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The Hybrid Power Grid of Cape Verde: A Reference System for the Renewable Transition

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Abstract—**New technologies and methods are tested in different benchmarks and reference systems as a common practice in both academia and industry. However, researchers and engineers find extremely difficult to find decent reference models that manage to capture the particularities of modern and near-future power systems. That is, networks with a relative large rate of power electronic-interfaced devices, low inertia, high shares of volatile generation, etc. This work aims to present a novel Reference Benchmark System based on the real grid of Cape Verde; a small African country. The dataset, Openly Accessible in an online repository, is conveniently divided in different files covering an almost unlimited number of classic and state-of-the-art analysis such as: power flow, stability, reliability, resiliency, etc. All the data was provided by Electra and Cabeólica, respectively, the local System Operator and largest renewable utility of the country. The dataset has two main purposes: to serve as a common validation environment for diverse proposals, and to mind the research gap between microgrids and continental power systems as its capacity ranges from dozens to hundreds of MW. As an example, we present a relatively simple study of the grid's strength in DigSilent Power Factory. Three different metrics are used, Short-Circuit Capacity, X/R and voltage sensitivity. Such analysis can be used, for instance, to identify the best location for an energy storage system aiming to provide voltage control.**

I. Introduction

There has been an increasing focus on research and development regarding the transition from fossil-fuel based to Renewable Energy Sources (RES) over the past few years. As of today, RES penetration rates of 20 % are everyday business in many countries, which increasingly target a full transition over the next few decades. As more parties get involved in energy transition aiding product development, there is an increasing need for standardization of the analysis in order to develop decent, comparable and trustworthy evaluations. [1]

Researchers and engineers worldwide find themselves into trouble when trying to find relevant reference systems. Examples of available benchmark systems widely used in scientific literature are: the 2-area 4-machine [2], 6-bus [3], 9-bus system [4], the WSCC system [5], IEEE 14-bus [6], IEEE 33-bus [7], the 68-bus [8], and the IEEE 69-bus [9]. Most of them correspond to imaginary systems that were designed in order to exemplify or analyze very concrete phenomena. Thus, each particular researcher must complete the dataset as they see fit in order to use them. Additionally, they have very limited relevance, specially when considering RES penetration rates above 20 %, power-electronic interfaced technologies, or sector coupling. A deeper analysis of the limitations can be found in [1].

Adding new parameters to any of the aforementioned systems is, on the first hand, complex and time consuming as this kind of information is not easy to find. While on the other, it usually leads to defining unrealistic networks, thus hindering the relevance of the analysis. In general, the selected network must capture the transition from low to high rates of RES penetration, while also allowing full deployment. It should include new technologies such as energy storage systems or demand response. Regarding resiliency, it should be weak enough as to represent a realistic challenge, but remain stable under steady-state conditions. Then, regarding line capacities, the reference system should include certain limitations as to observe congestions, potential contingencies, etc. It should also include some minimal structural adaptability by means of switches; allowing to modify the topology in a realistic manner.

Overcoming these and other limitations, a benchmark for isolated hybrid power systems was presented in [1]. There, a reference dataset suitable for all kinds of static and dynamic studies common in scientific literature was presented. The benchmark presents two different isolated systems based on the islands of São Vicente & Santiago in Cape Verde. Whose data was provided by Electra, the local System Operator (SO) and Cabeólica, the largest renewable utility of the country.

This paper has three targets, to discuss the purpose of such a benchmark, to the describe the latest additions to the dataset's repository [10] and to showcase its usefulness. The later is done by evaluating the grid strength using metrics such as: Short-circuit capacity, X/R and voltage sensitivity. The analysis was developed using the software DIgSILENT - PowerFactory.

The structure of the paper is as follows: Section II presents the purpose for this reference system, while Section III describes the data repository. Then, Section IV briefly introduces the grid strength metrics employed for the exemplary study.

Subsequently V presents the studied grid along with the most relevant results. Later, Section VI discusses the outcome of the study. Finally, Section VII concludes the paper.

II. PURPOSES

There is an increasing concern in scientific literature regarding the relevance and replicability of simulated results as exemplified by [11]. Particularly, that paper points to microgrids, given the number of manufacturers and researchers claiming unrealistic usefulness of their products. In fact, given the reduced size of such systems (in terms of installed power) it is relatively easy to have testing facilities with real equipment. That is specially true when comparing with applications for large power system.The problem then is both how to validate and compare different proposals. Therefore, there is a clear need for a reference system that: ensures the study relevance, is suitable for a many different studies, and allows to replicate results. In addition, this reference system aims to foster international collaboration and to speed up the renewable transition in Cape Verde by directing attention and resources towards the needs of a region with scarce economical resources.

