating electricity [1].

In order to make the service less costly, more reliable and to meet the growing trend in energy consumption, Cape Verde government launched an ambitious action program that aims to make 50% of Cape Verde's electricity consumption, by 2020, renewable-based. One of the main axis of the program relies on promoting the investment in renewable energy by independent power producers and public-private partnerships [2]. In [1] Gesto Energy identifies renewable energy projects. Some of them were selected due to their competitiveness when compared with the

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existing fossil fuel-based generating units. The selected projects are assumed to become fully operational by 2020.

Santiago is the Cape Verde Island where the investment on renewable generation will be bigger. To maximize renewable energy penetration (wind, solar and waste), one of the selected projects is a 20 MW rated off-stream Pumped Storage Hydropower (PSH) plant. A technical, economical and environmental feasibility study carried out by Gesto Energy pointed out three potential geographical locations for the PSH plant: Chã Gonçalves, Mato Sancho and Ribeira dos Picos.

The subject of this work came from the need to overcome the integration challenges of the PSH plant in 2020 Santiago's electricity network. The main goal is to find the best location and connection point of the PSH plant, assessing the impact of this energy storage system, in each location, on power system stability. The main contribution of this work is to help the integration of renewable energy in Santiago Island.

This paper is composed of 5 Sections, including the present one. Section 2 introduces the case study of this work. A brief description of the current (2015) Santiago MV distribution and transmission grid, existing generating units and peak consumption is performed. Then, the main aspects of the future (2020) electricity network are introduced, such as the expected load growth rate (2015 to 2020), the new renewable generating units specified in [1] and the main project specifications of the PSH plant. Finally, the suggested connection points of the PSH plant, in each location, in the 2020 grid single line diagram are presented. Section 3 begins with a summary of the methodology used to accomplish the main goal of this study. Then, the different scenarios of demand and renewable resources created to study the grid are presented, followed by a description of the main aspects concerning steady-state and dynamic modeling of the grid in PSS/E 33 of Siemens. In Section 4 the results of the simulations performed are presented and analyzed. Section 5 draws the conclusions of this work.

2. Case Study

The current power system of Santiago Island is comprised by three thermal power plants, one wind power plant, and one solar power plant. Palmarejo thermal power plant has 11 fuel oil generating units with a total installed capacity of 76.34 MW; Gamboa thermal power plant, 3 diesel generating units with a total installed capacity of 7.45 MW and Assomada thermal power plant, 4 diesel generating units with a total installed capacity of 3.92 MW. The wind power plant has an installed capacity of 9.35 MW and consists of 11 wind turbines Vestas V-52 (DFIG technology) of 850 kW each. Finally, the solar power plant has a maximum power of 5 MWp.

The MV electricity network consists of a 20 kV distribution system and a 60 kV transmission system. All generating units are directly connected to the distribution system. Since the production is mostly gathered in south, the transmission system transmits power from the south to the center and north of the island, and it is comprised of three substations (SS): Palmarejo 20/60 kV SS; New S.Filipe 20/60 kV SS and Calheta 60/20 kV SS. The transmission system single line diagram is shown in Figure 1.

In 2015, the peak load was 29.33 MW. Based on a demand growth assessment developed by Gesto Energy [1], it is expected for load to grow 27% by 2020. Furthermore, according to Electra, two other loads are to be considered: a 7 MW desalination plant and 2 MW corresponding to the installed capacity of a casino. In this study, it was assumed that these two loads consume their installed capacity. Thus, for 2020 the expected peak load is 46.15 MW.

Concerning production, 2020 grid scenario has five more wind power plants (2 with an installed capacity of 3.40 MW, 2 of 6.80 MW and 1 of 18.70 MW) comprising Vestas V-52 850 kW and a 5 MW waste power plant. Summing up, 2020 Santiago's power system case study has a total installed capacity of 145.9 MW, from which 87.70 MW are thermal units, 48.5 MW of wind turbines, 5 MW of solar power and the remaining 5 MW of waste power.

The PSH plant in project for 2020 Santiago Island is of off-stream type i.e. both reservoirs are independent of a natural stream flow so stored potential energy relies entirely on water that has been previously pumped. It will have an installed capacity of 20 MW distributed over two 10 MW hydro units, each one with a reversible Francis turbine sharing the same penstock. For the generator/motor technology, Gesto Energy proposed conventional single-speed synchronous machines complemented with flywheels to compensate the slow response time of conventional hydro power plants with regard to the fast power fluctuations associated with intermittent renewables, such as wind and solar. In this study this combination was replaced by DFIMs.

