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An ultra-capacitor for frequency stability enhancement in small-isolated power systems: Models, simulation and field tests ☆

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HIGHLIGHTS

- A simple but still accurate model of an ultracapacitor (UC) is proposed.
- The model is validated by using data recorded during field tests of a 4 MW/5 s UC.
- A good agreement has been found between real and simulated power.
- The model accurately represents the UC response for frequency stability analysis.

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ABSTRACT

The most relevant issue in operation of isolated power systems is frequency stability. Frequency stability is concerned with the ability of generators to supply the loads at an acceptable frequency after a disturbance. Frequency stability is governed by the kinetic energy stored in the generator-prime mover rotating masses and the prime mover frequency primary regulation. If frequency excursions are not within +/−2.5 Hz range, cascade tripping of the remaining generators can occur because of generator over/under frequency protections tripping. Energy storage systems can contribute to frequency stability enhancement if their discharging is governed by a frequency controller.

Endesa is leading a research project on testing the state of the art of energy storage systems for several applications (peak-shaving, voltage control, frequency control) in several isolated power systems of the Canary Islands. Several applications are being investigated. One of them consists on the application of a 4 MW–5 s ultracapacitor (UC) for frequency stability enhancement of the La Palma power system.

This paper reports the dynamic model developed for time domain simulation and controller design of frequency stability, and field tests undertaken to validate models and the controller settings. A simple but still accurate model is presented. The proposed model takes into account the UC's state of charge (SoC) and it represents the dynamics of the power electronics by means of a non-linear first-order model. The frequency control consists of droop control and inertia emulation. Ramp rate limits, power limits and SoC are also taken into account in the frequency control. In comparison with the recorded field tests, the proposed model is able to accurately represent the response of the UC for the purpose of frequency stability analysis.

1. Introduction

Frequency stability is a major concern of power systems. Frequency stability is concerned with the ability of generators to supply the loads at an acceptable frequency after a disturbance [1]. Frequency instability usually occurs after large generation-load imbalances. Isolated power systems are especially sensitive to generation-load imbalances due to their small size. The small size implies that the power system has less capacity to react to generation-load imbalances and that less inertia is available compared to large interconnected power systems. Further, every generator infeed presents a substantial portion of the total demand. In isolated power systems, generator trippings constitute large generation-load imbalances, leading to pronounced frequency deviations [2]. If frequency excursions are not within +/−2.5 Hz range, cascade

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tripping of the remaining generators can occur, initiated by their over/under-frequency protections.

The ability of a power system to maintain the generation-load equilibrium (and thus maintain frequency within an acceptable range) still mainly relies on synchronous generators. They provide a natural way of maintaining system frequency within acceptable limits through their inertial responses. In addition, the responses of their speed governors and load–frequency controllers limit and cancel frequency deviations. These so-called primary and secondary controls require synchronous generators to supply a certain reserve, i.e., they cannot be generating at their maximum or minimum power [3]. Primary frequency control is a proportional control. The inverse of the gain of the control is usually known as droop [4].

The increasing penetration of renewable energy sources poses a major challenge to frequency stability [2]. On the one hand, their intermittent nature continuously creates load-generation imbalances and currently, they do not contribute to frequency control through their inertia, because this kind of generation is usually connected to the power system through a stage of power electronic converters. On the other hand, renewable energy sources are usually operated in such a way that they generate as much power as possible and therefore, they do not provide upward reserve so far. Thus, other resources are sought to provide the necessary power support in case of load-generation imbalances ([5,6]). Energy storage devices are adequate to be used to provide frequency support services. Energy storage devices can be rapidly discharged after a disturbance (e.g., a generator tripping).

Different energy storage devices have been studied ([7–19]). Magnetic energy storage units have been proposed for load frequency control in [7]. In [8], flywheel energy storage units have been used in conjunction with a variable-speed wind generator so that the combination of both can respond to frequency deviations. The ability of a battery energy storage system to contribute to power system stability has been analyzed in [9]. The impact of a battery energy storage system on the operation of an isolated power system with variable load and wind generation has been studied in [10]. The problem of dimensioning the battery energy storage system has been addressed in [11].

