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Hardware and Control Implementation of Electric Springs for Stabilizing Future Smart Grid With Intermittent Renewable Energy Sources

Chi Kwan Lee, Member, IEEE, Balarko Chaudhuri, Senior Member, IEEE, and Shu Yuen Hui, Fellow, IEEE

Abstract—In this paper, the details of practical circuit and control implementation of an electric spring for reactive power compensation and voltage regulation of the ac mains are presented. With Hooke’s law published three centuries ago, power electronics-based reactive power controllers are turned into electric springs (ESs) for regulating the ac mains of a power grid. The proposed ES has inherent advantages of: 1) ensuring dynamic load demand to follow intermittent power generation; and 2) being able to regulate the voltage in the distribution network of the power grid where numerous small-scale intermittent renewable power sources are connected. Therefore, it offers a solution to solve the voltage fluctuation problems for future power grids with substantial penetration of intermittent renewable energy sources without relying on information and communication technology. The proof-of-concept hardware is successfully built and demonstrated in a 10-kVA power system fed by wind energy for improving power system stability. The ES is found to be effective in supporting the mains voltage, despite the fluctuations caused by the intermittent nature of wind power.

Index Terms—Inverter, power smoothing, renewable energy sources, smart grids.

I. INTRODUCTION

WITH many countries setting new legislations to decarbonize power generation by 20% by 2020 [1]–[3], the use of renewable energy generation has become a global research and development topic. The imminent increase in intermittent and distributed renewable power sources, known or unknown to the utility companies, has raised concerns about the stability of future power grid with substantial renewable power generation. In existing power systems, power is generated by the power companies in a centralized manner to meet the load demand, that is, power generation follows the load demand. For future smart grids with heavy penetration of intermittent and distributed renewable power sources, the new requirement of control paradigm will be for the load demand to follow power generation [4], [5]. This new requirement has triggered new research into modern demand-side management.

So far, recent research activities focused on several demand-side management approaches to fulfill the new control paradigm. Literature review for the period of 2005–2012 showed that demand-side management approaches to fulfill the new control paradigm [6] can be broadly summarized as follows: 1) scheduling of delay-tolerant power demand tasks [7]–[9]; 2) use of energy storage to alleviate peak demands [10]; 3) real-time pricing [11]–[13]; 4) direct load control or on–off control of smart loads [14]–[16].

Although these methods have their own advantages, they also suffer certain inherent limitations. Scheduling of load demand can be done in terms of days or hours, but such method cannot cope with real-time power fluctuation. Energy storage is an ideal solution, but it is either expensive (such as battery) or not geographically available (such as water reservoirs). Real-time pricing can play a certain role and is effective for some price-conscious large customers, but it may not be applicable to ordinary domestic consumers. Traditionally, power companies use direct load control to shed power loads for avoiding power system collapse, but such central control may not be effective for future power grid with substantial decentralized and intermittent renewable energy sources at the distribution networks. On–Off control of electric loads such as water heaters and air conditioners has been proposed, but such approach could be intrusive and cause inconvenience to the consumers. Recent research based on wide-area measurements for feeding information to a data center for central and regional controls has been examined. Data transfer is usually based on information and communication technology (ITC), such as wireless communications, satellite synchronization, and internet/intranet control. This approach should be effective under normal operating conditions, but may be paralyzed when the wireless communications systems are disabled in extreme weather or atmospheric conditions (such as strong solar storms) and/or when the internet is hacked.

In this paper, a new approach to demand-side management based on the electric spring (ES) concept is described. ESs are reactive power controllers [17], [25] that can be embedded in noncritical loads such as electric water heaters,
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air conditioners, and lighting systems and turned them into a new form of smart loads. They provide reactive power compensation for voltage regulation of ac mains of the power grid. Because of the distributed nature of installations, they provide local voltage support over the distribution network of the power grid. They have an inherent advantageous feature that they can ensure the load demand to automatically follow the power generation profile in real time, without reliance on ICT, smart metering or wide-area measurements. The original concept was described in [25]. Subsequent research led to the theoretical framework of the ES concept, which had the potential to control both active and reactive power [26] and reduce energy storage requirements in a power grid [27]. This is the first paper that covers the detailed practical hardware design and control implementation of an ES for voltage regulation of distribution line. It is tested in a power grid fed by an intermittent wind power profile. Its abilities in stabilizing a fluctuating ac mains and shaping the load demand to follow the wind power profile are demonstrated. The differences among the ESs, static var compensation (SVC) and static synchronous compensator (STATCOM) are also included.

