Electric Spring for Voltage and Power Stability and Power Factor Correction

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***Abstract*-- Electric Spring, a new smart grid technology, has earlier been used for providing voltage and power stability in a weakly regulated/stand-alone renewable energy source powered grid. It has been proposed as a demand side management technique to provide voltage and power regulation. Buildings provide a great avenue to implement electric spring effectively. In this paper, a new control scheme is presented for the implementation of electric spring, in conjunction with non-critical building loads like central air conditioning system. This control scheme would be able to provide power factor correction of the system, voltage support, and current balance for the critical loads, such as the building's security system, in addition to the existing characteristics of electric spring of voltage and power stability. Thus, the improvised control scheme opens new avenues for utilization of the electric spring to a greater extent by providing voltage and power stability and enhancing the power quality in the renewable energy powered microgrids.**

***Index Terms*—Demand Side Management, Electric Spring, Power Quality, Renewable Energy**

I. Introduction

Renewable Energy Sources (RESs) like solar and wind are indispensable components for a sustainable future. However, their intermittent and unpredictable nature poses an issue of power and voltage instability in the grid. Various methods have been proposed on both the source-side and load-side to mitigate this intermittency. Demand Side Management (DSM) has been used actively as a method to attenuate the effects of renewable energy intermittency. Various methods such as direct load control, load scheduling, energy storage etc. are used to implement DSM. However, they can either not be used in real-time like load scheduling or might be intrusive to customer like direct load control. A new approach to DSM, Electric Spring (ES) was introduced by Rui et al. in [1, 2] which is able to provide voltage and power stability. Throughout [1-8] they utilize only reactive power compensation to provide voltage support in real-time and dynamic load shedding for non-critical loads.

A unity power factor is desirable in an ac system to improve efficiency, reduce losses, increase relative current, economical advantages on grid-side equipment etc. [9, 10]. Power factor correction methods like static capacitors and shunt condensors work well in conventional grid. Their placement is determined by the reactive load and losses in the distribution system. With increase in non-linear loads and advancement in power electronic devices such as DSTATCOM [11, 12] are being employed to improve the power quality. In future grids with substantial renewable energy, it is desired that we look at power factor correction as a DSM issue.

Buildings have great potential to implement the concept of ES as illustrated in [6, 13] through various non-critical loads such as air-conditioners and electric heaters. The concept of ES can be extended further to improve the power factor in a renewable energy powered microgrid. As ES is implemented through an inverter and by utilizing its potential of both active and reactive power compensation [14] this could be achieved. The real power compensation has been utilized to improve power balance in a three phase system [15] and to improve power factor without any voltage or power regulation [16]. In this paper, we demonstrate implementation of electric spring through an improvised control scheme to provide both the power and voltage stability and overall power factor correction in renewable energy powered microgrid, an aspect which hasn't been explored yet.

In section II of the paper the characteristics of a conventional and improvised electric spring are illustrated. Also, single phase to dq transformation is discussed. The modelling of ES and the improvised control scheme are explained and proposed in Section III. In section IV, through a simulation study first the performance of conventional ES is discussed in section. The improvised control is applied to the same system and the results are presented. Also, a comparative analysis is performed between the two control schemes, i.e., conventional input-voltage control and improvised input-voltage-input-current control scheme. Final remarks and conclusions are drawn in section V.

II. Operating Principles of Electric Spring

A. *Review of earlier versions of Electric Spring*

The concept of Electric Spring was introduced by drawing parallels to a traditional mechanical spring [1]. In a weakly regulated grid, it could be realized through an inverter and is attached in series with non-critical load, such as air conditioners, as shown in Fig. 1, to form a *smart load*. In parallel to this smart load, critical loads like a building's security system are connected. Earlier

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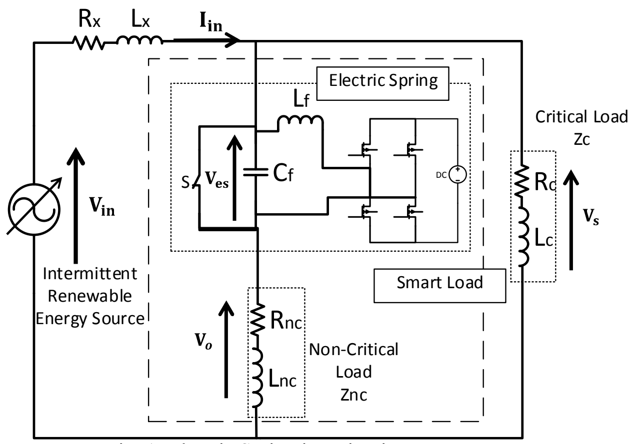

