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# Electric Springs—A New Smart Grid Technology

Shu Yuen (Ron) Hui, *Fellow, IEEE*, Chi Kwan Lee, *Member, IEEE*, and Felix F. Wu, *Fellow, IEEE*

**Abstract**—The scientific principle of “mechanical springs” was described by the British physicist Robert Hooke in the 1660’s. Since then, there has not been any further development of the Hooke’s law in the electric regime. In this paper, this technological gap is filled by the development of “electric springs.” The scientific principle, the operating modes, the limitations, and the practical realization of the electric springs are reported. It is discovered that such novel concept has huge potential in stabilizing future power systems with substantial penetration of intermittent renewable energy sources. This concept has been successfully demonstrated in a practical power system setup fed by an ac power source with a fluctuating wind energy source. The electric spring is found to be effective in regulating the mains voltage despite the fluctuation caused by the intermittent nature of wind power. Electric appliances with the electric springs embedded can be turned into a new generation of smart loads, which have their power demand following the power generation profile. It is envisaged that electric springs, when distributed over the power grid, will offer a new form of power system stability solution that is independent of information and communication technology.

**Index Terms**—Distributed power systems, smart loads, stability.

## I. INTRODUCTION

A MECHANICAL spring is an elastic device that can be used to: i) provide mechanical support; ii) store mechanical energy; and iii) damp mechanical oscillations [1]–[4]. When a mechanical spring is compressed or stretched, the force it exerts is proportional to its change in displacement. Potential energy is stored in the mechanical spring when the length of the spring deviates from its natural length. The principle of the mechanical springs has been described by Robert Hooke in 1678 [5]. The Hooke’s law states that the force of an ideal mechanical spring is:

$$\mathbf{F} = -k\mathbf{x} \quad (1)$$

where  $\mathbf{F}$  is the force vector,  $k$  is the spring constant and  $\mathbf{x}$  is the displacement vector. The potential energy ( $PE$ ) stored in the mechanical spring is

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

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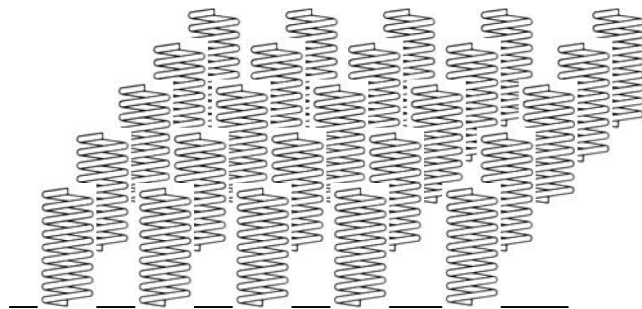


Fig. 1. An array of distributed mechanical springs (like those used in supporting a mattress).

Mechanical springs have been widely deployed in many daily applications such as suspension springs for beds and vehicles. The common use of mechanical springs in an array form, such as the spring support for a mattress as shown in Fig. 1, is a highly reliable mechanical support structure because it remains effective even if a few mechanical springs fail to function. Despite its significance, the mechanical spring concept has not been extended to the electric field for over three centuries.

In this paper, the practical realization of an electric spring is reported. The physics of an electric spring based on the Hooke’s law is first described. Then the operating modes, limitations, and practical implementation of the electric spring are explained. Finally, for the first time, the use of an electric spring for stabilizing the voltage of a power system fed by dynamically-changing wind energy is successfully demonstrated. It is discovered that electric spring has tremendous potential in mitigating stability problems of future power systems with substantial intermittent renewable energy sources.

## II. BASIC PRINCIPLES AND REALIZATION OF ELECTRIC SPRINGS

### A. Principles of Electric Spring

Analogous to a mechanical spring, an electric spring is an electric device that can be used to: i) provide electric voltage support; ii) store electric energy; and iii) damp electric oscillations. Analogous to equation-1, the basic physical relationship of the electric spring is expressed as

$$q = \begin{cases} C v_a & \text{inductive mode} \\ -C v_a & \text{capacitive mode} \end{cases} \quad (3)$$

$$q = \int i_c dt \quad (4)$$

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.

Equation (3) shows that dynamic voltage regulation (i.e., voltage boosting and reduction) functions of the electric spring can be controlled by the charge stored in the capacitor. Equation (4) indicates that the charge ( $q$ ) control can be realized by using

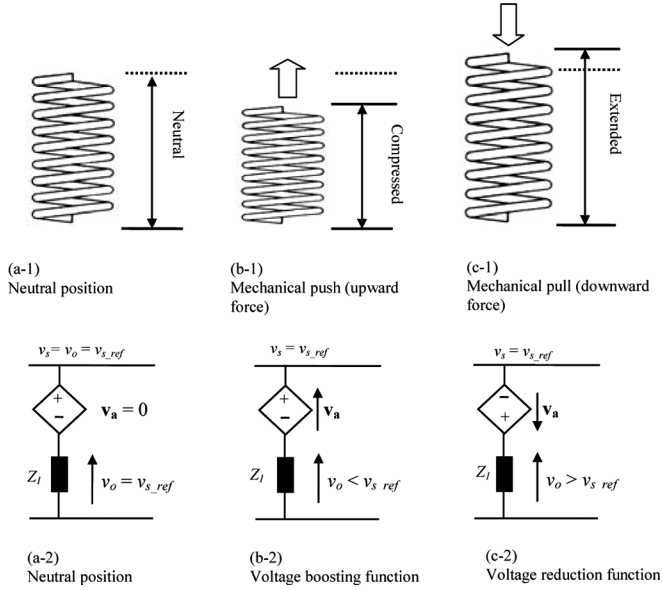


Fig. 2. Analogy of a mechanical spring and an electric spring.