Taking into account the identified potential geographical locations for the PSH plant, the connection points to the MV grid are the ones shown in Figure 1. For the PSH plant in Chã Gonçalves or Mato Sancho, two possible connection points were considered. For PSH Chã Gonçalves, both suggested connection points are in 60 kV side of Palmarejo SS and New S.Filipe SS, respectively. Both connections are made with an overhead line 16 km long. For PSH Mato Sancho, one of the connection points is in 60 kV side of Calheta SS, with a 21.56 km overhead line; the remaining one is a 8 km double cable connection to the 20kV distribution system. For the PSH plant in Ribeira dos Picos, the suggested connection point is in the existing 60 kV overhead line that connects Palmarejo SS to Calheta SS. The projected overhead line is 1.5 km long, and the connection to the transmission system is 30 km distant from Palmarejo SS and 8 km distant from Calheta SS.

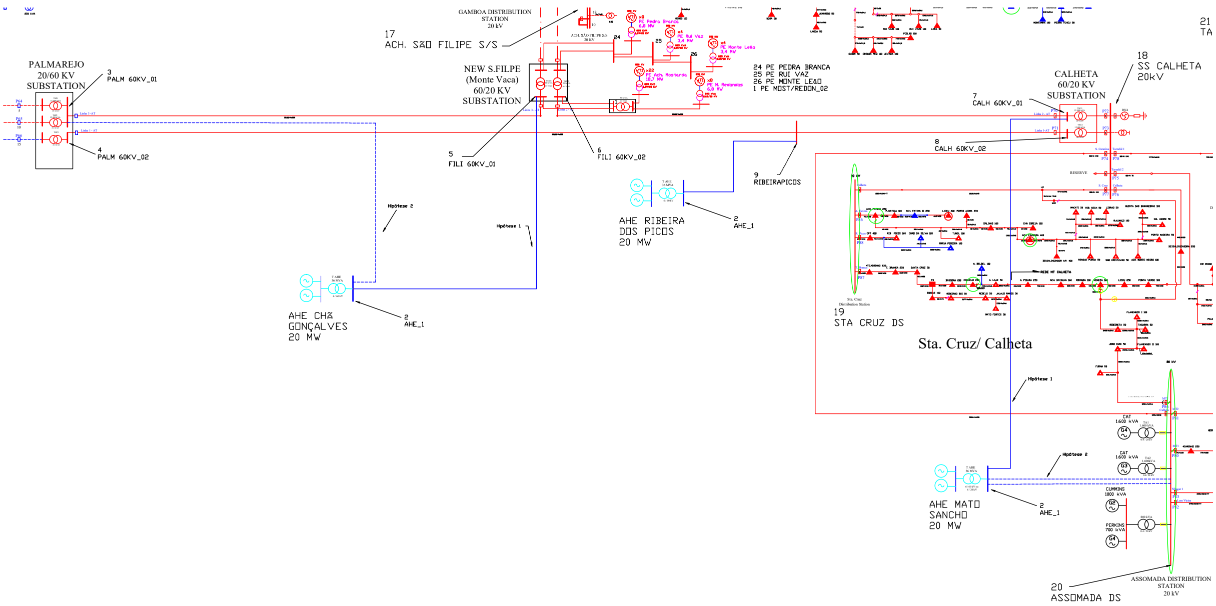

Figure 1. Suggested connection points of the PSH plant in Santiago's MV grid single line diagram.

3. Simulation Scenarios and Models

The grid case study was dimensioned in PSS/E 33 of Siemens to represent all branches, generating units and consumption points of the current island electricity grid together with the new 2020 projects. Load and renewable resources scenarios were created so that grid performance could be studied in different load and for different renewable power levels.

For power flow purposes, all grid components were sized according to Electra's data set. To study the dynamic performance of the grid, it was associated a dynamic model for the different generating technologies so their specific response to a grid disturbance could be accounted for.

The models were properly sized to best represent the existing generating technologies in Santiago Island. The new 2020 generating technologies were sized based on PSS/E grid test cases and other relevant studies. More information about the models' parameters can be found in [3].

