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Load-side Demand Management in Buildings using Controlled Electric Springs

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***Abstract*—With increasing use of renewable energy and the advancements in smart grids, demand side management has been a keen topic of interest. Buildings, both commercial and residential, have great potential in implementing load-side demand management in renewable energy source powered microgrids. Electric Spring, a smart grid technology, is able to provide instantaneous voltage support and load power shedding. Thus, providing an astute solution to the voltage instability problem associated with such microgrids. In this paper, an implementation of electric spring is presented, in conjunction with building loads like central air conditioning system, to demonstrate its properties of voltage support, load power shedding, and reactive power compensation.**

Keywords—electric springs; demand management; building energy efficiency; renewable energy sources; smart grids; microgrids; inverters.

I. INTRODUCTION

Many countries including Singapore are vigorously moving towards creating a sustainable environment, by increasing the reliance for power on Renewable Energy Sources (RES) such as solar, wind etc. [1]. With abundance of high rise buildings, Singapore plans to implement large scale solar test beds in 30 precincts, and reduce its energy intensity (per dollar GDP) by 35% from 2005 levels by 2030 [2, 3]. USA also plans to increase share of renewable energy to 20% by 2020 [4]. Unpredictable and intermittent nature of RES along with their expected high penetration in grids and microgrids may pose problems of voltage instability.

A new concept of Electric Spring (ES) was introduced in [5, 6] to provide dynamic voltage regulation. A paradigm shift in reactive power compensation was implemented with “input-feedback and input voltage control” compared to the traditional aspect of “output-feedback and output voltage control”. It was demonstrated in [7] that the energy storage requirements were reduced in former scheme in comparison to the latter. The authors also proposed embedding of ES in existing non-critical loads, such as electric heaters, so as to develop smart loads to dynamically regulate power to critical loads.

With buildings using around 40% of total electricity in many countries and to reduce their energy footprint, they seem a logical focus point to incorporate electric springs [8, 9]. Energy usage of buildings in Singapore is illustrated in Fig. 1 [10]. As air conditioning accounts for 50% of energy usage in a building, the central air conditioning system can be used as a non-critical load for a whole commercial building.

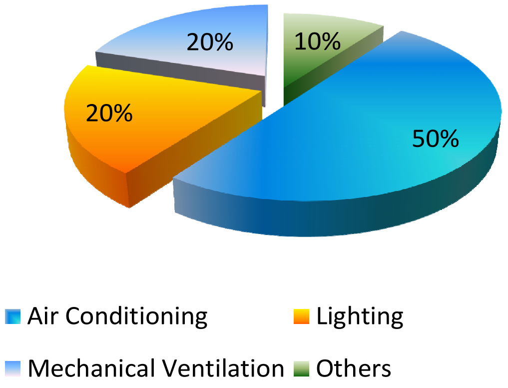

Fig. 1. Breakdown of energy consumption within a building (Singapore)

In this paper, the basic principles of operation of an ES are explained in Section II. To augment the existing research, an Electric Spring implemented through a full bridge pulse width modulation (PWM) based inverter is proposed and explained in Section III. Further, it is tested on MATLAB® *Simulink* platform and demonstrated how an ES can help in shaping reactive and active power and provide instantaneous voltage support in Section IV. The ES is attached to a substantial single non-critical load, like central air-conditioning system, so to create smart load which follow renewable power generation. Such a system can be attached directly to existing facilities without encroaching on costumer comfort. A full bridge PWM inverter can deliver twice the power of a half bridge inverter topology employed in [11] and also the number of capacitors used is reduced to one. Another advantage with this scheme is elimination of even order harmonics, thus improving power quality and reducing harmonic losses.

II. BASIC PRINCIPLES OF ELECTRIC SPRING OPERATION

A. Analogy of Mechanical Spring with the Electric Spring

A mechanical spring can generate force, governed by Hooke’s Law [12], given by (1) and stores potential energy equal to (2).

