Development and Control of Electric Spring to Improve the Stability of Future Smart Grid with Intermittent Renewable Energy Sources

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***Abstract*— British physicist Robert Hook described the concept of "Mechanical Spring" in the 1660's and after three centuries the concept of mechanical spring is implemented in electrical regime called as "Electric Spring". This paper mainly focuses on details of practical circuit and control implementation of Electric spring for voltage regulation and reactive power compensation of the AC mains. The voltage fluctuations problem due to substantial impact of intermittent Renewable energy sources is solved by Electric Spring. Electric Spring is effective in stabilizing the grid having intermittent renewable sources and enabling load demand to follow power generation. The change of concept from Output voltage control (traditional reactive power compensators) to Input voltage control (Electric Spring concept) of reactive power is also highlighted in the paper. Unlike traditional reactive power compensation technique, this technique handles not only reactive power but also automatic power regulation in non-critical loads. This is an advantageous feature which enables non critical load with embedded electric spring to be adaptive by future power grid. Hence the Electric Spring concept provides a new form of power system stability solutions without relying on communication technology.**

Keywords*— Distributed power systems, voltage fluctuation, stability, smart loads, smart grid, Electric spring (ES)

I. INTRODUCTION

In traditional power system the power is generated according to the load demand and usually the power demand is more than generation. In smart grid there are many sources such as wind, solar etc. that can be used to meet this local demand. But main problem with these sources is the voltage fluctuations due to change in environmental condition. Hence if we able to compensate these voltage fluctuations then we will have constant supply. The dynamic and changing nature of power generation in these sources makes prediction of real time power generation difficult. When the penetration of such dynamically changing and uncertain elements in the overall power grid also increases [1]. Thus, future smart grid systems may face severe uncertainties and potential voltage stability problems because numerous power sources known or unknown to the utility companies will exist in the power systems in a distributed manner.

As we know that the mechanical spring is an elastic device that can be used to store mechanical energy, to provide mechanical support and to damp mechanical oscillations. When the mechanical spring is stretched or compressed the force exerts is proportional to its change in displacement. When length of spring deviates from its natural length the potential energy (P.E) is stored in the mechanical spring.

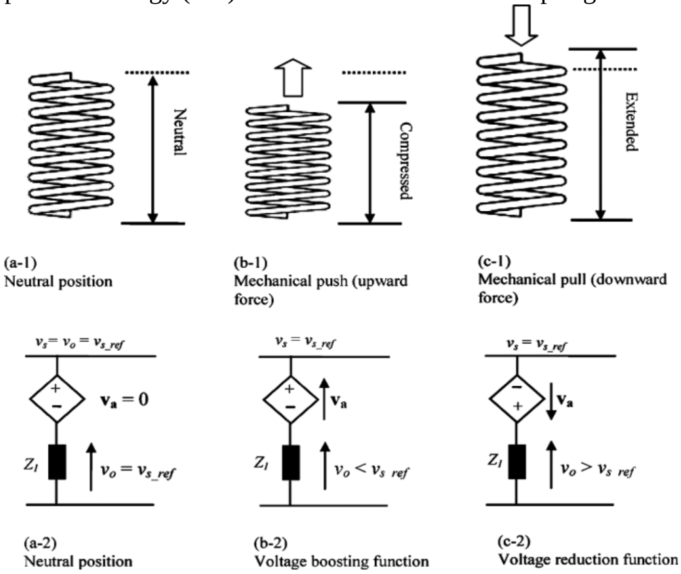


Fig. 1 Analogy of mechanical spring and electric spring.

The mechanical spring have been widely used in many daily applications such as suspension spring for beds and vehicles. Over three centuries the mechanical spring concept has not been extended to the electric field. In this paper the electric spring (ES) concept suggest a method based on Hooke's law of mechanical spring realized in electric system. Electric spring is nothing but a special type of reactive power compensator which improves the voltage profile of the power system. For stabilizing and supporting the power supply the smart loads with embedded electric spring distributes across the distribution network is a new control example required for future power system.

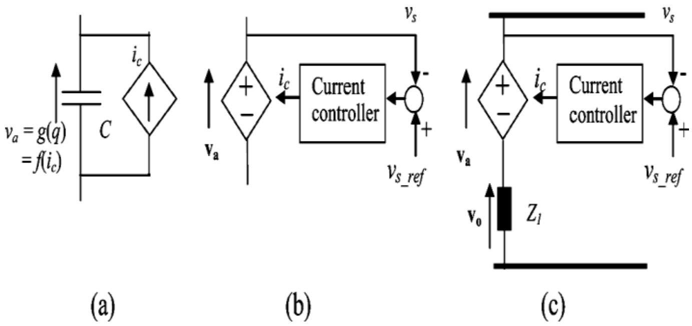


Fig. 2 (a) An electric spring in form of a capacitor fed by controlled current source. (b) Schematic of an electric spring with input voltage control. (c) An electric spring in series with a dissipative load for energy storage, voltage support and damping.