Fig. 1. Electric Spring in a circuit

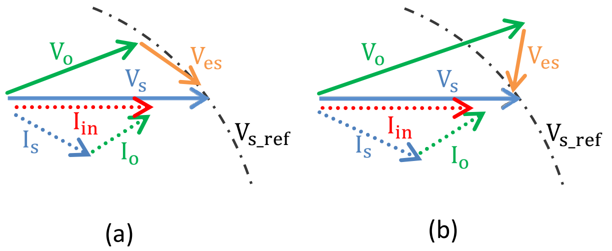

Fig. 2 Phasor diagrams of Voltage and Current for PFC and Voltage Support in (a) Under-voltage conditions (b) Over-voltage conditions. V_s, V_o, and V_{es} are voltages across critical load, non-critical load, and electric spring, respectively and I_s, I_o, and I_{in} are currents through critical load, non-critical load, and line current, respectively.

versions of ES implemented an input-voltage control scheme to generate reactive power compensation in order to provide dynamic voltage and power regulation to critical loads. As a result, the non-critical load voltage and power vary dynamically in accordance to the fluctuations in the weakly regulated grid due to intermittent renewable energy power.

In order to provide only reactive power compensation from electric spring, the compensation voltage, V_{es} should be perpendicular to non-critical load current, I_o [6, 16]. The electric spring voltage is governed by:

$$V_s = V_o + V_{es} \tag{1}$$

In a distribution system, with various inductive and capacitive loads, a substantial reactive power injection can worsen the power factor of system and lead to reduced efficiency. Thus, a feature of power factor correction can be incorporated in the ES along with existing characteristics of voltage and power regulation.

By utilizing a dc source such as a battery to power the inverter, as illustrated in Fig.1, both active and reactive power compensation could be obtained from an ES. This property of ES could be utilized to shape the line current, I_{in}, to be in phase with line voltage, V_s. Phasor diagrams in Fig. 2 demonstrate how the electric spring compensation voltage, V_{es}, could help improve the power factor in the distribution system and provide dynamic voltage and power support in a system with resistive-inductive loads i.e., it has an overall lagging power factor.

In under-voltage case, the ES injects a combination of capacitive and real power in the system, so as to boost up the line voltage, V_s to the reference value of 230 Volts and to regulate that the line voltage, V_s and line current, I_{in} remain in phase. In over-voltage case, the ES injects a combination of real and inductive power in the system, to perform the similar functions of line voltage regulation and power factor correction.

B. Single Phase dq Transformation

dq rotating frame transformation is widely used for three phase system for analysis and control. It is used for transformation between rotating and stationary frames. The concept has also been extended to single phase system to achieve a simpler control and analysis.

However, at least two independent variables are required to create a dq system, Thus, the concept of orthogonal imaginary circuit was introduced [17-19]. Two variables: the real (voltage or current) and the imaginary, which is identical in characteristics to real variable but has a 90° electrical phase shift with respect to real variable, are utilized for the transformation. If the real signal, V_r is given by (2) then the imaginary signal, V_i would be as indicated in (3). For simulation purposes, imaginary variable could be realized by integrating the real signal over one time period, as illustrated in (4) and Fig. 4.

$$V_r = A\sin(\omega t + \theta) \tag{2}$$

$$V_i = A\sin\left(\omega t + \theta - \frac{\pi}{2}\right) = -A\cos(\omega t + \theta) \tag{3}$$

$$V_i = \omega \int_t^{t+\tau} V_r \, dt \tag{4}$$

dq transformation for signal V_r is performed using a transformation matrix T_r given in (5) and *dq* components rotating in a synchronous reference frame are generated using (6).

$$T_r = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = T_r \begin{bmatrix} V_r \\ V_i \end{bmatrix} = X_M \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \tag{6}$$

Thus, by using single phase dq transform, a time-varying ac signal can be converted to dc values and an appropriate controller could be designed for the inverter.

