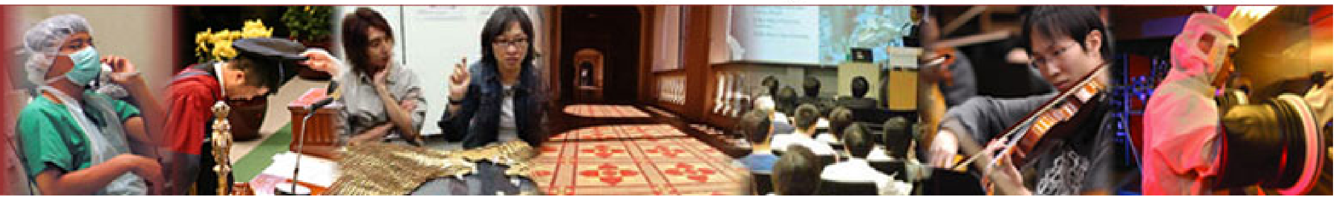

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Use of Hooke's Law for Stabilizing Future Smart Grid – The Electric Spring Concept

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***Abstract*— Hooke's law for mechanical springs was developed in the 17th century. Recently, new power electronics devices named "electric springs" have been developed for providing voltage regulation for distribution networks and allowing the load demand to follow power generation. This paper summarizes recent R&D on electric springs and their potential functions for future smart grid. Electric springs can be associated with electric appliances, forming a new generation of smart loads which can adapt according to the availability of power from renewable energy sources. When massively distributed over the power grid, they could provide highly distributed and robust support for the smart grid, similar to the arrays of mechanical springs supporting a mattress. Thus, the 3-century old Hooke's law in fact provides a powerful solution to solving some key Smart Grid problems in the 21st Century.**

I. INTRODUCTION

The injection of intermittent renewable power into the power grid through grid-connected power inverters, without considering power system stability, has been identified as a key factor for causing destabilization of the electric grids, causing potential blackouts, weakening voltage and causing damage to industrial equipment [1]. The gradual increase of renewable energy sources, known or unknown to the power companies is expected to increase the chance of power grid instability, particularly when the penetration of renewable energy becomes a significant portion of the total power generation in future smart grids [2]. Renewable energy sources that are of intermittent and distributed nature make it impossible for power companies to determine instantaneous power generation. It is stated in [3] that too large amount of renewable electricity production in the grid as a whole, or just locally, will endanger the reliability and quality of the supply to other network users and that the injection of active power along a medium-voltage feeder or to low-voltage network will reduce the voltage drop and may even result in an overvoltage. The increasing use of grid-connected inverters for renewable electric power generation without considering the stability of power grids has become a concern to power industry.

The new control paradigm where load demand is made to follow the power generation in future smart grid with substantial penetration of renewable energy sources has led to new technological challenges. In order to achieve balance between power generation and demand, various load demand management methods have been previously proposed. Examples include load scheduling [4]-[6], use of energy storage [7], electricity pricing [8]-[10], direct control or on-off control of smart loads [11]-[13] etc. However, most of these methods are suitable for load demand management in the time frame of hours and are not suitable for instantaneous energy balance in real time. Energy storage could be regarded as the most effective means for instantaneous energy balancing [14]. However, the cost of battery storage is almost exponentially proportional to the capacity of the storage, making it prohibitive to install large-scale energy storage. In addition, disposed batteries would cause another environmental concern. Although batteries are considered as essential elements in future smart grid, it is preferable to reduce their size for cost and environmental reasons.

This paper reports and summarizes recent research and developments of electric springs (ES) for future power grids. Based on the Hooke's law, electric springs are electric versions of their mechanical counterparts. They have interesting potentials to stabilize future power grid with substantial penetration of intermittent renewable power generation.

II. APPLICATION OF HOOKE'S LAW TO STABILIZING POWER GRID

A. Hooke's Law in the Mechanical Domain

The Hooke's law published in 1660 provides the relationships of the force and displacement as follows:

$$\mathbf{F} = - k\mathbf{x} \tag{1}$$

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where **F** is the force vector, k is the spring constant and **x** is the displacement vector. The potential energy (PE) stored in the mechanical spring is:

$$PE = \frac{1}{2}kx^2 \quad (2)$$

Mechanical springs have been employed for daily applications such as suspension systems in beds and vehicles for providing mechanical support and absorbing mechanical vibrations. The array of many individual mechanical springs under a bed is a highly robust support system, because the overall system is highly stable even if some individual springs fail. Such concept can be adopted in taming the intermittent nature of wind and solar power generation in future power grid.