3.1. Load and Renewable power Scenarios

A daily load and available renewable power forecast for 2020 was made based on a load curve with the generation dispatch of a day of January 2015. The main assumptions taken were that consumption behavior would not change from 2015 to 2020 and the wind and solar conditions of that day would occur again. According to Electra, there are no substantial differences between summer and winter peak load in Santiago Island. In January, Santiago Island has high wind speeds and yearly average solar irradiances. The load and available renewable power scenarios selected to study the grid are summarized in Table 1. The 4 hours of the day intend to represent different load levels (off peak, mid peak and on peak) and different renewable resources scenarios (wind and solar). The waste power plant generates its installed capacity in every scenario.

Table 1. Load and available renewable production scenarios.

Scenario	Load [**MW**]	Available renewable power		
		Wind [**MW**]	Solar [**MW**]	Waste [**MW**]
06:00h	26.592	38.864	0	5
09:00h	34.926	41.973	0.839	5
13:00h	38.542	43.527	2.320	5
20:00h	46.146	37.309	0	5

3.2. Simulation Models

From a power flow perspective, all generating units are modeled as a conventional source with a specified active power output, a reactive power range, and a bus voltage to regulate (PV bus). For thermal units, one of them was specified as the swing bus; the others, their real power output (or de-commitment) is stated when the economic dispatch is performed. For the renewable generating units, their real power output is defined based on the scenario being studied.

For the short-term dynamic analysis, the thermal units are modeled by the generator GENSAL (salient pole synchronous machine), the DC excitation system IEEET1 and the diesel machine with associated speed governor DEGOV1. The waste power plant is also modeled by GENSAL and IEEET1, but no governor was associated, so this plant does not supply primary frequency regulation. To model the dynamic performance of the DFIG wind turbines the WT3 generic wind turbine model is used. For the solar power plant, the model used is the one available in PSS/E model library. Both wind and solar power plants have under/over voltage and frequency relays. For the wind power plants, under voltage relays' parameters were set to simulate fault ride-through capability.

Concerning the PSH plant, when both hydro units are dispatched, they run in same direction: both are in generating mode or in pumping mode, according to system conditions. Also, mode transitions were not a subject in dynamic simulation studies. Thus, the generating and pumping modes are studied separately. In a steady-state approach, the two hydro units are modeled each as a conventional source connected to the same PV bus. Their real power output is set when the dispatch is performed (positive sign power if in generating mode, negative sign power if in pumping mode). For the dynamic analysis were used the new generic models launched in January 2016 by Siemens PTI for adjustable speed PSH plants employing DFIMs. For both generating and pumping models, there are two types of models: model that simulates the dynamic performance of a single hydro unit and penstock; and model that simulates the dynamic performance of a common penstock shared by up to four hydro units.

For pumping mode, the plant is modeled by PSHPM1 (PSH plant in pumping mode with a single hydro unit). This model was chosen due to misbehave of the model PSHPM4 that accounts for up to four units. So, for pumping mode scenarios, the PSH plant was modeled as a single hydro unit equivalent to the lumped unit, both in steady-state and dynamic simulations. This incident brings some constraints, e.g. the inability to simulate load shedding disconnecting only one hydro unit. The speed adjustment considered for this operation mode ranges from +6% to -4% of the synchronous speed. The wicket gates are controlled to an optimum position in accordance with the current power command. This optimum position is given by a characteristic that provides the optimal gate position as a function of the desired MW output. The optimal power/gate relationship used in this model is the one provided as an example by Siemens PTI.

In generating mode the hydro units are modeled each by PSHGN4. No modeling of a bifurcation into two individual penstocks (each feeding one unit) was made so the response of the two units should be equal to that of the lumped unit. Prime mover governor controls the wicket gates so the desired mechanical power can be achieved. The speed is adjusted for the optimum speed to generate the current power command. This optimum speed is given by a characteristic that provides the optimal speed as a function of the desired MW output. The optimal power/speed relationship used in this model is the one provided as an example by Siemens PTI. This characteristic admits speed adjustments from +15% to -10% of the synchronous speed.

These models developed by Siemens PTI are still in their infancy and further development is under way. Design of these models and details of their functionality can be found in [4]. Note that these characteristics introduced above are very much specific of the turbine-pump design and can be obtained by the manufacturers. No such data was available, justifying the use of the examples provided by Siemens PTI.