II. Operating Principle of ES

A. From Mechanical Springs to ESs

Hooke’s law [18] states that the force of an ideal mechanical spring is as follows:

\[ F = -kx \]  

(1)

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 as follows:

\[ PE = \frac{1}{2}kx^2. \]  

(2)

Analogous to a mechanical spring, an ES is an electric device that can be used to: 1) provide electric voltage support; 2) store electric energy; and 3) damp electric oscillations. Analogous to (1), the basic physical relationship of the ES is expressed as [25] follows:

\[ q = -Cv_a \]  

(3)

\[ q = \int i_c dt \]  

(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. The energy storage capability of the ES can be seen from the potential electric energy stored in the ES is as follows:

\[ PE = \frac{1}{2}Cv_a^2. \]  

(5)

Therefore, the capacitor \( C \) serves as the energy storage element for the ES. Equation (4) shows that the charge (\( q \)) can be altered using a controlled current source. Therefore, the bouncing action of the ES can be practically realized with the use of power electronics-based reactive power controller. Comparisons of the formats of (1) and (3), and those of (2) and (5) highlight the similarities between the mechanical spring and ESs [25].

![Fig. 1. Simplified connection diagram of an ES.](image1)

![Fig. 2. Vectors diagrams of ES operates under (a) inductive mode and (b) capacitive mode with an inductive load.](image2)

B. Operating Principle of ESs

As an ES should provide a function for damping electric oscillations, it is necessary to connect the lossless ES in series with a dissipative electric load (such as a water heating system or a refrigerator or a combination of them). Fig. 1 shows a simplified connection diagram of an ES. The output of the ES is connected to a noncritical load to form a smart load [25]. The noncritical load can be a single or a group of electric loads that can tolerate some degrees of voltage variation without causing significant inconvenience to the user. Examples are electric water heaters and some public lighting systems. For reactive power compensation, the ES only processes the reactive power and the compensation voltage vector \( V_a \) is perpendicular to the noncritical load current \( I_o \). Therefore, it generates either inductive or capacitive reactive power to the power system. Unlike traditional FACT devices such as SVC and STATCOM that handle pure reactive power only, the ES is a new smart-grid device that can alter both active and reactive power. Although its structure resembles a static synchronous series compensator (SSSC) [19]–[21], it differentiates itself from a SSSC by the following: 1) employing an input voltage control rather than an output voltage control; and 2) having the ability to alter the active and reactive power in the series-connected noncritical load.

The vectors diagrams of an ES operated under inductive and capacitive modes with an inductive load are shown in Fig. 2. The vectorial sum of the noncritical load voltage \( V_o \)
and the compensation voltage \( V_a \) is equal to the supply voltage \( V_S \). With the observation of the vector diagrams, \( V_o \) can be boosted or suppressed by \( V_a \) which is generated by the ES. Therefore, the power consumption of the noncritical load can be controlled. Mathematically, the mains voltage \( V_S \) of the power line and the ES operated under inductive or capacitive mode can be expressed as follows:

\[
V_S^2 = (V_o \cos \phi)^2 + (V_o \sin \phi \pm V_a)^2
\]

where \( \phi \) is the power factor angle of the noncritical load. The vector direction of the compensation voltage \( V_a \) under the inductive mode [Fig. 2(a)] and the capacitive mode [Fig. 2(b)] is given in (7) as follows:

\[
V_o = \begin{cases} 
+V_o & \text{inductive mode} \\
-V_o & \text{capacitive mode}.
\end{cases}
\]

Solving (6), the noncritical load voltage \( V_o \) can be expressed as (8) as follows:

\[
V_o = \frac{-2V_o \sin \phi \pm \sqrt{(2V_o \sin \phi)^2 - 4(V_a^2 - V_S^2)}}{2}
\]

\[
= -V_o \sin \phi + \sqrt{V_o^2 \sin^2 \phi - V_a^2 + V_S^2}
\]

(taking the positive root).