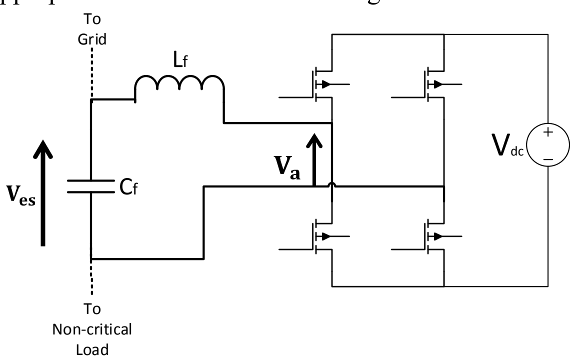

Fig. 3. Inverter used to implement Electric Spring

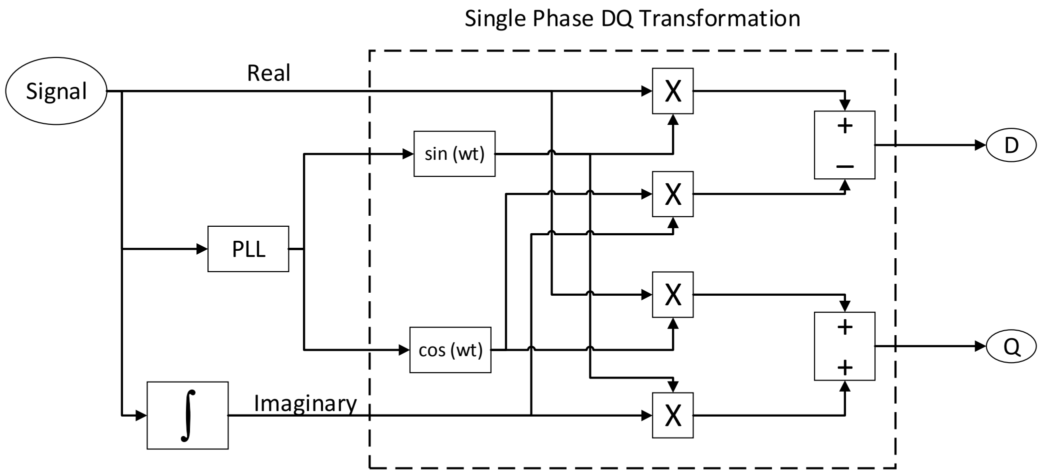

Fig. 4. Single phase to dq transformation

III. Modelling and Control of Improvised Electric Spring

A. Dynamic model of an Electric Spring

An electric spring can be realised through an inverter and its power circuit is shown in Fig. 3. The dynamic model of ES [20] can be realised using KVL and KCL. Effective Series Resistances (ESR) of filter inductor, L_f and capacitor, C_f are neglected and it is assumed that all devices of inverter are lossless. KVL and KCL are applied on the ac side of inverter and are written as:

$$V_a - V_{es} = L_f \frac{dI_{es}}{dt} \tag{7}$$

$$V_s = Z_{nc}.I_o + V_{es} \tag{8}$$

and

$$C_f \frac{dV_{es}}{dt} = I_{es} + I_o = I_{es} + I_{in} - \frac{V_s}{Z_c} \tag{9}$$

Because of high frequency LC filter, only fundamental components would pass through. The fundamental component of terminal voltage, V_{1a} (of a full bridge inverter) is as given by (10).

$$V_{1a} = V_{dc}\, m(t) \tag{10}$$

where $m(t)$ is the modulation index and V_{dc} is the dc link voltage of the inverter.

The state space equation of the system is given as:

$$\frac{d}{dt}\begin{bmatrix} I_{es} \\ V_{es} \end{bmatrix} = \begin{bmatrix} 0 & -1/L_f \\ 1/C_f & 0 \end{bmatrix}\begin{bmatrix} I_{es} \\ V_{es} \end{bmatrix} + \begin{bmatrix} 1/L_f \\ 1/Z_cC_f \end{bmatrix}\begin{bmatrix} mV_{dc} & V_s \end{bmatrix} + \begin{bmatrix} 0 \\ 1/C_f \end{bmatrix} I_{in} \tag{11}$$

The state space equation can be written in real and orthogonal imaginary form as below:

$$\frac{d}{dt}\begin{bmatrix} I_{es\_r} \\ I_{es\_i} \end{bmatrix} = -\frac{1}{L_f}.\begin{bmatrix} V_{es\_r} \\ V_{es\_i} \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} m_r \\ m_i \end{bmatrix} V_{dc} \tag{12}$$

and

$$\frac{d}{dt}\begin{bmatrix} V_{es\_r} \\ V_{es\_i} \end{bmatrix} = \frac{1}{C_f}.\begin{bmatrix} I_{es\_r} \\ I_{es\_i} \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} I_{in\_r} \\ I_{in\_i} \end{bmatrix} - \frac{1}{Z_cC_f}\begin{bmatrix} V_{s\_r} \\ V_{s\_i} \end{bmatrix} \tag{13}$$

where subscript r denotes real variable and i denotes orthogonal imaginary of the real variable.