For both generating and pumping models, it was necessary to state the water column time constant T_w as it accounts for the delay imposed by the hydraulic circuit to the PSH plant response time. Table 2 summarizes the T_w values relative to the operation of the PSH plant at rated power. This parameter is the only one that differs in the modeling of the PSH plant for each geographical location since the penstock length and diameter are specific to the project location. For pumping mode, T_w has negative value due to the sign convention adopted for this operation mode.

Table 2. Water column time constant of the PSH plant.

PSH plant site	T_w **[seconds]**	
	Pumping mode	Generating mode
Chã Gonçalves	-1.80	2.50
Mato Sancho	-1.69	2.31
Ribeira dos Picos	-1.73	2.35

Frequency relays were modeled to disconnect the PSH plant instantly when wide frequency deviations occur. It was also modeled for PSHPM1 an under frequency relay to simulate load shedding when frequency is below 48 Hz for more than 0.2 seconds.

4. Results and Analysis

Both 06:00h, 09:00h and 13:00h scenarios have more renewable power available than the required to satisfy consumption. However, this is not true concerning reactive power, as the reactive power injected by the renewable sources revealed to be insufficient to meet the required by the load.

Hence, thermal units were dispatched to help in reactive power generation. In order to maximize renewable energy penetration, their real power output was specified to the minimum required to operate the unit. Concerning the PSH plant, both hydro units were dispatched to maximize its contribution to reactive power generation (thus minimizing commitment of thermal units). Since there is surplus renewable power, the hydro units are in pumping mode, consuming -7.5 MW each. This dispatch gives flexibility to the operation of thermal units since it allows the PSH plant to increase consumption when it is necessary to decrease generation. Wind power was curtailed to eliminate the surplus renewable power and to accommodate the thermal units. In 20:00h scenario, the PSH plant was defined to be in generating mode, injecting each hydro unit 5 MW. Thermal units were also dispatched due to lack of reactive power generation. Only two types of thermal units were dispatched, both from Palmarejo thermal power plant: 11.350 MW rated Wärtsilä units and 5.582 MW rated Caterpillar units. Table 3 summarizes the thermal units commitment.

Table 3. Thermal units commitment.

Load & Renewable Scenario	Grid Scenario		
	Chã Gonçalves	**Mato Sancho**	**Ribeira dos Picos**
06:00h	WART 5	WART 5	WART 5
09:00h	WART 5	WART 5, 6	WART 5
13:00h	WART 5, CAT 1	WART 5, 6	WART 5, CAT 1
20:00h	WART 5, 6	WART 5, 6, 7	WART 5, 6

4.1. Steady-state simulations
The connection of the PSH plant in 2020 Santiago's grid revealed overloaded branches only with the PSH plant in Mato Sancho connected to the 20 kV distribution system, which is why this connection hypothesis for location Mato Sancho was excluded for further studies. With all other PSH plant connection points, no overloaded branches were registered.

Regarding bus voltage profile, in grid with PSH plant in Chã Gonçalves a 3.6 Mvar capacitor bank had to be connected to the 20 kV side of Calheta SS so it could be possible to keep bus voltages in peak hour (20:00h) above 0.95 p.u., in Santa Cruz and Santa Catarina (regions electrically far from the main island's production stations). With PSH plant in Mato Sancho or Ribeira dos Picos, this voltage limit violation no longer occurs, due to the fact that these two PSH plant sites are near to Santa Cruz and Santa Catarina, increasing bus voltages with the injection of reactive power near the regions. Although steady-state studies didn't point out the need to install a capacitor bank in grid scenarios with PSH plant in Mato Sancho or Ribeira dos Picos, its use has proven to be beneficial for the grid voltage profile and especially for the reduction of reactive power losses, which are significantly high in Santiago Island.

The grid with the PSH plant in Mato Sancho revealed a lower renewable energy penetration when compared to grid scenarios with PSH plant in Chã Gonçalves or Ribeira dos Picos. The connection point of PSH Mato Sancho to the grid, such as the voltage drop on its connection line limit the reactive power injected by the PSH plant, which leads to the need to have more or bigger rated thermal units operating.

4.2. Dynamic simulations
For dynamic studies two types of grid disturbances were applied: simulation of a 3-phase fault on the 20 kV side of WART 5 transformer - the fault is cleared tripping the transformer which leads to the disconnection of the thermal unit; and simulation of the loss of one of the three 60 kV transmission lines.

