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IMPLEMENTATION OF ELECTRIC SPRING FOR ENHANCING VOLTAGE AND POWER STABILITY WITH POWER CORRECTION

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***Abstract* —** *ES 'Electric Spring' which called as smart gird device which used to dispatch active and reactive power in the system which is connected between the Gird and Load or demand and supply. It has been proposed as the demand side management technique to provide voltage and power regulation. In this paper, a new scheme is presented for the implementation of the electric spring, along with non-critical building loads like electric heaters, refrigerators and central air conditioning system. This is the control system provide power factor correction, voltage support, and power balance for the crucial loads for example like the building's security system, in addition to the existing characteristics of an electric spring of voltage and power stability. The proposed control scheme is compared with the original ES control scheme where only reactive power is injected. The updated control system opens with the new way for the use 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.*

Keywords: *Demand Side Management, Electric Spring, Power Quality, Single Phase Inverter, Renewable Energy.*

I. INTRODUCTION

A microgrid is a collection of distributed generators, loads and energy storage systems which are recently expected to be installed massively. A microgrid is connected to the local generating units and also to the national grid to increase the security and reliability of the power system. Installing a microgrid involves several benefits such as: it is more environmentally friendly because it uses the renewable resources with low or zero emission generators, it aims at reducing the number of failure of the utility grid during the peak load demand, it increases the overall energy efficiency of the power system being the users close to the renewable sources, it lends some financial benefits whilst it generates some or all of energy requirements for its users. On the other hand, modern electric power systems with new distributed renewable power sources such as wind power and solar power have seen significant penetration of intermittent renewable energy sources. The recently developed technology related to the concept of smart grid in power systems also contributes to make the system more complex. The increasing use of renewable energy sources contributes further to the arising power quality problems like voltage and frequency that must be controlled to an acceptable standard and also, to maintain an energy balance between supply and demand. There are other shortcomings related to microgrid protection, implementation, maintenance, energy storage system spaces and resynchronization with the utility grid. That is becoming more and more serious problem and has been a great threat to the security of electric power systems and the national economy. A serious action must be considered to mitigate these shortcomings and improve the power quality being supplied to the customers and relief more transmission capacity.

One of the emerging, innovative, and new technologies in smart grid area is the electric springs (ES). Since 1660s, when the British scientist Robert Hooke described the principle of the mechanical spring, there were no serious attempts during these three centuries to extend the principle of the mechanical spring to an electrical concept. Electric spring is a power inverter connected in series with a non-critical load. It has great potential to stabilize the future smart grid by regulating the main voltage despite of the fluctuation of the output power of the intermittent renewable energy sources. It can be integrated with home appliances allowing the load to follow the intermittent generation of renewable energy sources.

This is unlike the previous idea that depends on generating enough energy to cover the load demand either completely or partially. One of the applications of using the electric spring in the smart grid is to decrease the required capacity of energy storage in the power system. ES system extension usage gives a new vision of the power system stability that will not depend in any way on communication technology. ES relies on a local voltage controller to regulate the main voltage bus instead of using communication tools to receive the required commands to do the action.

II. PROPOSED SYSTEM

A. Operating Principles of Electric Spring

The concept of Electric Spring was invented by drawing parallels to a traditional mechanical spring. In a RES powered microgrid, it allowed to pass through an inverter and is attached in series with the non-critical load, such as electric heaters, refrigerators and air conditioners, as shown in Fig. 1, to form a smart load. In parallel to this smart load, critical loads for example building's security system are connected. Earlier versions of electric spring used input-voltage control scheme to generate reactive power compensation in order to provide voltage and power regulation to critical loads in steady state. As a result, the non-critical load voltage and power varies in accordance with the fluctuations in the weakly regulated grid due to continuous power from RESs. In order to provide only the reactive power compensation from the electric spring, the compensation voltage i.e. ES voltage, Ves should be perpendicular to non-critical load current, The electric spring voltage is given in equation (1) where Vs is line voltage, Vnc is the non-critical load voltage, and Ves is ES voltage.

$$\vec{V_s} = \vec{V_{nc}} + \vec{V_{es}} \qquad (1)$$

In a distribution system which has various inductive and capacitive loads, a substantial reactive power injection can disturb the power factor of system and lead to reduced power efficiency. Thus, a feature of power factor correction can be included in the ES with the existing characteristics of voltage and power regulation. By utilizing a dc source for example battery to power the inverter, as shown in Fig. 1, both reactive power and active allowance could be gained from an ES. This property of ES could be used to shape the line current, Iin , to be in phase with line voltage, Vs. Phasor diagram in Fig. 2 shows how the electric spring compensation voltage, Ves, help improve the power factor in the distribution system and provide voltage and power support in steady state in a system with resistive-inductive loads with an overall lagging power factor.