B. Hooke's Law in the Electric Domain – Electric Spring

An ES is analogous to a mechanical spring that it can be used to (i) provide electric voltage support, (ii) store electric energy and (iii) stabilize system operation [15][16]. Analogous to (1), the basic physical relationship of the electric spring is expressed as:

$$q = -Cv_a \quad (3)$$

where q is the electric charge stored in a capacitor with capacitance C, v_a is the electric potential difference across the capacitor and i_c is the current flowing into the capacitor.

The energy storage capability of the ES can be seen from the potential electric energy stored in the capacitor:

$$PE = \frac{1}{2}Cv_a^2 \quad (4)$$

so the capacitor C serves as the energy storage element for the electric spring.

III. Electric Springs and their Potential Applications in Future Power Grid

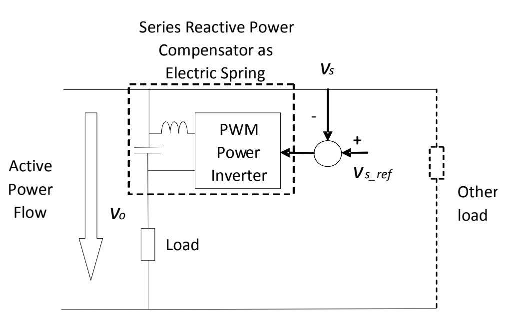

Fig.1 An electric spring setup based on an input-voltage control loop

Electric spring technology emerged in 2010 as a means of dynamic demand side management [15]. The basic principle is to include an input-voltage control loop in a grid-connected power inverter (Fig.1) to regulate the mains voltage and simultaneously enable variation of some of the loads to follow the intermittent nature of the renewable power generation. In the first version [16], the ES is connected in series with a non-critical load which can tolerate a certain range of mains voltage fluctuation (Fig.1). The first version of ES essentially uses the grid-connected power inverter as a reactive power compensator which can regulate the mains voltage in the presence of mains voltage fluctuation caused by the intermittent nature of renewable power generation.

The second version of ES incorporates an active energy source (i.e. battery) with the power inverter [15]. The full details of the steady-state analysis are reported in [17]. This version provides both active and reactive power compensation and therefore is advantageous for voltage and frequency stability in power grid.

This section summarizes functional features that have recently been reported.

A. Voltage regulation in power grid with intermittent power generation

In a typical power grid (e.g. a microgrid) with both traditional and renewable power generation (Fig.2), the intermittent power generation is a factor that can cause instability. A typical setup is reported in [16] which uses a power inverter to represent the conventional power plant and another power inverter with a recorded wind speed profile to emulate an intermittent renewable energy source. The intermittent power is injected into the mains. Fig.3 shows the measured mains voltage of this setup without and with the ES activated. The nominal main voltage is set at 220V. Before the ES is activated, the intermittent power causes voltage fluctuation in the first period from 0s to 720s. The wind profile is repeated in the second period from 720s to 1440s with the ES activated. The ES is successful in stabilizing the mains voltage in the presence of intermittent power injection. The dynamic variation of the ES voltage is also recorded in Fig.3. Thus electric spring action acts as a voltage suspension system for the mains voltage.