Using (5) and (6) the dq transformation for (12) and (13) can obtained and state space equations would be (14) and (15).

$$\frac{d}{dt}\begin{bmatrix} I_{es,d} \\ I_{es,q} \end{bmatrix} = -\begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} I_{es,d} \\ I_{es,q} \end{bmatrix} - \frac{1}{L_f}\begin{bmatrix} V_{es,d} \\ V_{es,q} \end{bmatrix} + \frac{V_{dc}}{L_f}\begin{bmatrix} m_d \\ m_q \end{bmatrix} \tag{14}$$

and

$$\frac{d}{dt}\begin{bmatrix} V_{es,d} \\ V_{es,q} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} V_{es,d} \\ V_{es,q} \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} I_{es,d} \\ I_{es,q} \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} I_{in,d} \\ I_{in,q} \end{bmatrix} - \frac{1}{Z_cC_f}\begin{bmatrix} V_{s,d} \\ V_{s,q} \end{bmatrix} \tag{15}$$

Analyzing (14) and (15) a controller could be designed for the electric spring.

B. Improvised Control Scheme

A simple control scheme is developed using Kirchhoff's Law and single phase dq transformation. The line current, $I_{in,}$ in the system in Fig. 1 can be written as (15) which can be rearranged to define the electric spring compensation voltage, V_{es}, in terms of line current, I_{in}, and line voltage, V_s as shown in (17).

$$I_{in} = \frac{V_s - V_{es}}{Z_{nc}} + \frac{V_s}{Z_c} \tag{16}$$

$$V_{es} = \frac{Z_{nc}}{Z_{eff}}.V_s - Z_{nc}.I_{in} \tag{17}$$

where $Z_{eff} = R_{eff} + j\,X_{eff} = \frac{Z_{nc}\,.\,Z_c}{Z_{nc} + Z_c}$

Single phase dq transform could be applied to (17) to

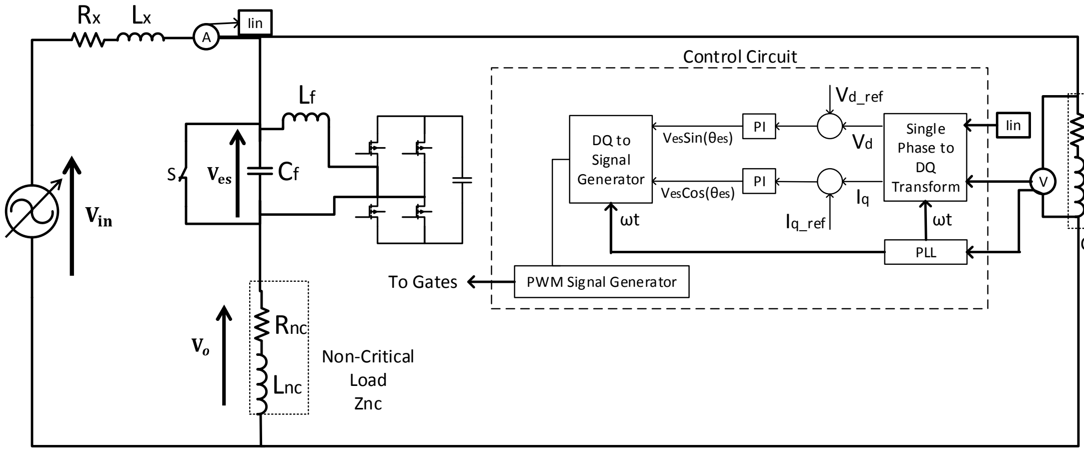

Fig. 5 Improved Control Circuit for power factor correction and voltage support using Electric Spring

obtain (18) and (19). The control action can be applied to $V_{s,d}$, $V_{s,q}$, $I_{in,d}$, and $I_{in,q}$ to generate the dq components of compensation voltage, $V_{es,d}$ and $V_{es,q}$. dq to Real-Imaginary transformation could be employed to generate the reference voltage.

$$R.V_{es,d} - X.V_{es,q} = V_{s,d} - R_{eff}.I_{in,d} - X_{eff}.\ I_{in,q} \quad (18)$$

$$X.V_{es,d} + R.V_{es,q} = V_{s,q} - X_{eff}.I_{in,d} - R_{eff}.\ I_{in,q} \quad (19)$$

where $R + j\,X = \frac{Z_{eff}}{Z_{nc}}$ and is dimensionless.

Making use of the dynamic model derived in the previous subsection and the above equations, the controller can be designed. In this control scheme, as depicted in Fig. 5, the phases are synced by a Phase Locked Loop (PLL) block using V_s as the reference signal. Thus, the q component of line voltage becomes zero. An advantage of using single phase dq transform is that parameters of the converter are DC, hence the inductor becomes short and capacitor becomes open. Thus from (14) and (15) the following (20) and (21) could be obtained.

$$m_d \propto -I_{in,q} \quad (20)$$

$$m_q \propto k_1 I_{in,d} - k_2 V_{s,d} \quad (21)$$

where k_1 and k_2 are constants.

