Reduction in Voltage Fluctuations for Critical Load using Electrical Spring

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Abstract— Project mainly focuses on the general idea of “electrical spring” and its simulation. Electrical spring is found to be an effective solution over the voltage fluctuation where the power generated from wind source is penetrated into the power grid. This electrical spring addresses the main issues like reactive power management, voltage fluctuations and, power quality. This stability control is possible because of new innovatory technique of ‘input voltage control’ which creates smart load and provide constant voltage supply to critical load. This paper consists of simulation of electrical spring and its result using MATLAB simulink. The simulation result shows that the proposed theory has capability of compensating voltage fluctuation in future smart grid.

Key words: Critical Load, Electrical Spring

I. INTRODUCTION

A Mechanical spring is an elastic device that can be used to:

1) Provide mechanical support;
2) Store mechanical energy; and
3) Damp mechanical oscillations.

When a mechanical spring is compressed or stretched, the force it exerts is proportional to its change in displacement. Potential energy is stored in the mechanical spring when the length of the spring deviates from its natural length. The principle of the mechanical springs has been described by Robert Hooke in 1678. The Hooke’s law states that the force of an ideal mechanical spring is:

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

Where F is the force vector, K is the spring constant and x is the displacement vector. The potential energy stored in the mechanical spring is:

$$PE = \frac{1}{2} Kx2 \qquad (2)$$

Mechanical springs have been widely deployed in many daily applications such as suspension springs for beds and vehicles. The common use of mechanical springs in an array form, it is a highly reliable mechanical support structure because it remains effective even if a few mechanical springs fail to function. Despite its significance, the mechanical spring concept has not been extended to the electric field for over three centuries.

II. PRINCIPLES OF ELECTRIC SPRING

Analogous to a mechanical spring, an electric spring is an electric device that can be used to:

1) Provide electric voltage support;
2) Store electric energy; and
3) Damp electric oscillations.

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

$q = Cva$ inductive mode

$q = -Cva$ capacitive mode (3)

$q = \int ic\, dt$(4)

Where, q is the electric charge stored in a capacitor with capacitance ,va is the electric potential difference across the capacitor, and is the current flowing into the capacitor. Equation (3) 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 (4) indicates that the charge(q) control can be realized by using a controlled current source.

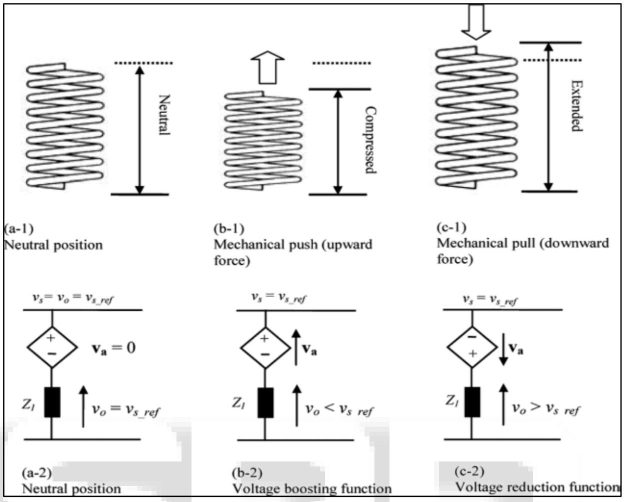


Fig. : Analogy of Mechanical spring and Electric spring

Therefore, an electric spring can be represented as a current-controlled voltage source. An analogy of the mechanical spring and an electric spring under 3 conditions are illustrated in fig is connected in series with a dissipative electric load Z1.The neutral position of an electric spring is a reference voltage at which the spring is designed to maintain. The series arrangement of the electric spring and Z1 across the ac mains is used to maintain the ac mains voltage Vs to its nominal reference level (e.g., 220 V), which is considered as the neutral position. Similar to the mechanical spring that can develop mechanical force in either direction when the displacement is changed from the neutral position, an electric spring can provide voltage boosting and voltage reduction functions as illustrated in fig. The electric spring voltage can be generated practically by dynamically controlling the electric potential difference across a capacitor with a current source Ic.

