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Reactive Power Compensation at Load Side Using Electric Spring

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***Abstract**: Electric spring is a recently proposed concept to enhance the stability of future smart grid with renewable energy sources. Electric spring along with noncritical loads can form smart load which can be used to regulate the voltage at the point of distribution system where it is connected. In this paper, electric spring is implemented using Simulink. By observing the voltage waveforms with and without electric spring, the effectiveness of electric spring in regulating mains voltage is verified.*

***Index Terms:** demand management, electric spring, reactive power compensation, smart loads, stability.*

I. Introduction

The increasing awareness of climate change has encouraged many governments worldwide to adopt policies that call for the implementation of renewable energy sources. Presently, power generation companies produce electrical energy in a centralized and unidirectional manner. A balance of power generated and load demand is an essential condition for maintaining stability of power grid. In order to maintain power system stability, the control paradigm used in existing power systems is to have “the power generation follow the load demand”. In the emerging smart grids, the renewable power sources such as wind and solar will be installed in a distributed manner and power generation could be bi directional. These distributed renewable energy sources make it difficult to precisely predict the power flow within the smart grid and it will not be easy to control the power flow centrally within the smart grid systems. Therefore, there is a need of change in the existing control paradigm with penetration of dynamically changing renewable energy sources. In the new paradigm “load demand has to follow power generation”.

In order to achieve power balance various methods have been proposed like use of energy storage, real time pricing, scheduled load shedding, direct ON-OFF control etc. [1]-[4]. Scheduled load shedding has been a traditional method in load power control. However, such a method is not useful for maintaining dynamic power balance in real-time. Smart loads With ON/OFF control for electric loads, such as refrigerators and air-conditioning systems, have been proposed for real-time power balance. However, turning off of electrical appliances may cause inconvenience to and opposition from consumers. Energy storage could be regarded as the most effective means for instantaneous energy balancing. However, the cost of battery storage is very high. In addition, disposed batteries would cause another environmental problem. Although batteries are considered as essential elements in future smart grid, it is more desirable to reduce their size for cost and environmental reasons. The use of “Electric Springs” has recently been proposed as a novel and simple way of distributed voltage control enabling effective demand-side management without any need for communication [5]. A paradigm change 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”. Electric Springs can be used for various applications in the power system domain like voltage regulation, three phase power balancing, mitigation of voltage and frequency fluctuations and it is also demonstrated that the performance of electric spring is better than the existing FACTS controllers like the STATCOM [6]. It is utilized to stabilize the voltage of critical load, through modulating noncritical load voltage. Critical loads like sophisticated and medical electrical load, etc. are sensitive to the change of voltage, and they are connected to the grid directly. Noncritical loads like water heaters, lighting systems, etc. are able to tolerate voltage fluctuation, to certain extend without causing much inconvenience to the customers and they are connected in series with electric spring.

II. Basic Principles Of Electric Spring Operation

A mechanical spring is an elastic device that can be used to provide mechanical support, store mechanical energy and to damp mechanical oscillations. When a mechanical spring is stretched or compressed, the force applied is proportional to its change in displacement. Potential energy is stored in the mechanical spring when the length of the spring varies from its natural length. The principle of the mechanical springs has been described by Robert Hooke in 1678 [7]. The Hooke’s law states that the force of an ideal mechanical spring is:

$F = -kx$ (1)
where F is the force, k is the spring constant and x is the displacement vector. The potential energy stored is given by:

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

An analogy is used to introduce the concept of electric spring, which will: 1) Provide voltage support; 2) store electrical energy; 3) damp electrical oscillations.
The analogous equations are given by:

$$q = \begin{cases} Cv_a \\ -Cv_a \end{cases} \quad (3)$$

$$q = \int i_c dt \quad (4)$$

Where q is the electric charge stored in a capacitor with capacitance C, v_a is the electric potential difference across the capacitor, and i_c is the current flowing into the capacitor. Equation (3) shows that voltage regulation (i.e., voltage boosting and reduction) functions of the electric spring can be controlled by the charge stored in the capacitor. Equation (4) indicates that the charge control can be implemented using a controlled current source. Therefore, a current-controlled voltage source can be used to represent an electric spring [5].

