A Multipurpose Reference System Based on the Hybrid Power Grid of Cape Verde

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Abstract—Reference systems are key enabling platforms facilitating the evaluation and comparison of different methods and technologies prior to prototyping and field deployment. In the context of the energy transition, where the number and diversity of the grid-related research is ever expanding, we propose a reference system based on two islands of Cape Verde. These isolated power systems capture the behaviour of mid & large size grids ranging from 20 to 100% renewable energy penetration, accommodating a very diverse technological mix. The topology is based on the real transmission system as of 2021, considers sector coupling and the role of power electronics-interfaced units. The Open-Access data was provided by the local system operator and the largest renewable utility of the country. The main objective is to enable off-the-shelf usage by minimizing the amount customization required for any possible study. In that way, it is suitable for a range of traditional and modern studies such as: power flow, energy management, control, stability, reliability, resiliency etc. We showcase the usefulness of this reference system with four short studies regarding grid strength, frequency stability, optimal sizing & placement of battery systems and synthetic inertia provision.

Index Terms—Reference power system, isolated power system, minigrid, benchmark power system.

I. INTRODUCTION

The energy transition is a technological trend motivating to cover our demand as much as possible with renewable energy sources (RES). Such shift from traditional to green units poses a number of well-known challenges and possibilities stimulating an ever-growing development of new methods, products, and services from both academia and industry. Reference and benchmark systems are used in this context to enable analysis, comparison and validation of the results. Such systems should resemble a relevant topology, capture a particular phenomena and provide enough data in order to be suitable for a particular study. However, finding meaningful reference systems is an increasingly difficult task due to the difficulties in reflecting the increasing complexity of modern power systems. Particularly when targeting to perform different static and dynamic studies on the same system.

There are a number of proposed topologies in scientific literature such as the IEEE 39-bus 10 machine system, which was originally developed to study transient stability, but dismissed basic data such as line lengths [1]. The IEEE 6, 14, 30, 33, 57, 69, 118, and 300-buses define imaginary systems with high transmission losses for the purpose of evaluating different power flow methods [2]–[6]. In addition, [2] also presents the IEEE 17, 30, and 145-buses aimed at dynamic studies, while [7] modifies the 33-bus allowing to compute unbalanced power flow. Then, the 2-area 4-machine was designed.
to study small signal stability and inter-area oscillations [8]. More recently, [9] presented a distribution system targeting hardware-in-the-loop simulations considering the inclusion of distributed generation for power flow and basic dynamic studies. The IEEE 68-bus focuses on capturing the dynamics of FACTS and SVCs [10]. The 9-bus system focuses on dynamic simulations of high inertia systems [11]. The 3-machines 9-bus system was designed evaluate voltage sensitivity [12]. A better example of reference system is found in [13] where the IEEE 12-bus system is presented. It is the first document entirely dedicated to define a system. Its purpose is to support wind integration studies focusing on short electromagnetic transients (EMT) simulations. Then, the CIGRÉ European HV grid is extended with a multi-terminal DC grid and full converter based generation units in [14]. Lastly, in [15], 4 microgrids corresponding to [3]–[6] are interconnected and new additional data is included aiming to generalize the model. The simplified Australian 14-generator system from [16] is modified in [17] with fictitious units and data to allow transient studies. A residential microgrid system is proposed based on a distribution system in [18] to study unbalance control applications. Furthermore, the interested reader is referred to [19] for a more thorough review of standard systems.

The aforementioned systems result outdated specially when considering RES penetration rates above 20%, power-electronic interfaced technologies, flexibility, or sector coupling [19]. In general, they do not represent a realistic layout due to their size, or the fact that were developed for a particular study, thus only capturing realistically a small range of dynamics. Particularly, [15] aimed to address some of the limitations of the previous standards by presenting sufficient data to conduct static, dynamic, reliability, and resiliency studies. However, it is again based on imaginary systems which can result myopic by unwillingly overlooking particular phenomena. Nevertheless a system addressing the mentioned issues must, first, capture the transition from low renewable rates to full deployment. Second, it should consider new power-electronic interfaced technologies such as storage systems and demand response. Third, it should be weak enough as to represent a realistic challenge, but remain stable under steady-state conditions; with a voltage level ranging from 0.95 to 1.05 pu in load dominated buses, while allowing up to 1.1 pu in those presenting bulk generation; as these are the usual limits stated in grid codes. In addition, it should present certain transmission limitations in order to observe congestions, and potential contingencies. Lastly, it should be possible to modify the meshed/radial topology in a realistic manner via switches.