As we know that grid is very sensitive equipment of power system which does not tolerate any deviation/fluctuation on its terminal in any parameter like voltage and frequency etc. But the renewable energy sources are having varying supply which totally depends on the environmental condition such as wind speed in case of wind power system. Hence these renewable energy sources cannot be directly connected to grid, if we do so, then the total grid will collapse. Hence it is must to make the supply of renewable energy sources as constant by eliminating voltage fluctuation from its supply. This is the main motive of the present thesis to compensate the voltage fluctuation so as to increase the usage of RES in own network which will definitely help in eliminating power grid problem.

The voltage support is generally required to reduce voltage fluctuation at a given terminal of transmission line. Reactive power compensation in transmission systems also improves the stability of the ac system by increasing the maximum active power that can be transmitted. Already there is some research work done on reactive power compensation they are as follows: The description of linearity was presented by Hooke's i.e. 'extension is proportional to force' [3]. Hooke's also recognized the behavior of material that returns to its original shape after loading is removed. The fundamentals of UPFC and modeling techniques using an EMTP simulation package, development of a conventional feedback control scheme which makes the UPFC induce power fluctuation in transient states and new technology of real and reactive power coordination controller for a UPFC were seen in [4-6]. The UPFC are used to control the power flow through an electrical transmission line connecting various generators and loads at its sending end and receiving end. The new control algorithm for three phase three wire series active power filter is based on generalized p-q theory concept. With this algorithm this filter compensates for the harmonics and reactive power that was generated by nonlinear loads such as thyristor rectifier and diodes [7].

The use of static VAR generators to improve voltage regulations, stability and power factor in ac transmission and distribution systems and how the reactive power affects power system operations, the challenges to voltage control in power systems and to provide background information on the mathematical challenges associated with voltage control and reactive power supplies[8-9]. This paper presents an energy efficiency comparison of the electromagnetic and electronic ballast systems under both full power and dimming conditions [10]. for controlling the output from individual DG's that were installed in micro grid the author developed an energy control system because as we know that DG's uses an renewable energy sources have an unstable output and this can negatively affect existing electric power system [11]. To control the active power supplied by distributed generation system while compensating harmonics and reactive currents caused by non-linear loads using shunt active power filter were seen in [12].

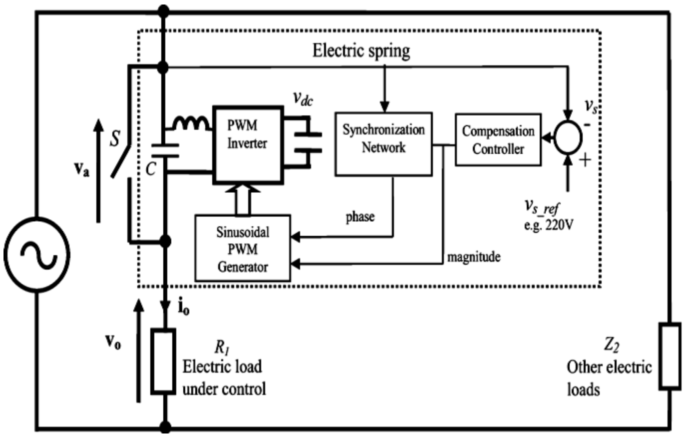


Fig. 3 Control block diagram of electric spring.

The earlier technology shows that the traditional series reactive power compensators use output voltage control for a reactive power controller, but the proposed technology demonstrate characteristics different(input voltage control) from traditional devices such as series reactive power controller. The effects of this subtle change of control methodology and the interactions between the electric springs and energy storage in a power grid, which have not been previously addressed. Unlike STATCOM, Static VAR Compensation, and UPFC technologies, electric springs offer not only reactive power compensation, but also automatic load variation in non-critical loads (with electric springs embedded). The main contributions of this paper are:

- MATLAB simulation model of Electric spring for single phase circuit.
- Analysis of the different modes of operation of ES circuit.
- Implementation of Electric Spring Simulink model for 3 phases system.
- Operation of Electric Spring circuit during power fluctuation due to renewable energy source is examined.
- Analysis the different results of circuit when connected to 3 phase system.

