Grenze International Journal of Engineering and Technology, Special issue

Electric Spring with Improvised Control for Voltage Regulation and Power Factor Improvement

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***Abstract*—The Electric Spring is a promising new technology that has immense potential to stabilize future power grids that have a large number of renewable energy sources connected to them. Based on Hooke's law for mechanical springs (hence the name 'Electric Spring') it is a versatile reactive power controller that not only helps in regulating the grid voltage by controlling real and reactive power flow but also stores electric energy and damps out electric oscillations. The unique aspect of the Electric Spring that differentiates it from ordinary reactive power controllers is that it adopts an "input feedback - input voltage control" as compared to the "output feedback - output voltage control" in traditional RPCs. This subtle change in control strategy helps in making loads connected to the grid adaptive to the availability of intermittent renewable power generation, thus achieving effective demand-side management capabilities. In this paper an improvised control scheme for the Electric Spring based on the synchronous frame control method for single phase full-bridge inverters is presented. With the help of MATLAB simulations it is proved that this method can provide fast dynamic voltage regulation and power quality improvement for the grid.**

***Index Terms*— Electric Spring (ES); power quality; reactive power controllers (RPC); demand side management (DSM); smart loads; smart grids; dq control.**

I. INTRODUCTION

With the environmental damage caused by large-scale and indiscriminate use of fossil fuels being of great concern, there has been concerted effort all over the world to switch to cleaner sources of energy, leading to the proliferation of renewable sources of energy such as solar and wind. With rapid technological advancements in the area of alternate sources of energy coupled with improved economic feasibility, these have become indispensable for a sustainable future. In fact, a substantial fraction of electricity in some nations is already being generated by solar panels, concentrated solar plants, and onshore and offshore wind turbines, and many more nations or states thereof have ambitious targets of up to 50% penetration of renewable generation over the next decade or two[23]. However due to the intermittent and unpredictable nature of these sources, allowing more and more penetration of power through RES for generation of electrical power poses serious stability issues to the existing power grid. Besides causing voltage and power instability such large-scale penetration of RES in the grid will lead to wider power quality issues and affect

Grenze ID: 01.GIJET.3.2.19

the reliability of electrical power distribution. These concerns led to the concept of the 'Smart Grid' which advocates a paradigm shift towards demand management as compared to generation management, which has been the traditional power management strategy in power grids so far. Some of the key demand side management (also referred to as demand dispatch) strategies used include techniques such as Real Time Pricing where the consumer is charged according to the demand, Peak Demand Management with the help of energy storage devices like batteries, Direct Load Control (or on/off control) of smart loads and Load Scheduling. Of these, providing battery storage to alleviate peak demand happens to be the best possible solution, but it has a number of drawbacks like limited life, high initial cost and the problem of safe disposal. Further, due to their inherent complexity many of these methods cannot be used in real-time especially since most of them require the use of some sort of communication network. It is in this context that the Electric Spring, a novel, path-breaking approach to demand side management was introduced by Rui et al. in [1], [2] which, besides achieving satisfactory demand side management is also able to provide voltage regulation and power stability to the grid using a unique "input voltage feedback - input voltage" control as opposed to the traditional "output voltage feedback – output voltage control".

Electric spring (ES) is a new smart grid technology, realized with basic power electronic circuitry that can provide voltage, power and frequency stability functions in a distributed manner for future smart grids[2][17]. The salient features of the ES include the ability i) to provide reactive power compensation to maintain a stable mains voltage, ii) to provide active power control so as to enable the demand to follow the availability of renewable power in a continuous and instantaneous way, iii) to perform the above two operations instantaneously without the help of any complex IT or communication infrastructure [3][4]. Coupled with the use of adaptive noncritical loads which play a vital role in ES technology, it has great potential in enabling automated demand response (ADR), which in the near future is projected to have a crucial role in regulating the demand of commercial and residential buildings [11]. It has been estimated that in typical commercial and residential buildings, more than 50% of energy usage can be considered as due to noncritical loads such as heaters, refrigerators, air-conditioning systems, etc. [11]. Hence buildings present great potential to implement the concept of ES.