Aiming to satisfy the aforementioned limitations, the IEEE Cape Verde Reference System (CVRS) was presented in [20]. It covers two isolated power systems in the tens and hundred MW range respectively representing the transmission grids of two islands in the country (São Vicente & Santiago) as of 2021. The dataset includes information allowing to perform power-flow, energy management, control, planning and stability studies. Most of the data employed to build the CVRS has been obtained via bilateral agreements with the local system operator, Electra; and the largest renewable utility of the country, Cabeólica.

This revision of the CVRS benefits from the feedback provided by the research community, reduces the limitations of the preliminary version and expands the dataset with newly collected information provided by manufacturers of devices installed in the islands, diverse energy agencies, and other private entities. Overall, providing significant additions and revised information compared to the preliminary version. The aim is to increase the transparency and replace-ability of the studies by providing academic and industrial researchers with a complete, off-the-shelf, multi-purpose reference system based on real isolated grids. In that sense, we added more parameters describing fuel type, consumption, and operational limits of the existing units, both traditional and renewable, but also of other candidate technologies such as batteries, hydro pump storage, etc. Regarding topology, we included a more simplified version better suited for computationally expensive dynamic simulations such as EMT and hardware in the loop (HIL). The renewable resource and demand profiles were reviewed focusing on their usefulness for energy planning and scenario definition. Hence, besides the 365 days with hourly resolution, a 12 week equivalent period is included. Furthermore, transformers and cable parameters were reviewed and expanded. We added data regarding the number of customers and distribution transformers per bus in order to perform reliability analysis and reviewed the pre-defined outage scenarios to be used as benchmarks of high impact low probability events. Different 20 year long energy mix roadmaps capturing a progressive transition from the current 20% RES-share level towards 100% are included. These, allow to reproduce different configurations depending on the targeted study. Lastly, information regarding possible sector coupling applications with desalination, hydrogen, heat and transport sectors is also included.

Besides presenting the revised dataset, this paper aims to validate the suitability of the CVRS to resemble a modern and future isolated power system. This is done by summarizing the outcome of two very different studies, one analysing the grid strength and voltage sensitivity; while the other focuses on the frequency stability limits and the role of synchronous condensers. Subsequently, a new strategy optimally sizing and placing distributed battery energy storage system (BESS) consider minimum inertia requirements is proposed. This method allows to install lower capacity than a single aggregated BESS proposed by traditional methods and it is validated with EMT simulations in a Real-Time Digital Simulator (RTDS) environment under different RES penetration rates. Lastly, a virtual inertia (VI) compensation strategy is implemented allowing for the coordination of the aforementioned BESS with the existing governor-turbine systems contributing to frequency restoration. The suitability of this method is then validated with different inertia level scenarios.

The paper is structured as follows: Section II summarizes the existing system and its future goals. Section III describes the dataset’s contents focusing on its usage. Section IV focuses on the operational paradigm necessary to become an integrated energy system. While Section V presents several use cases for the CVRS, and Section VI concludes the paper.
II. THE EXISTING GRID IN CAPE VERDE

Situated in the Atlantic Ocean at 600 km from continental Africa, Cape Verde is a country composed by 10 islands. The capital, Praia is located in Santiago; the most industrialized and largest island of the archipelago in both size and population. While, São Vicente represents a mid-size island in the archipelago. Their respective capacity are in the hundred and tens of MW, thus allowing to capture a number of different grid’s dynamics and behaviour. Santiago’s model resembles that of a large power system while São Vicente minds the gap between micro- and mini-grid. Due to the distance among the islands and the depth of their waters, it is not economically feasible to interconnect them. They present 20% renewable shares yearly (wind and PV). Although, the government established the goals of reaching 50 and 100% RES by 2030 and 2050 respectively. Both models are designed based on the existing transmission network as of 2021, where most generation capacity is based on fossil-fueled synchronous machines. However, we consider the government milestones regarding renewable penetration by including information regarding storage systems and flexibility sources such as demand response applications. Ultimately enabling the definition of multitude of meaningful configurations suited for virtually any study [20], [21].

