Implementation of Electric Spring in Future Smart Grid for Reduction of Energy Storage Requirements

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Abstract**—** The electric spring is modern technology certified to be effective in stabilizing smart grid with substantial participation of intermittent renewable energy sources and enabling load demand to follow power generation. The unclear change from output voltage control of a reactive power controller presents the electric spring new aspects convenient for future smart grid applications. In this project, the effects of such unclear control change are highlighted, and the advantage of the electric springs in reducing energy storage requirements in power grid is theoretically shown and practically shown. In an experimental set up of a 90 kVA power grid. Traditional statcom and static var compensation technologies used for only reactive power compensation as well as random power variation in non-critical loads. These are such profitable features of electric spring enables non-critical loads with embedded electric springs to be adaptive to future power grid. Accordingly, the load demand can follow energy precaution, power generation and hence energy storage requirements can be reduced.

Keywords**—***Distributed power systems, stability, smart grid, energy storage*

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I. INTRODUCTION

The prevailing control example of power systems is to catalyze power to meet the load demand, Because of increasing use of alternating renewable energy sources, identified or unidentified to the utility companies, it is not possible to determine the immediate total power generation in real time. In order to get balance of power supply and demand, which is necessary factor for power system stability, the control example for future smart grid has to be shifted to "load demand following power generation" .

The scientific principle, the operating modes, the limitations, and the practical realization of the electric springs are reported. It is found that such new concept has vast potential in stabilizing future power systems with substantial penetration of intermittent renewable energy sources. This concept will demonstrate in a practical power system setup fed by an ac power source with a fluctuating wind energy source. The electric spring is initiate to be effective in regulating the mains voltage despite the fluctuation caused by the intermittent nature of wind power. Electric springs entrenched can be turned into a new generation of smart loads, their power demand following the power generation profile. Electric springs, when distributed over the power grid, will present a new form of power system stability solution that is independent of information and communication technology.

II. LITERATURE REVIEW

Various load demand management methods have previously been suggested.. Some examples comprise load scheduling [5]–[7], use of energy storage as a buffer [8], electricity pricing [9]–[11], direct control or on-off control of smart loads [12]–[14], etc.

However, most of these methods are appropriate for load demand management in the time frame of hours and are not suitable for instantaneous energy balance in real time. Energy storage is most likely the most useful means for immediate energy balancing [8]. In order to operate with fast transient, energy storage elements such as battery banks are installed with parallel connected super-capacitors which can absorb current at a earlier rate than chemical batteries [15]. Though, energy storage elements such as batteries are costly and disposed batteries are major sources of pollutants. Although they are considered to be necessary elements in future smart grid [15], it would be preferable to decrease their size for cost and environmental reasons.

In this project, an examination is conducted to examine the use of electric springs in reducing energy storage elements in future smart grid.

The electric spring idea [16], [17] was recently offered as a new smart grid technology for regulating the mains voltage of power grid with considerable irregular renewable power and for getting the new control example of load demand following power generation. Output voltage control used by traditional series reactive power compensators by changing from the output voltage control to the input voltage control for a reactive power controller, electric springs exhibit characteristics different from traditional devices such as series reactive power controller. The effects of this slight change of control modality and the interactions between the electric springs and energy storage in a power grid, which have not been before addressed, are emphasized with practical tests in this project. Statcom, Static Var Compensation, and UPFC technologies offers only reactive power compensation [21]–[26], but electric springs offers reactive power compensation, as well as automatic load variation in non-critical loads (with electric springs embedded). This useful feature provides the possibility of reducing energy storage requirements in future smart grid. This important point is first theoretically proved and then practically demonstrated in a 10 kVA experimental smart grid setup.

III. BASIC PRINCIPLES OF ELECTRIC SPRINGS

Electric springs are reactive power controllers with input voltage control instead of the traditional output voltage control used in series reactive power compensators. System operation details can be found in [17]. In this section, the basic principles of electric springs are summarized so as to help readers' understanding of the power flow analysis and the effects of the electric springs on reducing energy storage requirements in smart grid.