We regulate the d component of line voltage, $V_{s,d}$ and q component of line current, $I_{in,q}$ while the d component of line current, $I_{in,d}$ is allowed to vary dynamically. The direct (d) reference voltage signal, V_{d_ref} is calculated so as to regulate rms of line voltage to 230 Volts and quadrature (q) reference line current, I_{q_ref} is zero so that maximum power factor correction for the system is performed, such that line current, I_{in} is in phase with critical load voltage, V_s.

IV. Simulation Results – Conventional ES and Improvised ES

A system shown in Fig.1, with specifications as shown in Table I is considered. It was simulated on a MATLAB – *Simulink* platform. The reference line voltage, V_s is set to be 230 volts (rms). The system has an effective resistive-inductive load, and thus a lagging power factor.

In this system, two types of case are recorded: a) with conventional electric spring, providing only reactive power compensation; and b) with improvised electric spring, providing both real and reactive power compensation. Both systems are compared with each other on dynamic voltage and power regulation and power factor correction capabilities. The results are discussed in the subsections.

TABLE I. System Specifications

System voltage and Line impedance	
Line Voltage, Vs (rms):	Under-voltage: 220 Volt (rms)
	Over voltage: 240 Volt (rms)
Line impedance:	0.1 Ohms, 2.5 mH
Load specifications	
Non-Critical Load:	6.11 + *j* 0.44 Ohms
Critical Load:	11 + *j* 11 Ohms
Electric Spring Power Circuit	
Inverter Topology:	Single Phase Full H Bridge Inverter
Switching Frequency:	20 kHz
Regulated DC bus voltage:	400 Volts
Output Low Pass filter	
Inductance:	1.92 mH
Capacitance:	13.2 µF

A. *Case A: Conventional Electric Spring*

The electric spring with only reactive power compensation capabilities is used to provide dynamic voltage and power regulation.

In over-voltage scenario, the rms line voltage is kept at 240 volts, i.e., above the reference value. The ES, when turned on at *t*=0.5 seconds, reduces and maintains the rms line voltage at reference value of 230 volts by injecting inductive power in the system as shown in Fig. 6. Also, the voltage across the non-critical load decreases to 215 volts (rms). ES injects 2100 VAr in the system (Fig. 8) and as a result, the power factor of the system reduces from 0.965 (lagging) to 0.895(lagging) as depicted in Fig. 7. Thus, the power quality of the system worsens.

In under-voltage scenario, the rms line voltage is kept at 220 volts, i.e. below the reference value. ES is turned

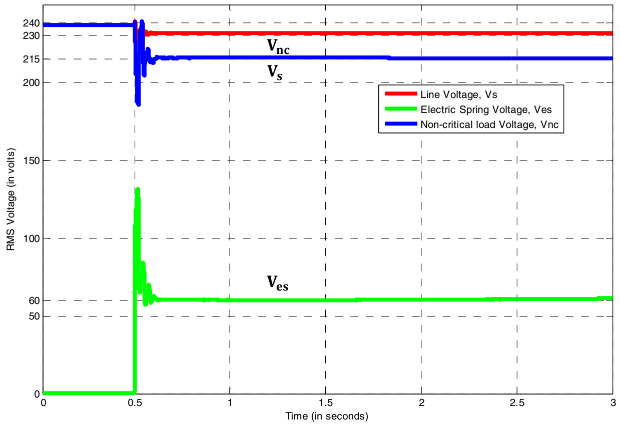

Fig. 6. Over-voltage, Conventional ES: RMS Line voltage, ES Voltage, and Non-Critical load voltage [ES turned on at t=0.5 sec]

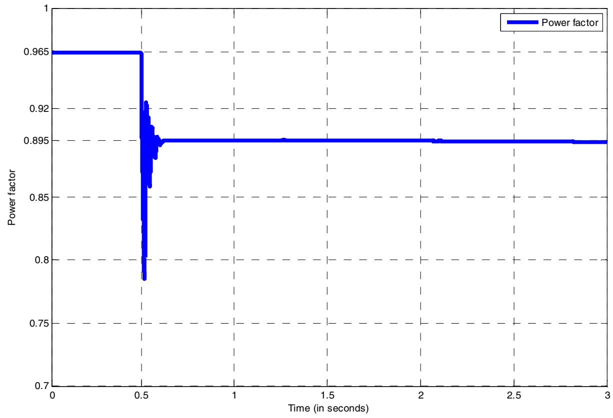

Fig. 7. Over-voltage, Conventional ES: Power Factor of system [ES turned on at t = 0.5 sec]