III. THE PROPOSED MODEL

The dataset includes two topological descriptions per island, one generic and another with a reduced number of buses in order to facilitate its use in real-time applications, EMT and HIL simulations. In addition, there are load and RES generation profiles with hourly resolution, information covering the type of electrical machines, cables, energy storage, controllable and uncontrollable loads, failure rates, down-times, etc. Lastly, it also includes different energy mix roadmaps spanning 20 years. In this way, the CVRF is, to the knowledge of the authors, the most complete Open-Source dataset available, allowing for an almost unlimited number of studies from traditional load flow, to different control architectures, stability, power quality, reliability, economic dispatch, etc.

The dataset is made available to the reader in an online repository constituted by a number of excel files (e.g., SantiagoData) containing a number of different sheets (e.g., Line Data) that divide the information into different categories conveniently prepared to cover a wide range of traditional and modern studies [22]. Note that several sheets share the name with the addition of Reduced, this indicates that its contents are related with the simplified topology, which was obtained by aggregating certain loads and buses. This is done in order to reduce the computational burden of certain simulations. Since it was impractical to present all the different tables in this paper, we review and expand the descriptions presented in [20] focused on the CVRS usage.

A. Topological Data

The complete single line diagram (SLD) of São Vicente is presented in Fig. 1a, while 1b depicts the simplified version. Similarly, 1c&d present the full and reduced versions of Santiago’s system. The switches (blue marks) are assumed open by default; their purpose is to modify the topology from radial to meshed structures, and correspond to those available for the SO. Note how the hollow triangles represent connection points between distant areas as to avoid overlapping lines.

Complementing the data provided by both Electra and Cabeólica, we included parameters from cables and transformer manufacturers [23]–[25]. The excel sheets presenting data relevant for load flow studies are:

1) Line Data: presents the line name ID, the from and to buses, type of conductor, number of parallel lines, length [km], resistance [Ω], and reactance [Ω].

2) Conductors: presents the conductor types related to those of the previous sheet, including: main conducting material, cross-section [mm²], Voltage rating [kV], resistance [Ω/km], reactance [Ω/km], capacitance [μF/km], current rating [kA], short-circuit current rating (SCCR) [kA], type of installation as Over-Head Line (OHL) and Underground Cable (UG). CIGRE recommends to allow overloading coefficients of 115 and 120% for long- (24 h) and short-time (15 min) horizons respectively [26]. However, the SO uses lower values of 105 and 110% due to line length, equipment age, and high temperature of the country. Note that the zero-sequence can be approximated as three times the positive-sequence [27].

3) Transformers: presents the information related to Line Data including: type ID, size [MVA], voltage rating [kV], positive and zero sequence resistance and reactance in per-unit (p.u.), and X/R [%]. The p.u. values correspond to the information shown in the equipment’s nameplate rating. The connection of all the transformers is considered as Dyn-11.

4) Load Data: presents active and reactive load along with the share of controllable and critical. The first are loads that could participate in demand response, while the latter are prevented from disconnecting during load shedding events.

B. Energy Mix

The current configuration of the island includes wind, solar, diesel and heavy fuel units. While there is currently no energy storage installed in the islands, there are plans to include a 1 MW/MWh Lithium-Ion Battery in the islands of Sal and São Vicente. Furthermore, a hydro pumped storage of 20/160 MW/MWh is planned for the island of Santiago. Note that we include information allowing the modelling of each governor, Automatic Voltage Regulator (AVR) and excitation system. This is a nearly impossible task provided their technological diversity and the limited data provided by the manufacturers, which are reluctant to share the equivalent transfer functions and related parameters. The excel sheets presenting data relevant for load flow studies are generally introduced here. Note how the column called Existing defines whether a particular units exists today in the system or if it is deemed suitable for early installation. The latter are meant to substitute traditional units with RES.

1) Traditional Generators: Covers the fossil fuel-based synchronous units stating: the type of generation unit, governor, apparent power [MVA], minimum running rates, Q limitations and R/X of the original synchronous generators, a
number of parameters regarding the governor, AVR, and excitation types of the machines. In general, the dataset includes the necessary parameters to replicate the generic governor models presented in [11] and the real one when available.