The rest of paper is organized as follows. Section II contains the overview of some basic concepts and formulae, control strategy and different operating modes; section III contains implementation of spring circuit for 3 phase system; section IV contains simulation results and discussion of different cases. Conclusions are summarized in section V.

II. Application of Hooke's Law for Stabilizing Power Grid

A. *Hooke's Law in the Mechanical Domain*

The principle of the mechanical springs has been described by Robert Hooke in 1678. The relationship between force and displacement are as follows-

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

Where F is force vector, k is the spring constant and x is the displacement vector. The negative sign indicates that this force is in the opposite direction of the force that's stretching or compressing the spring. The potential energy (PE) stored in the mechanical spring is,

$$P.E = \left(\frac{1}{2}\right) kx^2 \quad (2)$$

B. *Hooke's Law in the Electric Domain*

An electric spring is similar to a mechanical spring that can be used to provide electric voltage support, to store electric energy and to stabilize system operation [7]. Similar to the equation (1) the basic physical relationship of the electric spring is expressed as,

$$q = -Cva \text{ Capacitive mode} \quad (3)$$

$$q = Cva \text{ Inductive mode} \quad (4)$$

$$q = \int ic\, dt \quad (5)$$

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 electric spring can be seen from the potential electric energy stored in capacitor.

$$P.E. = \frac{1}{2} C\, va^2 \quad (6)$$

Equation (3, 4) shows that dynamic voltage regulation (i.e., voltage boosting and reduction) functions of the electric spring can be controlled by the charge stored in the capacitor. Equation (5) indicates that the charge q control can be realized by using a controlled current source.

C. *Basic Princilple of Electric Spring*

Analogous to a mechanical spring, an electric spring is an electric device that can be used to: i) provide electric voltage support; ii) store electric energy; and iii)damp electric oscillations. The equation (3) shows that the dynamic voltage regulation (i.e. voltage reduction and voltage boosting) function of the electric spring can be controlled by the charge stored in the capacitor. The equation (4) is shows that the charge (*q*) control can be realized by using a controlled current source. Therefore electric spring can be represented as a current controlled voltage source. During voltage deep it boosts the voltage level up to a required value and during overvoltage it compresses the excess voltage, hence it is used to regulate the voltage level of the power system to a particular value. An analogy of mechanical spring and electric spring under three different conditions are shown in figure.1 in which an electric spring is connected in series with electric load Z_1. The reference voltage of the electric spring is a neutral position of the electric spring at which spring is designed to maintain. To maintain the ac mains voltage V_S to its normal reference level $V_{S\text{-ref}}$, the arrangement of electric spring in the series with Z_1 across the ac mains. This condition considered as neutral position. When displacement is changed from the neutral position analogous to mechanical spring that can develop mechanical force in either direction, an electric spring can provide voltage boosting and voltage reduction function as shown in figure.1

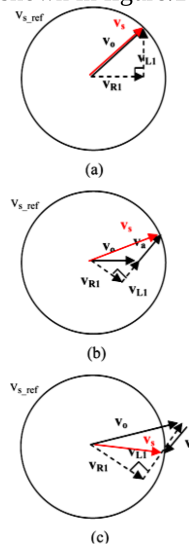
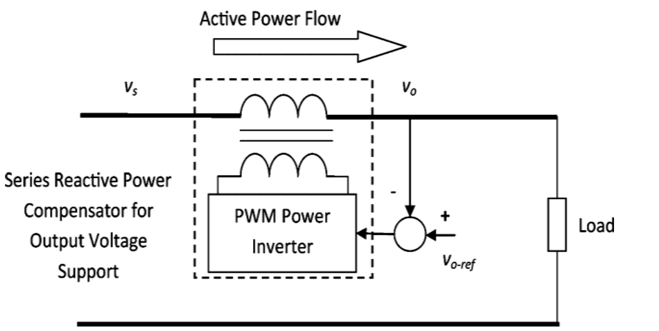


Fig. 4 Operating modes of electric spring to maintain Vs to Vs_ref for a non-critical load (a) Neutral (Va = 0). (b) Inductive mode (non-critical load power reduction for voltage boosting). (c) Capacitive mode (non-critical load power boosting for voltage reduction).