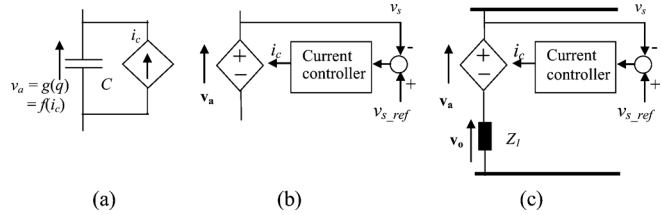


Fig. 3. (a) An electric spring in form of a capacitor fed by a controlled current source. (b) Schematic of an electric spring with input-voltage control. (c) An electric spring in series with a dissipative load for energy storage, voltage support, and damping.

a controlled current source. Therefore, an electric spring can be represented as a current-controlled voltage source [6]. An analogy of the mechanical spring and an electric spring under 3 conditions are illustrated in Fig. 2, in which an electric spring is connected in series with a dissipative electric load  $Z_1$ . The neutral position of an electric spring is a reference voltage at which the spring is designed to maintain. The series arrangement of the electric spring and  $Z_1$  across the ac mains is used to maintain the ac mains voltage  $v_s$  to its nominal reference level  $v_{s\_ref}$  (e.g., 220 V), which is considered as the neutral position. Similar to the mechanical spring that can develop mechanical force in either direction when the displacement is changed from the neutral position, an electric spring can provide voltage boosting and voltage reduction functions as illustrated in Fig. 2. The electric spring voltage  $v_a$  can be generated practically by dynamically controlling the electric potential difference across a capacitor  $C$  with a current source  $i_c$  [Fig. 3(a)] under a closed loop control [Fig. 3(b)]. The charge control in (3) provides a means to generate an electric voltage in both directions to boost or reduce the mains voltage in a power system. This control makes the dynamic voltage support function of the electric spring feasible.

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

$$PE = \frac{1}{2} C v_a^2 \quad (5)$$

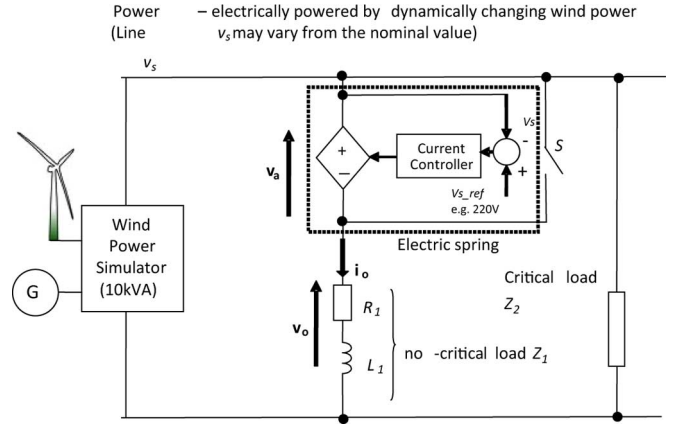


Fig. 4. Schematic of the experimental setup with an electric spring connected in series with a resistive-inductive load  $Z_1$ .

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

Since an electric spring should provide a function for damping electric oscillations, it is necessary to connect the lossless electric spring in series with a dissipative electric load (such as a water heating system or a refrigerator or a combination of them) as shown in Fig. 3(c). The use of the series-connected electric load  $Z_1$  is two-folded. Firstly, it provides a mechanism to dissipate electric energy for damping purpose. Secondly, it will be shown in the analysis that the voltage ( $v_o$ ) across the electric load  $Z_1$  and the electric spring voltage  $v_a$  can change in a special manner that the load power consumption of  $Z_1$  will follow the variation of the renewable power generation. This unique feature of the electric spring offers a new solution to supporting the mains voltage in future power systems with intermittent renewable energy source. The series connection with the load  $Z_1$  makes the electric spring behaves like a “voltage suspension,” analogous to the mechanical suspension spring [7] for a mechanical load (such as a vehicle).

The electric system in Fig. 4 is used to illustrate the concept and the operating limits of an electric spring. This system consists of an unstable ac power supply generated by a wind power simulator supplemented by an ac power source. Due to the intermittent nature of wind, the power generated will be dynamically changing and the ac voltage of the bus bar will vary with wind power. In this system, an electric spring is installed in series with an electric load  $Z_1$  as previously explained. Together, the electric spring and  $Z_1$  form a “smart load.” The dissipative load  $Z_1$  is termed a “noncritical” load because it can be operated at an ac voltage supply ( $v_o$ ) with some degree of voltage fluctuation. Examples of “noncritical” loads include electric water heaters, refrigerators, and lighting systems [27]. Generally, the electric load  $Z_1$  can be represented as an inductor  $L_1$  in series with a resistor  $R_1$ . Other electric load  $Z_2$  that requires a well-regulated mains voltage is termed a “critical” load.

The electric spring operation of (3) is essentially the dynamic control of an electric field in the capacitor. It can be realized with a simple closed-loop control using the nominal mains voltage  $v_{s\_ref}$  as the reference. By varying the energy stored in electric field of the capacitor in a sinusoidal manner with the objective of keeping the rms value of  $v_s$  equal to  $v_{s\_ref}$ , an alternating

electromotive force (e.m.f.) with controllable magnitude at the mains frequency can be generated across the capacitor as the electric spring voltage ( $v_a$ ). To ensure that this adjustable ac voltage source is lossless like an ideal mechanical spring, the vectors of  $\mathbf{v}_a$  and  $\mathbf{i}_o$  must be perpendicular. The current vector  $\mathbf{i}_o$  can either lead the voltage vector  $\mathbf{v}_a$  the by  $90^\circ$  (capacitive mode for voltage boosting) or lag  $\mathbf{v}_a$  by  $90^\circ$  (inductive mode for voltage reduction).

### B. Practical Implementation and Characteristics of Electric Spring

In electrical engineering term, this electric spring is a special form of reactive power controller. In the last two decades, power electronics based reactive power controllers (RPC) have been developed in power industry to control power flow in high-voltage transmission lines [8]–[17] and for dimming lighting systems [18], [19]. Their simplified control schematics are illustrated in Fig. 5(a) and 5(b), respectively. In these applications [8]–[19] of series RPC, the input of the RPC is always  $v_s$  and the output  $v_o$  is regulated to a constant level (i.e., a traditional “output-feedback and output-voltage control” of  $v_o$  is adopted). It is important to note that the electric spring differentiates itself from previous use of RPC with the adoption of an “input-feedback and input-voltage control” as shown in Fig. 5(c). By regulating the input voltage  $v_s$  and letting the output voltage  $v_o$  to fluctuate dynamically (i.e., a new input-voltage control), such RPC would: i) provide the voltage support as an electric spring and ii) simultaneously shape the load power to follow the available power generated by renewable energy source. Such subtle change in the control strategy of a RPC from output control to input control offers new features and functions for power and voltage control [26]. This new discovery provides the opportunity to apply the electric spring for balancing the instantaneous power of the load demand and the generated power [20], [21] for future smart grids with substantial renewable energy sources.