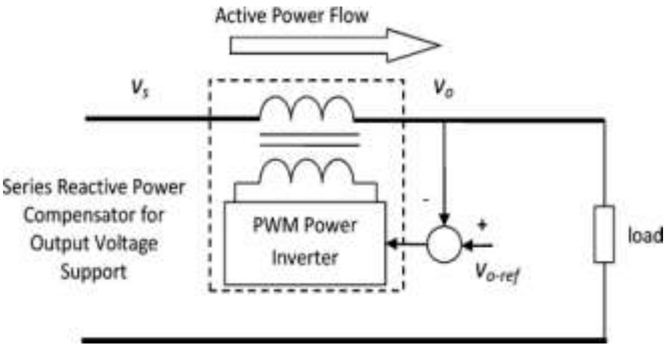

Fig. 1. "Output voltage control" of a series reactive power compensator.

Fig. 2 shows the installation of a single-phase electric spring connected in series with a non-critical load. The electric spring includes a power inverter with a dc bulk capacitor on the dc side and an inductive-capacitive (LC) filter on the ac side of the power inverter (Fig. 3). The four freewheeling diodes of the power inverter act like a diode rectifier which rectifies the ac voltage into a dc one (V_{dc}) across the bulk capacitor. In the power inverter to produce a controllable ac voltage v_a across the filter capacitor the pulse-width-modulation switching method is adopted. The output voltage of the electric spring is controllable ac voltage. To pure reactive power control, the electric spring voltage and the current vector must be perpendicular. The input voltage control loop described in Fig. 2 is designed to produce v_a dynamically with the purposed of regulating the ac mains voltage to a reference value.

The electric spring vector equation is:

$$\mathbf{v}_o = \mathbf{v}_s - \mathbf{v}_a. \tag{1}$$

Assuming that a certain time-varying power generation P_{in}, which may comprise of a base power profile (generated by an ac generator) and an discontinuous renewable power profile, is fed to the distribution line in Fig. 2, the power balance equation can be expressed as

$$P_{in} = \frac{v_s^2 - v_a^2}{R_1} + \frac{v_s^2}{R_2}$$

$$P_{in} = P_1 + P_2 \tag{2}$$

Where R_1 and P_1 are the resistance and power consumption of the non-critical load respectively; and R_2 and P_2 are the resistance and power consumption of the critical load respectively; v_s and v_a are the root- mean-square values of the ac mains and electric spring voltage respectively.

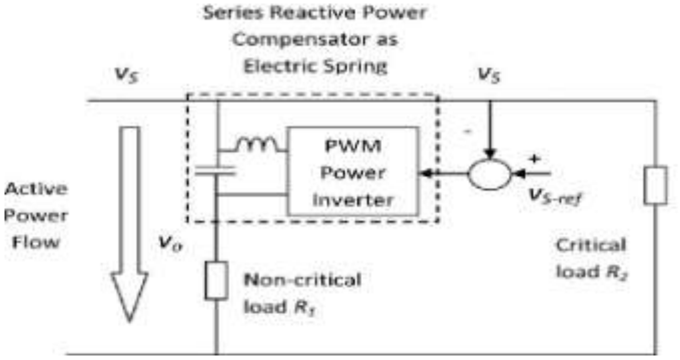

Fig. 2. Arrangement of an electric spring connected in series with a non-critical load (using the "input voltage control") [18].