A. Study Relevance

What a better way of ensuring the relevance of a study than by using a real network. That is the idea behind the reference system, which depicts the state of two islands in the 10s and 100s MW range respectively as of 2020.In this way, both small and large systems are characterised. Thus minding the gap between microgrid and large power system analysis; which usually range in the kW and GW/TW respectively. In addition, it includes information regarding the expected evolution of the system towards an scenario with 100 % RES integration.

B. Replicability of Results

The simplest way to ensure replicability of results is by ensuring data consistency among different studies. This is achieved by providing a complete dataset, not expecting researchers to modify or add new parameters. Then, in this way, different groups developing their own energy management systems can test them in the same conditions, which simplifies their comparison and evaluation.

C. Suitable for many studies

One the reasons traditional reference systems do not fulfil the specific requirements discussed in [1] is that they were developed for a particular type of study. Thus, their datasets are limited. The Cape Verde benchmark bypasses this problem by presenting an holistic dataset covering multitude of different studies. Illustrating this, Table I highlights a number of studies that can be currently conducted with the available data in the repository.

TABLE I: Suitable Suggested Studies (reproduced from [1]).

Topic	Potential Studies
Topology Planning	• Grid expansion • Radial vs Meshed operation
Power Flow Analysis	• Island Interconnection • Black-start • Inverse Current Flow Assessment
Control	• Distributed, robust, data-driven Control • RES-based frequency support • Demand Response strategies
Energy Management	• Dispatch strategies • Unit Commitment, Market Clearance • Uncertainty Effect on Dispatch
Stability	• Inertia constant estimation & evolution • Small signal stability • Impacts of topological changes
Reliability	• Reliability Index Evaluation • Cascading Event Identification • Fault & protection studies
Resiliency	• Extreme Event Definition & Modelling • RES-based Resiliency Dependency • Damage & Losses caused by extreme events

D. Foster International Collaboration

As aforementioned, the complete datasets are Open-Access. Then, the authors would like to encourage users to rise requests via the contact email. If they find that the dataset falls short at any given moment, we would do our best to coordinate with the local companies in order to provide the missing data. Thus keeping the relevance of the reference system. This implies that the dataset is still ”alive” and evolving for the foreseeable future based on the feedback received from the scientific community in order to accommodate their needs. This information exchange has the potential of creating new connections among researchers that might decide to work together. In fact, this paper is a clear example of this potential, as the authors belong to different research groups across Europe.

E. Speed up Renewable Transition in Cape Verde

Given the limited resources of Cape Verde, getting researchers to test and evaluate new solutions in their grid is a great way of obtaining high quality analysis virtually for free. This could also attract new investments, funds, etc. to the country.

III. DATA REPOSITORY

The dataset is Open-Access and available as an online repository [10]. Briefly, it consists on a set of tables and files characterising the transmission network of Cape Verde’s

TABLE II: Grid strength's typical metrics.

Grid Strength Metric	**Strong Grids**	**Weak Grids**
SCR	>10	<10 or <5
SCC	>0,9	<0,9
X/R = xrr	>0,7	<0,5

islands. The core of the dataset is a number of excel files (e.g. SantiagoData) that characterize the data defining the system's topology. Said files contain different sheets (e.g. Line Data) categorizing the information. There have been a number of additions worth mentioning since its publication. First, complete DigSilent PowerFactory models were added along with additional data regarding the synchronous units and governors, as well as inertia values. In the future, the dataset is expected to include RTDS models of the islands and high-resolution renewable resource metrics.

IV. GRID STRENGTH

A formal unified definition of grid strength (or stiffness) is missing from scientific literature. However, it can be agreed that it is a characteristic of a power system related to its stability limits. Generally, a strong or stiff grid is that in which voltage (or frequency) do not vary dramatically during faults, transients or contingencies and vice versa. However, it is possible for a particular grid to be strong in terms of voltage and weak for frequency and vice versa. [12]

In general, An electric power system considered as weak presents higher voltage sensitivity. Which means that, in case of disturbances, voltage levels are easily modified. There are several metrics to evaluate this phenomenon and approaches simulating their effects. In this section, four of them are presented, however, it should be noted that they are co-dependent. A summary of typical values for the different metrics characterising strong and weak grids is presented in Table II.

A. Short-Circuit Capacity (SCC)

It is defined as the available fault current at a specific location of the power system. Consequently, fault currents are directly proportional to system strength.