### III. OPERATIONS AND LIMITATIONS OF ELECTRIC SPRINGS

For a load that can be divided into two parts: a noncritical load  $Z_1$  and a critical load  $Z_2$ , as in Fig. 4. By connecting an electric spring in series with the noncritical load, we can ensure that the voltage and power at the critical load to remain constant when the line voltage feeding the load fluctuates. Such an arrangement of load will be called “smart load.” The aim of the electric spring in the application example of Fig. 4 is to restore  $v_s$  to the nominal value of the mains voltage  $v_{s\_ref}$  at the location of the device installation. Let  $P_{in}$  be the dynamically-changing input power. The general power balance equation for the system in Fig. 4 is

$$\begin{aligned} P_{in} &= \left(\frac{v_o}{Z_1}\right)^2 \text{Re}(Z_1) + \left(\frac{v_s}{Z_2}\right)^2 \text{Re}(Z_2) \\ P_{in} &= P_1 + P_2 \end{aligned} \quad (6)$$

where  $v_o$  and  $v_s$  are the root-mean-square values of the noncritical load voltage and the ac mains voltage, respectively;  $\text{Re}(Z)$  is the real part of  $Z$  that represents the resistive element  $R$ .  $Z_1$  is

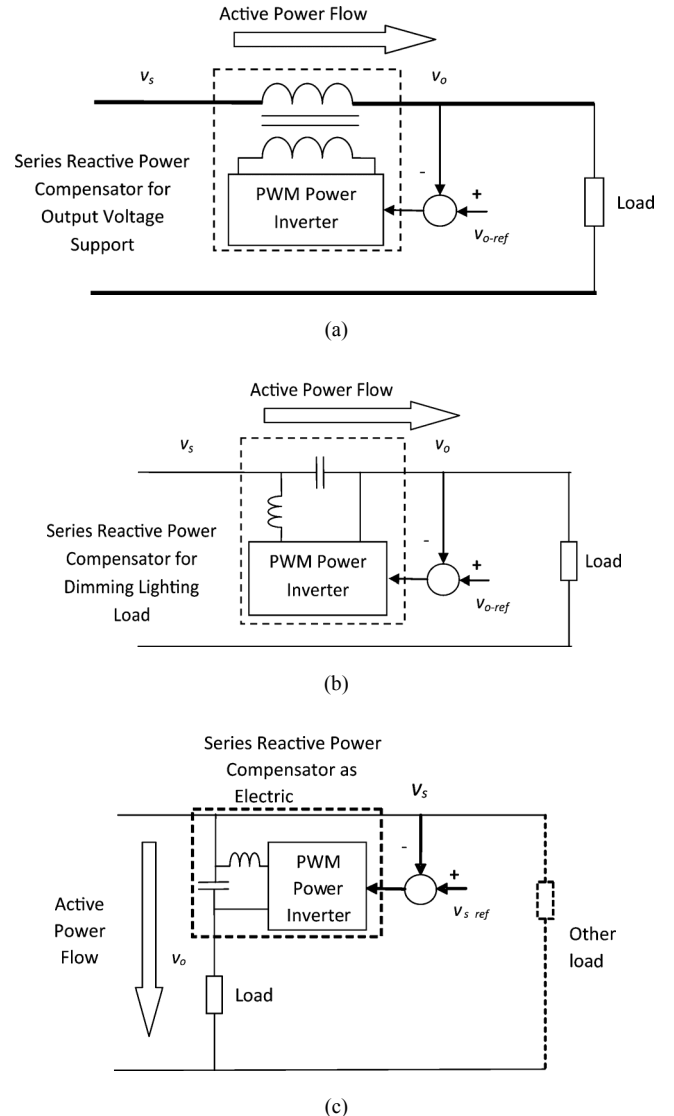


Fig. 5. (a) Simplified control schematic of series reactive power compensator for output voltage support in transmission ( $v_o$  regulated) [9]–[15]. (b) Simplified control schematic of series reactive power compensator as a central dimming systems ( $v_o$  regulated) [18], [19]. (c) Simplified control schematic of series reactive power compensator as an electric spring ( $v_s$  regulated).

the impedance of the “noncritical” load and  $Z_2$  is the impedance of the “critical” load.

The vector equation for the electric spring is

$$\mathbf{v}_o = \mathbf{v}_s - \mathbf{v}_a. \quad (7)$$

Equation (6) shows that, if the mains voltage is regulated by the electric spring at the nominal value  $v_{s\_ref}$ , the second power term  $P_2$  should remain constant for the critical load. If the power generated  $P_{in}$  cannot meet the full power for both  $P_1$  and  $P_2$ , the input-voltage control of the electric spring will generate a voltage vector  $\mathbf{v}_a$  to keep  $\mathbf{v}_s$  regulated at  $\mathbf{v}_{s\_ref}$ . From (7), the voltage vector  $\mathbf{v}_o$  across  $Z_1$  will be reduced and so the power consumption ( $P_1$ ) of  $Z_1$  will also be reduced. Therefore, if the electric spring performs well,  $P_2$  for the critical load should remain constant as expected and  $P_1$  for the noncritical load should follow the power generation profile.

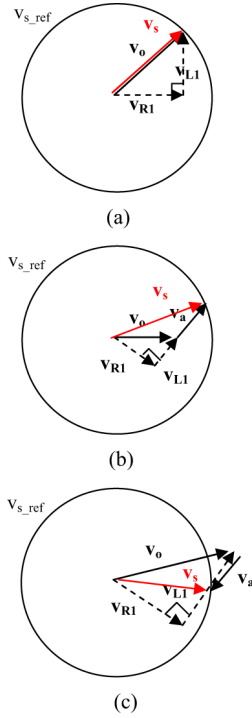


Fig. 6. Operating modes of the electric spring to maintain  $v_s$  to  $v_{s\_ref}$  for a noncritical load comprising a resistive-inductive load. (a) Neutral ( $v_a = 0$ ). (b) Inductive mode (noncritical load power reduction for voltage boosting). (c) Capacitive mode (noncritical load power boosting for voltage reduction).