The ES needs to operate under two major conditions: (a) when the line voltage, Vs is less than the reference line voltage, Vref (RMS value of 230 Volt) called as the under-voltage case and (b) when the line voltage is more than the reference line voltage called as the over-voltage case. In the under-voltage case, as shown in Fig. 2(a), the ES injects a combination of capacitive and the real power in the system, so as to boost the line voltage, Vs to the reference value of 230 Volt and to regulate the line voltage, Vs and the line current, the Iin remain inphase. In the over-voltage case as shown in Fig. 2(b), the ES injects real and inductive power in the system, to perform functions like line voltage regulation and power factor correction. In Fig. 2, Vin, Vx, Vs, Vnc, and Ves are the input voltages. They are the voltage across line impedance, line voltage, non-critical load voltage, and ES voltage, respectively and Is, Inc, and Iin are the critical load current, non-critical load current and line current, respectively. Also, Rx + jXx is the line impedance of the power circuit, where Xx =

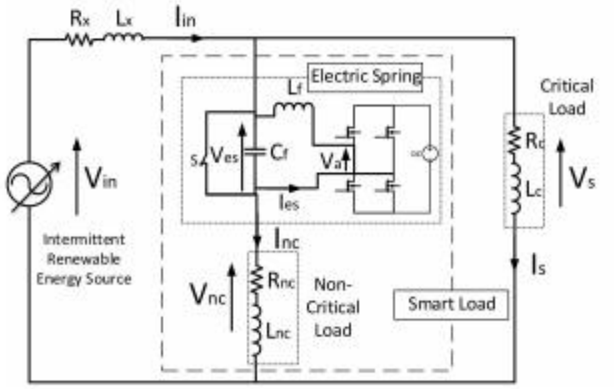


Fig. 1. Electric Spring in a circuit

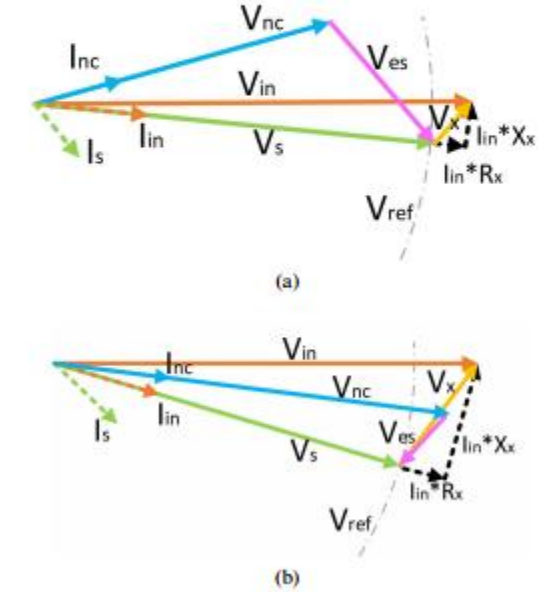


Fig. 2. Phasor diagrams of Voltage and Current for PFC and Voltage Support in (a) Under-voltage conditions (b) Over-voltage conditions

wLx and Lx is the line inductance.

