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Fuzzy Based Electric Springs for Distributed Voltage Control

Asst.Prof.V.Sunil Kumar Reddy
Dept.of Electrical and Electronics Engg.
MIRCET,Piler,Chitoor
Andhra Pradesh, India
e-mail-skit07250@gmail.com

M.Tech.Scholar E.Subramanyam
Dept. of Electrical and Electronics Engg.
MIRCET,Piler,Chitoor
Andhra Pradesh, India
e-mail-subbu.esg@gmail.com

Abstract **– Electric spring which was developed recently has become the effective means of enhancing the load voltage regulation and stability of the system. This paper deals about the use of electric spring for distributed voltage control. The basic idea behind this is to maintain the constant voltage across the critical (C) loads by varying the power consumption of non-critical (NC) loads with the help of electric springs. A comparison is made between distributed voltage control using electric spring and general single point STATCOM control in terms of reactive power handling capability noncritical load voltage variation.A low-voltage single-phase power system with different types of loads has been built for the realization of electric springs. Simulation results show the effectiveness of electric springs in maintaining good voltage regulation and lead to demand side response.**

Keywords **– Demand side response, electric springs, distributed voltage control, STATCOM (Static compensator).**

I. INTRODUCTION

Generally in power system power is generated according to load demand and this is normally more than the power generation. So in order to meet the excess load demand we need rely on non conventional energy sources like renewable. But because of renewable sources the voltage fluctuations takes place due to change in environmental conditions. The large injection of renewable energy sources into the system through power inverters is becoming the reason for destabilization of power grids which is causing unusual block outs and poor performance of equipment.

Besides renewable sources, in the medium and low voltage distribution network the voltage fluctuations are caused due to nonlinear and unbalanced loads. Voltage control in distribution system especially across sensitive loads or critical loads can be achieved by tap changing transformer, static compensator (STATCOM), and switched capacitors/reactors etc.Here Critical loads are the loads which are insensitive to voltage fluctuations and always require quality supply.

The new concept of electric springs (ES) has been evolved recently for efficient means of distributed voltage control without need of any communication. The basic idea behind this concept is to control the voltage across the sensitive or critical loads by varying the power consumption of non-critical loadsand leads to the demand side response. Because of this it is possible to penetrate large amount of intermittent renewable resources without the requirement of large capacity energy storage. This paper gives an idea about the realization of electric springs from mechanical springs, and the modeling of controller circuit of ES using fuzzy logic. Here the focus is to compare the distributed voltage control using ES to single point controller STATCOM.

II. BASIC CONCEPT OF ELECTRIC SPRING

In medium and low voltage distribution networks, the demand side management (DSM) and voltage control are generally handled separately. But, by separating the loads into critical (C) loads which require uninterruptable supply and constant voltage and non – critical (NC) loads which are less sensitive to voltage variations, combined achievement of both DSM and voltage control is possible. One way to achieve this is use of Electric Springs.

1. Realization of Electric Spring from Mechanical Spring-when mechanical spring is under stretch or compression it exerts force which is proportional to its displacement change. The principle of mechanical spring is realized by Hook's law which states that,

F= -Kx here F=Force vector, K=spring constant & x=Displacement vector Similar to equation (1), the relation for ES are also derived as

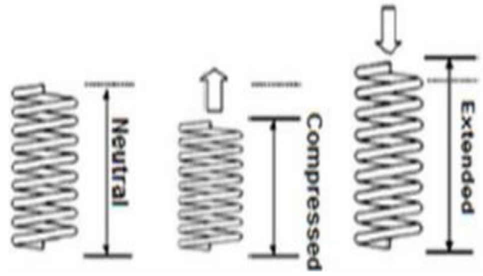
$$q = \int Icdt \quad (2)$$

$$q = C\ VES \quad \text{Inductive mode} \quad (3)$$

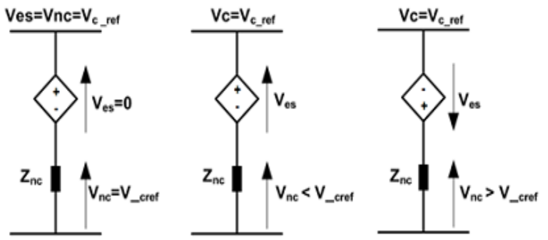
$$q = -C\ VES \quad \text{capacitive mode} \quad (4)$$

The control function of ES is explained by equations (3) & (4).