This explanation becomes obvious if  $Z_1$  and  $Z_2$  are considered as pure resistive loads  $R_1$  and  $R_2$  respectively. The scalar (6) will become

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

$$P_{in} = P_1 + P_2. \tag{8}$$

If  $v_s$  is kept constant by the electric spring, the only variable on the right-hand side of (8) is the electric spring voltage  $v_a$ . Critical load power  $P_2$  is a constant. The variation of  $v_a$  will reduce  $P_1$  so that the sum of  $P_1$  and  $P_2$  will follow the profile of  $P_{in}$ . In other words, the electric spring allows the load power consumption to automatically follow the power generation—which is the new control paradigm required by future power systems with substantial intermittent renewable energy sources [20], [21].

Like a mechanical spring which cannot be extended beyond a certain displacement, electric spring also has its operating limits. Fig. 6(a)–6(c) shows the vector diagrams of the system (Fig. 4) with the electric spring under three operating modes for a noncritical load comprising an inductive-resistive load (e.g., a lighting load). The circle in the vector diagram represents the nominal value of the mains voltage  $v_{s\_ref}$  (e.g., 220 V). The vectors are assumed to rotate in an anticlockwise direction at the mains frequency (e.g., 50 Hz). Fig. 6(a) depicts the situation when the electric spring is in a “neutral” position in which  $v_a = 0$ . This refers to the situation that the power generated by the renewable power source (such as a wind farm) is sufficient to meet the load demand and simultaneously maintain  $v_s$  at the nominal value of  $v_{s\_ref}$ . Fig. 6(b) represents the situation when power reduction in  $Z_1$  is needed in order to keep  $v_s$  at  $v_{s\_ref}$ .

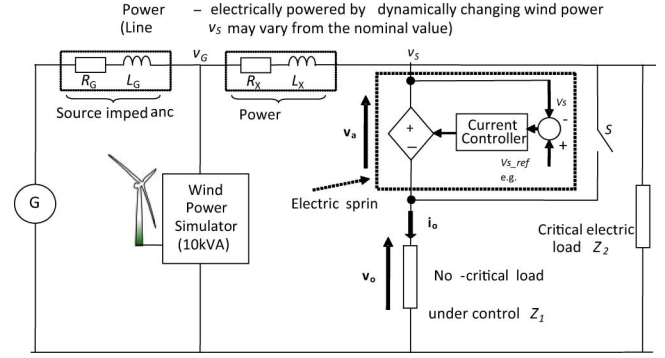


Fig. 7. Schematic of an electric power system with an electric spring connected in series with a dissipative electric load  $Z_1$ .

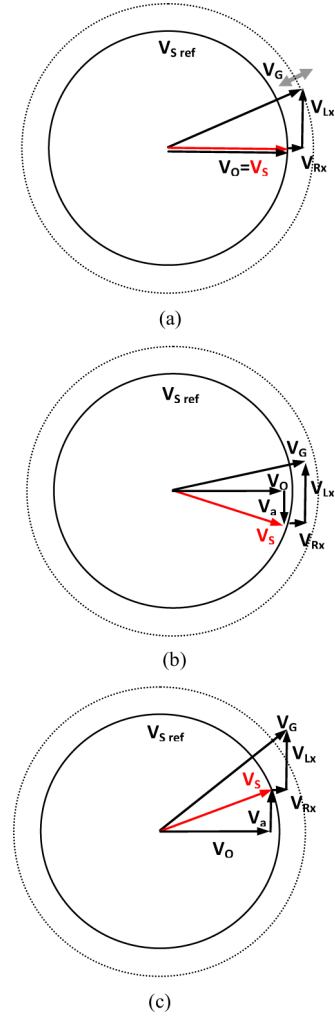


Fig. 8. Operating modes of the electric spring to maintain  $v_s$  to  $v_{s\_ref}$  for a resistive noncritical load in a power system with source impedance of a network box. (a) Neutral  $v_a = 0$ . (b) Capacitive mode. (c) Inductive mode.

Here  $v_a$  is positive (making  $v_o$  less than  $v_{s\_ref}$ ) in order to provide the “power reduction” function under the inductive mode of the electric spring.

If the generated power is higher than the load demand,  $v_s$  will exceed  $v_{s\_ref}$ , resulting in an over-voltage situation. In order to regulate  $v_s$  at  $v_{s\_ref}$ , Fig. 6(c) shows that the electric spring can provide “power boosting” function by operating under the capacitive mode. Here  $v_o$  is increased, with respect to its value in Fig. 6(b), in order that the load  $Z_1$  can consume more power

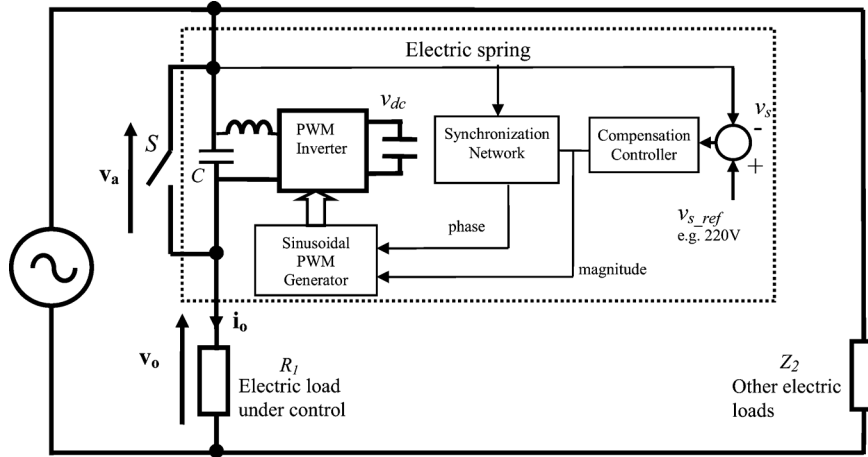


Fig. 9. The experimental setup for the electric spring (with control block diagram).

generated by the renewable energy source to keep the power balance. The scalar equation for electric spring voltage vector  $v_a$  under the capacitive mode [Fig. 6(b)] and inductive mode [Fig. 6(c)] is given in (9).

$$v_a = \begin{cases} -v_c & \text{for capacitive mode} \\ +v_c & \text{for inductive mode} \end{cases} \quad (9)$$

where  $v_c$  is the voltage of the filter capacitor of the power inverter.