Besides voltage regulation, the concept of ES can be extended further to improve the power quality, including power factor and reduction of harmonics in a renewable energy powered grid [7]. As ES technology developed over the years starting from around 2010, the ES has evolved in both form and capability. The first generation ES (ES-1) [1] could perform voltage support by controlling reactive power exchange alone since it did not include any energy storage mechanism, besides contributing to primary frequency control [1] [8]. Later versions of ES were developed with energy storage (ES-2) [3] or additional converter in back-to-back (BTB) configuration [15] that had the capability of exchanging active and reactive power simultaneously. Thus, more diverse functions like voltage distortion reduction [10], power factor correction [11], and three-phase imbalance reduction [12], in addition to voltage and frequency regulation [13] could be achieved.

This paper is organized as follows: section II describes the basic operating principle and realization of the ES, section III outlines the proposed control scheme, and simulation study and results are discussed in section IV.

II. BASIC PRINCIPLE AND WORKING OF ES

A. Analogy Between Mechanical and Electric Spring

Electric springs can be considered as electric versions of their mechanical counterparts. The relationship between force and displacement of a mechanical spring as given by Hooke's law is:

$$F = -kx \qquad (1)$$

Where *F* is the force vector, *k* is the spring constant and *x* is the displacement vector, and the potential energy (*PE*) stored in the mechanical spring is given by:

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

Mechanical springs have been used for providing mechanical support in applications such as suspension systems in beds and vehicles and it is seen that the overall system is highly stable even if some individual springs fail. The same concept can be extended to the electrical realm for dealing with the intermittent nature of power generation using renewable energy sources in future power grids, thus helping to stabilize grid voltage and power.

Analogous to equation (1), the basic physical relationship of the electric spring is expressed as

$$q = Cv_a \quad \text{Inductive mode} \qquad (3)$$

$$q = -Cv_a \quad \text{Capacitive mode} \qquad (4)$$

and $$q = \int i_c \, dt \qquad (5)$$

Where q is 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.

Equations (3) and (4) show that dynamic voltage regulation (i.e., voltage boosting and reduction) functions of the electric spring can be controlled by controlling the charge *q* stored in the capacitor which in turn can be controlled by using a controlled current source, as shown by equation (5). Hence, an electric spring can be represented as a current-controlled voltage source [2]. An analogy of the mechanical spring and an electric spring under 3 different conditions is illustrated in Fig. 1, in which an electric spring is connected in series with a dissipative electric load.

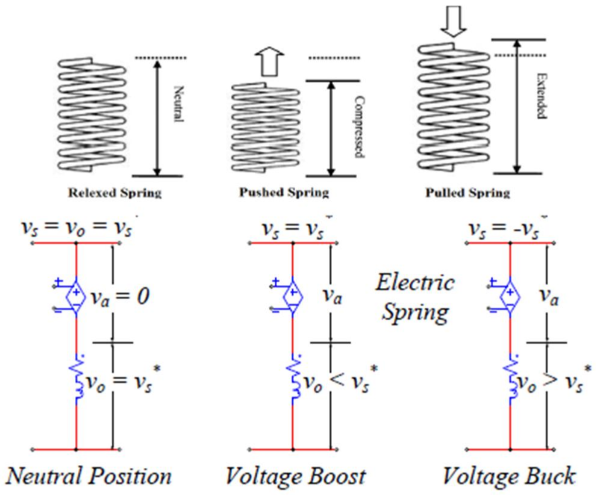

Fig.1 Analogy between a mechanical spring and an electrical spring

B. Working of ES in a Power System

The basic concept and working of an ES used in a power system is illustrated in Fig. 2.

Due to the intermittent nature of the renewable energy power supply, the power generated and ac voltage of the bus bar will vary dynamically. An electric spring is installed in the system in series with a dissipative load termed as a "noncritical" load, so called because it can withstand a fair amount of variation in it's voltage and power. The ES together with the noncritical load forms a "smart load". On the other hand loads that require a well-regulated mains voltage are called "critical" loads.

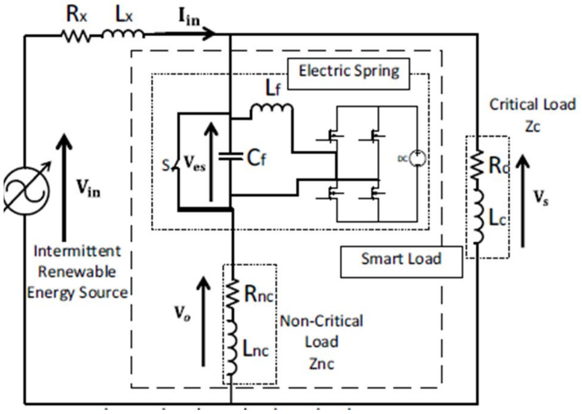

Fig 2. Power system with ES incorporated into a "smart load"

The series-connected non-critical load provides two functions - first, it provides a mechanism to dissipate electric energy for damping purposes. Second the voltage across the non-critical load and the electric spring changes in a special manner so that the power consumption of the combination will follow the variation of the renewable power generation at every instant. The series connection of ES with the load makes it behave like a “voltage suspension,” analogous to the mechanical spring suspension for a mechanical load (such as a vehicle or a mattress). 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.

