Battery Energy Storage System in a 100% renewable network. Case study of Brava Island.

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Abstract. With the growth in energy demand that has recently occurred and the increasing of renewable energy penetration, the biggest challenge to the electrical networks is to meet this development in a safe, economical and sustainable way. Energy Storage Systems (ESSs), and specifically Battery Energy Storage Systems (BESSs) have proven to be crucial elements in this paradigm change by contributing to increasing the renewable penetration and by mitigating the operational problems that arise from it. The Brava Island, in Cape Verde, presents an energy plan to 2020, which aims to make the island 100% renewable with the help of a BESS. Thus, the objective of this work is to study the possibility of operating the island network in 2020 with only renewable generation and a BESS, analyzing the system stability. For this, the simulation scenarios including the forecast of load and renewable resources for 2020 were built. The sizing/implementation of the network is done in PSS/E software. Stationary and transient studies are carried out to draw the necessary conclusions from this study. The analysis of the results, shows the dependence between the BESS and the stability of the network given the importance it showed in controlling the frequency and providing flexibility to the system.

1. Introduction

The developing countries are leading the rise in electricity demand largely because of the fast population growth that they present. In addition to this energy development, some questions arise about the dependence of fossil fuels (coal, gas and oil) as a primary energy source and the harmful consequences from the environmental, economic and geopolitical point of view. In the last decades, all this factors have contributed to many organizations like United Nations (UN), have established strategies that aim to shift the focus of conventional generations to renewables ones. Such as Cape Verde, a number of countries are committed to meeting ambitious targets based on energy models that propose the increase of renewable penetration and the reduction of the emission of greenhouse gases.[1]

With that, the grid faces new challenges related to the intermittent and stochastic nature of renewable energy sources, that represent the main challenge of not compromising the grid stability, with frequency variations or voltage fluctuations. Thus, to make renewable energy as the primary power source, it is necessary to solve the technical and practical problems caused by the intermittency of its generation, with the Energy Storage Systems (ESSs) being a crucial element in this paradigm shift. Within the ESSs, the Battery Energy Storage Systems (BESS) are one of the most mature storage technology and they can be use in a wide range of applications.

In this article as example of this, is studied the particular case of the Brava Island following the renewable energy plan of Cape Verde [2], developed by the energy consulting company GESTO Energy in 2011. It is the smallest island of Cape Verde and presents interesting levels of solar and wind resources. For 2020 it was established the goal of making the island's generation system 100% renewable, with the implementation of a wind and a solar power plants. Installing a BESS is also part of this goal being crucial in the aid of the integration of the renewables and to improve the stability and flexibility of the grid. Therefore, this article presents a feasibility study of the 100% renewable scenario, performing the scale of the BESS adjusted to the needs of the grid and analyzing the stationary and dynamic behavior of Brava electric system for the year of 2020.

2. Case Study

For the study's developed, the energy plan outlined in renewable energy plan of Cape Verde for Brava Island was followed, except for the cases in which more recent information was contrary to the forecasts projected therein. The most relevant occurrence was the demand forecast, that in the energy plan made in 2011 it was too much ambitious, like it was proved by most recent data. This made us to do re-forecast the demand to 2020, based on the most recent data (2015) and consequently to re-dimensioning the renewable projects that was in pipeline until 2020, to properly adjust installed power to demand.

2.1. Generation and distribution systems

With the objective of decommissioning the thermal power station of Brava island, that has 4 groups with a total installed power of 1,77 MVA, until 2020, it was planned the installation of a solar farm (Parque Solar da Furna- PSF) and a wind farm (Parque Eólico Vento Furnas-PEVF). Two 225 kW Vestas V29 wind turbines which has a DFIG that operates at 690 V will compose the wind power plant, with an installed power of 450 kW, while the solar farm will integrate 1600 PV modules of 225 Wp what means an installed power of 360 kWp.

Relatively to the MV distribution grid of the island, it operates at 2 different levels of voltage 6 kV and 20 kV, which feed 18 loads being the main one PT Vila, that corresponds to the main urban center of Brava island and represents about 30% of the total load of the island. The distribution grid has a radial configuration and it is composed by underground and overhead transmission lines.

2.2. Load, wind and solar forecast to 2020

To sizing the BESS and to formulate realistic simulation scenarios for 2020, it was necessary to make the forecast of the load curve and of renewable resources (wind and irradiation). The prevision of load evolution for 2020 is based on the load data supplied for 2015 by ELECTRA (entity responsible for the concession of the production and distribution of electricity on Brava island) and in the results of the study presented in [2] that predicts the evolution of demand based on the historical and in the growth expected to the different sectors (tourism, domestic demand, etc) of the island. So, the load curve obtained can be observed in figure 1.

About the forecast of the renewable resources it was considered that either the profile of irradiation or of the wind the will remain nearly equal to the actual ones, so it is used the profiles data of 2015. With this informations is possible to estimate the total available power generated by the renewable power plants, being the results shown in figure 1. The figure 1 data is the base of all the simulations developed.