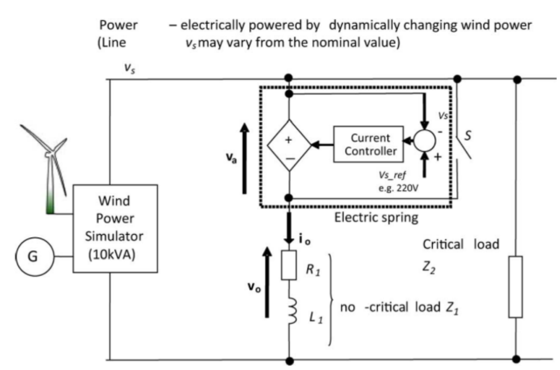

Fig.2 A typical experimental setup of a microgrid with traditional and renewable power generation [16]

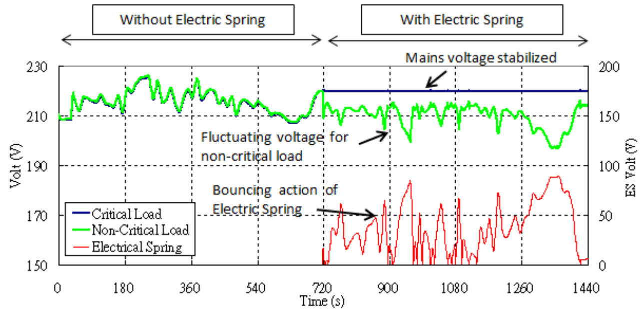

Fig.3 Experimental results of mains voltage in the setup with and without the ES

B. *Load demand following power generation*

An important feature of the ES is its automatic function to shape the non-critical load power to follow the profile of the power generation. This feature comes from the fact that, by keeping the mains voltage constant as its nominal value and allowing the output voltage of the electric spring (i.e. the voltage across the non-critical load) to fluctuate, the time-varying intermittent profile of the renewable power generation will be shifted to the power profile of the non-critical load, therefore achieving the new control paradigm of having the load demand following the power generation. Take the setup in Fig.2 as an example, the measured non-critical load power and critical load power are shown in Fig.4 with and without the ES. Before the ES is activated, the mains voltage fluctuates because of the intermittent power, so both critical and non-critical load power consumptions also fluctuate. Once the ES is enabled, the mains voltage is stable and so the power consumption of the passive critical load is also stable. The output voltage of the ES now fluctuates, leading to the fluctuating power of the passive non-critical load in the setup. Therefore, the ES can be used as a new demand-side management technique. It can be used together with supply-side management such as the risk-limiting dispatch principle [2] to achieve the new control paradigm where the load demand follows the power generation.

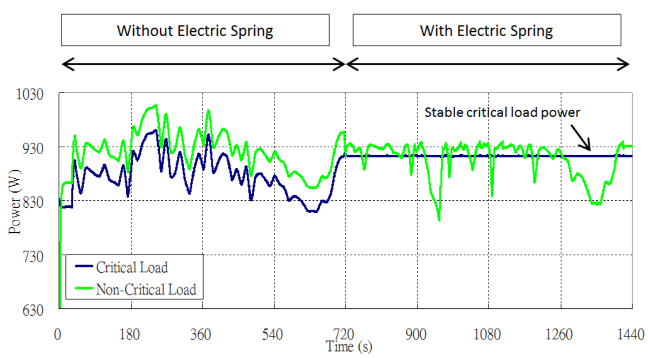

Fig.4 Power consumption of critical and non-critical loads.

C. *Reduction of energy storage*

Even though the ES allows the non-critical load power consumption to follow the time-varying profile of the power generation, it does not have unlimited capacity to do so. Therefore energy storage is still considered to be an essential part of future power grid. Fig.5 shows the schematic of a power grid with a bidirectional ac-dc power converter and an energy storage. Mathematical proof has been reported in [18] that the use of ES can ensure a reduction of energy storage because the ES allows the power consumption of the non-critical load to follow the power generation and therefore reducing the power imbalance of the power supply and demand. Fig.6 shows the measured total power, non-critical load power and battery power with and without ES. Before the ES is activated, the battery can act as an energy buffer to absorb or deliver energy so as to keep the mains voltage stable and therefore keep the non-critical load power constant. Note that the discharing (positive power) and charing (negative power) of the battery profile is just opposite the the fluctuation of the power generation. So the battery bears the full responsibility in balancing the difference of power supply and demand before the ES is used. After the ES is activated, it enables the non-critical load power to follow the power generation profile, thus reducing the power imbalance. Consequently, the charing and discharging power profile of the battery is significantly reduced. This feature of the ES is very important because the cost of battery is almost exponentially proportional to the battery capacity. The reduction of battery capacity implies that existing battery technology of medium and small capacities can play a realistic and practical role in maintaing power balance in power grid.