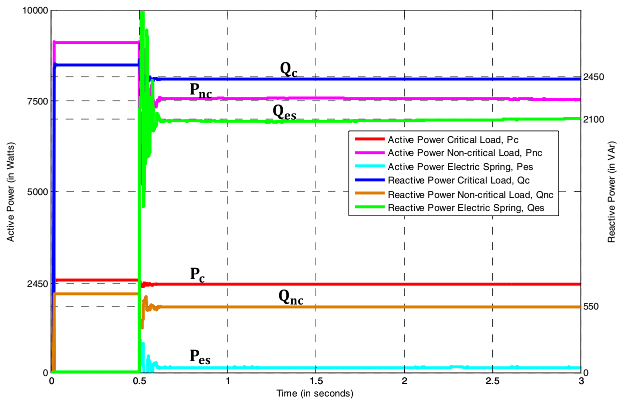

Fig. 8. Over-voltage, Conventional ES: Active and Reactive power across critical load, non-critical load, and electric spring [ES turned on at t=0.5 sec]

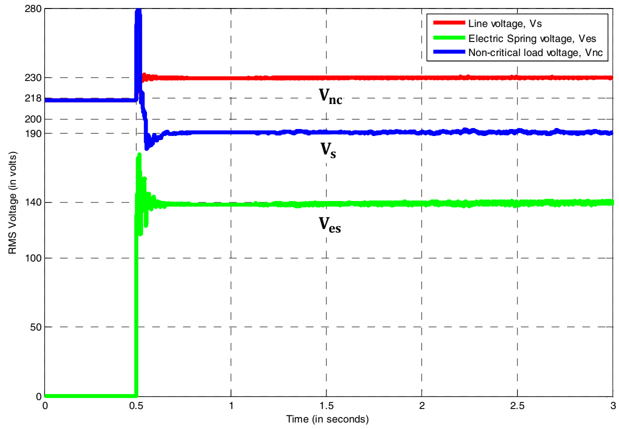

Fig. 9. Under-voltage, Conventional ES: RMS Line voltage, ES Voltage, and Non-Critical load voltage [ES turned on at t=0.5 sec]

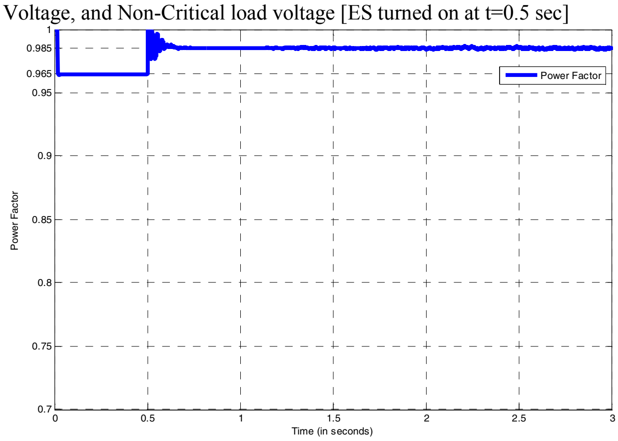

Fig. 10. Under-voltage, Conventional ES: Power Factor of system [ES turned on at t = 0.5 sec]

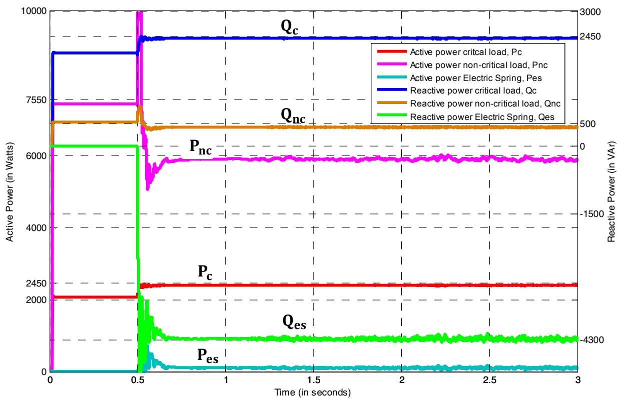

Fig. 11. Under-voltage, Conventional ES: Active and Reactive power across critical load, non-critical load, and electric spring [ES turned on at t=0.5 sec]

on at t=0.5 seconds and boosts up the line voltage to 230 volts as shown in Fig. 9. The voltage across the non critical load decreases to 190 volts (rms). ES injects a 4300 capacitive VAr in the system (Fig.11). As a result, the power factor of a resistive-inductive system improves to 0.985 (lagging) from 0.965 (lagging) as shown in Fig. 10. Although, the power factor has improved there's potential for more improvement.

B. *Case B: Improvised Electric Spring*

The improvised electric spring, with a new control scheme, is subjected to the similar scenarios as a conventional electric spring. This ES would be able to inject both real and reactive power in the system.