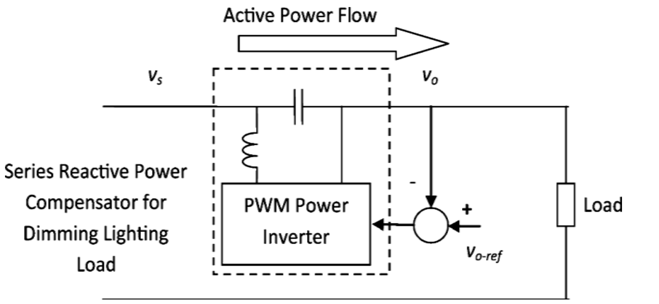
The electric spring voltage Va can be generated practically by dynamically controlling the electric potential difference across a capacitor C with a current source ic [figure. 2(a)] under a closed loop control [figure.2(b)]. The charge control in (5,6) provides a means to generate an electric voltage in both directions to boost or reduce the mains voltage in a power system. This control makes the dynamic voltage support function of the electric spring feasible.

D. *Control Strategy and Different Operating Modes of Electric Sring*

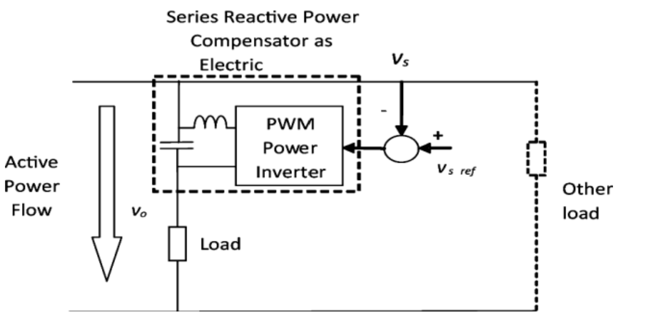
Figure 3 shows the control block diagram of electric spring. The difference between the actual ac mains voltage Vs and the reference mains voltage is fed to a compensation controller, which can be any suitable controller such as a proportional-integral (PI) controller or a lead-lag compensator. The output of the compensation controller provides a control signal for Pulse-Width-Modulated (PWM) generator. A synchronization network is used to provide the phase information for the PWM generator, which generates the switching signals for the power semiconductor switches of a power inverter to generate a high-voltage sinusoidal PWM voltage waveform. The dc voltage of the power inverter is usually obtained from a capacitor which is charged through the anti-parallel diodes of the inverter switches (like a diode rectifier with an output dc capacitor). The PWM voltage generated by the power inverter is filtered by a low-pass LC filter so that an auxiliary sinusoidal voltage Va can be created. The test is conducted to determine the different modes of spring which includes i) Neutral mode ii) capacitive mode and iii) inductive mode conditions Vs = 220V (50Hz) and R1 = 51.4.When the spring operates in neutral mode i.e. no compensation is provided. The waveforms of mains voltage (Vs), non-critical load voltage (Vo), the electric spring voltage (Va) and electrical spring current (which is same as the non-critical load current) are shown in figure.8. In this case, Vo is essentially equal to Vs as the Va is only 6 V rms for a 220V mains.



(a)



(b)



(c)

Fig. 5 (a) Control schematic of series reactive power compensator for output voltage support in transmission [9]-[15]. (b) Schematic of series reactive power compensator as a central dimming system[18], [19]. (c) Schematic of series reactive power compensator as an electric spring.

When the spring operates in capacitive mode, the waveforms are shown in figure 9. It can be observed that electric spring current leads the electric spring voltage. Here negative reactive power is provided by the electric spring and Vo is smaller than Vs.Then the spring operates in the inductive mode and the waveforms are shown in figure 10. In this mode it can be seen that electric spring current can be controlled to lag the electric spring voltage. Here electric spring injects positive reactive power into the system to provide voltage support. The figure 4(a)- 4(c) shows the vector diagrams of the system (figure. 3) with the electric spring under three operating modes for a noncritical load comprising an inductive-resistive load (e.g., a lighting load).The circle in the vector diagram represents the nominal value of the mains voltage V_{S-}ref (e.g., 220 V). The vectors are assumed to rotate in an anticlockwise direction at the mains frequency (e.g., 50 Hz).Figure. 4(a) depicts the situation when the electric spring is in a “neutral” position in which V_a=0.This refers to the situation that the power generated by the renewable power source (such as a wind farm) is sufficient to meet the load demand and simultaneously maintain V_S at the nominal value of $V_{S\text{-ref}}$. Figure. 4(b) represents the situation when power reduction in Z_1 is needed in order to keep V_S at $V_{S\text{-ref.}}$ Here V_a is positive (making V_0 less than $V_{S\text{-ref}}$) in order to provide the “power reduction” function under the inductive mode of the electric spring. If the generated power is higher than the load demand V_S will exceed $V_{S\text{-ref}}$ resulting in an over-voltage situation. In order to regulate Vs at V_{S_ref}, Fig. 4(c) shows that the electric spring can provide “power boosting” function by operating under the capacitive mode.