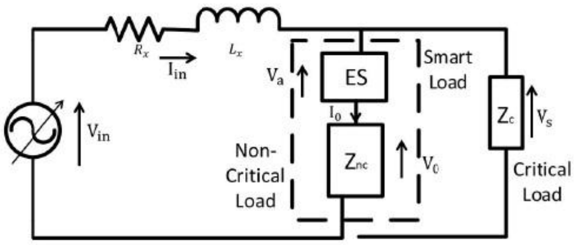


Figure 1. Overview of electric spring in series with noncritical load

An electric spring is an ingenious device installed in series with noncritical load(s), like water heaters and air conditioning systems, which can withstand voltage fluctuations in a renewable energy based micro grid. This series connection is used to maintain voltage at the point where device is connected V_s, to the reference value V_{sref}. As shown in Fig. 1 the critical load is connected in parallel to the smart load consisting electric spring and noncritical load. The voltage across it is V_s. Also, electric spring can be utilized for both active and reactive power compensation. The compensation voltage V_a have to be perpendicular to the noncritical load current Io in order to make electric spring lossless (Fig. 1). This means for a resistive-inductive load V_a should be leading Io by 90° and provides capacitive compensation and vice-versa for resistive capacitive load. It is explained through vector diagrams in Fig. 2 [5]. The phasor sum of noncritical load voltage V_o and ES voltage V_a is equal to the voltage at PCC. The vector equation for voltage can be written as:

$$V_s = V_o \pm V_a \quad (5)$$

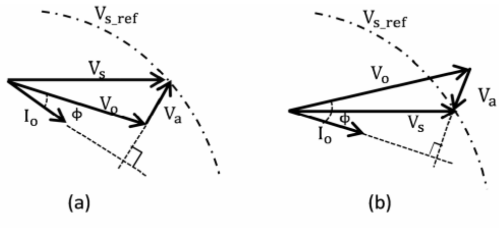


Figure 2. Phasor diagram of Electric Spring (a) inductive mode (b) capacitive mode

When the rms voltage across the critical load is less than the reference rms voltage V_{sref}, the ES voltage boosts it up to the reference value by adjusting the voltage across the noncritical load V_o. Similarly, if the rms voltage V_s exceeds reference voltage, ES will suppress it to the reference value. ES will manipulate the noncritical load current Io and in turn varies circuit current I_{in} to maintain the equation:

$$V_{in} - I_{in}(R_x + jwL_x) = V_s = V_{sref} \quad (6)$$

III. Circuit Realisation Of Electric Spring

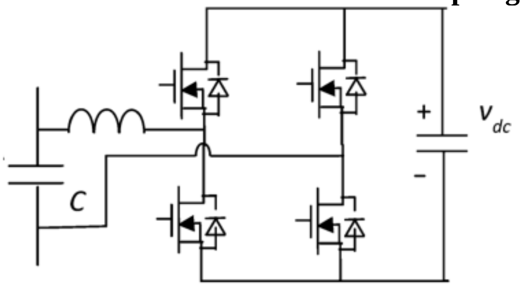


Figure 3. Full H bridge inverter employed in the scheme

Electric spring is realised using a single phase full bridge inverter as shown in Fig. 3[9]. A full H bridge inverter with a bulky capacitor on dc side and a LC filter on ac side is used. The PWM signals from PWM generator is given to MOSFET gates. This will control the voltage across capacitor C on ac side, i.e. the electric spring voltage. The four freewheeling diodes will form the diode rectifier circuit, which rectify ac voltage into dc and charge the bulky capacitor [8]. The maximum voltage attainable with full bridge topology is twice that of with half bridge topology and hence reduces the switching currents to half of the latter [9]. This will reduce stress experienced by switches and consequently life expectancy of electric spring increases. With half bridge inverters there is always possibility of generation of even harmonics due to non identical capacitances; however with full bridge configuration such possibility is completely eliminated.