2) Renewable Generators: Presents the installed Solar Photovoltaic (PV) and Wind (Wx) capacity, where x represents a cardinal direction as N, S, E or W. This accounts for differences in wind direction, and natural shadowing caused by the island’s orography; thus capturing the coincidence factor of spatially distributed wind farms (WF). PV dismisses the x-factor due to its uniform distribution.

3) Storage: Presents energy storage units deemed feasible by the SO by stating: type, capacity [MWh], power [MW], charging and discharging efficiencies, initial, minimum, and maximum State of Charge (SOC) in [%].

4) Synchronous Generators: Allows to develop models of the synchronous machines existing in the islands and provides ranges to help define new units by stating: synchronous reactance, transient reactance, sub-transient reactance (normal and saturated), transient OC time constant, sub-transient OC time constant, stator resistance, and leakage reactance.

5) Asynchronous Generators: It allows to define additional induction machines by means of the stator resistance and leakage inductance, magnetizing inductance, rotor resistance and leakage inductance referred to the stator.

6) Wind Turbines: Presents the basic modelling parameters related to the wind turbines. That is: nominal power & voltage, number of poles, Ia/In, R/X and class. Note that these are relatively small onshore models.
C. Demand and Renewable Profiles

The dataset includes demand-related parameters and renewable generation availability. The first are computed by Electra using lumped hourly measurements at different PMUs and meters distributed around the system during days without any blackout. The latter are built using publicly available data from solar and wind atlas, that is global horizontal irradiance and wind speed [28], [29]. The collected information was monthly mean of resource availability and the average hourly profiles for each month. We approximated weekly averages applying linear interpolation on the monthly averages. Subsequently, the profile is computed by simple multiplication of the mean hourly value for each month times the weekly average. Thus creating a grid of 24 hours/day times 52 weeks/year corresponding to the annual hourly profiles. This values are subsequently normalized between 0 and 100 obtaining the power availability of a renewable plant in the system as % of its installed power. While these values lack physical meaning they constitute an accurate statistical representation of the yearly renewable availability. By considering the typical full load hours of wind power ranging from 30 to 40% for onshore and from 40 to 50% for offshore WFs while 15 to 25% for solar farms [30]; the results can be validated. The existing WF and SF sites, obtain respectively 47 and 21%; which results consistent given that Cape Verde is an island, thus blurring the division between on- and off-shore.

In this way, the CVRS provides two time series representing both load and renewable generation profiles. The first is referred to as Yearly Profile, which includes hourly values for a typical year of 52 weeks. The second receives the name of Equivalent Week Profile, which considers the modelling of a year using 12 full weeks (84 days), while keeping chronological relevance during the whole horizon as in [31]. Whereas, if higher resolutions are needed, techniques such as those described in [32], [33] can be used. These time series are used by multiplying the value of a given hour by the total power presented in either Load Data or Renewable Generators sheets. Briefly, the sheets include percentage values as:

1) Weekly Load Profile: Peak load per week of the year.
2) Daily Load Profile: Peak load from Monday to Sunday.
3) Seasonal Load Profile: Peak load depending on the season of the year, day and hour.
4) Hourly Load Profile: Time series corresponding to hourly demand profile over a typical year of 52 weeks.
5) Hourly Solar Profile: Time series of hourly power availability from solar power over a typical year of 52 weeks.
6) Hourly Wind Profile: Time series of hourly power availability from wind power over a typical year of 52 weeks. The WFs present a cardinal direction index (N, S, E, W) corresponding with the x-factor of Renewable Generators.
7) Equivalent Week Profile Load/Solar/Wind: Similar time series of a 12 week equivalent year, for a total of 84 days based on [31]. These complementary profiles, available for demand, solar and wind; are particularly useful for expansion planning studies.

D. Reliability & Resiliency

These two characteristics are deeply interconnected, the first measures a system’s failure rate while the second evaluates its restoration capacity. Reliability is commonly assessed with metrics such as SAIFI, SAIDI, CAIDI, IEED, and IALSD [34]–[36]. While resiliency is studied using relevant extreme events (high impact low probability) that have or could lead to some kind of power system failure [37]. The CVRS includes the following data in order to facilitate these kind of studies:

1) Customers: Presents the number of normal and critical customers and distribution transformers (DT) that feed them. It is assumed that critical transformers feed exclusively critical consumers and vice versa. The total number of customers is known, however, due to privacy issues the per bus amount is estimated based on the nominal load of each bus.
2) Failures: Presents the Failure Rate (FR) and Duration (FD) per line as [failures/year] and [hour], respectively. FR is computed using the failure index [failures/(year*km)] and line length from the Conductors sheet. Transformers assume a FR of 0.25 failures/year while their FR, was obtained combining technical literature and talks with the SO.
3) Substation Reliability: Presents the FR and FD for different elements like circuit breakers (CB), DT and busbars.
4) Outage Scenarios: Presents a number of predefined faults distributed throughout the year to be used in reliability or dynamic studies. It includes: Time of the year as week (W), day (d), hour (h); outaged element, affected buses, load [kW], customers number and duration in hours. A longer description of this events can be found in [20].

IV. Future Development

In the context of the energy transition, every power system is shifting from the fossil fuels towards renewables, and from purely electrical towards integrated energy systems via demand response and sector coupling. In this sense, we include information regarding other energy sectors, enabling demand response and propose different energy mix roadmaps over a 20 year horizon from 2021. This information is included, first, to simplify scenario definition resembling a progressive transition from current 20% RES penetration level towards 100%. Second, to provide relevant information regarding sector coupling possibilities allowing to have a better overview of the global energy needs and trends. Overall, providing researchers with as many alternatives as possible when configuring their scenarios.

There are 4 roadmaps: Base, business as usual (BAU), Optimal and Green. The first is based on the discussions held with Electra and Cabeólica. It responds to their knowledge of the system and estimations regarding funding and technical capability as system stability is, at present, a major concern. The remaining are based on the outcome of two different studies targeted at each of the islands based on an optimal hourly generation expansion planning problem [38]. Briefly, BAU limits RES shares to 20% and does not allow reserve provision from renewable units. Optimal removes those limitations and merely finds the most cost efficient generation mix...
and operation. While Green includes the government milestones regarding RES penetration as 50 and 100% in 2030 and 2040 respectively. Subsequently, the future development sheets are then:

5) GEP: Includes information regarding the roadmaps as number of units, type, size, fuel, and commissioning year.

6) Flexibility: Covers flexibility enabling applications such as: water desalination via reverse osmosis, hydrogen production via electrolyzers, heat and transport.

V. Case Studies

Two different studies covering grid strength and frequency stability conducted using the model of São Vicente showcase the usefulness of the proposed CVRS. Subsequently, we propose and optimal sizing and placement method for distributed BESS, validated via RTDS. Lastly, we enhance the default frequency provision capabilities of the BESS with VI. However, the main purpose of these study cases is to showcase the usefulness and versatility of the CVRS.

A. Grid Strength

In [39] a methodology assessing the grid strength of a given network is presented and evaluated using São Vicente’s network. The objective was to identify suitable locations for connecting energy storage aiming to provide voltage control, while the monitored metrics were short-circuit capacity, X/R and voltage sensitivity. The model, implemented in DlgSILENT Power Factory, considered maximum power production from all generation units as a worst case scenario. Concluding that the island presents a weak grid with narrow variations regarding voltage sensitivity; yet it recommends bus 1 as the best location to install a capacitor bank.

B. Frequency Stability

In [40] the effects on system stability of phasing out the fossil fuel based generation in favour of wind power is studied. The authors explore the possibility of repurposing the existing synchronous generators as synchronous condensers (SC) for inertia support. Frequency stability is assessed considering a renewable penetration rate of 70% along with an step load increase of 10% and a line to ground short circuit. The study uses the simplified São Vicente network implemented in an EMT RTDS. Besides understanding the benefits of SC to support frequency stability via inertia provision, the study also highlights the need of imposing RES-based reserve provision.

C. Optimal Sizing and Placement of a Grid-Supporting Battery

BESS can contribute to frequency stability in renewable based systems. However, successful implementation relies heavily on planning via optimal sizing, location, and operation; as this allows the efficient utilization of transmission capacity and helps adjusting power flow, increase renewable penetration, and reduces power losses [41], [42]. In this work, we determine the optimal size and location of a distributed BESS aimed at frequency support to minimize the total investment and operation cost while satisfying power system constraints in the simplified São Vicente network of Fig. 1b. The advantage of distributing BESS is threefold: grid congestion chances are reduced, required total capacity is minimized, and coordinated action achieves a more homogeneous response, which is key for such weak isolated power systems. The optimization problem was solved using MATLAB and MATPOWER, while the results were validated in RTDS.