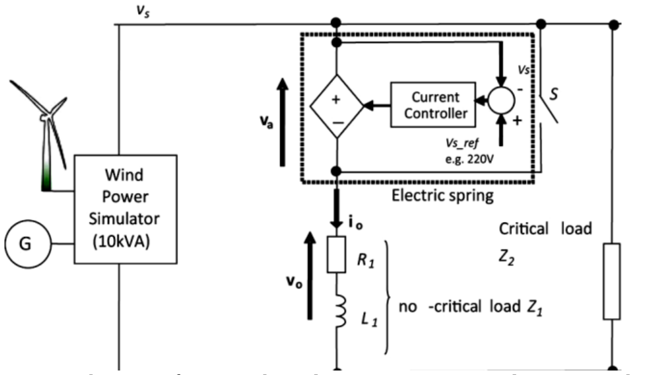


Fig. 6 Schematic of setup with an electric spring connected in series with a load $Z_{1.}$

In power system there are several forms of applications of shunt and series reactive power controllers [9]-[10]. In the last two decades reactive power controllers (RPC) have been developed in power industry to control power flow in high voltage transmission lines [11]–[12] and for dimming lighting systems. In traditional uses of series reactive power controllers for voltage regulation, the output voltage of the power controller is usually regulated. Their simplified control schematics are illustrated in figure 5(a) and 5(b), respectively. It is important to note that the electric spring differentiates itself from previous use of RPC with the adoption of an “input-feedback and input-voltage control” as shown in figure 5(c). By regulating the input voltage Vs and letting the output voltage Vo to fluctuate dynamically (i.e., a new input-voltage control), such RPC would: i) provide the voltage support as an electric spring and ii) simultaneously shape the load power to follow the available power generated by renewable energy source. Such subtle change in the control strategy of a RPC from output control to input control offers new features and functions for power and voltage control.

III. PRACTICAL EVALUATION

A. Operation of Electric Springin an Unstable Power Grid fed by Intermittent Renewable Energy Sources

The electric system in figure.6 is used to illustrate the concept and the operating limits of an electric spring. This system consists of an unstable ac power supply generated by a manually ac power source. In this system, an electric spring is installed in series with an electric load Z1 as previously explained. Together, the electric spring and Z1 form a "smart load." The dissipative load Z1 is termed a "noncritical" load because it can be operated at an AC voltage supply (Vo) with some degree of voltage fluctuation. Examples of "noncritical" loads include electric water heaters, refrigerators, and lighting systems. Generally, the electric load Z1 can be represented as an inductor L1 in series with a resistor R1. Other electric load Z2 that requires a well-regulated mains voltage is termed a "critical" load. The non-critical loads are the electric equipment and appliances that can be subject to variation of mains voltage. Critical loads are the electric loads that required well regulated mains voltage such as life supporting medical equipment.

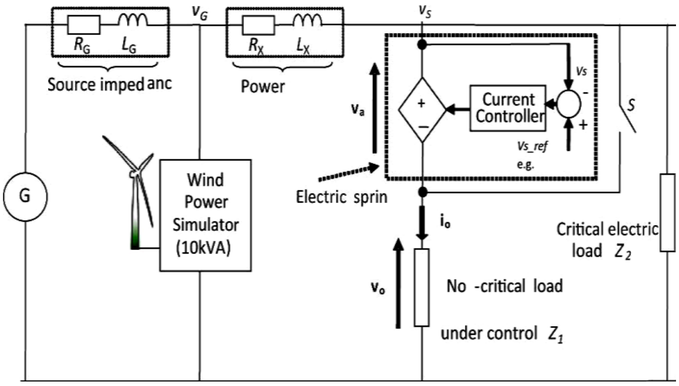


Fig. 7Schematic of an electric power system with an electric spring.