The SCC is the amount of power flowing at a given point in case of a short circuit. It is mainly dependent on the rated voltage and the absolute value of grid impedance, which can be measured at this point. It should be noted that the current contribution of power electronic-interfaced devices is usually considered as zero when computing SCC. Although, there are new proposed metrics to recalculate SCC including them [13].

B. Short-Circuit Ratio (SCR)

SCR is defined as the ratio between SCC and nominal power in the considered point of connection (bus). It is one of the most commonly used metrics classifying grids as weak or strong. Large values of SCR characterize strong grids, therefore presenting high short circuit currents and low voltage sensitivity. Reciprocally, weak grids have low values of SCR, low short circuit currents and high voltage sensitivity. Nevertheless, the fact that a grid is strong or weak is only important under fault conditions, as, during regular operation it does not present any theoretical effect.

There is no consensus when defining SCR values. Traditionally, it is accepted that grids with SCR $<$ 10 are weak, however, in more recent publications it is suggested to use SCR $<$ 5 as power electronic devices are more and more common and reduce this rations. Power electronics standards generally use an SCR of 4 to justify weak grids. [14]

C. X/R ratio

Also referred to as Xrr, it represents the impedance/resistance ratio of a grid. Briefly, weak grids are characterised by high grid impedance and low xrr, thus prominently resistive [15]. It is computed as follows:

$$R_g = \frac{Z_g}{\sqrt{1+xrr^2}} \tag{1}$$

$$X_g = \frac{Z_g}{\sqrt{1+\left(\frac{1}{xrr}\right)^2}} \tag{2}$$

Where Z_g, R_g, and X_g stand for grid's impedance, resistance and reactance, while xrr does so for X/R ratio. Then, we can define Z_g in terms of SCR as:

$$Z_g = \frac{U_g^2}{SCR \cdot S_n} \tag{3}$$

Where U_g and S_n stand for grid voltage and nominal power. In this way, grid strength can be defined in terms of SCR and xrr, which is the usual approach in traditional power system analysis. In general, for higher values of xrr, the more influence have changes in reactive power over voltage levels. Which complementary, also means that variations in active power do not have a lot of effect on voltage levels.

D. Voltage Sensitivity

Intuitively, voltage sensitivity is a metric of how much voltage varies depending on other parameters. It can be defined in different ways, we follow the definition according to the Jacobian of the Newton-Raphson method for load flow analysis [16]. Which can be expressed as:

$$S = J\,V \tag{4}$$

Where S is the complex power in matrix form ($P + jQ$), V stands for Voltage level and J does so for the Jacobian Matrix. Expanding this in terms of active, reactive power and magnitude and angle of the voltage we obtain:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J1 & J2\\ J3 & J4\end{bmatrix}\begin{bmatrix}\bar{V}\\ V^{\theta}\end{bmatrix} \tag{5}$$

Where P and Q stand for Active and Reactive power. While $\bar{V}$ and V^{θ} stand for the magnitude and angle of the voltage. Note that the Jacobian has been divided into 4 quadrants, each of them pointing towards different dependencies between power and voltage as:

$$J = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} = \begin{bmatrix} \frac{\delta P}{\delta \bar{V}} & \frac{\delta P}{\delta V^{\theta}} \\ \frac{\delta Q}{\delta \bar{V}} & \frac{\delta Q}{\delta V^{\theta}} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} V^{\theta} \\ \bar{V} \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{VP} & S_{VQ} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{7}$$

Now we can formally define voltage sensitivity as S_{VP}, and S_{VQ} or $\frac{\delta \bar{V}}{\delta P}$ and $\frac{\delta \bar{V}}{\delta Q}$. This parameter is different for every bus in the system and varies based on both topology and current state of the grid. It is a general practice to dismiss the effect of P over V. This is generally acceptable as lines tend to present high X/R rations, which makes the impact of Q more relevant and allows to dismiss P. However, both the influence of P and Q are considered on this study as we expect certain areas of the network to be weak; that is, present a low X/R ratio. Readers can refer to [16] for a more formal approach to this topic. Then, sensitivity is defined as the ratio between a change of one of the variables due to the change of the other variable. In this manner, Voltage sensitivity gives a good overview of how will change the voltage due to a change in the power output. Therefore, it is important to avoid the location in the grid where $\frac{\delta \bar{V}}{\delta P}$ or $\frac{\delta \bar{V}}{\delta Q}$ are low. The higher the value, less will the voltage change due to power variations.

V. Grid Strength Evaluation

Located at 600 km from the west coast of Africa, Cape Verde is a country conformed by 10 islands. Although the benchmark currently contains data of two of them, the focus of this work is solely on São Vicente. Which represents a mid-size island in the archipelago in the 10s of MW range. Therefore, too large for the typical microgrid standard, yet again, small enough to present a potentially weak grid.