The corresponding noncritical load current \( I_o \), active and reactive power \( P_S, Q_S \) of the entire smart load can be analytically obtained as follows:

\[
I_o = \frac{V_o}{Z_1} = \frac{V_o}{\sqrt{R_1^2 + X_1^2}}
\]

\[
P_S = V_o I_o \cos \phi = \frac{V_o^2 \cos \phi}{Z_1}
\]

\[
Q_S = V_o I_o \sin \phi + V_a I_o = \frac{V_o^2 \sin \phi + V_o V_a}{Z_1}
\]

where \( Z_1 \) is the impedance of the noncritical load. The characteristic of the noncritical load \( V_o \) (normalized to the rated mains voltage \( V_S \)) against the compensation voltage \( V_a \) at different power factor angles is plotted in Fig. 3. The active power \( P_S \) and reactive power \( Q_S \) characteristics normalized to the rated power are plotted in Figs. 4 and 5, respectively.

Depending on the power factor of the noncritical load, the ES can, in principle, perform active and/or reactive power controls (which make it fundamentally different from traditional FACT devices such as SVC and STATCOM) [26]. For instance, the change of compensation voltage \( V_a \) can simultaneously provides reactive power compensation and load shedding to the power system when the power factor of the noncritical load is close to unity. Generally, the active power consumption can be altered when an ES is connected to a load with nonunity power factor. With the use of input voltage \( V_i \) control mechanism and letting the noncritical load voltage \( V_o \) to fluctuate dynamically, the ES can be a useful apparatus for shaping the load demand to follow the electric power generation. This important feature of an ES can improve the instantaneous power balance, power quality, and stability of the future electric power grid with high penetration of intermittent renewable energy sources in real time.

III. PRACTICAL IMPLEMENTATION

A. Power Inverter Circuit

A variety of power inverter topologies such as single-phase, three-phase, and two-level or multilevel inverters [22], [23]
can be used to implement an ES. Fig. 6 shows the power inverter circuit of an ES that is practically implemented by a single-phase half-bridge power inverter. To observe the performance changes of the power system with and without an ES installation, a mechanical bypass switch is connected across the output terminals during the experiments. A sinusoidal pulsewidth-modulated (PWM) control signal is generated by the control circuit to provide the gating signals for the power switches. Thus, a turn-on snubber should be included to overcome the problem. In this ES prototype, an Undeland snubber is used. It includes the turn-off overvoltage and turn-on over-current protections for the power inverter. The PWM voltage output of the inverter is filtered by the low-pass LC filter hence the compensation voltage is sinusoidal. In a PWM inverter, the power switches could suffer from the high turn-on loss because of the high recovery current generated from the freewheeling diodes and the turn-off snubber capacitors. Thus, a turn-on snubber is included to overcome the problem. In this ES prototype, the ES can be substantially improved. The detail specifications of the power inverter prototype are summarized in Table I.

B. Control Circuit

It is important to note the differences between the proposed ES and other traditional reactive power compensation methods such as SSSC and dynamic voltage restorer. Traditional reactive power compensators: 1) use the output-voltage control for regulating the output voltage of the reactive power converters; and 2) handle reactive power only. ESs: 1) adopt input-power control for regulating the input voltage of the reactive power converters; and 2) provide additional load shedding functions (i.e., real power control) for the noncritical load.

The control of the ES differentiates itself from the traditional SSSC using output-voltage control method. With the input-voltage control mechanism, an ES regulates the mains voltage $V_s$ (which is the input voltage of the reactive power controller) by controlling the power flow to the noncritical load and allows the noncritical load voltage $V_{nl}$ (which is the output voltage of the reactive power controller) to fluctuate dynamically. This means that the output voltage of the ES is not dynamically regulated. The noncritical load power is shaped simultaneously to follow the available power generated by the power system. Therefore, it is a new demand-side management method that can satisfy the new control paradigm of having the load demand following the power generation.

A simplified control block diagram of the ES is shown in Fig. 7. The ES requires two closed-loop controllers to operate. With the analysis in Section II, the reactive power is directly shaped simultaneously to follow the available power generated by the power system. Therefore, it is a new demand-side management method that can satisfy the new control paradigm of having the load demand following the power generation.