The simulation of the 3-phase fault led to the tripping of the PSH plant, during the short circuit, for the plant sites Mato Sancho (generating mode, 20:00h) and Ribeira dos Picos (both operating modes, all scenarios[1]). The tripping of the PSH plant was performed by the under frequency relay, as a result of the frequency decay at the connection bus of the PSH plant to the grid.

In pumping mode, the loss of the PSH plant can be managed by the power system, mainly due to the wind turbines pitch control, which decreases the wind power injected into the grid. Figure 2 shows the response of the frequency at Palmarejo thermal power plant 20 kV bus for the grid case with PSH plant in Ribeira dos Picos, 13:00h. As can be seen, the event causes an exceeding of mechanical power, thus causing a positive frequency excursion. Figure 3 shows the response of mechanical power and electrical power of one of the 49 wind turbines operating, where the action of the pitch control is illustrated. The system reaches an acceptable steady-state operation point.

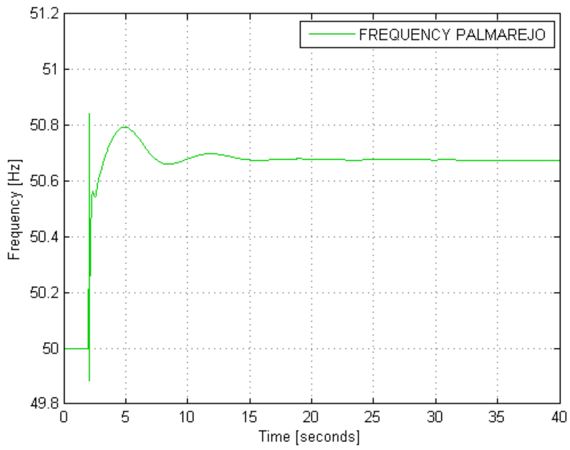

Figure 2. Frequency at Palmarejo PS bus, 13:00h RP.

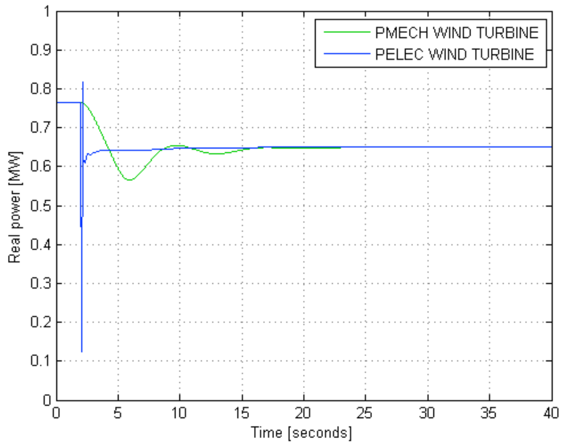

Figure 3. Wind turbine mechanical power and electrical power, 13:00h RP.

In generating mode, the loss of the PSH plant led to critical grid scenarios. Because of the major generation loss, frequency gets below the minimum acceptable value 48.5 Hz in less than 10 seconds. The loss of the PSH plant also causes a major reactive power deficiency, leading to a marked decrease in system voltages. Figure 4 and Figure 5 illustrate the fundamental simulations results. In grid case with the PSH plant in Ribeira dos Picos (Figure 4), the remaining thermal unit WART 6 gets overloaded and system voltages get below the minimum acceptable value 0.90 p.u.. Under voltage relays start disconnecting wind turbines at 12.1 seconds of simulation. At t= 22 seconds the system collapses. For the grid case with the PSH plant in Mato Sancho (Figure 5), the system reaches a steady-state operation point – albeit unacceptable – mainly because the wind turbines can keep their terminal voltage above 0.90 p.u., thus preventing wind turbines' under voltage relays from tripping.

With the PSH plant in Chã Gonçalves, the simulated fault no longer causes the loss of the PSH plant, for both connection points suggested for this plant site. As a result, the system reaches an acceptable steady-state operation point, both in pumping mode and generating mode scenarios.

[1] For 09:00h and 13:00h scenarios, the simulated fault also causes the tripping of the solar power plant by the performance of the under voltage relays.