1) Problem Formulation: The objective is to minimize the overall active and reactive power production costs as formulated in (1). Then, (2) expresses the cost functions of either active or reactive power (X). Particularly, BESS includes costs related to investment, operation and maintenance. Table I summarizes in details the average cost function parameters selected in this study [43].

\[
\text{Cost}(X) = xX^2 + yX + z
\]

Equations (3) and (4) establish power balance constraint; while (5) and (6) bound bus voltage magnitude and angle at each bus respectively. The branch power limits between bus i and j are represented in equations (7) and (8). Then, the minimum and maximum capacity bounds of the different units are defined with (9) and (10). Lastly, the minimum inertia requirement to ensure that the system operates in a stable and secure condition, δ, is defined by (11), where the total inertia provided by the SG, SC, BESS, and wind turbine should be at least equal to δ. In this study, we assumed that BESS can provide inertia support up to 110% of the rated power of BESS due to the limitation of power electronics inverters.

| TABLE I Cost Function Parameters [$/kVA] |
|---|---|---|
| SG | 0.11 | 5 | 150 |
| SC | 0 | 12.28 | 110 |
| BESS | 0 | 11 | 100 |

\[
\sum_{n=1}^{N} P_{u} - P_{d} = 0, \quad \forall n, \forall u \in B \cup G \cup S \cup L \quad (3)
\]

\[
\sum_{n=1}^{N} Q_{u} - Q_{d} = 0, \quad \forall n, \forall u \in B \cup G \cup S \cup D \cup L \quad (4)
\]

\[
V_{n} \leq V_{u} \leq V_{n}, \quad \forall n \quad (5)
\]

\[
\theta_{u} \leq \theta_{n} \leq \theta_{u}, \quad \forall n \quad (6)
\]

\[
P_{i,j} \leq P_{i,j} \leq P_{i,j}, \quad \forall n \quad (7)
\]

\[
Q_{i,j} \leq Q_{i,j} \leq Q_{i,j}, \quad \forall n \quad (8)
\]

\[
P_{u} \leq P_{u} \leq P_{u}, \quad \forall u \in B \cup G \cup S \quad (9)
\]

\[
Q_{u} \leq Q_{u} \leq Q_{u}, \quad \forall u \in B \cup G \cup S \quad (10)
\]

\[
\delta \leq \frac{\sum_{n=1}^{N} P_{u}}{P_{u}}, \quad \forall u \in B \cup S \cup G \quad (11)
\]
2) **Simulation Results:** The most suitable buses for the BESS are identified based on $V$ magnitudes. MATPOWER is used to compute the required parameters of the power flow problem; resulting on a tie among buses 7, 24, 26, 33, 37, and 47 as the preferred locations for BESS integration. Then, the optimization problem is solved using the interior point optimizer (IPOPT) for different scenarios considering various demand levels [44]. The scenarios define 10, 35 and 50% of the rated design capacity. Thus representing off-peak, current and future peak loads [20]. Only the SG at bus 1 is in operation, as those in buses 50 and 51 are re-purposed as SCs; while the WF on bus 48 assumes 70% available power.

Fig. 2 shows the BESS' location-dependent optimal size [MVA] for each scenario. A 1-MW BESS system should be installed in all buses, but 37. Off-the-shelf lithium-ion batteries available in the market can be used in this system.

Subsequently, the system is modeled in RTDS in order to validate the optimization results via dynamic simulation. The simulation results for scenario 2 with and without BESS during a 5% homogeneous load step increase is shown in Fig. 3.

The system including BESS presents a 36% higher nadir and slower rate of change of frequency; recovering up to 49.95 Hz after 5 seconds. On the other hand, the original system is only able to reach 49.87 Hz.

BESS integration ensures higher power reserve capacity available for the SG to react during any eventuality. Moreover, SC suffer less mechanical stress during inertial response. Overall combining SCs and BESS significantly enhances the frequency recovery of renewable-based systems.

### D. System Inertial Response

Low-inertia power systems must maximize the exploitation of their natural response and combine it with VI support to ensure safe operation. After exploring the stability limits of the São Vicente network, a VI architecture suitable for distributed BESS of the previous section is proposed in this study case. Governor-turbine and load-generator models are respectively used to represent the SGs and frequency controllers of São Vicente. The proposed VI controller is derived from the method presented in [45] by removing the damping coefficient.