This paper focuses on a UC storage system providing frequency support to a real isolated power system. Due to their characteristics, UCs can be used to provide frequency support services [13]. In [14], a UC has been preferred to a battery because of its high power density. However, UC have usually been proposed to be used in conjunction with other energy storage systems. The use of a hybrid system with fuel cells and a UC has been proposed in [15], where the fuel cells are intended for slower transients and the UC for faster transients such as generator trippings. Fuel cells and UCs have also been studied in [16] because UCs can supply a large amount of power but it cannot store a significant amount of energy. The impact of distributed generation including a battery and a UC has been analyzed in [17]. A battery system together with a UC has been studied for dynamic wind energy support in [18]. The combined use of a flywheel, a battery and a UC has been proposed in [19].

In order to evaluate the behavior of the system, an adequate model of the UC is needed. Several models of UCs have been presented in the literature. Different RC network models have been compared in [20]. A third order model has been found to be accurate enough [21]. In [22], equivalent electrical circuits and thermal models have been presented and adjusted by using laboratory tests. A similar objective is pursued in [23], where a linear recursive model has been employed. In [24], a model that can represent the electrical behavior of a UC for a wide range of frequencies has been studied and its parameters have been identified. The aging of a UC has been assessed in [25] by evaluating the evolution of the estimated parameters of an electrical model.

All the previously presented models focus on the electrical and thermal behavior of the UC. However, UCs are connected to power systems through a stage of power electronic converters and an appropriate control is applied to these converters in order to obtain the desired response from the UC. The control of the output current of a UC has been studied in Ref. [26]. A detailed representation of the power electronics has been used in [27] to simulate the impact of a magnetic storage, a fuel cell and an UC. A detailed model of both the electrical behavior of the UC and the power electronics has been used in [15].

When the size of the power system to be analyzed increases, such a detailed modeling increases the simulation time and the benefits of including so many details in the simulation fade out. Further, frequency dynamics are governed by rotor and speed-governor dynamics, being much slower than the behavior of electrical and power-electronic transients [2]. Moreover, detailed models have many parameters that are difficult to adjust in order to make the model response coincide with the real response of the system. In these cases, simpler models that only include the main dynamics of the system are preferred because they are easier to understand, it is easier to tune a small number of parameters, and because simulation time is reduced [28]. Finally, simplified models should be focused on their application, i.e., the interesting dynamics of the system regarding the application under study should be included in the model [29].

This paper presents a simple but still accurate model to represent the behavior of a UC-based power module for the analysis of frequency dynamics and frequency stability. The proposed model is intended to reflect the response of the UC as seen by the power system. The model includes a representation of the UC based on its state of charge (SoC), a simplified model of the power electronic converter and control based on a non-linear first-order model, and the main characteristics of the frequency control. In addition, this paper validates the proposed model with a full-scale UC-based power module. The parameters of the proposed model are tuned and validated by means of field measurements recorded at the generator station of the La Palma power system. These measurements have been obtained from dedicated tests carried out with the real UC-based power module in operation. The tests consisted in controlled generator trippings. First, an open-loop validation is carried out, where uniquely the UC model is contemplated and assessed. In a second step, the simulated response of the complete model of the La Palma power system is compared with the real, measured response of the power system. This is referred to as closed-loop validation.

2. Ultracapacitor model

In this section, the model for the UC-based power module (from now on, UC model) is presented. The model includes both frequency and voltage control, a simplified representation of the power electronic converters and its control, and the UC's state of charge (SoC). Since this paper focuses on frequency stability and since frequency and voltage control can be made almost independent by means of an appropriate *d*–*q* axes representation, only the model related to frequency control will be detailed. Note also that voltage control was deactivated during the field tests of the UC.

2.1. General structure of the UC model

An overview of the UC simulation model is presented in Fig. 1. The frequency control measures system frequency and computes the active power set point for the UC. The voltage control measures

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