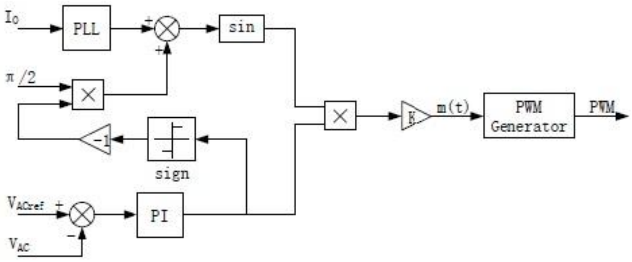


Figure 4. Control blocks of electric spring

The control circuit is shown in Fig. 4. The dynamic changes of the DC link and losses are ignored in this model [10]-[11]. Therefore electric spring will exchange only reactive power with the grids. The reference signal required by the PWM inverter is generated by decoupling scalar value of modulation index and phase of the sine wave. The modulation index, m can be calculated by comparing critical load voltage (rms) V_s with reference voltage V_{sref}. The phase of noncritical load current is obtained through a PLL. Depending on noncritical load characteristics, the phase angle is shifted by 90 degrees leading or lagging. Thus, the reference signal will be obtained as

$$V_{PWM\_ref} = m sin(wt + \theta) \qquad (7)$$

IV. Simulation Of Electric Spring

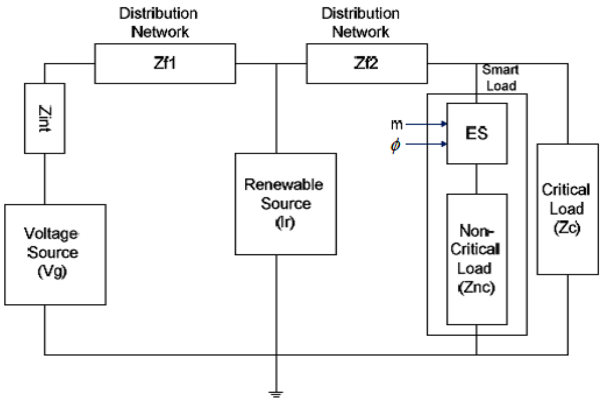
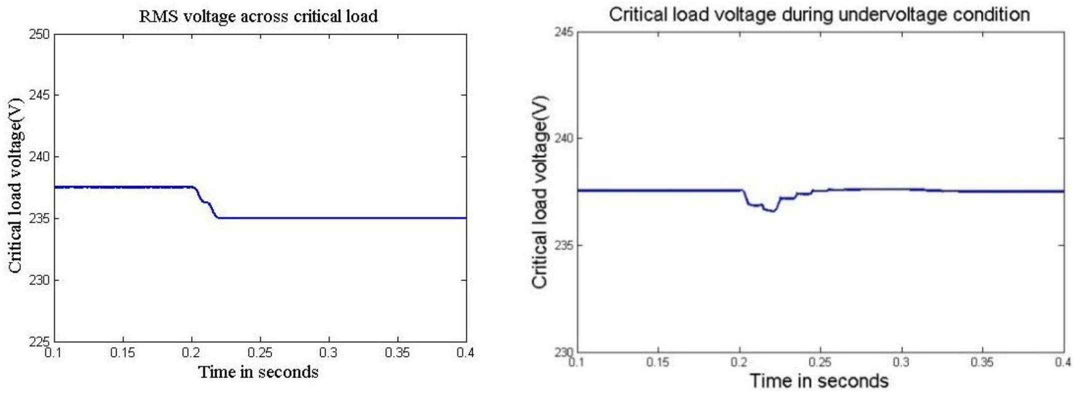