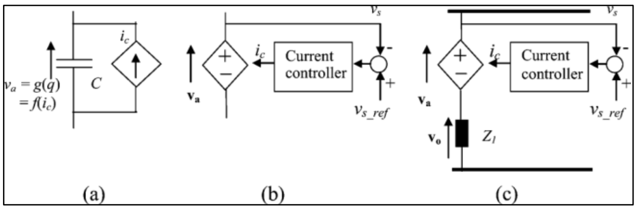


Fig. : (a) An electric spring in form of a capacitor fed by a controlled current source. (b) Schematic of an electric spring with input-voltage control. (c) An electric spring in series with a dissipative load for energy storage, voltage support and damping.

The charge control in (3) 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. The energy storage capability of the electric spring can be seen from the potential electric energy stored in the capacitor:

$$PE=1/2Cva^2$$

So the capacitor C serves as the energy storage element for the electric spring. Since an electric spring should provide a function for damping electric oscillations, it is necessary to connect the lossless electric spring in series with a dissipative electric load (such as a water heating system or a refrigerator or a combination of them) as shown in Fig. The use of the series-connected electric load Z_1 is two-folded. Firstly, it provides a mechanism to dissipate electric energy for damping purpose. Secondly, it will be shown in the analysis that the voltage V_0 across the electric load Z_1 and the electric spring voltage V_a can change in a special manner that the load power consumption Z_1 will follow the variation of the renewable power generation. This unique feature of the electric spring offers a new solution to supporting the mains voltage in future power systems with intermittent renewable energy source. The series connection with the load Z_1 makes the electric spring behaves like "voltage suspension," analogous to the mechanical suspension spring for a mechanical load (such as a vehicle).

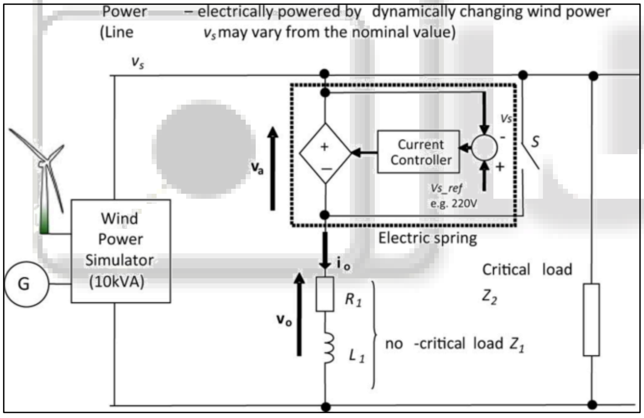


Fig. : Schematic of the experimental setup with an electric spring connected in series with a resistive-inductive load.

The electric system in Fig 3.1.3 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 wind power simulator supplemented by an ac power source. Due to the intermittent nature of wind, the power generated will be dynamically changing and the ac voltage of the bus bar will vary with wind power. In this system, an electric spring is installed in series with an electric load Z_1 as previously explained. Together, the electric spring and Z_1 form a "smart load." The dissipative load Z_1 is termed a "noncritical" load because it can be operated at an ac voltage supply V_0 with some degree of voltage fluctuation. Examples of "noncritical" loads include electric water heaters, refrigerators, and lighting systems. Generally, the electric load Z_1 can be represented as an inductor L_1 in series with a resistor R_1. Other electric load Z_2 that requires a well-regulated mains voltage is termed a "critical" load. Among various methods for load management, the electric spring (ES), which is based on power electronics technology, can instantaneously balance the power consumption and generation. This technique has the advantage over existing demand side management and energy storage solutions in that:

1) It can control the load to reduce the fluctuation of the generator.
2) It can flatten the voltage fluctuation caused by unstable power generation in real time.

Based on Hooke's law; the ES can handle reactive power to stabilize line voltage for critical loads. ES can reduce the capacity of energy storage by up to 50%. By replacing capacitors with batteries on the DC side, the ES possesses more diverse operating modes which can provide both real and reactive power compensations, and their combinations. With such a favourable feature, it is expected that the ES, as a decentralized approach, can also be used to improve the power quality of the distribution (low-voltage) power grids. Conventionally, single centralized techniques such as the series and shunt VAR compensators are used at the high voltage level to improve the performance of AC power systems by providing:

1) Load compensation and
2) Voltage support.