C. Practical Implementation of ES

An ES is implemented using either a half bridge or full bridge inverter of single phase or three phase type, based on the load requirement. Fig. 2 shows the implementation using a single phase full H-bridge inverter. The vector equation for the electric spring is

$$V_S = V_O + V_{es} \tag{6}$$

By using a battery to power the inverter, as shown in Fig. 2, both active and reactive power compensation can be obtained from an ES and effectively the line current I_{in} can be shaped to be in phase with line voltage V_s thus improving the power factor. Phasor diagrams in Fig. 3 demonstrate how the electric spring voltage, V_{es} can help improve the power factor in the distribution system and provide dynamic voltage and power support in a system with lagging power factor.

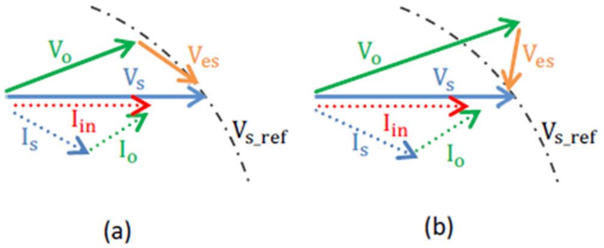

Fig. 3 Phasor diagrams of voltage and current for voltage regulation and power factor correction in conditions of (a) under-voltage, and (b) over-voltage

In under-voltage case, the ES injects a combination of capacitive and real power into the system, so as to boost up the line voltage to the reference value of supply voltage and also to regulate the line voltage to be in phase with line current, as shown in Fig. 3(a). In over-voltage case, the ES injects a combination of real and inductive power into the system, to perform the similar functions of line voltage regulation and power factor correction as shown in Fig. 3(b).

III. CONTROL CIRCUIT

A simple control circuit can be realized using Kirchhoff’s Law and single phase *dq* transformation as illustrated below. Referring to fig. 2 the line current I_{in} can be written as (7) below using Kirchhoff’s Law which can then 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 (8).

$$I_{in} = \frac{V_s - V_{es}}{Z_{nc}} + \frac{V_s}{Z_c} \tag{7}$$

$$V_{es} = \frac{V_s(Z_c + Z_{nc})}{Z_c} - I_{in}Z_{nc} \tag{8}$$

Converting the control variables V_s and I_{in} to the synchronously rotating reference frame we get their d and q axes components, V_{s_d} and V_{s_q} respectively. The control action can then be applied to these components to generate the *dq* components of compensation voltage V_{es_d} and V_{es_q} . Inverse *dq* transformation is then applied to obtain the ES control signal V_{es} . A suitable controller can thus be designed. The main advantage of using single phase *dq* transformation is that all alternating quantities (voltage and current) get converted to dc, which makes the inductor appear as shorted and capacitor as open circuited, thus making the control quite simple and straightforward. The block diagram of the basic ES control circuit is as shown in Fig. 4 below.

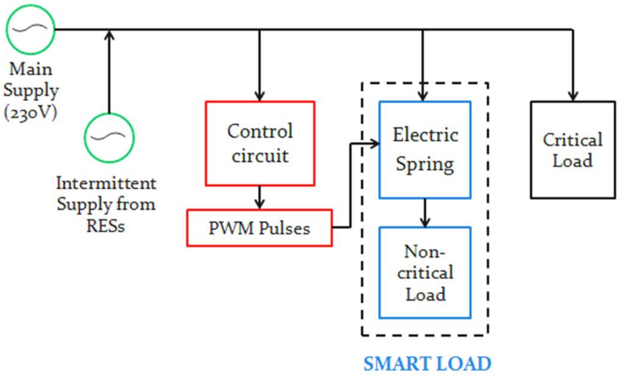

Fig. 4 Block diagram of ES control circuit

The proposed control scheme of ES in Matlab is shown in Fig. 5. Simulations are performed for two different types of critical loads – a resistive inductive load of (*500 +j942)* Ω and a non-linear load comprising of a single phase diode bridge rectifier connected to an RL load of (*20+j31.4* Ω). The non-linear load is used to study the harmonics correcting capability of the ES along with voltage regulation. The non-critical loads used are resistive having values of 50 Ω and 10 Ω.