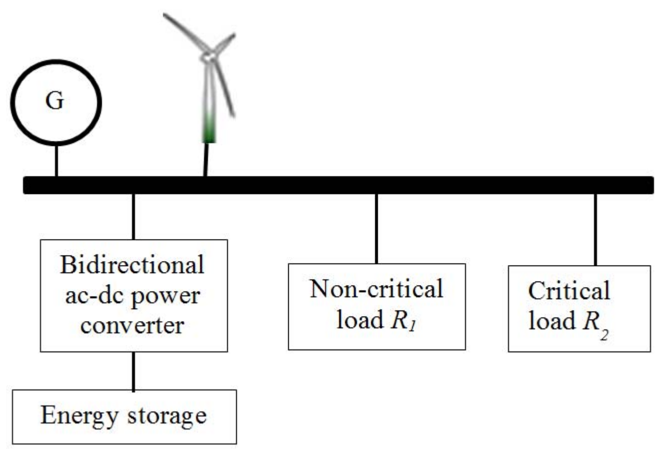

Fig.5 Schematic of a power grid

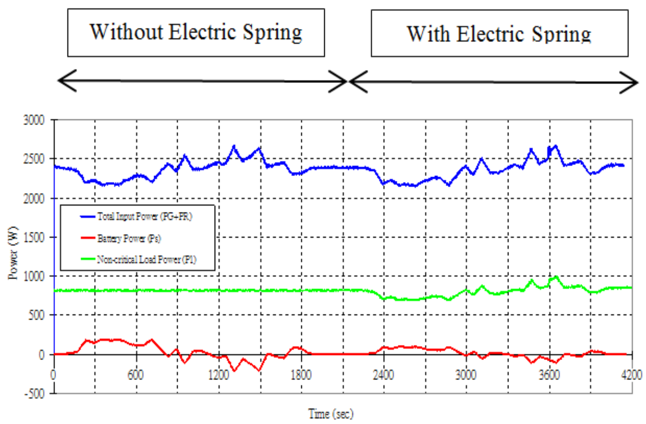

Fig.6 Measured total power (blue), non-critical load power (green) and battery power (red) with and without ES [18]

D. Use of Distributed ES with Droop Control

Normally, the mains voltage value varies within a certain tolerance and is not identical at every point along the distribution line. Fig.7 shows a typical voltage variation along a distribution line. To enable the distribution of ES over the distribution network, it is essential that each ES can be installed to support its location-dependent mains voltage. The droop control concept has been proposed in [19] to allow coordinated operation of multiple ESs. The droop control has the advantage of requiring local information only. Therefore, a large group of ESs can be installed in a distributed manner to provide stability support for the power grid. Fig.8 shows the block diagram of the droop control implementation in the control loop of the ES. The local voltage reference Vsx* depends on the local voltage Vsx at which the ES is installed and the nominal mains voltage Vs*. The reactive power compensation of the ES will regulate the local mains voltage at Vsx*.

The droop control has been demonstrated in [20] for a distribution line with three ESs. Fig.9 shows the measured reactive power compensation behaviors of three ESs distributed in the same power line with and without the droop control [20]. Without the droop control, the three ESs work against one another. With the droop control, they work in a cooperative manner. This important feature enables a large group of small ESs to work collectively without any requirements for communication among the ESs.