Specifically, series compensators actively modify the transmission parameters and shunt VAR compensators change the equivalent impedance of load. A unified PQ conditioner integrating the series- and shunt active filters to address the issues of voltage flicker and reactive power. In recent years, static VAR compensators employing thyristor-switched capacitors (TSCs) and thyristor-controlled reactors (TCRs) are the dominant solutions for such applications, due to their simple structures, convenient implementation, and affordable price. The emergence of flexible AC transmission systems (FACTS) based on these advanced power electronic technologies opened a new area for the operation of transmission systems. It is worth to mention that such modern techniques are based on large-capacity be compensators that conduct power quality improvement in a centralized manner. However, in future power systems where renewable energy sources are connected to power grids in a distributed manner, installing decentralized power compensators in numerous small capacities at the load side can be more favourable than the centralized approach .Here, the ES are numerous in quantity and they act simultaneously to achieve voltage stability and power compensation. Thus, they can be perceived equivalently as a decentralized type of series reactive power compensators (RPC) which has the power factor (PF) correction features. This paper demonstrates the use of ES to perform tasks similar to that of RPC and power factor correctors (PFC), but at the low voltage distribution level in achieving voltage stability in grids with renewable sources through input voltage control and power quality improvement through input current control.

III. SIMULATION

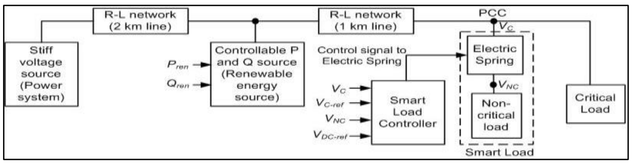


Fig. : Block diagram of the Electric Spring

Fig. shows the block diagram of the overall test system which is modelled in MATLAB/SIMULINK. A voltage source is used to model the bulk power system. The active and reactive power fluctuation from the renewable energy source (Pren, Qren) is modelled by a controllable current injection at the point of connection with the network. The amplitude of the current is determined by the active and reactive power exchanged. Two segments of the network are modelled by lumped R-L equivalent. The smart load comprising the ES and a resistive non-critical load in series and the critical load are connected at the PCC. The smart load controller controls the voltage injected by the ES in series with the non-critical load. For simplicity, both the critical and non-critical loads are assumed to be purely resistive to start with. Towards the end of Section V, simulation results for resistive - inductive (RL) loads with 0.95 (lagging) power factor is presented to show the validity of the model.

The averaged circuit model is shown in Fig. below. Note that the DC link dynamics is not considered, i.e. (V)DC = (V)DC-ref is assumed

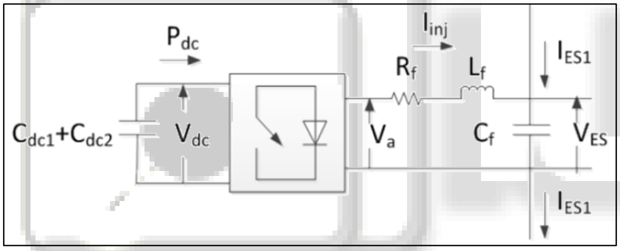


Fig. : Power circuit of Electric Spring

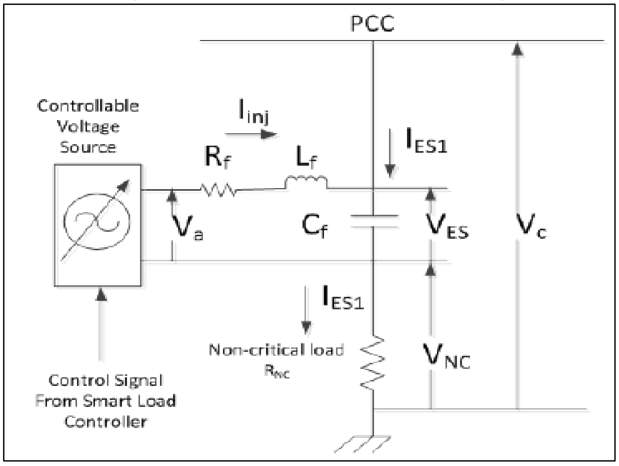


Fig. : Model for the power circuit of Smart Load and Electric Spring

It should also be noted that, the reactance of the filter capacitor Cf is very high for the fundamental frequency and was neglected for system level simulations. Also, VES and Va are almost in the same phase as the real power exchange through the inverter is negligibly small. For a system level simulation these arguments are valid and therefore simplify the control law.