In a power system context, analysis of the electric spring can be carried out for other types of noncritical loads such as a water heater (i.e., a resistive load). Fig. 7 shows a modified experimental setup in a power system including the source impedance of the power supply and power cable. Due to the presence of the impedance of the network box, the voltage at the generator side is labeled as  $V_G$  and the mains voltage at which the electric spring is located is labeled as  $V_s$ . The operating modes are illustrated in Fig. 8(a)–8(c). It has been demonstrated in Fig. 4 that a smart load, when operated in a stand-alone mode, maintains constant voltage and power for the critical part of the load. When a smart load is connected to a power distribution system as in the case of Fig. 7, interactions between the system impedance and the smart load, as well as the voltage and power characteristics of the power supply, will affect the performance of the smart load. Due to the injection of both real and reactive power from distributed power sources in future smart grid, the electric springs can be operated dynamically under neutral, capacitive or inductive mode with the objective of regulating the mains voltage.

#### IV. PRACTICAL EVALUATION

In order to practically evaluate the performance and operating modes of the proposed electric springs, 3 different experiments have been set up at the Maurice Hancock Smart Energy Laboratory at Imperial College. a) The first test is to power the electric spring with its series-connected electric load using a standard ac power source so that the performance of each operating mode can be examined. The electric spring voltage and current are measured under the three operating modes. b) The second test is to program the electric spring with power reduction function and test it in the setup of Fig. 4. An unstable power source is created in the form of a wind power simulator, which is formed by

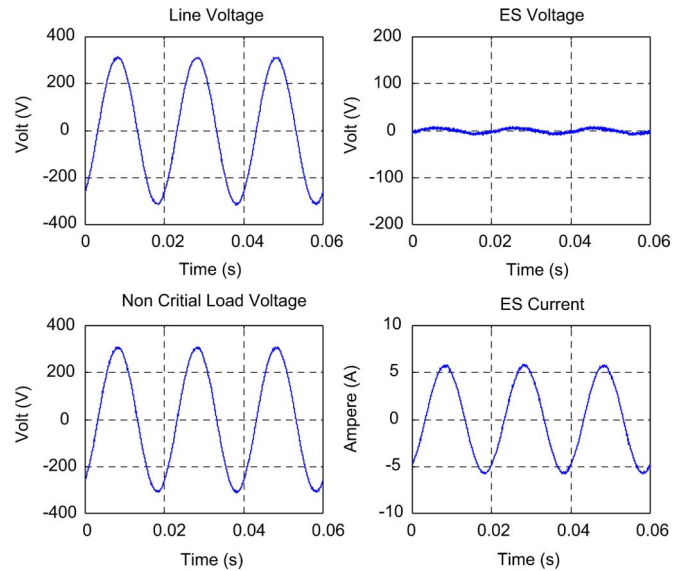


Fig. 10. Measured steady-state electric spring waveforms under “neutral” mode.  $V_a = 4.5$  Vac,  $Q_{ES} = 17.5$  Var. [Electric spring voltage is near zero.]

generating electric power by a power inverter following a pre-recorded wind speed profile and a base power profile of the ac generator. The purpose is to check the voltage support capability of the electric springs and also the relationship of the intermittent renewable power (from the wind power simulator) and the load consumptions in the noncritical and critical loads. c) The last test is to check the performance of the electric spring in a power system setting as shown in Fig. 7. In this case, both voltage boosting and voltage suppression operations are evaluated.

#### A. Operation of an Electric Spring as a Novel Smart-Grid Device

Fig. 9 shows the practical setup of the first test. Using the input voltage control method, the voltage error is fed to a compensation controller which generates the magnitude control signal for the sinusoidal PWM generator. Via a synchronization network, a phase control signal is also fed to the sinusoidal PWM generator, which in turn provides the gating signals for the power inverter. The PWM voltage output of the inverter is filtered by the low-pass LC filter so that the electric spring voltage is sinusoidal. The phase control signal ensures that the

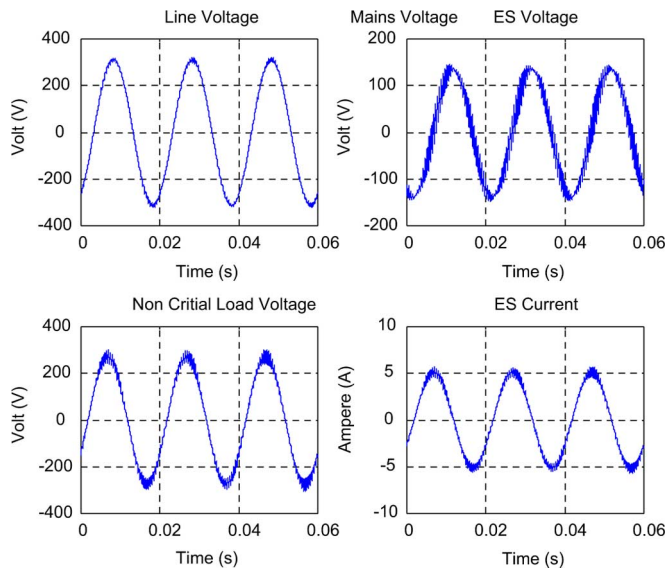


Fig. 11. Measured steady-state electric spring waveforms under “capacitive” mode.  $V_a = 97.9$  Vac,  $Q_{ES} = -349.9$  Var.

electric spring current is either leading or lagging the electric spring voltage by  $90^\circ$ . The test conditions are  $V_s = 220$  V (50 Hz),  $R_1 = 51.4 \Omega$ .

When the electric spring (ES) is operated near the neutral position, the measured waveforms of the mains voltage ( $v_s$ ), noncritical load voltage ( $v_o$ ), the ES voltage ( $v_a$ ), and the ES current (same as the noncritical load current) are recorded and shown in Fig. 10. In this case,  $v_o$  is essentially equal to  $v_s$  as the  $v_a$  is only 4 V rms for a 220 V mains. Fig. 11 shows the corresponding waveforms when the ES is operated in the capacitive mode. It can be observed that the ES current leads ES voltage. Here negative reactive power is provided by the ES and  $v_o$  is smaller than  $v_s$ . Then the ES is operated in the inductive mode and the corresponding waveforms are shown in Fig. 12. It can be seen that the ES current can be controlled to lag the ES voltage. Under the inductive mode, the ES injects positive reactive power into the system to provide voltage support.