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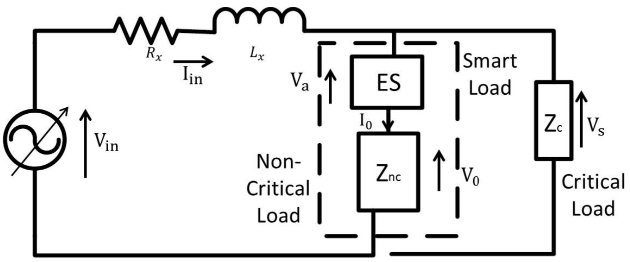

Fig. 2. Overview of ES in series with a non-critical load in a circuit

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

$$\mathrm{PE} = \frac{1}{2}k\mathrm{x}^2 \tag{2}$$

where **F** is the force vector, *k* is the spring constant and **x** is the displacement vector. An analogy is derived to introduce the concept of electric spring, which would be able to: 1) provide voltage support; 2) store energy; and 3) damp electric oscillations [13]. Thus, the equations analogous to (1) and (2) become as follows:

$$q = \begin{cases} Cv \\ -Cv \end{cases} \tag{3}$$

$$\mathrm{PE} = \frac{1}{2}Cv^2 \tag{4}$$

Voltage v of capacitor can be controlled by controlling charge q through it, which in turn can be controlled by current i_c through it, as shown by (5). Thus, an Electric Spring can be realized in a circuit with current-controlled voltage source [5].

$$q = \int i_c dt \tag{5}$$

B. Operating principles of an Electric Spring

An electric spring is an ingenious device, which can be installed in series with non-critical load(s), like a central air-conditioning system, which can bear voltage fluctuation in a renewable energy based microgrid, as illustrated in Fig. 2. This series connection is utilized to maintain voltage at device installation $\mathbf{V_s}$ to the reference value $\mathbf{V_{s\_ref}}$. As shown in Fig. 2 the critical load is attached in parallel to the smart load comprising of ES and non-critical load, and the voltage across it is $\mathbf{V_s}$. Also, ES can be utilized for both active and reactive power compensation [14].

For an ES to be lossless, the compensation voltage vector $\mathbf{V_a}$ has to be perpendicular to the noncritical load current $\mathbf{I_o}$ (Fig. 2). This means for a resistive-inductive load $\mathbf{V_a}$ should be leading $\mathbf{I_o}$ by 90° and gives capacitive compensation and vice-versa for an inductive compensation. It is illustrated through vector diagrams in Fig. 3. The phasor sum of the noncritical load voltage $\mathbf{V_o}$ and the compensation voltage $\mathbf{V_a}$ is equal to the voltage at device installation $\mathbf{V_s}$. In steady-state condition, vector equation for voltage can be written as:

$$\mathbf{V_s} = \mathbf{V_o} + \mathbf{V_a} \tag{6}$$

When the rms voltage across the critical load V_s is less than the reference rms voltage V_{s_ref} (230 Volts), the ES boosts it up instantaneously to the reference value, by adjusting the voltage across the non-critical load $\mathbf{V_o}$. Similarly, if the rms voltage V_s exceeds the reference voltage the ES will suppress it to the reference value V_{s_ref}, by allowing non-critical load voltage to vary dynamically. In other words, ES will manipulate the current $\mathbf{I_0}$ and in turn $\mathbf{I_{in}}$ in the circuit, of Fig. 2, such that (7) is maintained.

$$\mathbf{V_{in}} - \mathbf{I_{in}}\,(\mathrm{R_x} + \mathrm{j\omega L_x}) = \mathbf{V_s} = \mathbf{V_{s\_ref}} \tag{7}$$