2.3. BESS

With the renewable energy projects identified in subsection 2.1, it is intended to install on the island an energy storage system that allows them to be integrated in order to guarantee

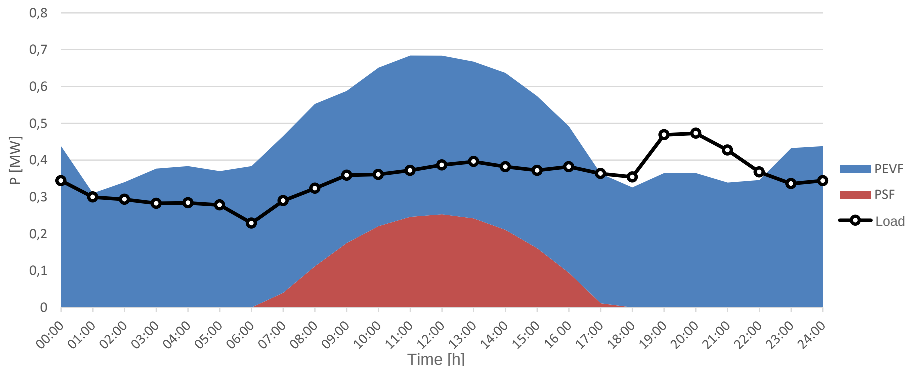

Figure 1. Load curve and available power generated by the renewables facilities.

the island's energy sustainability with a 100% renewable generation penetration. The storage system to be introduced is a secondary battery, namely a lithium-ion battery. The choice of this technology is motivated by the odd technical characteristics that it presents relatively to high efficiency and density of energy/power comparatively to the other BESS technologies. To serve as interface between the network and the BESS a Voltage Source Converter (VSC) is the natural choice for the bi-directional converter, once it allows independent control of active and reactive power.

The battery to be installed would be used mainly in for energy applications, what means that its main objective is associated with the cost of operating the electrical system, helping to improve the profitability of the same enabling the increase of renewable penetration. So, what is desirable is that in periods when renewable production is excessive in relation to the load, the excess can be stored in the battery to later use when more suitable allowing the time shifting of energy. However, this should also contribute to voltage and frequency regulation in order to maintain network stability.

3. Implementation

All the studies were made using the PSS/E software developed by Siemens. All the elements of the network are modeled using the program libraries models, namely the BESS is modeled by "CBEST" and "PAUX1" whose detailed information can be obtained in the manual [3].

Four simulation scenarios (I to IV) were studied, where each of which characterizes a different load/generation scenario. The scenario I corresponds to the off-peak period (6:00); the scenario II corresponds to the moment when the available renewable generation is maximum (11:00); the scenario III corresponds to a intermediate scenario (16:00); and the scenario IV corresponds to peak period (20:00).

The sizing of the BESS is based on the followings steps: **1-** Calculate power surplus/deficit ($P_{dif}(t)$) between the available renewable power ($P_{ren_{disp}}(t)$) and the load power ($P_{load}(t)$) of each hour. So, $P_{dif}(t) = P_{ren_{disp}}(t) - P_{load}(t)$; **2-** Calculate the average energy required for the battery (E_{bat}). Thus, $E_{bat} = \sum_{j=1}^{24} P_{dif}(t) \times \Delta t$, where Δt is the period of dispatch equals to 1 hour; **3-** Calculate the real capacity needed (E_{bat_N}) based on the influence of depth of discharge (DoD %), autonomy (Aut) and battery aging (Fc %). Therefore, $E_{bat_N} = \frac{Fc \times E_{bat} \times Aut}{DoD}$, where $Aut = 1\ day$, $DoD = 85$ % and $Fc = 110$ %; **4-** Choose the nominal power P_n of the BESS based on the reactive power required in the worst case (IV), assuming a power factor of 0,9 to the BESS, and also in the charge/discharge time. In table 1 are shown the sized technical features of the BESS to be implemented in the study case.

The dispatch of the battery is planned always respecting their technical features namely the

Table 1. BESS technical features.

Technical Feature	Value
$P_n[MW]$	0,875
E_{bat_N} [MWh]	3,5
V_{out} [V]	400
Discharge/charge time [h]	4

capacity (DoD) and the following assumptions: 1- the BESS should be kept in service 24 hours a day; 2- the last unit to be dispatched and which is responsible for meeting network losses is the battery; 3- negative power corresponds to BESS charging; 4- the state-of-charge (SoC) has to do a daily cycle.

4. Simulations

4.1. Power Flow

The results obtained from the simulations in steady state regime are presented for each of the study scenarios introduced, in table 2.

Table 2. Power flow results for Brava 100% renewable system.