### B. Operation of an Electric Spring in an Unstable Power Grid fed by Intermittent Renewable Power (a Demonstration of Load Demand Following Power Generation and Voltage Support)

Fig. 13(a) shows the second practical setup for a three phase system. The per-phase schematic is illustrated in Fig. 13(b). The electric spring is programmed with the voltage support function. The intermittent renewable power source is created by the power inverter which generates power according to a prerecorded intermittent wind profile and the base power profile of 1.2 kW. A prerecorded wind profile of 30 minutes (1800 s) with the based power is fed to a power inverter to generate a weakly regulated ac mains voltage pattern in the bus bar. Both the smart load and the critical load are connected across the power lines. After a 5-min interval of programmed voltage at 220 V as a separation (from 1800 s to 2100 s), the same 30-min wind-driven voltage pattern was repeated from 2400 s. The electric spring of the smart load is deactivated in the first voltage pattern by

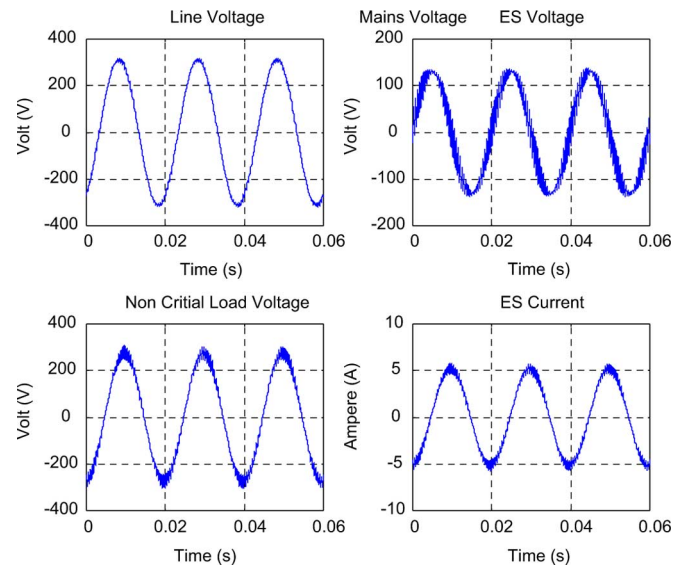
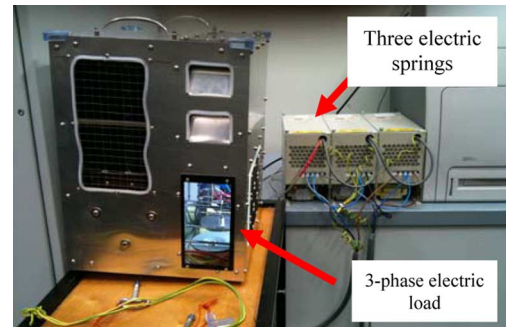
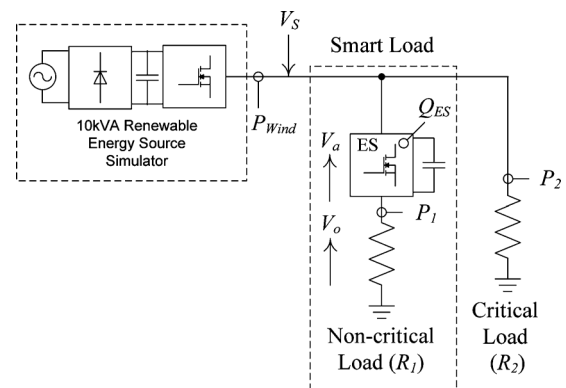


Fig. 12. Measured steady-state electric spring waveforms under “inductive” mode.  $V_a = 94.3$  Vac,  $Q_{ES} = 348.4$  Var.



(a)



(b)

Fig. 13. (a) A photograph of the experimental setup with a three-phase electric load (consisting of a combination of resistors and lighting loads) and three electric springs (one for each phase). (b) Schematic of a practical implementation of a wind power driven electric power grid to demonstrate the power balancing using electric spring.

closing the bypass switch  $S$  and then activated in the second pattern with  $S$  open.

According to (7), the vector of  $\mathbf{v}_s$  is equal to the vectorial sum of  $\mathbf{v}_o$  and  $\mathbf{v}_a$ . Fig. 14 shows the measurements of the (scalar) rms values of the mains voltage  $v_s$ , the noncritical load voltage  $v_o$  and the voltage of the electric spring  $v_a$  before and after the

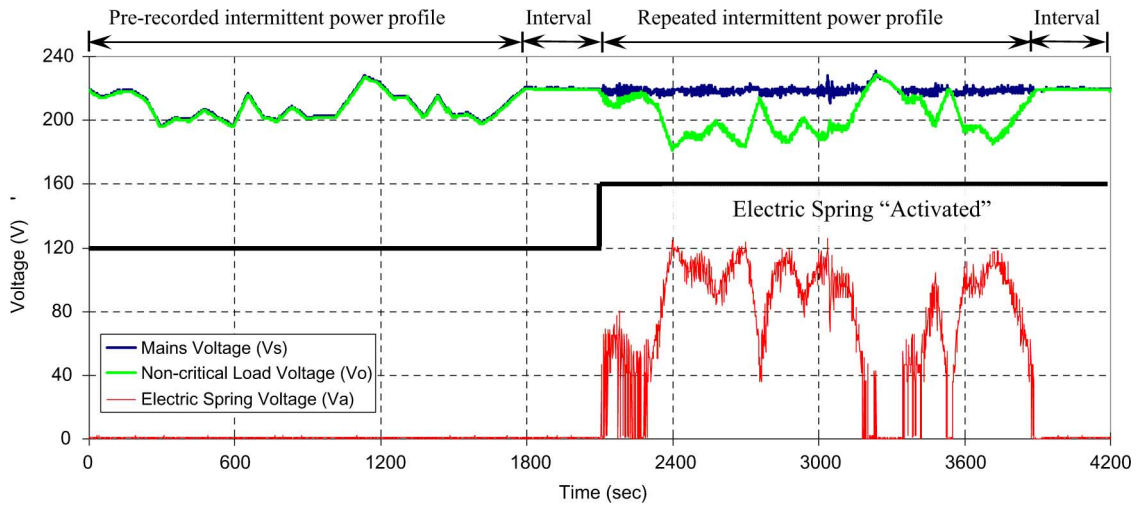


Fig. 14. Measured root-mean-square values of the mains voltage  $v_s$ , noncritical load voltage  $v_o$  and electric spring voltage  $v_a$  before and after the electric spring is activated. [Electric spring is programmed for voltage boosting function only.]