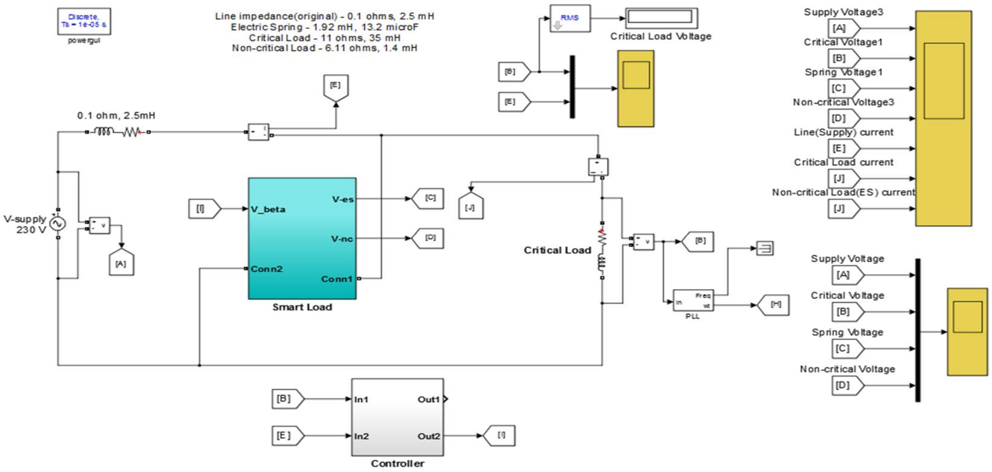

Fig. 5 Simulation circuit of basic ES control scheme

The details of the controller and ‘smart load’ which includes the inverter-fed ES with non-critical load are shown below in Fig. 6 and Fig. 7 respectively. The subsystem for converting the single phase voltage and current feedback signals to synchronously rotating *dq* frame is shown in Fig. 7.

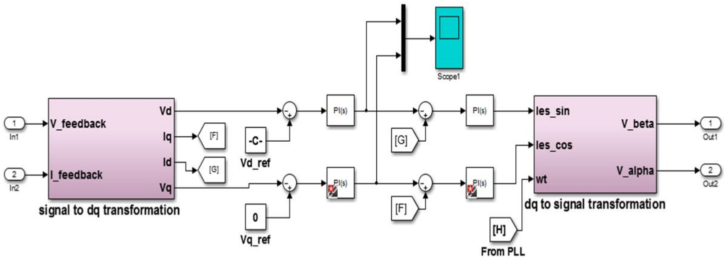

Fig. 6 ES controller subsystem details

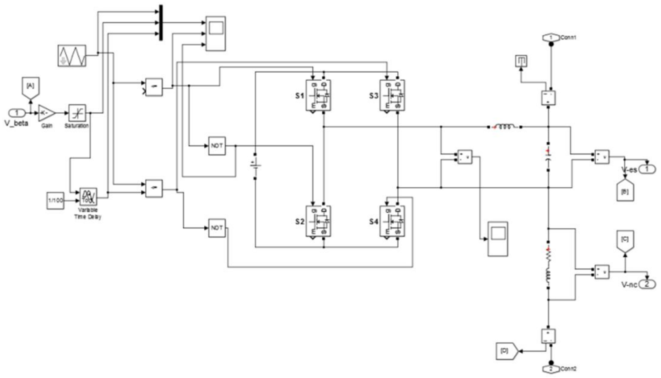

Fig. 7 Subsystem representing the ‘smart load’ consisting of ES with H-bridge inverter and non-critical load