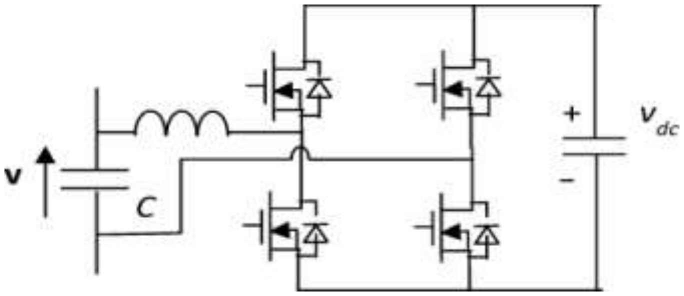

Fig. 3. Power inverter used as a reactive power controller.

Renewable energy sources can be wind and solar energy sources. Non-critical loads refer to electric equipment and appliances that can be subject to a fairly large variation of the mains voltage. Examples include electric heaters, refrigerators and lighting systems. Critical loads refer to electric loads that require a well-regulated mains voltage, such as life-supporting medical equipment and computer controlled equipment.

Equation (2) indicates that, if the electric spring can regulate v_s, P_2 should be constant and P_1 should follow the time-varying profile of the discontinuous power generation as shown in Fig. 4.

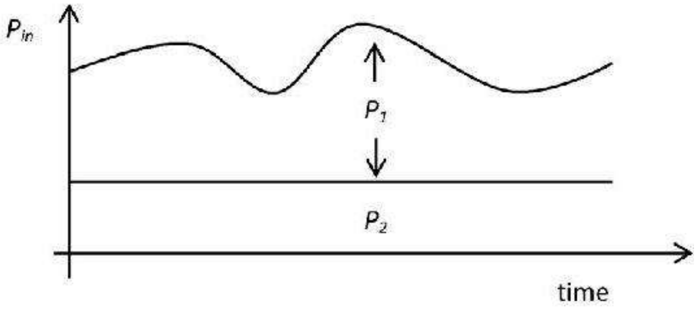

Fig. 4. Power profiles of non-critical load — - and critical load - — - when the mains voltage ■ is regulated by the reactive power controller [17].

Let the rated power of the non-critical load when the electric spring is not activated (i.e., $v_a = 0V$) be:

Where v is at its nominal rated value.

Let the real power of the non-critical load power under the control of electric spring (i.e., $v_a \geq 0V$) be

$$P_1^{es} = \frac{v_s^2 - v_a^2}{R_1}. \tag{4}$$

It is clear from (3) and (4) that:

$$P_1^{\max} \geq P_1^{es}. \tag{5}$$

Equation (4) and (5) reveal the fact that the electric spring can vary the non-critical load power so that the load demand follows the power generation.

VI. PROPOSED WORK

Now consider a general power grid consisting of an ac generator,a renewable power source,energy storage, non-critical loads set and critical loads set as shown in Fig. 5. The power flow diagram is shown in Fig. 6

The power from the energy storage may be positive or negative depending on whether the storage device is discharging or charging.

The power balance equation of the power grid in Fig. 6 can be expressed as:

$$P_G + P_R + P_S = P_1 + P_2 \tag{6}$$

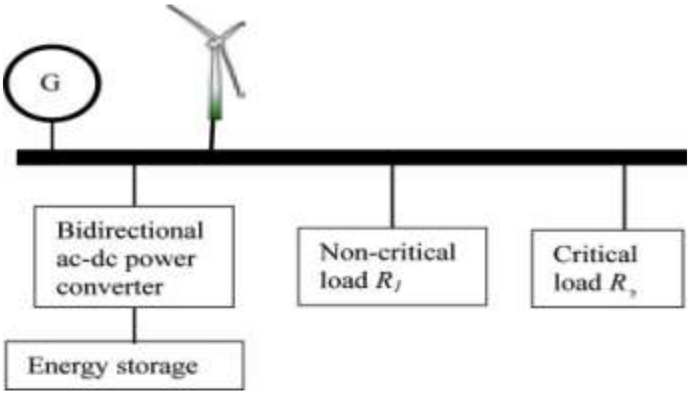

Fig. 5. Schematic of a power grid.