Fig. 6. Schematic of a single-phase half-bridge power inverter.

### TABLE I

<table>
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<th>ES Specifications</th>
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<tr>
<td><strong>Electric Spring Power Circuit</strong></td>
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<tr>
<td><strong>Inverter Topology:</strong></td>
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<tr>
<td><strong>Switching Frequency:</strong></td>
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<tr>
<td><strong>Regulated DC-Bus Voltage:</strong></td>
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<tr>
<td><strong>DC Bus Capacitance:</strong></td>
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<tr>
<td><strong>Inverter Output Voltage Range:</strong></td>
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<tr>
<td><strong>Power MOSFET:</strong></td>
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<tr>
<td><strong>Typical $R_{DSS}$:</strong></td>
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<tr>
<td><strong>Output Low Pass Filter:</strong></td>
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<tr>
<td>Measured Inductance:</td>
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<tr>
<td>Measured Equivalent Series Resistance:</td>
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<tr>
<td>Capacitance:</td>
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Fig. 7. Simplified control block diagram of an ES for reactive power compensation.

\[ M = \begin{cases} + \text{ inductive mode} \\
- \text{ capacitive mode} \end{cases} \]

Fig. 8. Relationship of the phase angle and active power consumption.

### TABLE II

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<th>ES SPECIFICATIONS</th>
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<tr>
<td><strong>NI Embedded Controller</strong></td>
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<tr>
<td><strong>Switching Scheme:</strong> Sinusoidal PWM</td>
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<tr>
<td><strong>Minimum to Maximum Modulation Index:</strong> 0.05 – 0.95</td>
</tr>
<tr>
<td><strong>Proportional and Integral Controller</strong></td>
</tr>
<tr>
<td><strong>Sampling Time (T_s)</strong></td>
</tr>
<tr>
<td><strong>Proportional Gain (K_p)</strong></td>
</tr>
<tr>
<td><strong>Integral Gain (K_i / T_s)</strong></td>
</tr>
<tr>
<td>AC line voltage: 20ms</td>
</tr>
<tr>
<td>DC bus voltage: 20ms</td>
</tr>
<tr>
<td>Proportional Gain (K_p): 30</td>
</tr>
<tr>
<td>Integral Gain (K_i / T_s): 5</td>
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The corresponding control parameters are summarized in Table II. The experimental results of the control loop response are recorded in Figs. 11–14.

### IV. EXPERIMENTAL SETUP

Fig. 9(a) shows a photograph of the smart-grid experimental setup in the Maurice Hancock Smart Energy Laboratory at Imperial College London. The photograph of the ES prototype and the controller is shown in Fig. 9(b). The experimental setup for evaluating the response of the ES under a weakly regulated power grid is shown in Fig. 10. A 90-kVA power inverter controlled by a digital signal processor is used to emulate a traditional electric power substation. The electric energy is transferred through the distribution network to a remote location, which is represented by the noncritical and critical load resistors. As an example, half of the loads in the remote location are equipped with ESs. A 10-kVA power inverter is used to emulate an intermittent renewable energy source. With the use of the instantaneous \( P - Q \) theory, the output active and reactive power \((P_R, Q_R)\) of the renewable energy source can be controlled to inject or absorb active and reactive power. Therefore, the power line voltage \( V_S \) is fluctuating around the nominal mains voltage value of 220 Vac because of the intermittent nature of the wind power. The detailed specifications of the power grid are summarized in Table III. A computer-based measurement and data acquisition system is developed to record the instantaneous voltage and current at different nodes of the power grid for recording the information of the active and reactive power flows.

This paper examines the capability of an ES (connected in series with a noncritical load) in improving voltage stability of a power grid with unstable mains voltage caused by the intermittent renewable power source. The ES, connected in series with a resistive load is programmed specifically to provide reactive power compensation for mains voltage regulation. Two sets of experiments are carried out with different levels of active or reactive power fluctuation generated by the renewable energy source simulator. The simulator is programmed to
follow a prerecorded wind power profile that repeats itself in every 360 s. During this experiment, the ES is deactivated in the first pattern (360 s) by closing the mechanical bypass switch. Afterward, it is activated in the second pattern with the bypass switch open. Therefore, the behavior of the power grid with and without ES installation can be observed and compared. The measured mains voltage $V_S$, noncritical load voltage $V_o$, ES reactive power $Q_S$, and noncritical load and critical load power ($P_{R1}$, $P_{R2}$) because of the reactive power changes in the power grid are plotted in Figs. 15–17. Similarly, the experimental results of the change of active power generation are shown in Figs. 18–20.