Similar to the previous subsection, rms line voltage is kept at 240 volts in over-voltage scenario and ES is turned on at t=0.5 seconds. The ES reduces the line volt--age to reference value of 230 volts shown in Fig. 12. It injects 1500 Watts and 1500 inductive VAr in the system (Fig. 14). The power factor of the system reduces to 0.93 (lagging) as shown in Fig. 13. Though the performance is not an optimal unity, it is better than the conventional ES which worsens the system power factor in over-voltage scenario. A conventional ES injects an inductive reactive power as shown in Fig. 8 to balance the line voltage, where as in this scenario the ES is equipped to provide both voltage support and PFC and thus has to inject a sm-

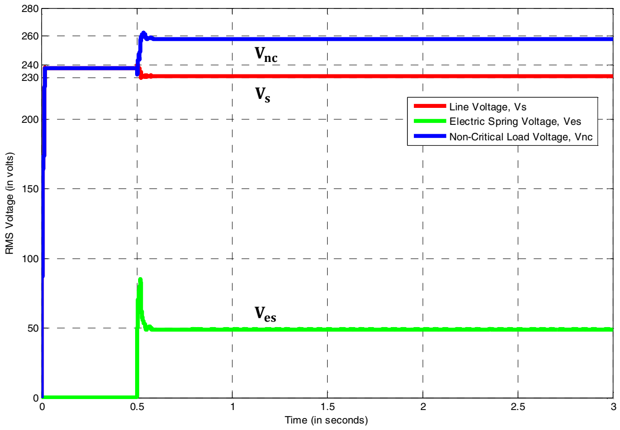

Fig. 12. Over-voltage, Improvised ES: RMS Line voltage, ES Voltage, and Non-Critical load voltage [ES turned on at t=0.5 sec]

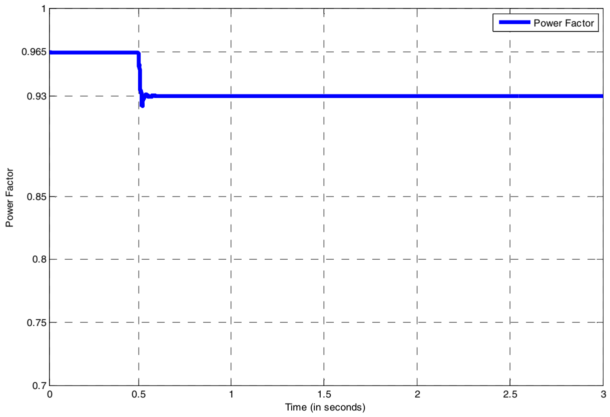

Fig. 13. Over-voltage, Improvised ES: Power Factor of system [ES turned on at t = 0.5 sec]

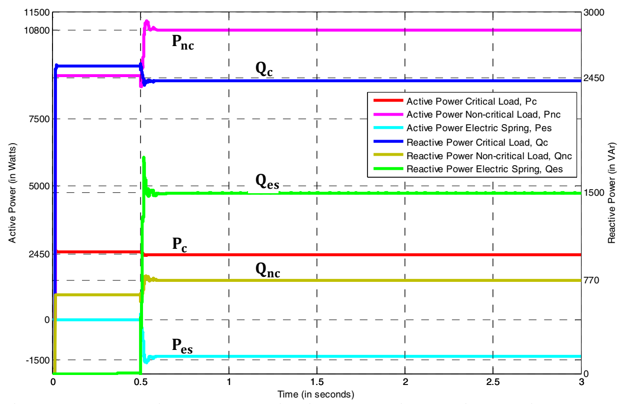

Fig. 14. Over-voltage, Improvised ES: Active and Reactive power across critical load, non-critical load, and electric spring [ES turned on at t=0.5 sec]

-all amount of active power to maintain the balance. As a result, voltage and active power consumption of non-critical load increases as shown by Fig.12 and 14.

In under-voltage scenario, ES boosts the rms line voltage from 220 volts to 230 volts when it is turned on at *t*=0.5 seconds as shown in Fig. 15. The ES absorbs 1000 Watts and injects 2850 capacitive VAr in the system as depicted in Fig. 17. The power factor of the system improves from 0.965 (lagging) to almost unity (Fig. 16). The voltage and power consumption of the non-critical load are reduced as visible from Fig. 15 and 17.