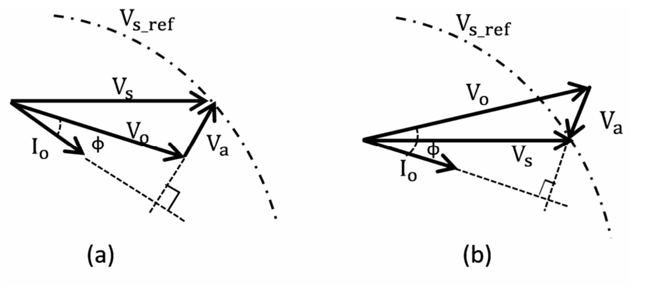

Fig. 3. Phasor diagrams of ES circuit parameters with a resistive-inductive load in (a) capacitive mode (b) inductive mode, where Φ is the power factor angle of non-critical load.

III. CIRCUIT REALIZATION OF AN ELECTRIC SPRING WITH BUILDING LOADS

A. Electric Spring usage in a building

Solar power in tropical countries like Singapore is intermittent in nature. Thus, it has been suggested to augment solar power with a secondary source such as a generator system. However, such a secondary storage is unable to provide instantaneous voltage support to certain loads. It has been suggested to include batteries for such conditions [15], but the hazards of disposal and their high capital and maintenance cost restrict their usage. Thus, it would be desirable to reduce their size for development of a sustainable environment.

Loads in a building can be categorized into two:

1) *Critical Loads*: which require constant voltage and power for their operation like the Security System of a building, and
2) *Non-critical Loads*: which can tolerate some degree of voltage and power fluctuation, like Central Air Conditioning system, Electric Heaters, etc.

When an electric spring is connected in series with a non-critical load, as depicted in Fig. 2, they form a smart load, which operates in a fashion such that voltage and power to critical load, connected in parallel to it, is maintained at a constant value despite the intermittent and fluctuating power from renewable energy source.

B. Control of an Electric Spring in a circuit

Using explanation of ES as a current-controlled voltage source and the phasor diagrams of Fig. 3, we propose realization of ES with a full H-bridge PWM Inverter. The control circuit is shown in Fig. 4.

The reference sine wave to be employed for the PWM inverter is generated by decoupling the scalar value of modulation index and phase of the sine wave. The modulation index, **m** is calculated by comparing the rms

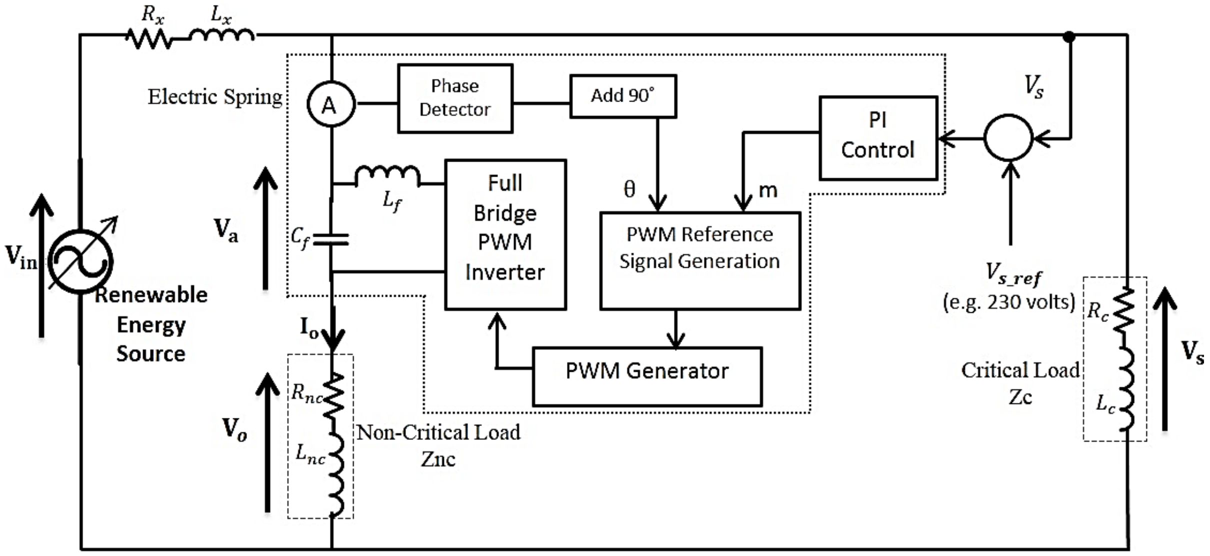

Fig. 4. Realization of Electric Spring in a Circuit with control block diagram for a resistive-inductive load in under-voltage condition with variable input voltage