The Single Line Diagrams (SLD) of the island's transmission network as of 2020 is presented in Figure 1. Note that this SLD corresponds to a simplified version of the actual system, however, it captures its most characteristic dynamics. Then, the switches, noted in blue on the SLD, are considered to be open, as this is the default operational position as declared by the local System Operator, Electra.

In order to observe the highest voltage deviation, all generators are assumed to provide 100 % of their nominal capacity. This scenario allows to identify buses with higher tendency to be out of their safe voltage limits. In general, that is ±10 % of nominal value. Figures 2a) and b) present the evaluated metrics related to grid strength; namely SCC and X/R. Most of the nodes present similar S_{cc} probably due to the short distances between buses which limit the impedance values. Thus,not allowing the appearance of significant voltage drops. On the other hand, Figures 3c), and d) show voltage sensitivities per bus; that is $\frac{\delta \bar{V}}{\delta P}$, and $\frac{\delta \bar{V}}{\delta Q}$. These parameters present a difference of one order of magnitude. In fact, the highest value of $\frac{\delta \bar{V}}{\delta P}$ (bus 1) corresponds to half the mean of $\frac{\delta \bar{V}}{\delta Q}$. Thus, it can be concluded that the voltage sensitivity is quite homogeneous in São Vicente. Lastly, note that, the sensitivity of bus 50 corresponds to 0 since it was arbitrarily chosen as the reference bus.

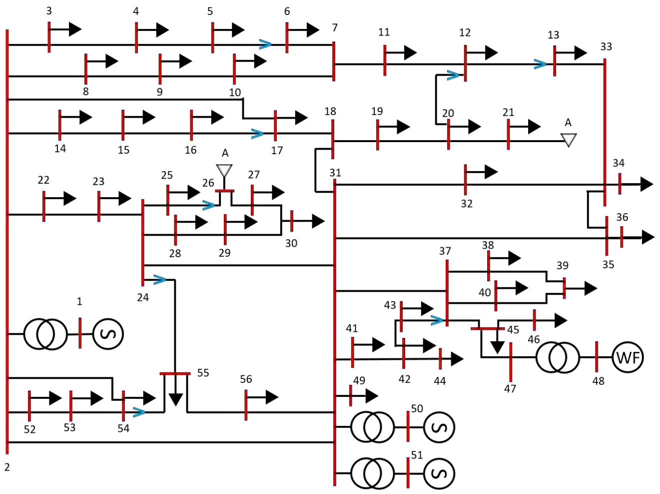
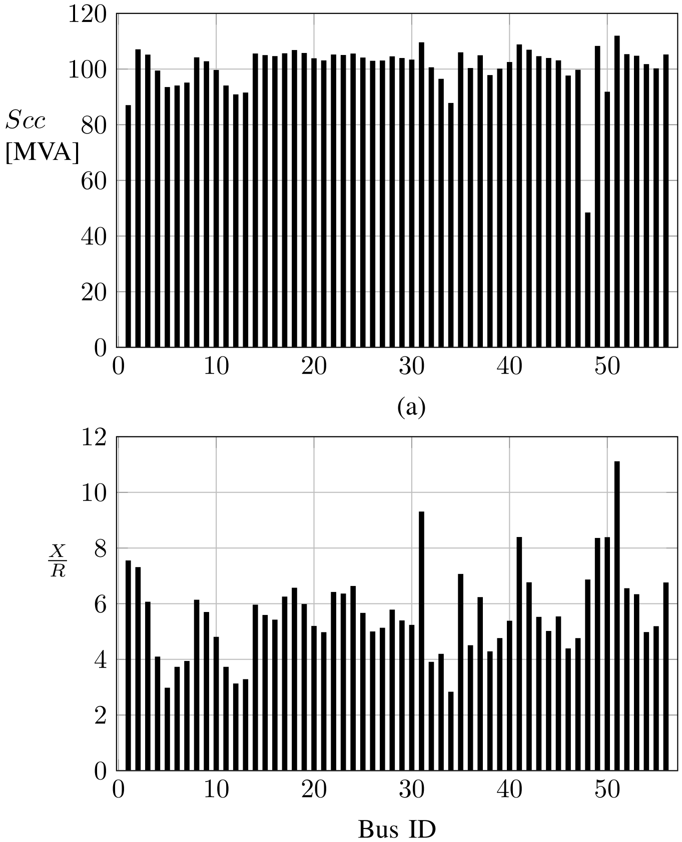


Fig. 1: SLD of São Vicente Island's Network.