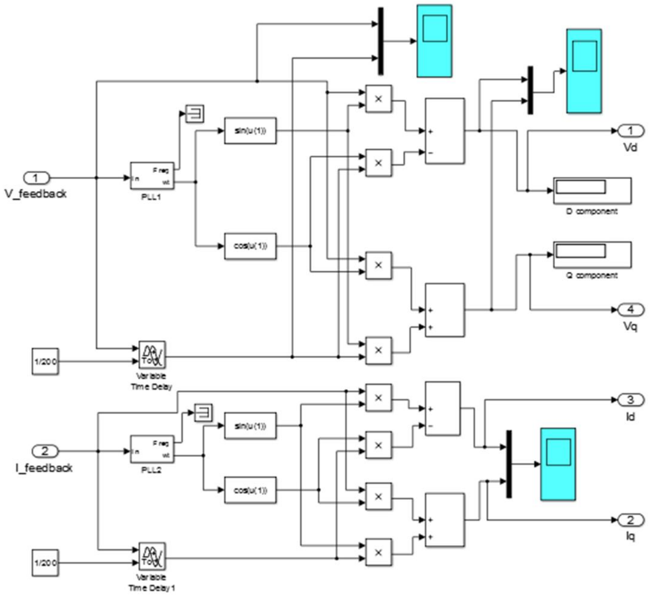

Fig. 8 Single phase to *dq* transformation of line voltage and current

The critical load voltage V_s and line currentI_{in} are the quantities that are fed back to the controller. These are first converted to their equivalent *dq* components and controlled using an inner current control loop and outer voltage control loop using PI control (for both loops) as shown in Fig. 6. The *d* component of line voltage V_{s_d} is regulated so as to make rms value of line voltage equal to the reference value, whereas the *q* component is set to zero so as to make the power factor unity. The regulated values of line voltage form the reference values for the line current *dq* components I_{in_d} and I_{in_q} as shown.

IV. SIMULATION RESULTS AND DISCUSSION

A simulation circuit as shown in Fig. 5 with specifications as shown in Table 1 is considered. Two sets of simulations have been performed with different voltage and parameter values. In the first one, a scaled down system at 120 V line voltages with a resistive-inductive load is studied, so as to enable easy implementation in further lab experiments. In the second simulation, a nonlinear load represented by a diode rectifier feeding an RL load is considered with a line voltage of 230 V. The results are given below.

The simulation results for a voltage sag of 8 volts (from 120 V to 112 V) in the first simulation is shown in Fig. 9 below. The drop in voltage is effected by switching on a 10 Ω resistor in parallel with the critical load at time t = 0.03 s to create a momentary sag. The ES is turned on at t = 0.06 s, and is seen to regulate the line voltage back to 120V (r m s).

TABLE I. SYSTEM SPECIFICATIONS

System Voltage and Line Impedance	
Line voltage, V_s (rms)	120 V, 230 V
Line impedance	0.1 Ω, 2.5 mH
Load Specifications	
Non-critical load	100 Ω, 10 Ω
Citical load (RL)	(500 + j942) Ω
Critical load (Nonlinear with RL load)	(20 + j31.4) Ω
Electric Spring Power Circuit	
Inverter topology	Single-phase full H-bridge
Switching frequency	12 kHz
DC bus voltage	200V
Output Filter	
Inductance	1.92 mH
Capacitance	13.2 μF

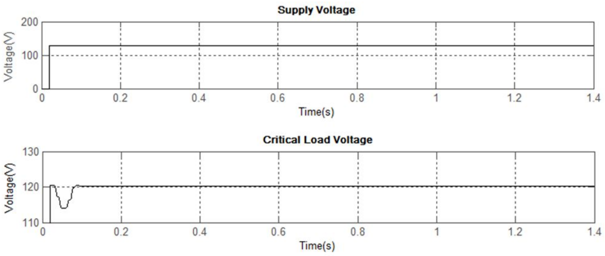

Fig. 9 Waveforms of supply voltage and regulated critical load voltage or line voltage (rms values) under voltage sag condition

The simulation results for the nonlinear load supplied by 230 V are shown in Fig. 10 and 11. Here a voltage sag of 12 V (from 230 V to 218 V) is effected by turning on a 25 Ω resistor in parallel with the critical load at time t = 0.05 s. The ES is turned on at time t = 0.1 s and it is seen that the voltage increases to 230 V within 5 ms (1/4 cycle). Further it is seen that the THD of input (line) current is improved from around 6.3 without the ES to 2.9 with the ES. The relevant waveforms are shown in Figs. 10, 11, 12 and 13 below.