Figure 5. Schematic diagram

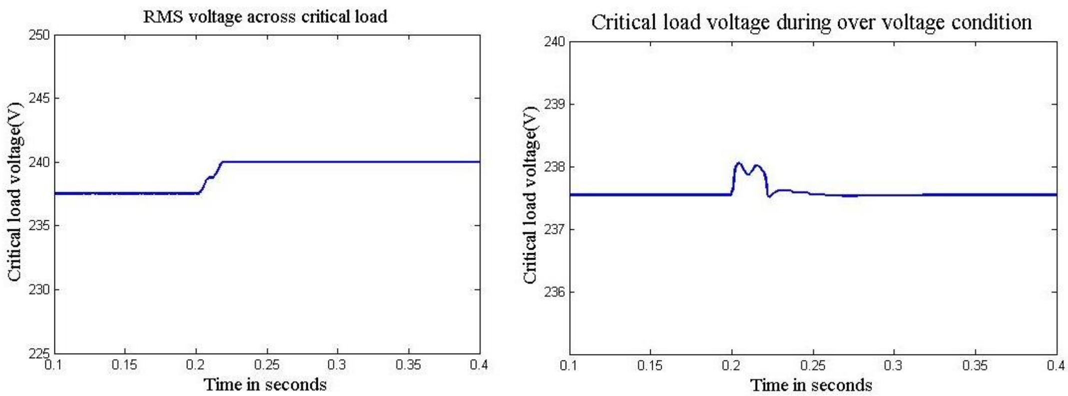
Fig. 5 shows the block diagram of the overall test system which is modeled in MATLAB/SIMULINK. The bulk power system is represented using a voltage source system. The active and reactive power fluctuation from the renewable energy source is modeled using a controllable current injection at the point of connection with the system. The amplitude of the current is determined by the active and reactive power exchanged. Two segments of the network are modeled by lumped R-L equivalent. The resistance and inductance of the line are 0.1 ohm and 2.5mH. The smart load comprising the electric spring and a resistive noncritical load in series and the critical load are connected at the PCC. The smart load controller controls the voltage injected by the electric spring in series with the noncritical load. For simplicity, both the critical and noncritical loads are assumed to be purely resistive. The resistance of critical load is 34.6 ohm and noncritical load is 80.4 ohm. In simulation process electric spring works in bucking and boosting models.The results when the system is subjected to under voltage conditions with and without electric spring are shown in Fig. 6. At 0.2s, current source injects a current into the system that leads the voltage at PCC. The reactive power consumption is increased, and the critical load voltage is decreased. The electric spring operates in capacitive mode, i.e. noncritical load current will lead the electric spring voltage by 90 degrees to increase the voltage to nominal value and injects sufficient amount of negative reactive power into the system to boost the voltage. The noncritical load voltage will decrease when electric spring is employed.



(a) (b)

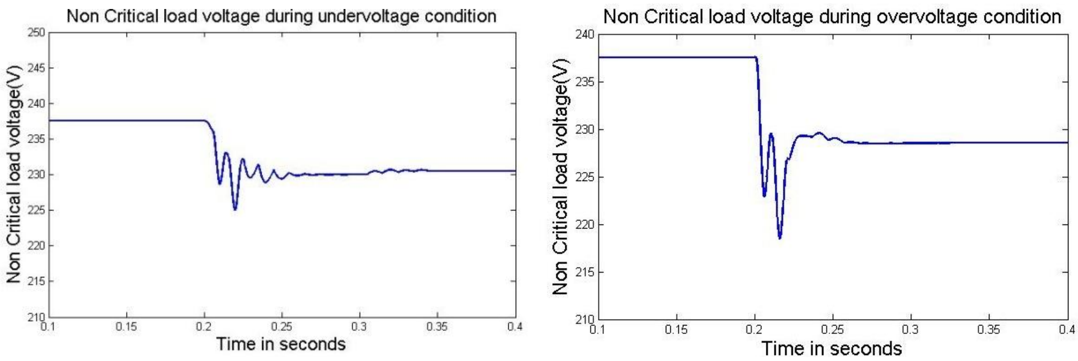
Figure 6. Critical load voltage during under voltage conditions (a) without electric spring (b) with electric spring

The action of electric spring during overvoltage condition is shown in Fig. 7. At 0.2s, current source injects a current into the system that lags the system voltage by 90 degrees. Without electric spring, critical load voltage increases after 0.2s. In order to regulate critical load voltage electric spring will operate in inductive mode, i.e. electric spring voltage leads noncritical load current by 90 degrees and injects sufficient amount of positive reactive power into the system. Fig. 8 shows noncritical load voltage for both under voltage and over voltage conditions. It can be noted that in both cases noncritical load voltage decreases when electric spring is employed due to increase in compensation voltage. Substantial penetration of electric spring with other noncritical loads in the grid can help to achieve the required reactive power compensation.