IV. MODULATION INDEX

As we have to maintain the voltage for critical load, if the voltage of main power system is decreases or increases it is required to inject or absorb the voltage according to the requirement.

This can be done by means of the electrical spring shunted in system across the critical load, while electrical spring voltage is control by controlling the modulation index of inverter.

It means, if the voltage (reactive power) is required to inject in the power system the modulation index is increases above zero value and if the voltage (reactive power) is required to absorb from the power system the modulation index is decreases. Similarly if there is no requirement of injection or absorption of voltage then the modulation index is maintain to zero.

By controlling the modulation index (M) of the pulse width modulated (PWM) inverter high quality PWM voltage waveform at the mains frequency can be generated.

The magnitude of the modulation index (M) is determined from the output of a PI compensator which drives the difference between reference voltage (Vc ref) and measured voltage (Vc) to zero.

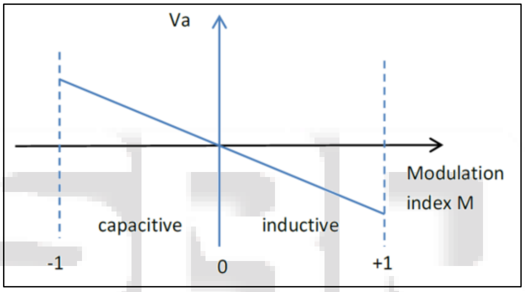


Fig. : Operating modes of reactive power controller as an electric spring (Electric spring voltage Va as a function of modulation index M)

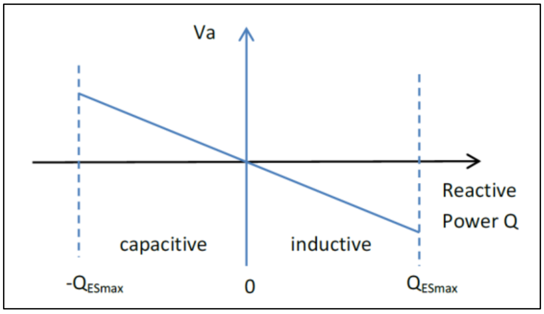
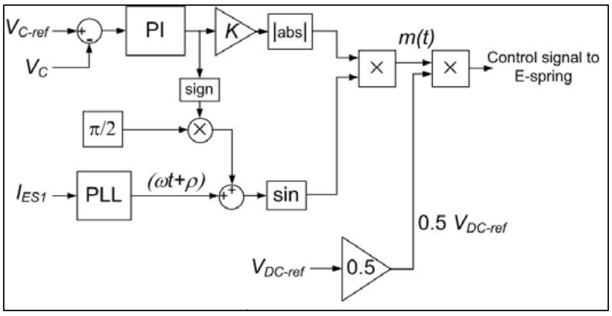


Fig. : Operating modes of reactive power controller as an electric spring (Electric spring voltage Va as a function of reactive power QESmax provided the electric spring)

V. ELECTRIC SPRING CONTROLLER

A block diagram of the ES controller modelled in MATLAB/SIMULINK is shown in Fig. Since the DC bus dynamics and the losses are neglected, the converter only exchanges reactive power with the AC system. Thus, the phase angle of the injected voltage is ± 90 degree (depending on the sign of the error between the reference and measured value of VC) with respect to ρ, the phase angle of IES1. As shown in Fig., a single-phase phase locked loop (PLL) is used to determine the phase angle of IES1.