The load can be divided into two parts, a non-critical load and critical load. The electric spring is connected in series with non-critical load at that condition we can ensure that the power and voltage at the critical load to remain constant when the line voltage feeding the load fluctuates. The arrangement of this type of load is called as 'smart load'. The main aim of this electric spring is to restore V_S to the nominal value of the mains voltage $V_{S\text{-}ref}$. The general power balance equation of figure 6 is,

$$Pin = \left(\frac{VO}{Z1}\right)^2 Re\ (Z1) + \left(\frac{VS}{Z2}\right)^2 \mathrm{Re}(Z2) \qquad (6)$$

$$Pin = P1 + P2 \qquad (7)$$

Where V_0 and V_S root-mean-square values of the noncritical load voltage and the ac mains voltage, respectively; Re (Z) is the real part of Z that represents the restive element R. Z_1 and Z_2 are the impedances of non-critical load and critical load. The vector equation for the electric spring is

$$Vo = Vs - Va \quad (8)$$

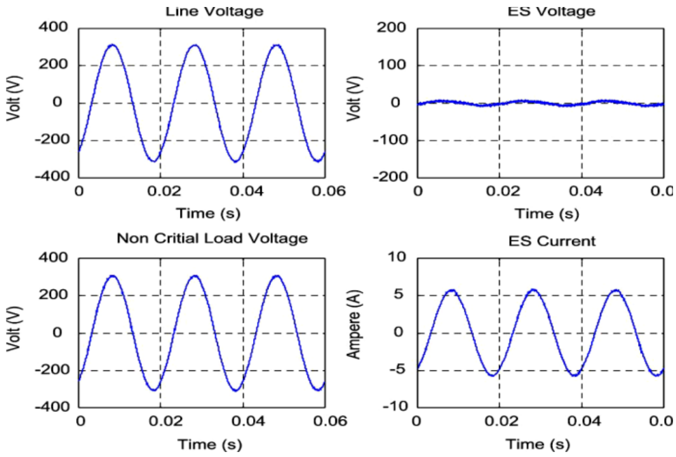


Fig. 8 Measured steady state electric spring waveforms under neutral mode.

At the nominal value $V_{S.\text{-ref}}$, equation (7) shows that if the mains voltage is regulated by the electric spring, the power P_2 should remain constant for the critical load. . If the power generated Pin cannot meet the full power for both P1and P2, the input-voltage control of the electric spring will generate a voltage vector Va to keep Vs regulated at V_S ref. From (8), the Voltage vector V_0 across Z1 will be reduced and so the power consumption P1 of Z1 will also be reduced. Therefore, if the electric spring performs well P2, for the critical load should remain constant as expected and P1 for the noncritical load should follow the power generation profile.

B. Operation of Electric Spring with Intermittent Renewable Power Injection

The figure 7 shows the modified setup of in a power system including the source impedance of the power supply. Due to the presence of the impedance of the network box, the voltage at the generator side is labeled as V_G and the mains voltage at which the electric spring is located is labeled as Vs. It has been demonstrated in figure. 5 that a smart load, when operated in a stand-alone mode, maintains constant voltage and power for the critical part of the load. When a smart load is connected to a power distribution system as in the case of figure. 7, interactions between the system impedance and the smart load, as well as the voltage and power characteristics of the power supply, will affect the performance of the smart load. Due to the injection of both real and reactive power from distributed power sources in future smart grid, the electric springs can be operated dynamically under neutral, capacitive or inductive mode with the objective of regulating the mains voltage.