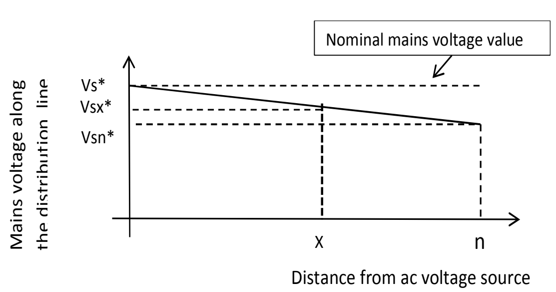

Fig. 7 Gradual reduction of mains voltage along a distribution line

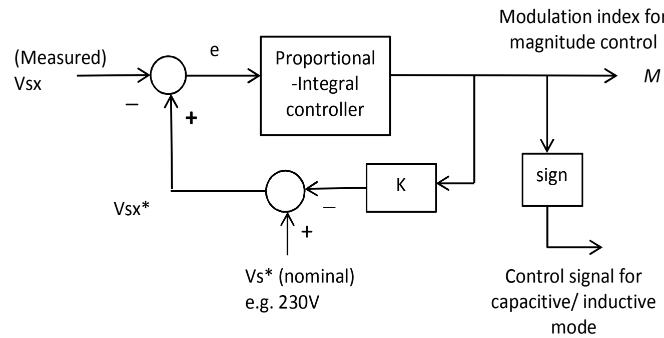

Fig.8 Proposed control scheme for providing an automatically adjustable reference voltage "Vsx_ref".

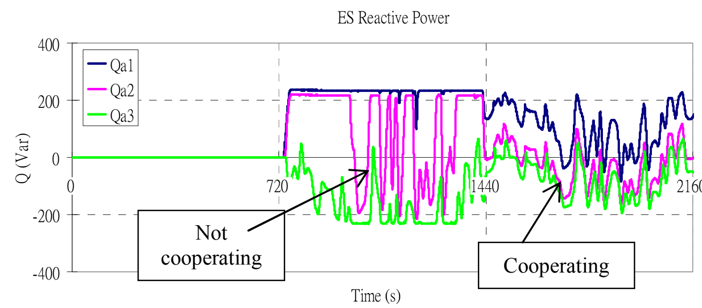

Fig.9 Measured average value of reactive power generated by the 3 electric springs (Q_{a1}, Q_{a2} and Q_{a3}) [20].

E. Use of ES with Active and Reactive Power Compensation

The functions of the ES can be substantially expanded if an active power source is incorporated into the power inverter [15] as shown in Fig.10. The ES can provide both active and reactive power compensation with eight possible operating modes [17] as follows:

1) inductive power (+jQes) compensation,
2) capacitive power (−jQes) compensation,
3) positive real power (+Pes) compensation,
4) negative real power (−Pes) compensation,
5) inductive plus positive real power (+jQes + Pes) compensation,
6) inductive plus negative real power (+jQes − Pes) compensation,
7) capacitive plus positive real power (−jQes + Pes) compensation;
8) capacitive plus negative real power (−jQes − Pes) compensation.

The capability of the ES to provide both active and reactive power compensation offers a new opportunity for the use of widely distributed ES to play a part in the voltage and frequency stability for the power grid, as well as power quality improvement for the electric loads. More research is needed to explore this potential for stability studies of power systems with large-scale renewable energy penetration.

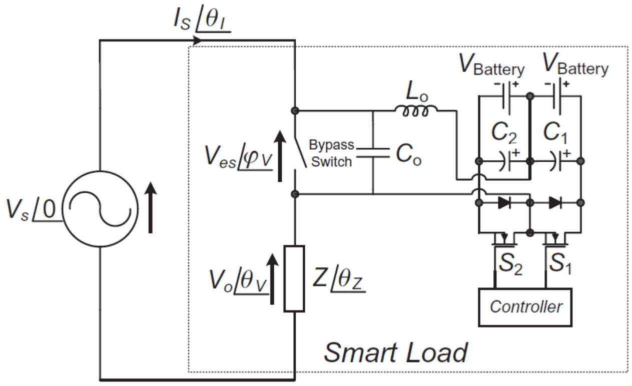

Fig.10 An electric spring with an active energy source [17]

IV. CONCLUSION

The intermittent nature of renewable power generation has been identified as a key factor that destabilizes power grid. Such instability problem is expected to deteriorate as the amount of intermittent renewable power generation increases. It must be stressed that power system stability must be considered for the design and control of grid-connected power inverters. In this paper, the recent research and development of the electric spring technology is summarized. The electric spring concept is proposed to tame the intermittent nature of renewable energy sources such as wind and solar power. It can be realized with the power electronics technology. The research conducted so far has confirmed several advantages of the ES such as voltage regulation, shaping the noncritical load demand to follow power generation profile, reduction of power supply and demand, reduction of energy storage, individual ESs working together without the help of information and communication technology and the possibility of providing both distributed voltage and frequency stability for power grid.

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