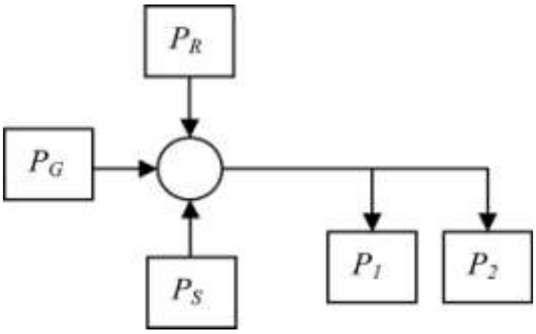

Fig. 6. Power flow diagram.

Where P_G is the power generated by the ac generator, P_R is the renewable power, and P_S is the power from the energy storage. P_S is positive when the battery is discharging and negative when it is charging.

Re-arranging (6) with the storage power as the subject of the equation,

$$P_S = \quad P_G \quad P_R + P_1 + P_2. \tag{7}$$

Without the electric spring, the energy storage requirement for a duration of T is:

$$E_S = \int_0^T P_S dt = -\int_0^T P_G dt - \int_0^T P_R dt + \int_0^T P_1^{\max} dt + \int_0^T P_2 dt. \tag{8}$$

With the electric spring, the energy storage requirement for the same duration is:

$$E_S^{es} = \int_0^T P_S dt = -\int_0^T P_G dt - \int_0^T P_R dt + \int_0^T P_1^{es} dt + \int_0^T P_2 dt. \tag{9}$$

The difference of the energy storage requirements with and without the electric spring can be obtained by subtracting (8) from (9), resulting in:

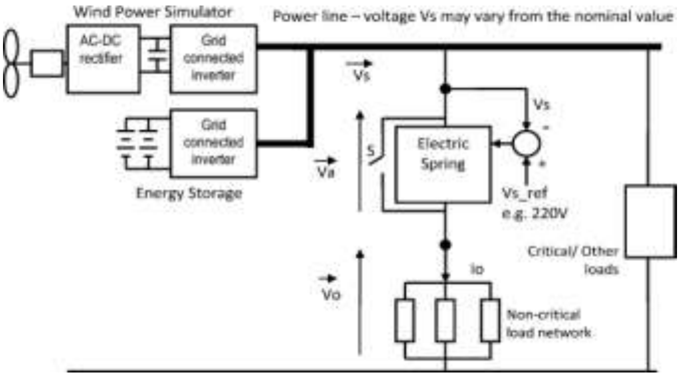

Fig. 7. Experimental setup based on the 90 kVA Smart Grid Hardware Simulation System at the Maurice Hancock Smart Energy Laboratory.

$$E_S \quad E_S^{es} = \int_0^T P_1^{\max} dt \quad \int_0^T P_1^{es} dt. \tag{10}$$

In view of (5),

$$\int_0^T P_1^{\max} dt \geq \int_0^T P_1^{es} dt. \tag{11}$$

so,

$$E_S \geq E_S^{es}. \tag{12}$$

Equation (12) shows that the use of the electric spring can theoretically reduces the energy storage requirements in the power grid.

V. CONCLUSION

In this paper, the differences between the output voltage control and the input voltage control of a reactive power controller are highlighted. While energy storage is an efficient but costly means to balance power supply and demand, an investigation is presented to show that electric springs can reduce energy storage requirements in a power grid. Electric springs permit the non-critical load power to vary with the renewable energy profile. By reducing the immediate power inequality of power supply and demand, electric springs permit the non-critical load demand profile to follow the power generation profile and reduce the energy storage requirements in power grid. This significant point has been theoretically proved and will practically confirm in an experimental setup. Due to the beneficial features such as enabling the load demand to follow the power generation, the reduction of energy storage requirements, the reactive power compensation for voltage regulation, and the possibility of both active and reactive power control [28], electric springs open a door to distributed stability control for future smart grid with substantial penetration of intermittent renewable energy sources.

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