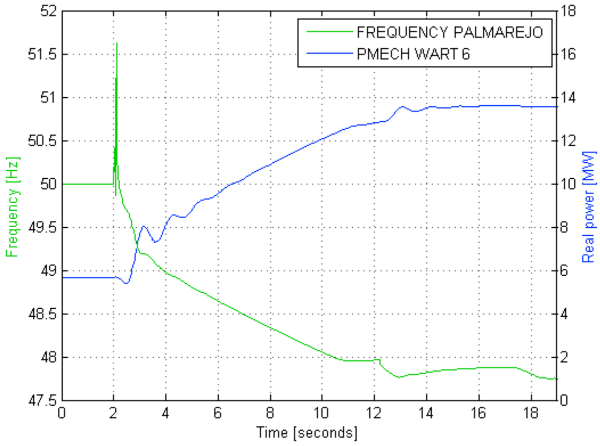

Figure 4. Frequency at Palmarejo PS bus and WART 6 mechanical power, 20:00h RP.

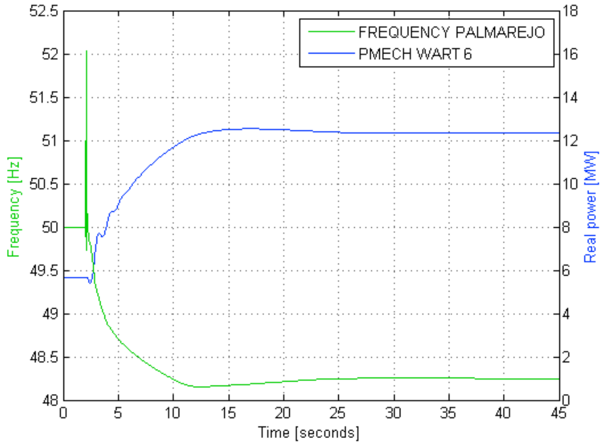

Figure 5. Frequency at Palmarejo PS bus and WART 6 mechanical power, 20:00h MS.

Figure 6 and Figure 7 illustrate the main system response results when the PSH plant Chã Gonçalves is in pumping mode, 13:00h. As can be seen, the PSH plant supplies primary frequency regulation (Figure 6), as the mechanical power required by the pumps decreases (less power drawn from the system) to control the under-frequency. An important contribution to arrest the frequency decay is also given by the stored kinetic energy in the rotating wind turbines that transiently supply additional power generation (Figure 7). However, frequency reaches 48 Hz as the wind turbines inertial response fades. To arrest the frequency decay the tripping of the PSH plant is performed.

Figure 8 and Figure 9 illustrate the main system response results when the PSH plant Chã Gonçalves is in generating mode. The frequency decay is arrested by the response of the governors of the remaining generators capable of supplying primary frequency regulation, which act to increase the mechanical power produced by their prime movers. Figure 9 only illustrates the mechanical power response of one hydro unit. The other hydro unit has identical response.

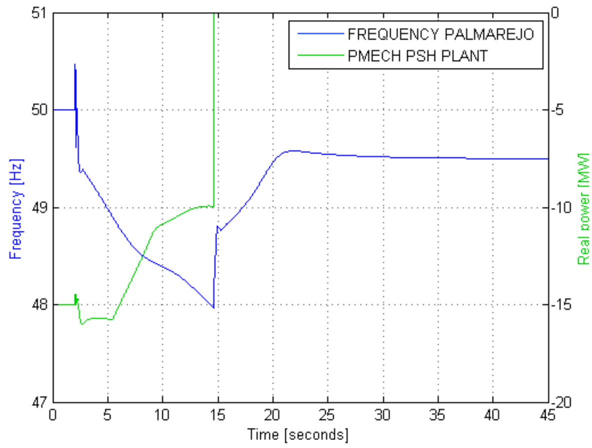

Figure 6. Frequency at Palmarejo PS bus and PSH plant mechanical power, 13:00h CG.

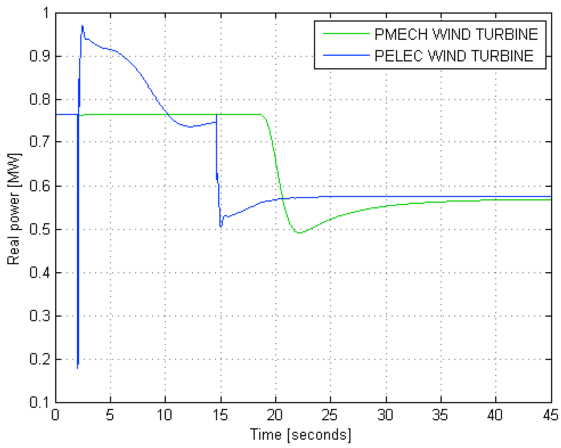

Figure 7. Wind turbine mechanical power and electrical power, 13:00h CG.