value of critical load voltage $\mathbf{V_s}$ with the reference rms voltage value of 230 Volts, i.e. V_{s_ref}. For calculating the phase $\boldsymbol{\theta}$ of the reference sine wave, firstly the phase of current through the non-critical load is detected. Depending on the non-critical load characteristic, i.e. resistive-inductive, resistive-capacitive or any other combination, the phase angle is shifted by 90 degrees leading or lagging. Thus, the reference signal $\mathbf{v_{pwm\_ref}}$ is as given by (8).

$$\mathbf{v_{pwm\_ref}} = \mathbf{m} \sin(\omega t + \boldsymbol{\theta}) \qquad (8)$$

where θ is either 90˚ leading or 90˚ lagging.

It is noteworthy that that the modulation index, **m** determines the magnitude of electric spring voltage V_a, i.e. the reactive power compensation and $\boldsymbol{\theta}$ the active power. When $\boldsymbol{\theta}$ is 90 degrees leading/lagging, the active power consumption is zero.

A full H bridge inverter, as shown in Fig. 5, is designed with a bulky dc capacitor on the dc side and an inductive-capacitive (LC) filter on the ac side. The PWM signals from the PWM generator are fed to the gates of the MOSFETs, which control the ac voltage across the capacitor C_f, i.e. the electric spring voltage $\mathbf{V_a}$. A diode rectifier circuit is formed by the four freewheeling diodes, which rectify ac voltage to dc and charge the bulky dc capacitor. Also, an ES can be practically realized as a self-powered device as well.

The maximum voltage achievable in an electric spring would be twice in a full H bridge inverter topology as compared to the half bridge technology employed in [11], hence reducing the switch currents to half of the latter [16]. Consequently, the devices would be less stressed in former in contrast to the latter, thus prolonging the life expectancy of the electric spring. Number of capacitances is reduced to one from two. With half bridge inverters there is always a possibility of even harmonic generation due to non-identical capacitances, however in the proposed scheme such a likelihood is completely eliminated. Thus, power quality in the circuit is maintained and harmonic losses are limited.

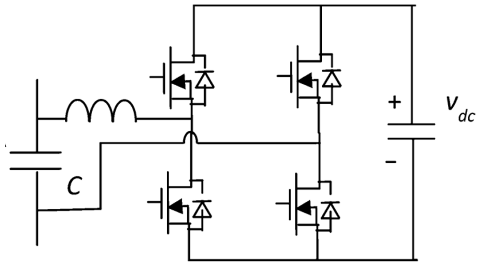

Fig. 5. Full H bridge inverter employed in the scheme

IV. SIMULATION RESULTS OF ELECTRIC SPRING WITH BUILDING LOAD

Fig. 4 shows the setup of the system to be used for purpose of validation and testing of the arguments presented in the previous sections. It was carried out through a simulation study on MATLAB® *Simulink* platform. The system was tested in under voltage (below the reference voltage) and over voltage (above the reference voltage) scenarios. The specification of the system is given in Table I.

Since the electric spring is employed in a microgrid, the line impedance is chosen like that for a typical distribution network cable with X/R ratio equal to 7.5 [17].

For incorporating the scheme of input-voltage control, the voltage error is fed to a proportional-integral controller to generate the magnitude of the reference wave. The phase control signal is generated by estimating the phase of the current through the non-critical load leg of the circuit and is shifted by 90º leading for a resistive-inductive load. For a resistive-capacitive load, the phase control signal is shifted by 90º lagging. The output of the full bridge PWM inverter is passed through a LC filter so as to obtain a sinusoidal voltage waveform.