B. Single-Phase d-q Transformation

The rotating frame d-q transformation is widely used in three-phase system for analysis and control. It is used for transformation of the d-q variables between rotating and as well as stationary frames. The concept has also been used in single-phase system to achieve a simpler control and analysis. However, at most two independent variables are required to create a d-q system. Thus, the concept of an orthogonal imaginary circuit was introduced in equation . Two variables i.e., the real means voltage or current and the imaginary, are utilized for the transformation. The imaginary variable is similar in characteristics with real variable but has a 90° electrical phase shift as compared to real variable. If the real sinusoidal signal, Xr is given by (2) then the imaginary sinusoidal signal, Xi would be as shown in (3); A is the amplitude of the signal and theta is the phase of the real sinusoidal signal.

$$X_r = A \cos(\omega t + \theta) \qquad (2)$$

$$X_i = A \cos(\omega t + \theta - \frac{\pi}{2}) \qquad (3)$$

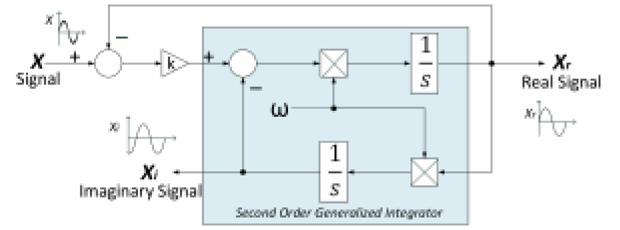


Fig. 3. Orthogonal Signal Generation using Second Order Generalized Integrator (SOGI)

The orthogonal signals is generated by using transport delay block, the inverse Park Transformation, and the Hilbert transformation. However, these methods have some features such as frequency dependency, high complexity, non-linearity, poor or no filtering. The Second Order Generalized Integrator (SOGI), as shown in Fig. 3, is used to generate the two orthogonal signals Xr(real variable) and Xi (imaginary variable) . The signal Xr has the equal magnitude and phase as the fundamental of the input signal (X). The clean orthogonal signals Xr and Xi are generated due to resonance of the SOGI at *w* i.e the grid frequency. This generates orthogonal signals, filters orthogonal signals without delay, and is frequency adaptive.
The single-phase d-q transformation for the signals Xr and Xi is done using a transformation matrix, Tr given in equation (4) and the d-q components rotating in a synchronously are generated using equation (5). An internal PLL is generated by using properties of the single-phase d-q transformation which would be used in the proposed improvised control scheme. For the purpose of the control scheme the line voltage Vs would be used as signal for generation of internal PLL as shown in Fig. 4; rated angular frequency (*wff)*, Here the 100 pi rps, is feed-forwarded in the internal PLL. The internal PLL ensures that the d-q transformation is independent of frequency variations and should also be able to generate clean real and imaginary signals. So by using the single-phase d-q transform, a time-varying ac signal can be converted to dc values and an appropriate controller is designed for the inverter.

$$T_r = \begin{bmatrix} cos(\omega t) & sin(\omega t) \\ -sin(\omega t) & cos(\omega t) \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = T_r \begin{bmatrix} X_r \\ X_i \end{bmatrix} = A \begin{bmatrix} cos\theta \\ sin\theta \end{bmatrix} \qquad (5)$$

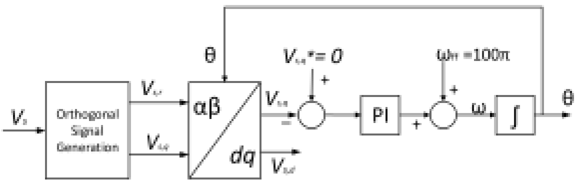


Fig. 4. Internal PLL using *d-q* transformation properties

C. Modeling and control of the improvised control spring.

The electric spring is realized through an inverter as shown in Fig. 1. The model of ES is realized using KVL and KCL. Effective Series Resistances (ESR) of the filter inductor, Lf and the capacitor, Cf are neglected and it is considered that all the devices of inverter are lossless. The voltage across the filter inductor is denoted by *V Lf* and the current through it is indicated by Ies, the voltage at the inverter terminal is denoted by Va, and the critical load impedance is Zc. KVL and KCL are applied on the ac side of the inverter and are written as:

$$\vec{V_a} - \vec{V_{es}} = \vec{V_{Lf}} = L_f \frac{d\vec{I_{es}}}{dt} \qquad (6)$$

$$\vec{V_s} = Z_c \vec{I_s} = Z_c(\vec{I_{in}} - \vec{I_{nc}}) \qquad (7)$$

$$C_f \frac{d\vec{V_{es}}}{dt} = \vec{I_{es}} + \vec{I_{nc}} = \vec{I_{es}} + \vec{I_{in}} - \frac{\vec{V_s}}{Z_c} \qquad (8)$$