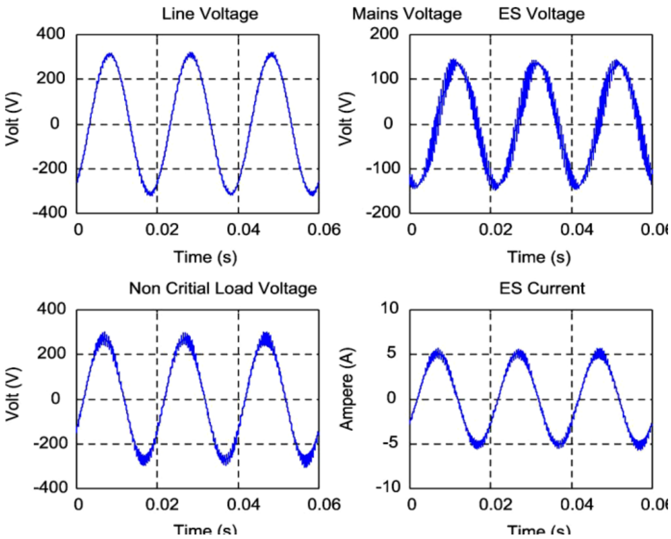


Fig. 9 Measured steady state electric spring waveform under capacitive mode

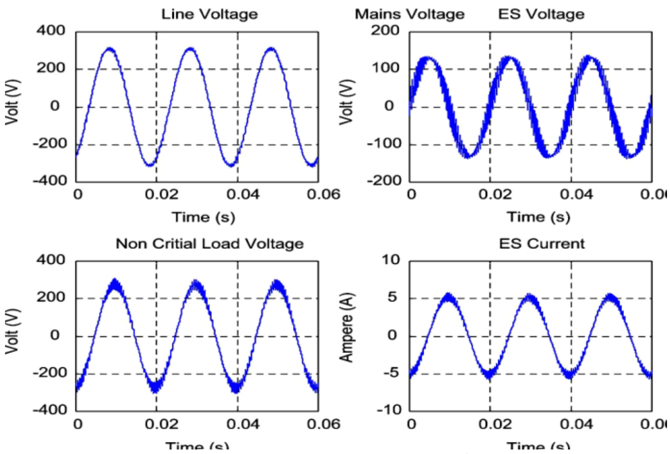


Fig. 10 Measured steady state electric spring waveform under inductive mode

IV. Results and Discussions

A. *Case (i) Electric Spring as Novel Concept*

In this case we have demonstrated the spring function for single phase network. The different operating modes (neutral, inductive and capacitive modes) are already explained under section 3. The figure 3 shows the actual control strategy of the spring circuit and the results of all operating modes are shown. Figure 8 shows operation in neutral mode. Figure 9 shows the capacitive mode and figure 10 shows inductive mode.

B. *Case (ii) Operation of Spring on Unstable Grid Connected to Intermittent Renewable Energy Source*

In this case demonstration of three phase circuit is done by using MATLAB/Simulink model. Here the intermittent renewable power source is created by power inverter which generates power according to predefined intermittent wind profile. A predefined wind profile is fed to inverter to generate ac mains voltage pattern in bus-bar. Both the smart load (non-critical load) and critical load are connected to the circuit. The predetermined wind profile values are repeating after every 2100ms. To separate the operation of circuit with spring and without spring are presented using bypass switch. In this test condition the spring is allowed to come into picture after 2000ms. Hence this enables us to observe the difference between the operation of circuit before as well as after introduction of spring to the power system. Here we can clearly see that when the bypass switch is closed the spring is deactivated, the non-critical load voltage (Vo) overlaps the unstable mains voltage (Vs). After 2000ms the spring is activated and the mains voltage is successfully boosted or supported to 220V.

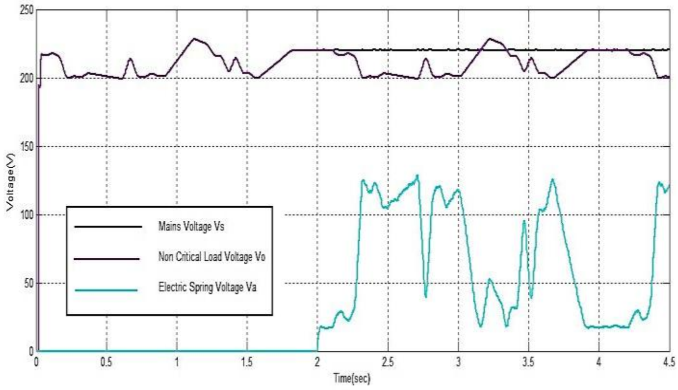


Fig. 11 Measured rms values of the mains voltage, non-critical load voltage and electric spring voltage before and after the spring are activated.

The bouncing action of the electric spring voltage can be seen from figure.11. The electric spring acts like a "voltage suspension spring" to maintain a constant mains voltage. It is noted that when the noncritical load voltage reaches 220 V (i.e., no voltage support is needed), the electric spring voltage drops to zero. The noncritical load voltage is reduced when the electric spring generates positive voltage to support the mains voltage. The consequential variation of provides an automatic mechanism to shape the load demand to follow the dynamic changes of the wind power profile. This effect can be observed from the practical power measurements of the smart load unit in figure 12.

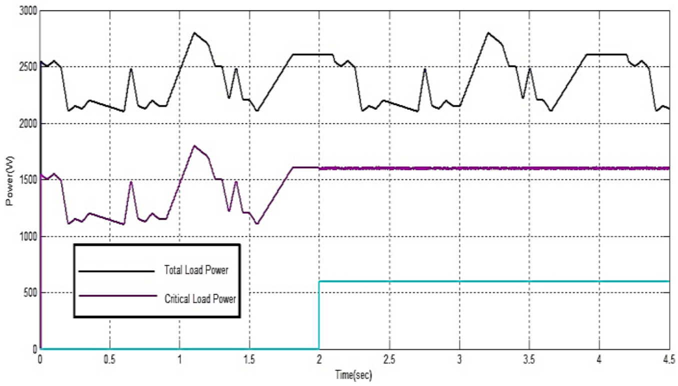


Fig. 12 Measured powers of critical loads and non-critical loads.