The results when the system is subjected to under voltage conditions are depicted in Fig. 6. The electric spring operates so as to boost up the critical load voltage from 210 Volt rms

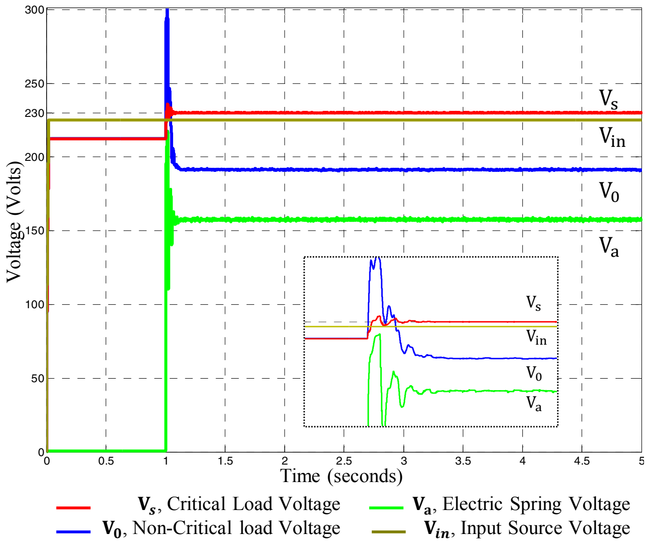

Fig. 6. RMS Voltages across critical load, non-critical load, electric spring and input voltage source in under-voltage condition. [Inset: RMS voltages from t = 0.95 to 1.15 seconds]

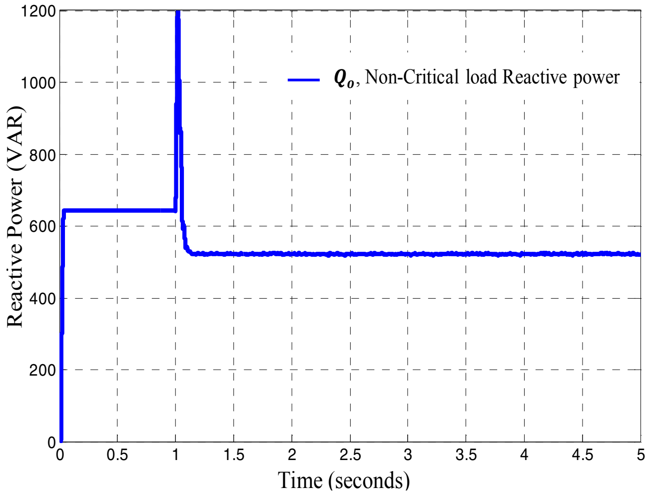

Fig. 7. Reactive Power consumption in the non-critical load in under-voltage conditions.

to the reference value of 230 Volt rms (V_{s_ref}). It is to be noted that the non-critical load voltage (V_o) falls when the device ES turns on at t = 1 seconds, so as to maintain the critical load voltage at the reference value. The ES operates in capacitive mode and injects negative reactive power into the system to boost the system voltage. Inset of Fig. 6 shows the rms voltages from t = 0.95 to 1.15 seconds, the critical load voltage stabilizes in two cycles, while response of electric spring settles in less than five cycles. The reactive power of the non-critical load is reduced when ES is employed as illustrated in Fig. 7. This highlights the reactive power compensation feature of ES. Ample penetration of ES with other non-critical loads in the microgrid can help reach the desired level of reactive power compensation. An interesting aspect of ES is load power shedding, shown in Fig. 8. When the ES is switched on, the non-critical load power is reduced so as to support the critical load power and maintain it at 4.4 kW.