(a)

(b)

Fig. 2: Grid Strength Metrics per bus: a) Scc b) X/R ratio

VI. Discussion

Despite simplistic, this comprehensive analysis allows to maximize the effect of potential grid reinforcements. In terms of short-circuit power, São Vicente's presents a value around 100 MVA. Then, SCR corresponds to a value of 10 MVA ap-

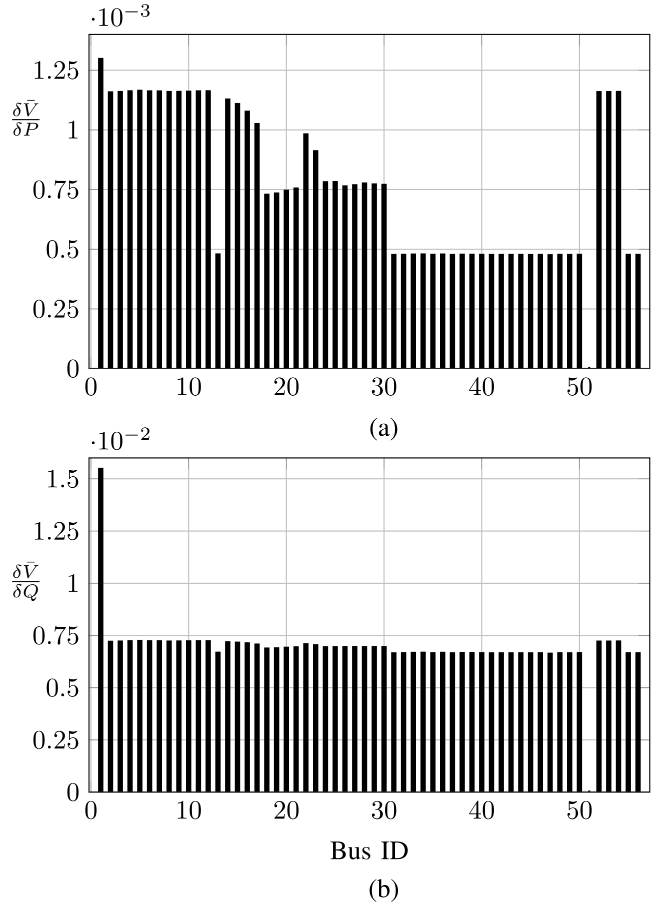


Fig. 3: Voltage sensitivity per bus: a) $\frac{\delta \bar{V}}{\delta P}$. b) $\frac{\delta \bar{V}}{\delta Q}$

proximately, which according to Table II, classifies it as weak. However, this allows to identify buses 31 and 52 as the best location for new production units; since these are the strongest connection points in the in SCR terms. Particularly, the voltage sensitivity analysis ($\frac{\delta P}{\delta \bar{V}}$) demonstrated that there are groups of buses in which the voltage is expected to present a similar behavior such as bus 1 to 16, (ignoring bus 12). Buses 16 to 30 and 31 to 50 can also be similarly aggregated. These groups are fundamentally caused by two topological factors: structure and line lengths. Structurally, meshed networks present lower sensitivity than radial ones. While short distances between buses also limit such factor and vice versa. As resulting from the voltage sensitivity analysis, it can be concluded that the system presents marginal variations between buses. Which means that, no bus present a major advantage or disadvantage for new installations from the voltage perspective. However, considering the X/R ratio, buses 31 and 51 present a clear advantage as those have the largest values. Nevertheless, by selecting the weakest bus (e.g. bus 1) the benefits of installing a voltage controlling unit (e.g. a condenser bank) is maximized. Lastly, it is worth mentioning that Distributed Generation Units (DGU) can be used to enhance the power quality factor by increasing the enforcement of the critical busloads. Particularly during periods of peak-demand, DGUs are capable of reducing voltage drops along the feeders. Their effect is increased if placed in the correct bus.

VII. CONCLUSIONS

Due to the energy transition politics, almost all electrical networks are facing an increasing of RES. Which ultimately difficulties SOs to maintain the safety operational margins. Therefore, an increasing number of researchers focus their work on power quality and reliability applications. Such proposals are tested in different benchmarks that are not always adequate, as most of them do not resemble real systems. In this paper, a new reference benchmark system based on two islands of Cape Verde is presented. Subsequently, a grid strength and voltage sensitivity study was conducted in the island of São Vicente as to exemplify the usefulness of the dataset. Despite its simplicity, this studies allow to identify which buses result more attractive to install voltage stabilizing units.

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