In over-voltage scenario, a 4% improvement from conventional ES is observed in power factor. The conven-

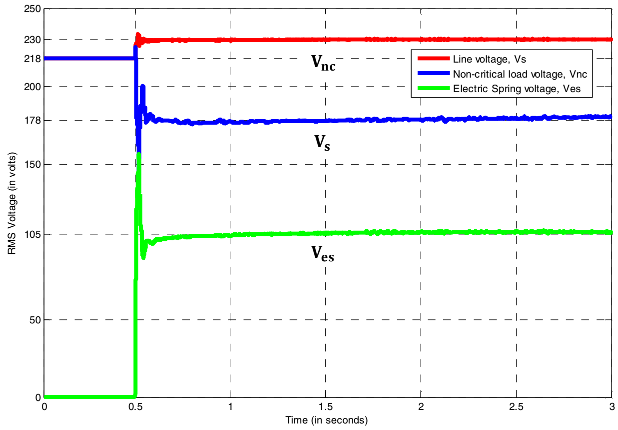

Fig. 15. Under-voltage, Improvised ES: RMS Line voltage, ES Voltage, and Non-Critical load voltage [ES turned on at t=0.5 sec]

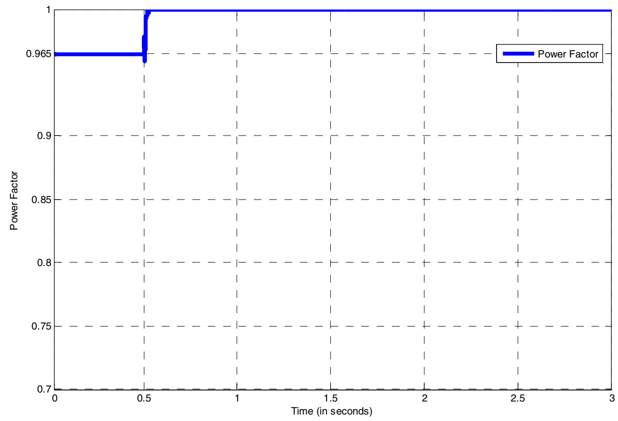

Fig. 16. Under-voltage, Improvised ES: Power Factor of system [ES turned on at t = 0.5 sec]

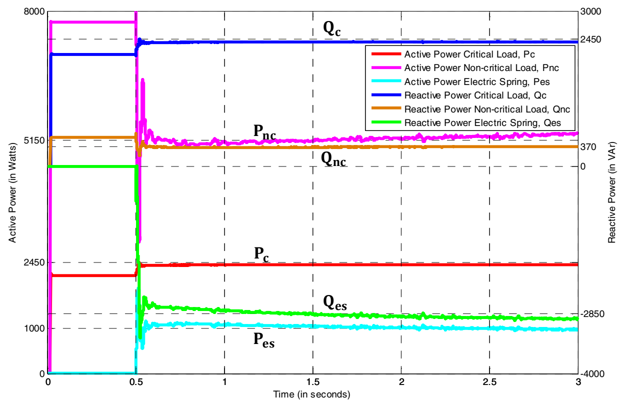

Fig. 17. Under-voltage, Improvised ES: Active and Reactive power across critical load, non-critical load, and electric spring [ES turned on at t=0.5 sec]

-tional ES injects only inductive power in the system, whereas the improvised ES injects both real and inductive power. While in under-voltage scenario, a 1.5% improvement is observed; the conventional ES injects only capacitive power and improvised ES injects both capacitive and real power in the system. Also, the harmonic injection limits in the system is maintained as dictated by IEC-61000-3-2 standards [21]. The 3rd, 5th and 7th harmonic currents in both scenarios and their respective standards are shown in Table II. Although the percentage improvement is not substantial for a single device, it could be envisioned that multiple of such devices when distributed across the future renewable powered grid, with poorer power factor and unstable voltage and power, should not just be able to support the grid but also provide power factor correction. The tasks associated with the stability and efficient and economic viability in such a grid could be solved using a single type of device i.e. electric spring.

TABLE II. HARMONIC CURRENTS IN SYSTEM

Harmonic	**Standard (IEC-61000-3-2)**	**Over-voltage Scenario**	**Under-voltage Scenario**
Third (3rd)	2.30	0.50	0.2
Fifth (5th)	1.44	0.30	0.1
Seventh (7th)	0.77	0.05	0.1

V. CONCLUSIONS

Electric Spring has been demonstrated, in this paper as well as earlier literatures, as an ingenious solution to the problem of voltage and power instability associated with renewable energy powered grids. In this paper, by implementation of an improvised control scheme it has been demonstrated that an Electric Spring a) maintains line voltage, b) power to the critical load, and c) improves power factor in the system. Also, the new 'input-voltage-input-current' control scheme is compared to the conventional 'input-voltage' control. It has been shown that using a single device voltage and power regulation and power quality improvement can be achieved. Although, only linear loads are used in this paper, in future it would be extended to non-linear loads. The current reference could be determined so as to supply harmonic content only from the electric spring.

It has been proposed that electric spring could be embedded in future appliances [1]. If many non-critical loads in the buildings are equipped with ES, they could provide a reliable and effective solution to distributed energy storage, voltage and power stability and in-situ power factor correction in a renewable energy powered microgrids. It would be a unique demand side management (DSM) solution which could be implemented without any reliance on information and communication technologies.

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