Scenarios				I	II	III	IV
Load			P (MW)	0,229	0,372	0,382	0,473
			Q (Mvar)	0,172	0,279	0,287	0,355
Renewable Generation	PSF		P (MW)	0,000	0,246	0,094	0,000
			Q (Mvar)	0,000	0,081	0,031	0,000
	PEVF	AG1	P (MW)	0,192	0,219	0,199	0,183
			Q (Mvar)	0,048	0,047	0,040	0,015
		AG2	P (MW)	0,000	0,219	0,199	0,000
			Q (Mvar)	0,000	0,047	0,040	0,000
BESS			P (MW)	0,038	-0,310	-0,108	0,293
			Q (Mvar)	0,134	0,144	0,201	0,368
Losses			P (kW)	0,50	1,91	1,70	2,60
			Q (kvar)	9,63	39,66	24,42	28,10

From the results of the power flow the analysis of them look over voltage, losses, overloads and production in the grid. A problem of overload emerged with the increase of the demand to 2020 in a transformer of the SS Nova Sintra, that was solved by the introduction in parallel of an equivalent transformer. Relatively to the voltages, all the buses operate within the limits assumed as acceptable ($\pm 5\%$ of the nominal voltage). The losses presented in table 2 reveal that the reactive power losses are the most relevant representing, on average, about 8% of the reactive power injected. Lastly, with the dispatch defined it is verified that 2,709 MWh of renewable energy is wasted which represents around 24% of wasted energy compared with the total available renewable energy (11,136 MWh).

4.2. Dynamic Simulation

The dynamic simulations are aimed for evaluating how the Brava island's grid behaves towards a certain contingency that affects the operation of the network and its steady state, thus proving the stability of the network. There were performed 3 different disturbances: **1-**Short circuit during $100ms$ on an electrically centric bus; **2-**Variation of irradiance; **3-**BESS out-of-service. The operating conditions to qualify the post-disturbance steady state are, in the case of frequency, that the system can operate safely if in steady state the frequency deviation does not exceed $\pm 1,5Hz$, i.e. the network must operate within the range of $48,5 - 51,5Hz$. For the permissible voltage limits after a disturbance, it is suggested that it does not exceed $\pm 10\%$ of the rated voltage, i.e. $0,9 - 1,1p.u.$.

For the first simulation, the main objective is verify how the grid reacts when a short circuit occurs. It was verified that the short circuit makes the voltage relays of the PV's actuate disconnecting them, which causes the loss of generation and consequently the drop of the frequency. For the worst scenario (II), the frequency stabilizes at $48,8Hz$ in the steady state. All the voltages remain within the limits and nd there were no overloads in either branches or machines.

For the second simulation, the main purpose is to test the impact of the variability of renewable resources on the stability of the grid. So, the simulation performed consists in varying the irradiance admitting the occurrence of cloudiness, which is reflected in a fast decrease of the irradiance incident on the PV's panels and consequently the power produced by them. The scenario II is the one where the solar penetration is highest, so it was used to study this perturbation. It was verified that this variation is well supported by the grid since no large fluctuations of voltage or frequency were observed. The system reaches to a steady state with a frequency of 49,05 Hz.

The last simulation studies a contingency that impose the disconnection of the battery of service. The results obtained proves what has expected, that the grid is unable to be supported only by the renewables and that the system ends up collapsing shortly after the battery runs out-of-service.

5. Conclusions

The main objective of this work was to study the technical feasibility of implementing in Brava island a 100% renewable generation system supported by a BESS, based on the renewable energy master plan of Cape Verde for 2020. With the reformulated demand forecast and the adjusted renewable facilities projects, it was made simulations on steady and dynamic state.

From the analysis of the power flow results it was possible to conclude that the actual MV distribution grid is not prepared to the peak demand, originating overcharges in a particular zone of the grid (SS Nova Sintra) that could be solved with branches in parallel (e.g. transformers) as it was suggested. The renewable power that is lost, in the dispatch made, corresponds only to 24% of the total available, which confirms an appropriate sizing of the renewable projects and BESS against the expected load. In addition, it was proved that the BESS has a key role in the production of reactive power and also in the integration of renewables in the grid.

The importance of the inertial control provided by the DFIG's and of the primary frequency control supported by the BESS is evident in the results obtained for the two first contingencies studied. It is its action that allows, that after each of the disturbances, the network reaches to stable operating point. With the last simulation (BESS out-of-service) has been proved that the system is not capable of working without the battery, because no other facilities has the capacity to respond to the fluctuations of frequency and voltage of the grid. Therefore, complementary studies (presented only in the thesis) were carried out in which the smaller of the thermal groups of the island is considered in the dispatch, and with that, is lost some renewable penetration but is gained flexibility to survive in transient phenomenas.

6. References

[1] IRENA, *Africa's Renewable Future: The path to sustainable growth* , 2013
[2] GESTO Energy Solutions, *Plano Energético Renovável- Cabo Verde*, 2011
[3] PSS/E, *Program Operation, Model Library*, October 2010