V. PRACTICAL RESULTS AND DISCUSSION

A. Response of ES Control Loop

Fig. 11 shows the measured step response waveforms of the ES operating from the capacitive mode to the inductive mode. The change of the control signal $M$ (i.e., the inverter modulation index) from $-1$ to $+1$ signifies the instant of the mode change. For reactive power compensation, the ES generates a compensation voltage $V_a$ that is 90° lagging behind the noncritical load current $I_o$ in the capacitive mode. In the inductive mode, $V_a$ is leading $I_o$ by 90°. The sampling time of the ac line voltage controller is 20 ms. The step response waveforms of ES operating from the inductive mode to the capacitive mode are recorded in Fig. 12. The vectors of $V_a$ and $I_o$ are consistently perpendicular in the reactive power compensation for regulating the mains voltage.

The time responses of the dc bus voltage controller in the capacitive and inductive modes are recorded in Figs. 13 and 14, respectively. When real power is absorbed into the dc
capacitor of the inverter, the vectors of \( V_s \) and \( I_o \) will deviate from their perpendicular relationship temporarily. This transient behavior can be observed indirectly from the control signal \( \theta \), which is also captured to explain the operation. When \( v_o \) is zero in the first 200 ms of Fig. 13(a), the initial \( \theta \) is 270° in the capacitive mode. When \( v_o \) is zero, \( V_s \) and \( I_o \) are in phase for the pure resistive noncritical load. As \( \theta \) is the angle between \( V_s \) and \( V_a \), the vectors of \( V_o \) and \( I_o \) are perpendicular. After the initial 200 ms, the ES comes into action. The dc bus is increased (by transferring energy into the dc capacitor) for providing the ES voltage \( v_o \). It can be seen that \( \theta \) now deviates from its initial value of 270° to 300° and then gradually settles down to ~300°. The steady value of \( \theta \) in Fig. 13(a) is not 270° because the ES acting as an equivalent capacitor in series with the resistive noncritical load will change the angle between \( V_s \) and \( I_o \). \( V_s \) and \( I_o \) are no longer in phase because of the presence of the equivalent capacitive of the ES working in the capacitive mode. The enlarged waveforms at the initial state and steady state of the step response in Fig. 13(a) are shown in Fig. 13(b). In the initial state, the spring voltage and current are in phase as real power is being transferred to charge the dc capacitor. Under steady-state condition (when the dc capacitor is fully charged to 200 V), \( V_o \) lags behind \( I_o \) by 90° and the function of the ES for reactive power compensation continues.

The smart load reactive power and the voltage across the noncritical load are shown in Fig. 16(a) and (b), respectively. The ES reduces the voltage of the noncritical load \( V_o \) and generates reactive power \( Q_s \) to the power system simultaneously. With the observation of the measured mains voltage and smart-load reactive power data, the ES generates positive (inductive) reactive power to suppress the mains voltage. If voltage support is required, the ES generates negative (capacitive) reactive power to the power grid. Therefore, the noncritical load power \( P_{R1} \) is automatically adjusted and the critical load power \( P_{R2} \) is kept constant, as shown in Fig. 17(a) and (b), respectively. These results confirm the successful operations of the input voltage control mechanism and the voltage regulation capability of the ES.

C. Response of ES to the Active Power Changes

To further examine the effectiveness of the ES in a power grid with high-penetration intermittent wind energy, the
Fig. 17. Measured (a) noncritical load power $P_{R1}$ and (b) critical load power $P_{R2}$ before and after the ES is activated. A repeated reactive power profile of 360 s is fed to the power grid [see Fig. 9(a)]. ES is programmed to activate from 360 to 720 s.