Because of the high frequency filter (*LfCf)*, only the fundamental component is allowed to pass through. Mathematically it is assumed that the fundamental component, Va, 1 is available at the inverter terminal voltage and is as given by equation (9), where ~m is the modulation signal and Vdc is the dc link voltage of the inverter.

$$\vec{V_a} = \vec{V_{a,1}} = \vec{m} \times V_{dc} \qquad (9)$$

Thus, equation (6) can be rewritten as:

$$L_f \frac{d\vec{I_{es}}}{dt} = V_{dc}\vec{m(t)} - \vec{V_{es}} \qquad (10)$$

Using equation (8) and (10) the state-space equations of the system are given as in equation (11)

$$\frac{d}{dt}\begin{bmatrix} I_{es} \\ V_{es} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L_f} \\ \frac{1}{C_f} & 0 \end{bmatrix}\begin{bmatrix} I_{es} \\ V_{es} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_f} \\ \frac{1}{Z_c C_f} \end{bmatrix}\begin{bmatrix} mV_{dc} & V_s \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{C_f} \end{bmatrix} I_{in} \qquad (11)$$

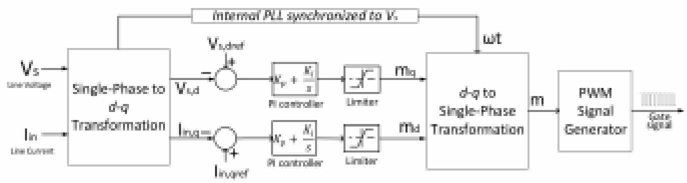


Fig. 5. Improved Control Circuit for power factor correction and voltage support using Electric Spring

The state-space equations can be written in the real as well as the orthogonal imaginary form as shown in equation (12) and (13), where the r denotes the real variable and the i denotes the orthogonal imaginary of the real variable. The transient phase error as a result of SOGI is ignored and the analysis is carried out in steady state.

$$\frac{d}{dt}\begin{bmatrix} I_{es,r} \\ I_{es,i} \end{bmatrix} = \frac{-1}{L_f}\begin{bmatrix} V_{es,r} \\ V_{es,i} \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} m_r \\ m_i \end{bmatrix} V_{dc} \qquad (12)$$

$$\frac{d}{dt}\begin{bmatrix} V_{es,r} \\ V_{es,i} \end{bmatrix} = \frac{1}{C_f}\begin{bmatrix} I_{es,r} \\ I_{es,i} \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} I_{in,r} \\ I_{in,i} \end{bmatrix} - \frac{1}{Z_c C_f}\begin{bmatrix} V_{s,r} \\ V_{s,i} \end{bmatrix} \qquad (13)$$

Using equation (4) and (5) the d-q transformation for equation (12) and (13) can be obtained and state-space equations would be shown in equation (14) and (15), where d denotes the d-component of the signal and the q denotes the q-component of the signal.

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

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

D. Improvised Control Scheme

An advantage of the single-phase d-q transformation is that the parameters of the converter are DC and in steady state. Thus, according to the analysis point of view, the rate of change in inductor current in d-q axes would be zero, i.e. (14) would be zero. Similarly, the rates of change in the capacitor voltage in d-q axes would be zero, i.e. the (15) would be zero. After solving these two equations and making them equal to zero, equations (16) and (17) are obtained. Further, solving these two equations, equation (18) is obtained which gives the d-q components of the modulation signal, md and mq. Using the inverse d-q transformation given by equations (19) and (20), the modulation signal ~m could be obtained which would generate the compensating voltage i.e. ES Voltage, Ves given by equation (21) is in steady state.

$$\begin{bmatrix} m_d \\ m_q \end{bmatrix} = \frac{1}{V_{dc}}\begin{bmatrix} V_{es,d} - \omega L_f I_{es,q} \\ V_{es,q} + \omega L_f I_{es,d} \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} V_{es,d} \\ V_{es,q} \end{bmatrix} = \frac{1}{\omega C_f}\begin{bmatrix} -\frac{V_{s,q}}{Z_c} + I_{es,q} + I_{in,q} \\ \frac{V_{s,d}}{Z_c} - I_{es,d} - I_{in,d} \end{bmatrix} \quad (17)$$