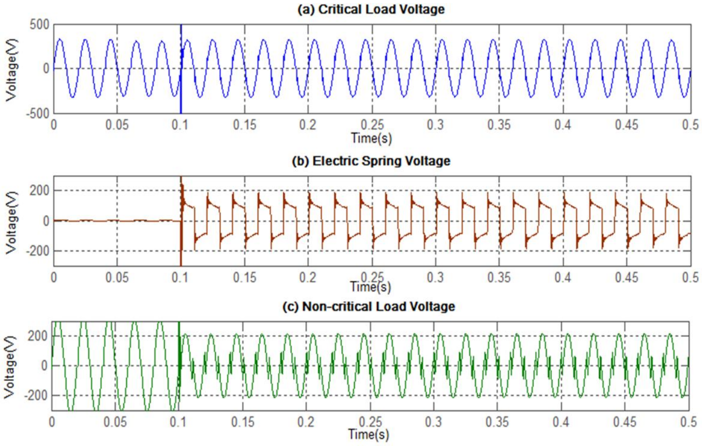

Fig. 10 Variation of (a) critical load voltage, (b) ES voltage, and (c) non-critical load voltage during voltage sag condition with nonlinear load

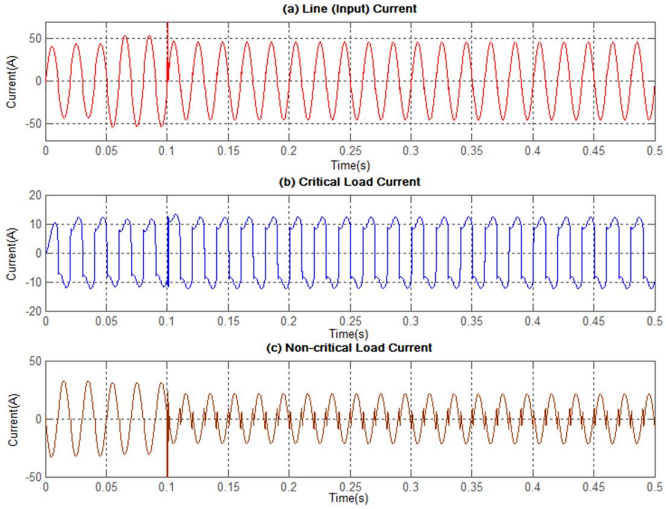

Fig. 11 Variation of (a) line (input) current, (b) critical load current, and (c) non-critical load current during voltage sag condition with nonlinear load

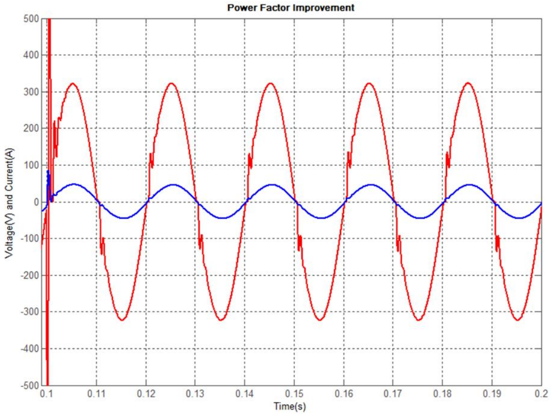

Fig. 12 Waveforms showing improvement in power factor

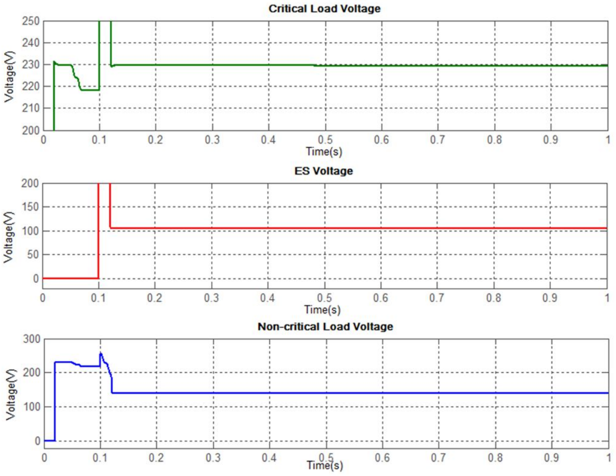

Fig. 13 Change in r m s values of critical load voltage, ES voltage and non-critical load voltage due to operation of ES in case of nonlinear load

V. CONCLUSION

Increasing integration of renewable energy sources into the grid and the ensuing problems of power grid stability and power quality issues have prompted research into methods of mitigating them, along with methods for effective demand side management. During recent years the ES has emerged as the most promising technique on this front. It has been proved that with suitable control strategies the ES not only helps in voltage and power regulation, but can also help in improving power factor and power quality in general, besides contributing to DSM. One such control technique for the ES has been illustrated in this paper, along with the relevant simulations. It has been demonstrated that with this control strategy the harmonic content of the input current can also be appreciably reduced when used in conjunction with non-linear loads such as rectifiers (which form a substantial proportion of modern day commercial loads), along with power factor improvement.

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