A. *Simulation circuit diagram*

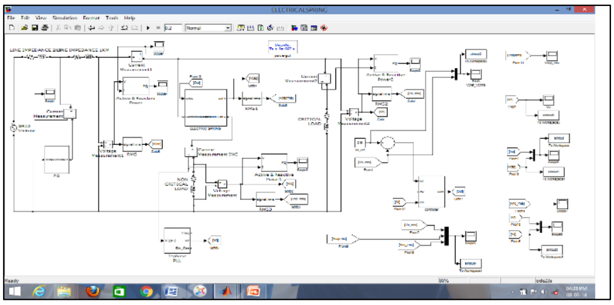


Fig. : Simulation circuit diagram

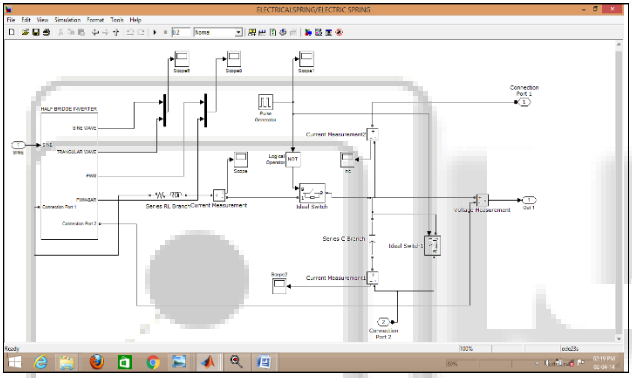


Fig. : Subsystem model of electric spring

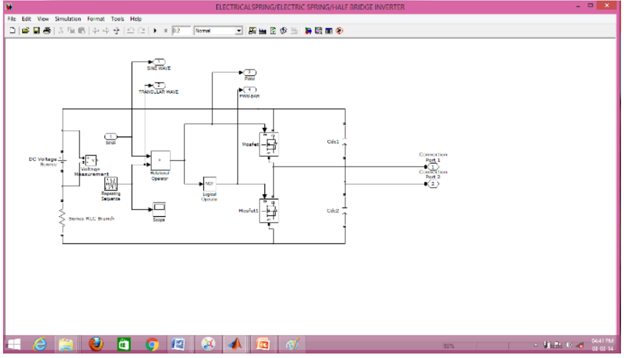


Fig. : Subsystem model of halfwave bridge inverter

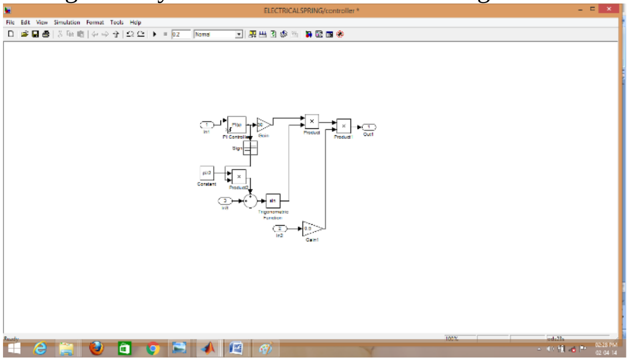


Fig. : Subsystem model of electric spring controller

VI. APPENDIX

A. *Data Sheet*

System and Loads	
Nominal Phase voltage (V1)	220 Vac
Non Critical Load Resistance (Ra)	50.5Ω
Other/ Critical Load Resistance (R)	53.0Ω

Network Box		
Distance	Resistance	Inductance (ḿḢ)
1km	0.1	1.22(ḿḢ)
2km	0.1	2.4(ḿḢ)

90KVA Power Source	
Open Circuit Voltage (Eg)	430
Short Circuit KVA (SSC)	36KVA
Short Circuit Impedance (Zg)	5.0
Transformer Reactance Ratio (X/R)	10
Equivalent Output Resistance (Rg)	0.5Ω
Equivalent Output Inductance (Lg)	16.3(ḿḢ)

Renewable Energy Source Simulator		
	Active Power (W) injected to thr grid	Reactive power (Var) injected to the grid
Steady state conditions @= 220Vac	250W	467Var (inductive)
Pre-recorded Active and Reactive Power Profile	250W	Reactive Power Profile

