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Performance analysis and evaluation of reactive power compensating electric spring with linear loads

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ABSTRACT

Reliance on renewable energy sources (RESs) such as solar and wind has increased to build a sustainable environment, however, their substantial implementation is hindered by their intermittency. Electric Spring (ES) is one of the technologies to mitigate the intermittent nature of the RESs. In an isolated RES powered microgrid, the ES in conjunction with the non-critical loads in a system like water heaters, refrigerators, and air-conditioners can regulate voltage of critical loads like security system, servers etc. This paper establishes the operating principles of the ES (with reactive power compensation only) and its interaction with RESs based on the understanding of AC power transfer between two sources. The accurate phasors in a system under two scenarios, with and without ES, are drawn. Also, performance of the ES is analyzed and evaluated with respect to variations in the loads (linear) and their types. It is augmented with analytical justifications and validated through simulations and experimental studies. Also, through analytical expressions, simulations, and experiments the importance of the non-critical load on the performance of the ES is illustrated. It is also highlighted that the compensation capabilities of the ES remain the same irrespective of the types of non-critical load.

1. Introduction

There has been an increased interest in microgrids powered with renewable energy sources (RESs) like solar and wind in countries all across the world including Singapore [1–3]. An increased penetration of intermittent power from RESs could cause destabilization of the microgrid [4]. A more reformed way of thinking to utilize this intermittency to an economical advantage to the consumer is required. Unlike a traditional grid where demand is non-interactive, the demand of the microgrid is interactive with the grid and can provide cost-effective reliability, balancing, and load-shaping support for the grid [5].

The concept of Electric Spring (ES) was introduced in [6,7] which utilized a power electronic converter to implement demand side management (DSM) and mitigate intermittency of RESs powered grids. The ES is employed in series with the building's non-critical (NC) loads like air-conditioners, refrigerators, water heaters etc. This series combination of the ES and the NC load is called a *smart load* which in turn is attached in parallel to building's critical loads like security system, servers etc. A system configuration is depicted in Fig. 1, where the ES is implemented using an inverter. Initially, in [7,6] the ES is introduced as a reactive power compensator which provided voltage and power stability to a constant impedance load. The capability of the ES to provide a combination of reactive power and real power injection and absorption is highlighted in [8]. Validation of the ES, proof-of-concept hardware, and proof that it could provide load power shedding for the NC load are presented in [9]. Insights on how buildings, an essential part of future microgrids, could serve as grounds for implementation of the ES are outlined in [10]. Analytical reasoning on how storage requirements would be reduced in a system with the ES is given in [11]. Various methods on how the ES could be used to implement power factor correction along with voltage stability in the system are discussed in [12–15]; this version of the ES utilized both real and reactive power compensation from a battery based ES. The dynamic model of the ES is presented in [16] and small-signal model and stability of multiple ESs is discussed in [17]. Frequency regulation using the ES is discussed in [18,19]. Other configurations of the ES have also been developed such as back-to-back ES [20] and DC ES [21–23].

This paper investigates into the operating principles and performance of the ES with only reactive power compensation capabilities, as the present literature has left significant gaps and lacks a deeper analysis. Most of the literature mention that the ES injects capacitive or inductive power in order to boost or reduce the critical load voltage [6,9,8,24,10,25]. The capability of real and/or reactive power compensation by the ES (with an active power source) is highlighted in [8], the authors have suggested that the behavior of such an ES should be according to the type of the noncritical load. However, such a statement

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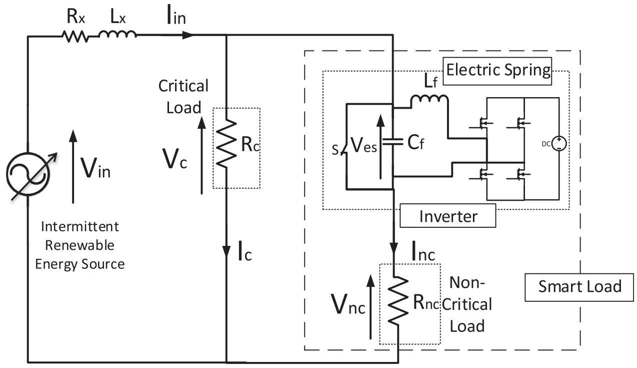

Fig. 1. Circuit diagram of an electrical power system with the electric spring.

cannot be extended for the ES with only reactive power compensation capabilities as considered in this chapter. It is asserted that for voltage regulation, using only reactive power compensation capability of the ES, the behavior of the ES shouldn't change with the type of the non-critical load. The phasor diagrams reflecting this are drawn. The performance of the ES is evaluated by changing the type of critical and the noncritical loads through extensive simulation and hardware experiments. A system with inductive line impedance has been considered and our simulations and hardware experiments prove that the ES injects reactive power to boost voltage in undervoltage conditions and absorbs reactive power to reduce voltage in overvoltage conditions. This is substantiated by valid theory and taking into account the interactions between the two AC power sources in the system, the RES and the ES, connected by an inductive line impedance. Such a theory hasn't been covered in any of the available literature yet to the best of authors' knowledge. To better understand the effects of adding the ES, phasor diagrams of the system both with and without the ES are drawn. Additionally, phasor diagrams according to the behavior of the ES with various non-critical load types are presented in this paper. The literature [16] claims that the performance of the ES is dependent on the ratio of critical and noncritical (NC) load impedances. However, in the pursuit of this research it is revealed ratio might not be enough to judge the performance of the ES. It is found that the performance of the ES relies on the wholesome contribution of the absolute value of the noncritical load impedance. Also, the performance of the ES is evaluated on variation of the impedances and types of critical and non-critical loads through extensive simulation and hardware experiments.