(a) (b)

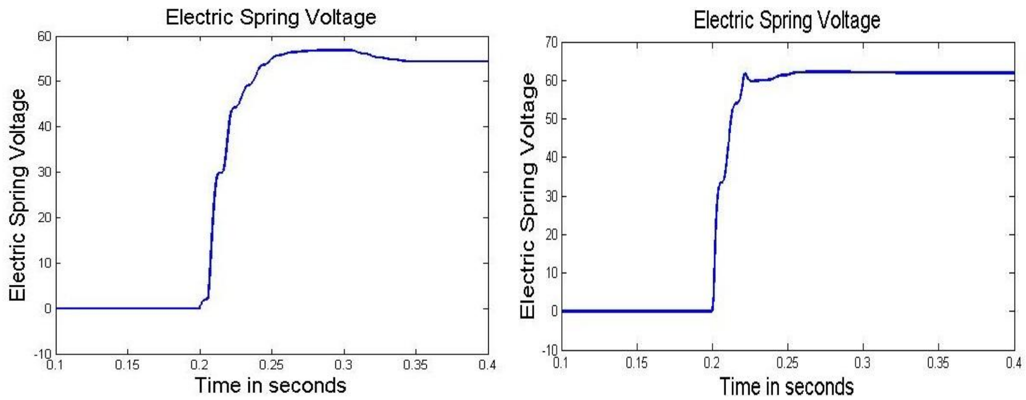
Figure 7. Critical load voltage during over voltage conditions (a) without electric spring (b) with electric spring



(a) (b)

Figure 8. Noncritical load voltage during (a) under voltage conditions (b) over voltage conditions

Fig.9. shows the electric spring voltage for both cases. At 0.2s, electric spring voltage changes to stabilize the critical load voltage. It can be inferred from the results that electric spring controls reactive power to regulate critical load voltage. It can also be observed that by keeping the mains voltage constant at its reference value and allowing noncritical load voltage to fluctuate, it is possible to achieve the new control paradigm of load demand following power generation (Fig. 10). At 0.2s source power will change due to injection of output current from controllable current source. Noncritical load will follow source power. Critical load power remains constant by the action of electric spring. Therefore electric spring can be implemented as new demand side management technique. Along with supply side management technique like risk limiting dispatch principle it is possible to achieve the new control paradigm.



(a) (b)

Figure 9. Electric Spring voltage during (a) under voltage conditions (b) over voltage condition

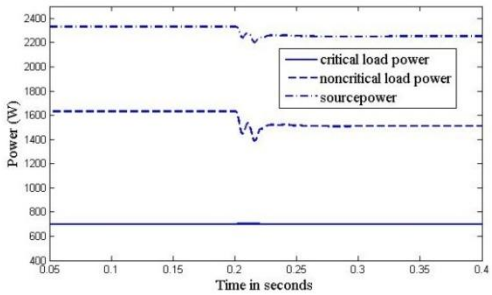


Figure 10. Measured source power, noncritical load power and critical load power during over voltage conditions

V. Conclusions

The use of renewable energy sources for power generation is increasing due to increase in fuel price as well as due to change in climate. The intermittent nature of renewable energy sources raises concerns regarding power system stability. Various demand side management techniques have been proposed like use of energy storage, ON-OFF control load etc. But all these methods have their own pros and cons and they are not suitable in real time scenario with penetration of distributed renewable energy sources. Electric spring is a new demand side management technology proposed to tame the intermittent nature of renewable energy sources.It is illustrated through simulation that electric spring can be implemented using a full H bridge PWM inverter along with noncritical loads such as water heaters. The results show that the voltage fluctuation can be stabilized effectively by electric spring. Even that the change of the DC link is taken in to account, the effects of reactive power fluctuation can be eliminated. This feature along with possibility of controlling active and reactive power confirms the argument that electric spring are insightful devices for stability control in renewable energy powered micro grids 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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