Electric Spring Power Circuit	
Inverter Topology	Single Phase Half Bridge Inverter
Switching Frequency	20kHz
Regulated DC- Bus Voltage	400Vdc
DC Bus Capacitance	C1=3000µF, C2= 3000µF
Inverter Output Voltage Range	0~134vac, Controlled by the Modulation Index
Power MOSFET	IRFP31N50L
Typical R_{DS} (m)	0.15Ω @ Id=31A
Output Low Pass Filter	
Measured inductance:	500µH@100Hz
Measured Equivalent Series Resistance	3Ω@100Hz

Capacitance	13.2μF		
NI Embedded Controller			
Switching Scheme:	Sinusoidal PWM		
Minimum to maximum duty -cycle	0.05 ~ 0.95		
Proportional and Integral controller	Sampling Time (Ts)	Proportional Gain (Kp)	Integral Gain (KpKi/Ts)
AC line Control Loop	20ms	30	5
DC bus Control Loop	20ms	20	1

VII. RESULTS & CONCLUSIONS

A. Result

Electric spring has following three different operating modes:

1) Voltage Support Mode:

In order to illustrate the voltage support capability of the ES, the reactive power consumed by the intermittent source was increased Without ES, this results in a reduction in line voltage below its nominal value of 220 V, as can be seen from the blue (solid) traces in both simulated response in Fig. with ES, the line voltage is quickly restored back to its nominal value as observed in simulation results.

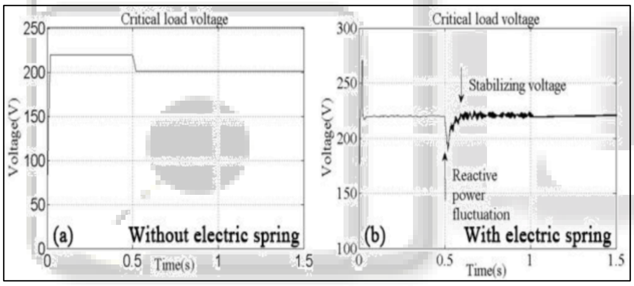


Fig. : Voltage Support Mode for critical load

B. Voltage Suppression Mode

To test the voltage suppression capability of the ES, an increase in line voltage was caused by reducing the reactive power consumed by the intermittent source Without ES, these results in an increase in line voltage above its nominal value of 220 V as is seen from the blue (solid) traces in both simulated response in Fig. with ES, the line voltage is quickly suppressed back to its nominal value as observed both in simulation and experimental results.

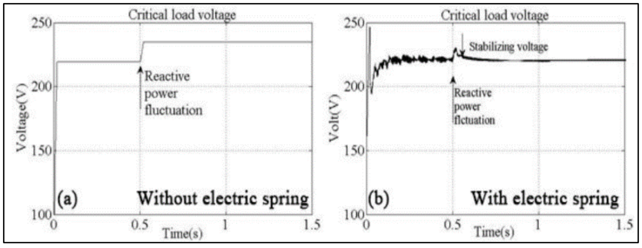


Fig. : Voltage reducing mode for critical load

C. Normal operating mode

If the mains (supply) voltage meets the requirement of electric spring then there is no busting or reduction of voltage in the system.

Operating modes	Voltage Across Critical Load	
	Without E.S	With E.S
A. Voltage Support Mode	200V	220V
B .Voltage Suppression Mode	240V	220V

Table :

VIII. CONCLUSION

The application of renewable energy can effectively alleviate the contemporary energy crisis and reduce the environmental pollution. But, it also generates considerable reactive power volatility to the grids and lowers voltage quality. By application of electric spring, these problems can be overcome.

The electric spring is a new technology that has attractive features including dynamic voltage regulation, balancing power supply and demand, power quality improvement, distributed power compensation and reducing energy storage requirements for future smart grid.

The effectiveness of an ES improves with the proportion of non-critical load. The simulation model is simple for inclusion into large-scale system simulation platforms and yet accurate enough to capture the dynamic behaviour of interest in terms of studying voltage and frequency stability.

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