In Section 2 of this paper, parallels from the AC power transmission system are drawn to study the interaction between the RES and the ES. Based on the theoretical knowledge, the behavior of the ES for voltage regulation, in undervoltage and overvoltage scenarios is formulated. Building on this understanding, the system phasor diagrams before and after implementation of the ES are drawn and explained in detail. Further, the impact of changes in system parameters like critical and non-critical impedances and their types and limitations of the ES are studied in Section 2 and validated through simulations and experiments in Section 3. Finally, conclusions from the analysis of operation and performance of ES are drawn in Section 5 and some remarks are made in Section 4.

2. Operating principles of electric spring

Before delving into the operating principles of the ES, it is necessary to grasp what happens when there are two active energy sources in a system. For simplification, a system like in Fig. 2 is studied with two energy sources labeled as G_S (RES) at sending end and G_R (ES) at the receiving end connected through a inductor of impedance, X [26]. The complex power at the receiving end (source G_R), S_R is given by (1) [26], where V_R and V_S are the voltages of sources G_R and G_S, respectively, I is the current flowing through line impedance, and δ is the power angle.

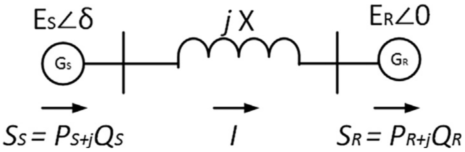

Fig. 2. Power transfer between two power sources.

$$\overrightarrow{S_R} = \overrightarrow{E_R I}^{*} = E_R\left[\frac{E_S\cos\delta + jE_S\sin\delta - E_R}{jX}\right]^{*} \tag{1}$$

In the case where there is no real power transfer between them, the power angle (δ) is zero and the system equations for real power (P_R) of source G_R and real power (P_S) of source G_S are given by (2) and for reactive power (Q_R) of source G_R and reactive power (Q_S) of source G_S are given by (3) and (4), respectively.

$$P_R = P_S = 0 \tag{2}$$

$$Q_R = \frac{E_R(E_S - E_R)}{X} \tag{3}$$

$$Q_S = \frac{E_S(E_S - E_R)}{X} \tag{4}$$

In (3) and (4) when $E_S > E_R$,Q_S and Q_R are positive, that means reactive power is transferred from source G_S to source G_R. This means that when lagging current flows through the inductive line impedance, receiving end voltage (E_R) is lower than the sending end voltage (E_S)). Conversely, when $E_S < E_R$,Q_S and Q_R are negative, that means reactive power is transferred from source G_R to source G_S. This implies when a capacitive current flows through the inductive line impedance, receiving end voltage (E_R) is more than the sending end voltage (E_R) [26].

This understanding from AC power transmission systems is applied to the system where the ES is deployed. In our problem statement, the isolated microgrid system consists of two energy sources namely the RES and the ES (Fig. 1) and power transfer between them would change the behavior of voltage at receiving end that is, critical load voltage, V_c. The ES doesn't exchange any real power with the RES. So, when a lagging current flows through the line inductance, critical load voltage would be reduced and when a leading current flows, critical load voltage would be boosted. For example, consider a system with only resistive critical and non-critical loads and the ES injects only reactive power. In this system, there are following two scenarios to be considered:

- *Undervoltage Scenario*: When the critical load voltage, V_c is less than its reference voltage, V_{ref}, the ES should inject reactive power to boost the critical load voltage. In other words, the ES should behave as a capacitor, so as to make the current through line inductance capacitive. The phasor diagrams of the system, before and after implementation of the ES are shown in Fig. 3a and b, respectively.
- *Overvoltage Scenario*: When the critical load voltage, V_c is more than its reference voltage, V_{ref}, the ES should absorb reactive power to reduce the critical load voltage. In other words, the ES should behave as an inductor, so as to make the current through line inductance inductive. The phasor diagrams for the system, before and after implementation of the ES are shown in Fig. 4a and b, respectively.

In Figs. 3a, b, 4a, and b, V_{in},V_c,V_{nc}, and V_{es} are the input voltage, critical load voltage, non-critical load voltage, and ES voltage, respectively and I_{in},I_c, and I_{nc} are the currents through line impedance, critical load, and non-critical load, respectively. The line resistance and reactance are designated by R_x and X_x, respectively. The system equations for the ES, as shown in Fig. 1, are given by (5)–(7) where, θ_c,θ_{nc} and θ_{es} are the phase angles of the critical load voltage, the non-critical load voltage, and the ES voltage, respectively, ϕ_{nc} is the phase angle of the