Fig. 18. (a) Prerecorded active power profile $P_2$ injected to the power grid using the 10-kVA renewable energy simulator. (b) Measured rms values of the mains voltage $V_s$ before and after the ES is activated. ES is programmed to activate from 360 to 720 s.

Fig. 19. Measured (a) reactive power of the smart load $Q_s$ and (b) rms values of the noncritical load voltage $V_{o1}$ before and after the ES is activated. A repeated active power profile of 360 s is fed to the power grid [see Fig. 12(a)]. ES is programmed to activate from 360 to 720 s.

Renewable energy source simulator is programmed to simulate a dynamically fluctuating wind power generator. Fig. 18(a) shows the prerecorded wind power profile of 360 s. Note that the maximum wind power is 1500 W. The penetration is up to 80% of the total load power demand (1872 W). Therefore, the electric power from the traditional power substation is only a small portion of total load demand. Because of the stochastic nature of wind speed, the output power, however, can be dramatically dropped to a very low value. Without energy storage system installed in the power grid, the high dynamic changes of wind power lead to instability in the power grid. In Fig. 18(b), the mains voltage $V_s$ is fluctuating in the region above and below the rated value of 220 Vac in the first half of the test when the ES is not in action.

Same as the previous test, the profile is repeated after 360 s and ES is activated. From the period of 360–720 s, the ES generates positive or negative reactive power to the power grid to regulate the mains voltage at 220 Vac successfully. In Fig. 19(a) and (b), the noncritical load voltage is reduced and the reactive power generated from the ES is following the mains voltage fluctuation. The noncritical and critical load power profiles are measured and shown in Fig. 20(a) and (b), respectively. The critical load power remains essentially the same. These results confirm the effectiveness of using ES to improve power system stability with high penetration of intermittent renewable energy source.

D. On the Reactive Power (kVA) Rating

In this experimental prototype (for demonstration purpose), the kVA rating is ~0.58 kVA. The kVA rating of an ES is the product of the variable voltage range of the ES and the rated current of the series-connected load. In this implementation example, the ES voltage range (Table I) is arbitrarily chosen at 134 V and the noncritical load current is 4.36 A (i.e., 220 V/50.5 Ω). The noncritical load voltage can be reduced to ~170 V, as shown in Fig. 19(b). The reactive power rating of an ES, however, could be much smaller in practice. ESs are supposed to be embedded in a new generation of smart loads that are adaptive to substantial mains voltage fluctuations. Examples of such smart loads include electric water heaters, refrigerators, and some public lighting systems. These types of smart loads (and their embedded ESs) will be distributed over the distribution power network as shown in Fig. 21. If the noncritical load voltage is to be reduced to not <200 V, for the same experimental setup, the ES voltage variation is reduced.
to −90 V, indicating that the kVA rating will be reduced from 0.58 to −0.39 kVA. Although individual ESs could have small kVA ratings, it is the collective efforts of many distributed ESs that would provide the distributed voltage support for the power grid.

VI. Conclusion

This paper describes the hardware and control implementation of an ES to form a smart load unit. The control method for the ES for reactive power compensation and mains voltage regulation was proposed and realized by a digital controller. The performance of the ES was analyzed and practically evaluated in a 90-kVA electric power grid. The voltage fluctuation of the power grid was created by a 10-kVA renewable energy source simulator. A prerecorded power profile was programmed into the simulator to create a weakly regulated power grid. It is found that the ES can automatically perform voltage support, suppression, and load-shedding functions in response to the dynamic needs of the power grid. It is envisaged that ES can be a useful apparatus for the stability control of future smart grid with substantial penetration of intermittent renewable energy sources. The significance of this ES-based stability control lies in the fact that these ESs can be distributed all over the power grid for decentralized stability control without any dependence on ITC, smart metering, and wide-area power management. It is a new methodology that can turn many noncritical loads into a new generation of smart loads that have their load demands automatically following power generation—which is the new control paradigm required for future power grid with distributed renewable power sources. The next stage of our research will include cost and performance comparison of ESs with other real-time demand-side management methods.

Acknowledgment

The authors would like to thank the Maurice Hancock Smart Energy Laboratory of Imperial College, London, U.K., for providing the facilities for testing the ESs.

References

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