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

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C. Case (iii) Operation of Electric Springon Grid Injected with Intermittent Renewable Energy Source

This case is clearly explained by block diagram shown in figure 7. In this case a smart load unit comprising a combination of resistors (representing water heaters) has been setup. Two power sources separated by a transmission network box are used in this test. An AC voltage source and an intermittent renewable voltage source are used together to simulate the situation when intermittent renewable power becomes a substantial portion of the total power generation. In order to simulate the wind power generation, a recorded wind profile is used for the power inverter to generate the wind power.

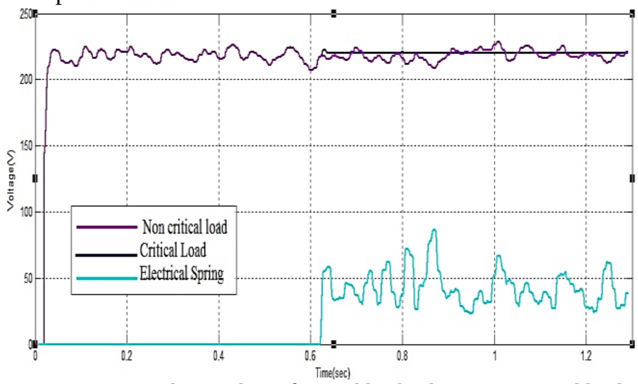

Fig. 13Measured rms values of critical load voltage, non-critical load voltage, and electric spring voltage before and after electric spring are activated.

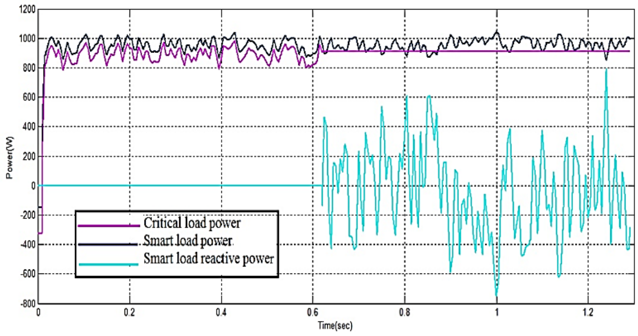

Fig. 14 Measured power of the critical load and smart load.

Similar to the previous case a predefined wind profile is fed to inverter to generate ac mains voltage pattern in bus-bar. Both the smart load (non-critical load) and critical load are connected to the circuit. The predetermined wind profile values are repeating after every 2100ms. To separate the operation of circuit with spring and without spring are presented using bypass switch. In this test condition the spring is allowed to come into picture after 620ms. Figure 13 shows the measurements of the (scalar) rms values of the critical load (mains) voltage, the noncritical load voltage and the voltage of the electric spring before and after the electric spring is activated. Before the electric spring takes action in the first half of the test, the mains voltage fluctuates in the region below and above the rated value of 220 V. Because the bypass switch is closed when the electric spring is deactivated, the noncritical load voltage overlaps with the unstable mains voltage in the first voltage pattern generated by the wind power simulator. However, it can be seen that, when the electric spring is activated in the repeated voltage pattern in the second half of the test, the mains voltage can be successfully regulated to 220 V. This result demonstrates the effectiveness of the electric spring in both voltage regulation and shaping the load demand to follow the wind power. These measurements confirm the scientific theory and the effectiveness of the electric spring in regulating the mains voltage of an unstable power system and in balancing the wind power and the load power dynamically shown in figure 14.

V. CONCLUSION

The control strategy, different operating modes and operation of electric spring is explained in this paper. By using MATLAB/Simulink software the Electric Spring is implemented for voltage boosting and voltage suppression operation to follow the fluctuating wind profile in a 10KVA power system fed by an AC power source and a wind fluctuation generator. If incorporated in power system the Electric Spring is highly effective and reliable solution for distributed energy storage, voltage regulation and damping operation for future power system and it is also independent of Information and Communication technology. Unlike traditional reactive power compensation techniques this concept not only provides the reactive power compensation but also variation of real power in Non critical load. Hence this concept turns many non-critical loads into new generation of smart load which have their load demand automatically following power generation profile which is new control strategy required in future power grid with distributed renewable energy sources.

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