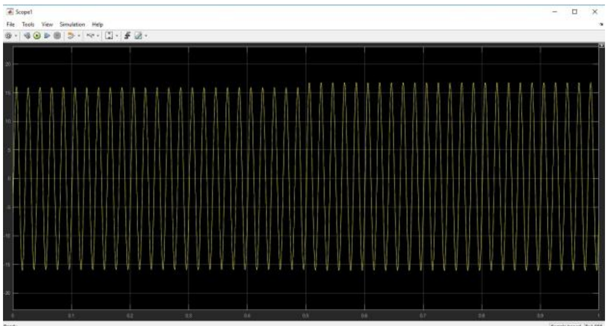
$$\begin{bmatrix} m_d \\ m_q \end{bmatrix} = \frac{1}{\omega C_f V_{dc}}\begin{bmatrix} -\frac{V_{s,q}}{Z_c} + I_{in,q} + I_{es,q} \\ \frac{V_{s,d}}{Z_c} - I_{in,d} - I_{es,d} \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} m_r \\ m_i \end{bmatrix} = T^{-1}\begin{bmatrix} m_d \\ m_q \end{bmatrix} \quad (19)$$

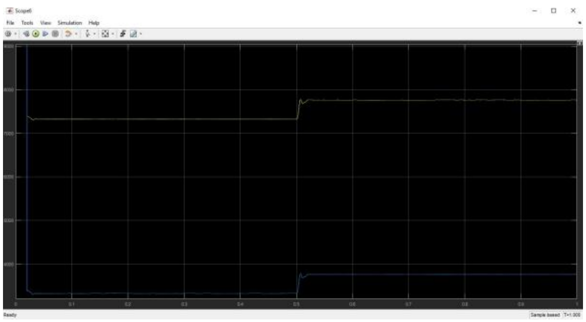
$$\vec{m} = \vec{m_r} \quad (20)$$

$$\vec{V_{es}} = \vec{m} V_{dc} \quad (21)$$

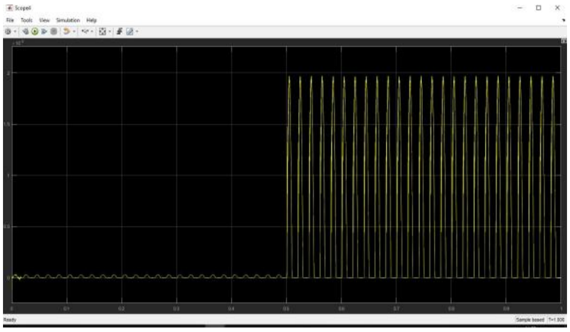
III. SIMULATION RESULTS



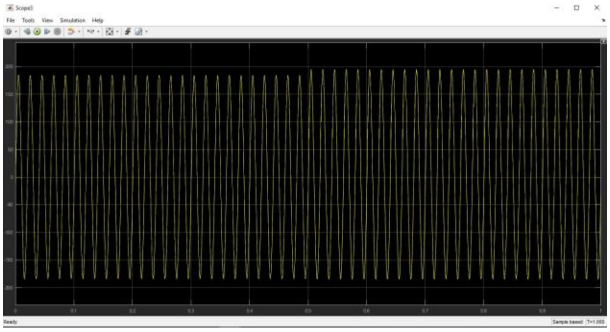
Current



Power _phasor



Source Current



Source_voltge

IV. CONCLUSION

In this paper, the Electric Spring was demonstrated as an immediate solution to the problem of voltage and power instability along with renewable energy powered grids. Further, by the implementation of the proposed improvised control scheme the improvised Electric Spring performed functions like (a) maintained line voltage to reference voltage of 230 Volt, (b) maintained constant power to the analytical load, and (c) enhanced total power factor of the system as to the ordinary ES. Also, the planned 'input-voltage-input-current' control scheme is compared to the ordinary 'input-voltage' control. It was shown, through simulation that by using a single device voltage and power regulation the power quality improvement can be achieved. It was also shown that the improvised control scheme is advantageous over the conventional ES with only reactive power injection. Also, it is proposed in the paper that electric spring could be used in future home appliances. If many non-critical loads in the buildings are consists of ES, they could provide a reliable and effective solution to voltage and power stability and the power factor correction in a renewable energy powered microgrids.

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