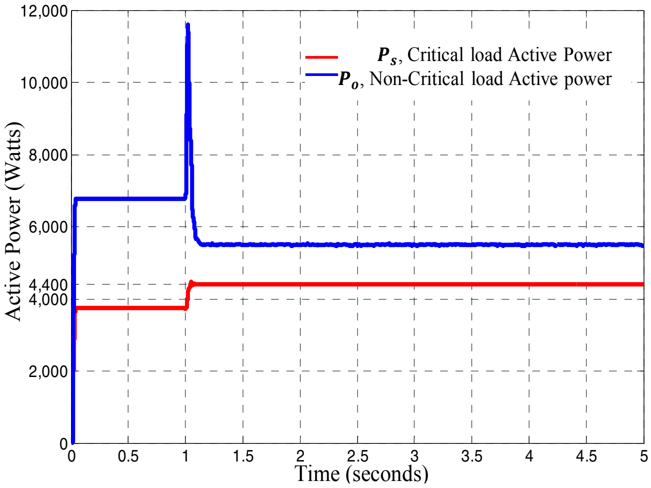

Fig. 8. Active Power consumption in critical and non-critical load in under-voltage condition

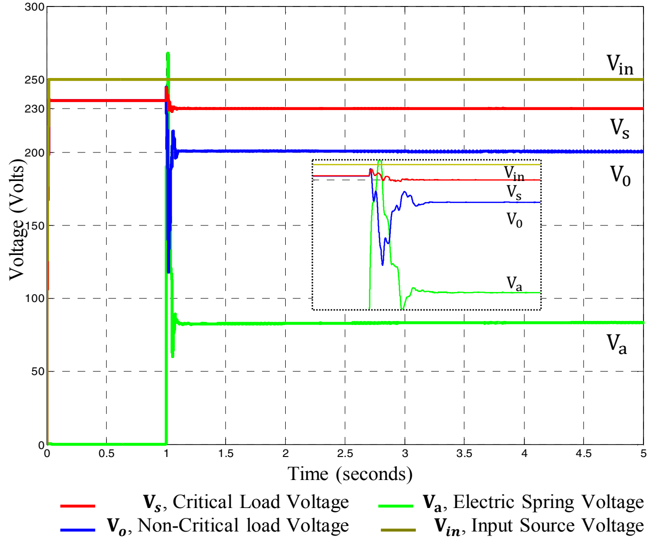

Fig. 9. RMS Voltages across critical load, non-critical load, electric spring and input voltage source in over-voltage conditions. [Inset: RMS voltages from t = 0.95 to 1.15 seconds]

TABLE I. SYSTEM SPECIFICATIONS

System voltage and Line impedance	
System Voltage, Vin (rms):	Under-voltage: 225 Volt (rms)
	Over voltage: 250 Volt (rms)
Line impedance:	0.1 Ohms, 1.22 mH
Load specifications	
Non-Critical Load:	7.0 Ohms, 1.398 mH
Critical Load:	11 Ohms, 3.930 mH
Electric Spring Power Circuit	
Inverter Topology:	Single Phase Full H Bridge Inverter
Switching Frequency:	20 kHz
Regulated DC bus voltage:	450 Volts
Output Low Pass filter	
Inductance:	1.92 mH
Capacitance:	13.2 µF

When a ES is implemented in an over voltage scenario, as depicted in Fig. 9, it reduces the voltage across the critical

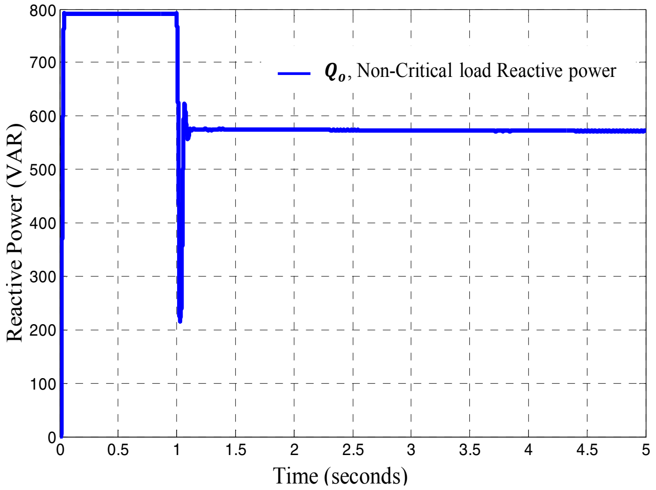

Fig. 10. Reactive power consumption in non-critical load in over voltage condition.