Two scenarios are defined based on the addition or not of the VI supportive BESS after a sudden 2% power mismatch. Then, each scenario is comprised of three cases attending to the number of SGs available: Case a) includes all three generators, Case b) removes the SG in bus 51, and Case c) presents only the SG in bus 1. The overall model is represented in Fig. 4, whose parameters are represented in Tables II and III. Note that a steady response is assumed for the WF [46].

$$P_{VI} = K_{VI} \cdot \frac{df}{dt}$$  \(\text{(12)}\)

The results of this study developed in MATLAB/Simulink, are presented in Fig. 5. The nadir frequency for the scenario
without VI support and the three cases are: 49.85, 49.78, and 49.44 Hz respectively. Thus surpassing the ±200 mHz threshold defining frequency events in systems such as continental Europe [47]. Then, regarding the scenario including the BESS-based VI, nadir frequency improves to 49.92, 49.89, and 49.81 Hz, respectively. Lastly, regarding oscillations, cases a) and b) are sufficiently damped as to present an acceptable behaviour. However in case c), the obtained wave forms point towards potential triggering of load shedding protections. Clearly, the larger the original frequency excursion, the higher the effect of the VI which positively contributes towards restoring the frequency in each case.

Regarding Tables II and III parameter sensitivities, \( K_s \) affects the speed of the system’s dynamic response, the time constants \( T \) are machine specific values related to the governor-turbine system. Then, \( R \) and \( \beta \) are proportional to the primary and secondary control response speed, respectively. Governor- and inertia-related constants are obtained from the CVRS, while \( R \) is obtained from [8], \( \beta \) and \( K_d \) are obtained from [48]. Note that both \( H \) and \( K_d \) are empirically approximated coefficients. The only parameter not extracted from the CVRS is \( K_{VI} \); which corresponds to a tunable controller coefficient, whose sensitivity analysis is presented in Fig. 6 according to the cases defined in Table IV. According to the figure, the higher the virtual inertia constants, the better frequency responses in terms of the damping and the frequency nadir. In this sense, VI provides effectively the same support as mechanical inertia.

Time constants are related to the plants response time after an step input; the higher the time constants, the higher VI response is delayed. In principle, Fig. 7 does not present significant sensitivity for the different time constants in terms of frequency. On the other hand, their effect is more clear in the rate of change of frequency (ROCOF) as covered in Table V. For instance, the case with \( K_{VI} = 0.01 \) shows how ROCOF is directly proportional to the time constants. Hence, a fast response from BESS anticipates ROCOF, minimizing the disturbance effect. Yet, the case where \( K_{VI} = 0.05 \) was the only
one presenting frequency nadir differences and higher sensitivity to time constants, showing that systems with higher VI constants will be more sensitive to the time delays. Therefore, there is a trade-off to be tuned between speed and strength of the response, opening the door to further analysis and optimizations.

VI. CONCLUSION

This paper presented a multi-purpose reference system aimed to support research in the transition towards 100% renewable systems, which is made available Open-Access in [22]. The vast majority of the data has been provided by Electra and Cabeólica, respectively the SO and largest renewable utility of Cape Verde. The CVRS includes two networks corresponding to the islands of Santiago and São Vicente as of 2021. Despite being based on isolated systems, they can be used for grid connected studies as well. The objective is to allow researchers, in a wide-spectrum of engineering-related fields, to develop solutions for the energy transition’s challenges in a accurate and very time-efficient manner by using an off-the-shelf dataset based on a real system. Thus ensuring, transparency, replaceability and relevance of their studies. The information included covers topology, generation & storage mix, demand and renewable profiles, reliability & resiliency-studies and the system’s possible future development. To the knowledge of the authors, this is the most extensive and complete dataset representing modern power systems based on a real system.

The usefulness of the presented reference system is exemplified with 2 study cases covering grid strength and frequency stability. Then a comprehensive study considering the optimal sizing and placement of a BESS is followed by a VI supporting strategy achieving an improved response under a sudden generation loss. All 4 study cases represent extremely relevant topics for current and future power system research in the context of the energy transition, whose development are facilitated by the CVRS.

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