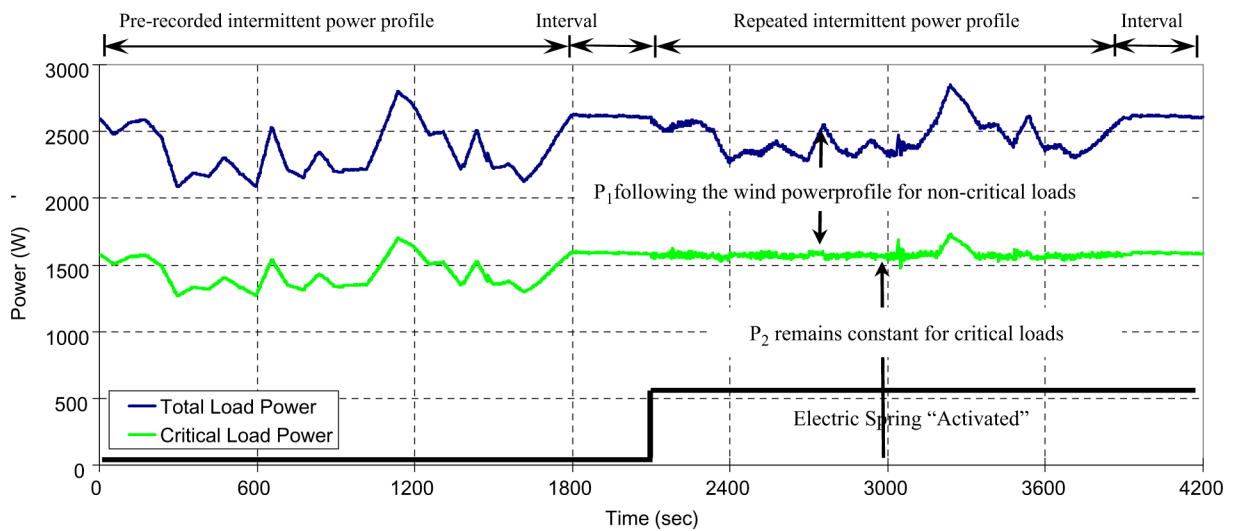


Fig. 15. Measured power of the critical load and noncritical loads [Electric spring is programmed for voltage boosting function only.]

electric spring is activated. Before the electric spring takes action in the first half of the test, the mains voltage fluctuates in the region below the rated value of 220 V in this study. Because the bypass switch  $S$  is closed when the electric spring is deactivated, the noncritical load voltage  $v_o$  overlaps with the unstable mains voltage  $v_s$  in the first voltage pattern generated by the wind power simulator. However, it can be seen that, when the electric spring is activated in the repeated voltage pattern in the second half of the test, the mains voltage can be successfully boosted or supported to 220 V.

The bouncing action of the electric spring voltage can be seen from Fig. 14. The electric spring acts like a “voltage suspension spring” to maintain a constant mains voltage. It is noted that when the noncritical load voltage  $v_o$  reaches 220 V (i.e., no voltage support is needed), the electric spring voltage  $v_a$  drops to zero. The noncritical load voltage  $v_o$  is reduced when the electric spring generates positive voltage to support the mains voltage. The consequential variation of  $v_o$  provides an automatic mechanism to shape the load demand to follow the dynamic changes of the wind power profile. This effect can be observed from the practical power measurements of the smart

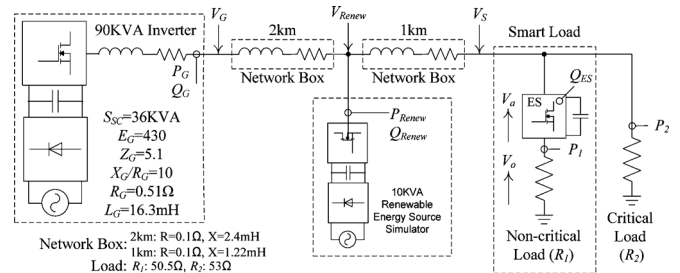


Fig. 16. Schematic of a practical implementation of an electric spring in series with an electric load  $Z_1$ .

load unit in Fig. 15. After the electric spring is activated, the noncritical load demand  $P_1$  varies with the wind power profile while the demand of other loads  $P_2$  remains essentially the same. This result demonstrates the effectiveness of the electric spring in both voltage support and shaping the load demand to follow the wind power. These measurements confirm the scientific theory and the effectiveness of the electric spring in supporting the mains voltage of an unstable power system and in balancing the wind power and the load power dynamically.



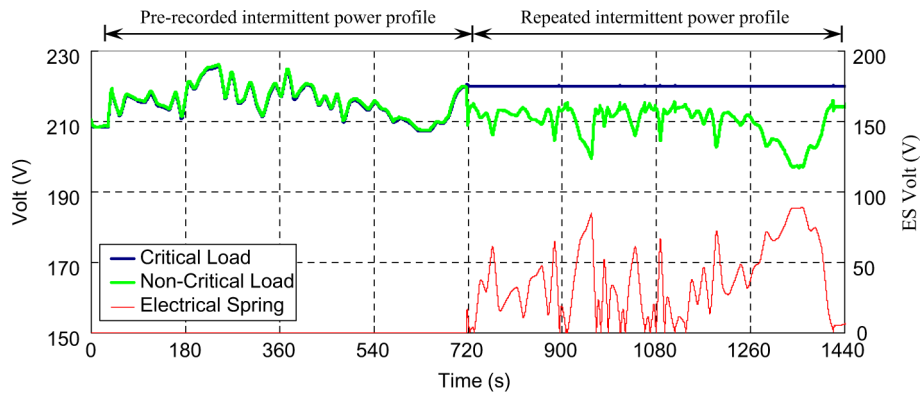


Fig. 17. Measured root-mean-square values of the critical load (mains) voltage  $v_s$ , noncritical load load voltage  $v_o$  and electric spring voltage  $v_a$  before and after the electric spring is activated. [Electric spring is programmed for both voltage boosting and suppression functions.]