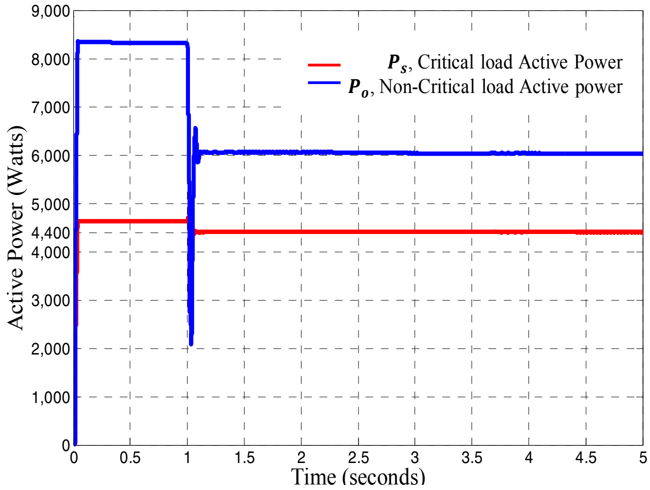

Fig. 11. Active power consumption in critical and non-critical loads in over voltage condition.

load and maintains it at the reference value of 230 Volt rms, when the ES is turned on at t = 1 seconds. Like the under voltage scenario, the critical load voltage stabilizes in two cycles and the response of electric spring settles in less than five cycles, as illustrated in inset Fig. 9 for t = 0.95 to 1.15 seconds. The ES operates in inductive mode and for a resistive-inductive load generates negative reactive power so as to provide voltage suppression. Similar to the under voltage scenario, the ES provides reactive power compensation to non-critical load as shown in Fig. 10. Also, the active power to the critical load is maintained at the constant value of 4.4 kW, after ES is switched on in Fig. 11.

It is notable that in both cases, non-critical load voltage V_o will be reduced due to increased value of the compensation voltage V_a. It can be inferred from the results that ES controls the reactive power so as to provide voltage support to the critical loads and automatic load power shedding. It is also observed that the problem of reactive power compensation can be solved using ES.

V. CONCLUSION

The concept of demand side management has been an age old [18], however with the evolution and growth of smart grid, it has become a necessity, to produce desired changes in utility's load shape. For this purpose various methods of load control were introduced like load scheduling [19], smart metering for building applications [20, 21], and direct load control (DLC) integrated with real-time pricing [22]. However they have limited potential like load scheduling and smart metering may be utilized for day-ahead planning, but not for instantaneous voltage support. The third method of DLC though effective in real-time might prove intrusive to customers and if not properly secured, can pose a threat to user privacy.

Electric Springs present themselves as an ingenious solution to the problem of instantaneous voltage instability in renewable energy powered microgrids. It is illustrated, in this paper through simulation study, that ES can be implemented using a full H bridge PWM inverter with building load such as central air conditioning system. The proposed concept of smart load can provide a) voltage support to the critical loads of a building like security system, b) automatic load power shedding through non-critical loads, and c) reactive power compensation to the non-critical loads, with ample penetration in current renewable energy powered microgrids. These features along with the possibility of control of active and reactive power [14], corroborate the argument that electric springs are insightful devices for stability control in renewable energy powered microgrids without any reliance on information and communication technologies, smart metering or wide-area management and without much investment on security aspect of demand side management.

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