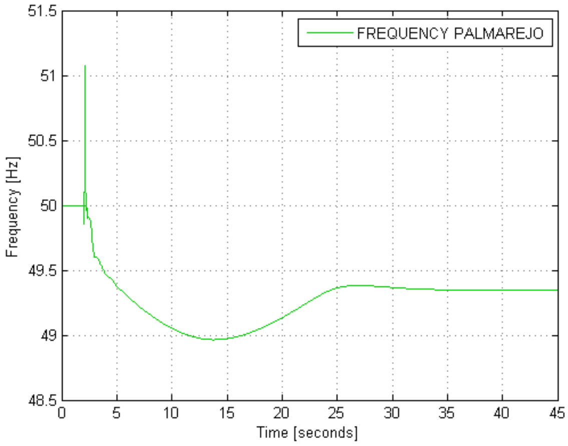

Figure 8. Frequency at Palmarejo PS bus, 20:00h CG.

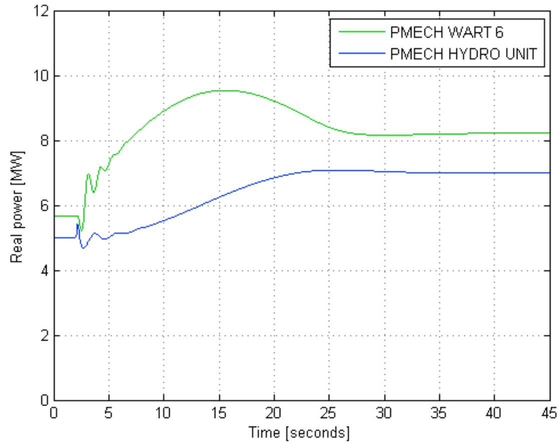

Figure 9. Hydro unit mechanical power and WART 6 mechanical power, 20:00h CG.

Overall, the results obtained indicate that the point where the PSH plant is connected to the grid can lead to the loss of this resource when in the system a 3-phase fault on the 20 kV side of WART 5 transformer occurs.

In the simulation of an outage in the transmission lines, some violations in grid operation were detected with the PSH plant in Mato Sancho and Ribeira dos Picos, both in pumping mode scenarios. The outage of the New S.Filipe – Calheta 60 kV overhead line causes a significant overload in Calheta SS transformers (around 140% and 190% in the worst case scenario) with the PSH plant in Mato Sancho, and some minor line overloads with PSH plant in Ribeira dos Picos. The outage of the Palmarejo – Calheta 60 kV overhead line causes a significant overload in Calheta SS transformers (around 130% and 180% in the worst case scenario) with PSH plant in Ribeira dos Picos. In the grid with the PSH plant in Chã Gonçalves, an outage in one of the three 60 kV transmission lines does not cause any overload or voltage limits violation, for both connection points suggested for this plant site. This result indicates that the power system with the PSH plant in Mato Sancho or Ribeira dos Picos is not n-1 secure.

5. Conclusions

In conclusion, the results of the steady-state and dynamic studies show that 2020 Santiago's grid with the PSH plant in Chã Gonçalves is the one that has the best performance. Even though in steady-state simulations the PSH plant in Ribeira dos Picos also confirmed to be a good option, it revealed clear disadvantages in dynamic simulations, such as the involuntary plant tripping and the failure to assure the n-1 security criteria in a grid disturbance likely to happen. The PSH plant in Mato Sancho revealed similar problems.

For the PSH plant in Chã Gonçalves there were studied two connection points to the grid, both with an overhead line 16 km long that did not reveal any significant differences in the results obtained. The grid with the PSH plant in Chã Gonçalves has an average of 82% of renewable energy penetration. An average of 3% of injected active power and 9% of injected reactive power are losses. It is necessary to install a capacitor bank of 3.6 Mvar to keep Santa Catarina and Santa Cruz bus voltages above 0.95 p.u. in peak hour.

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