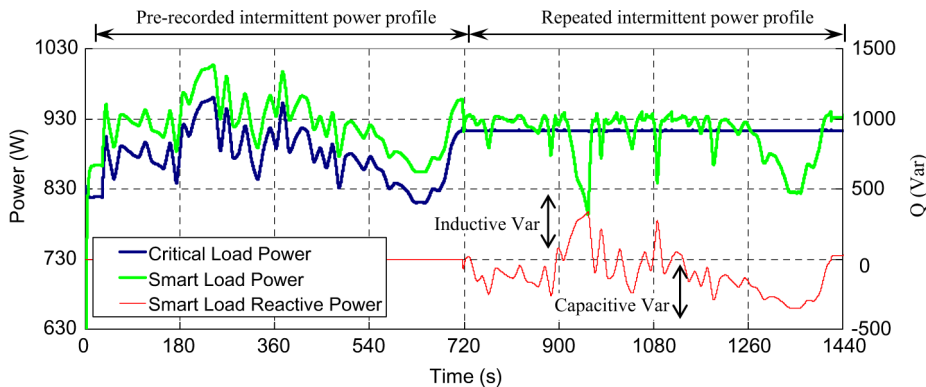


Fig. 18. Measured power of the critical load and smart load. [Electric spring is programmed for both voltage boosting and suppression functions.]

### C. Test of Electric Spring in a Power System With Intermittent Renewable Power Injection (a Demonstration of Dynamic Voltage Regulation via Reactive Power Compensation and Automatic Noncritical Load Shedding)

A smart load unit comprising a combination of resistors (representing water heaters) has been setup. Two power sources separated by a transmission network box are used in this test. The experimental setup is shown in Fig. 16. An ac voltage source (provided by a 90 kVA sinusoidal PWM power inverter) and an intermittent renewable voltage source (provided by a 10 kVA power inverter) are used together to simulate the situation when intermittent renewable power becomes a substantial portion of the total power generation. In order to simulate the wind power generation, a recorded wind profile is used for the power inverter to generate the wind power.

Since the electric spring is tested in the distribution network, the choice of the line impedance to resistance (X/R) ratio should reflect the value used for distribution cables. For distribution lines, the typical ratio of reactance and resistance (X/R) is typically in the range from 2 to 8 [28]. It should be noted that the cables under consideration are those used in the overhead cables linking houses from one to the other in streets (e.g in the distribution network of the residential area in Australia). For a modest 150 A (240 V) overhead distribution copper cable, a typical phase size of 500 should be chosen. According to [29], copper cable with a phase size of 500 has a line impedance  $X = 0.1202 \Omega$  and resistance  $R = 0.0247 \Omega$  per 1000 ft. The X/R ratio is about 4.87 (which is within the typical range of 2 to

8 for a distribution cable). In this test, the two transmission network boxes have X/R ratios of 7.5 and 3.8 respectively. These ratios are within the typical range for distribution cables in [28].

A prerecorded wind profile of 12 min (720 s) is fed to a power inverter to generate a weakly regulated ac mains voltage pattern in the bus bar. Both the smart load and the critical load are connected across the power lines. The same 12-min wind-driven voltage pattern was repeated from 720 s to 1440 s. The electric spring of the smart load is deactivated in the first voltage pattern by closing the bypass switch  $S$  and then activated in the second pattern with  $S$  open.

Fig. 17 shows the measurements of the (scalar) rms values of the critical load (mains) voltage  $v_s$ , the noncritical load voltage  $v_o$  and the voltage of the electric spring  $v_a$  before and after the electric spring is activated. Before the electric spring takes action in the first half of the test, the mains voltage fluctuates in the region below and above the rated value of 220 V. Because the bypass switch  $S$  is closed when the electric spring is deactivated, the noncritical load voltage  $v_o$  overlaps with the unstable mains voltage  $v_s$  in the first voltage pattern generated by the wind power simulator. However, it can be seen that, when the electric spring is activated in the repeated voltage pattern in the second half of the test, the mains voltage can be successfully regulated to 220 V.

The bouncing action of the electric spring voltage can be seen from Fig. 17. It is noted that the noncritical load voltage  $v_o$  is reduced when the electric spring generates positive or negative voltage to regulate the mains voltage. The consequential variation of  $v_o$  provides an automatic noncritical load power

shedding and generates reactive power to follow the dynamic changes of the wind power profile. This effect can be observed from the practical power measurements of the smart load unit in Fig. 18. After the electric spring is activated, the load demand of the noncritical load is shed and the reactive power is generated to follow the unstable mains voltage  $v_s$  whilst the demand of critical loads remains essentially the same. This result demonstrates the effectiveness of the electric spring in both voltage regulation and shaping the load demand to follow the wind power. These measurements confirm the scientific theory and the effectiveness of the electric spring in regulating the mains voltage of an unstable power system and in balancing the wind power and the load power dynamically.

## V. CONCLUSIONS

The Hooke's law on mechanical springs has been developed into an electric spring concept with new scientific applications for modern society. The scientific principles, operating modes and limits of the electric spring are explained. An electric spring has been practically tested for both voltage support and suppression, and for shaping load demand (of about 2.5 kW) to follow the fluctuating wind power profile in a 10 kVA power system fed by an ac power source and a wind power simulator. The electric springs can be incorporated into many existing noncritical electric loads such as water heaters and road lighting systems [26] to form a new generation of smart loads that are adaptive to the power grid. If many noncritical loads are equipped with such electric springs and distributed over the power grid, these electric springs (similar to the spring array in Fig. 1) will provide a highly reliable and effective solution for distributed energy storage, voltage regulation and damping functions for future power systems. Such stability measures are also independent of information and communication technology (ICT).

This discovery based on the three-century-old Hooke's law offers a practical solution to the new control paradigm that the load demand should follow the power generation in future power grid with substantial renewable energy sources. Unlike traditional reactive power compensation methods, electric springs offer both reactive power compensation and real power variation in the noncritical loads. With many countries determined to de-carbonize electric power generation for reducing global warming by increasing renewable energy up to 20% of the total electrical power output by 2020 [22]–[25], electric spring is a novel concept that enables human society to use renewable energy as nature provides. The Hooke's law developed in the 17th century has laid down the foundation for stability control of renewable power systems in the 21st century.

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