Fig.1 & Fig.2 represents the working principles of mechanical spring and electrical spring. Here the operation of electric spring under neutral position, voltage boosting position and voltage reduction position is shown. The neutral position of electric spring is maintained at reference voltage.



(a)Neutral (b) Mechanical push(c) Mechanical pull
Fig.1 working of mechanical spring .



(a)Neutral (b) Voltage boosting (c) Voltage reduction
Fig.2 working of electric spring.

The electric spring is a recently developed concept for distributed voltage control. These voltage compensators are connected in series with the noncritical loads as shown in Fig.1 the combination of which forms a smart loads. The electric springs inject a voltage *VES* in series with each non critical load (NC) & quadrature with current flowing through it in order to regulate the voltage across the critical loads. The voltage across non critical loads *VNC* is regulated but with in suitable limits and the power consumed by them also changes.

Suppose if the generation shortfall is occurred the voltage across the critical load is not going to be varied. It will be taken care by the non critical load like it will reduce its power consumption with the help of electric springs. Exchanging of reactive power is done just like in normal voltage compensators by injecting series voltage VES in quadrature with ES current.The electric spring is a recently developed concept for distributed voltage control.

These voltage compensators are connected in series with the noncritical loads as shown in Fig.3 the combination of which forms a smart loads. The electric springs inject a voltage *VES* in series with each non critical load (NC) & quadrature with current flowing through it in order to regulate the voltage across the critical loads. The voltage across non critical loads *VNC* is regulated but with in suitable limits and the power consumed by

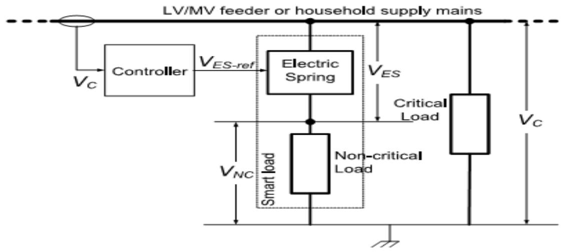


Fig.3 Electrical spring set up.

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III. COMPARISON OF ES WITH STATCOM

For the comparison of voltage controlling performance of Electric springs to STATCOM a simple test system is proposed as shown in Fig.4 The model consists of one constant voltage source as main power grid and one controllable renewable energy source as an intermittent source which cause fluctuations in active and reactive powers at the point of common coupling of critical loads.

As shown in the Fig.4 the loads need not to be a resistive. The above test system is modeled in MATLAB/SIMULINK using controllable voltage source representation.

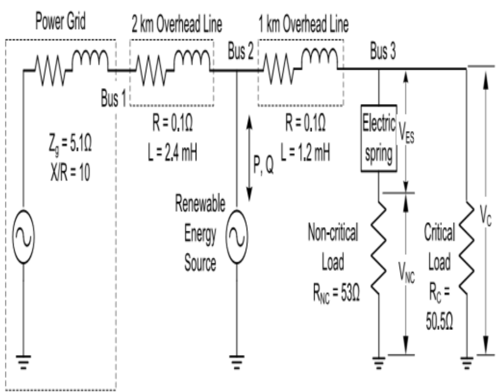

Fig.4 Simulation set up of electric power grid with intermittent renewable energy source.

The modeling and control of ES is discussed below with Fig.5.

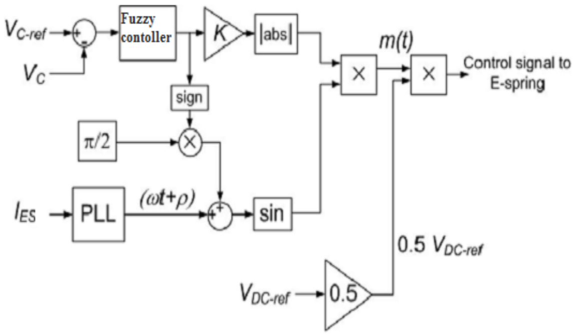

Fig.5 Block Diagram for Electric Spring Controller.

The phase angle of the injected voltage is ± 90 degree with respect to the phase angle (ρ) of*IES*. A single-phase phase locked loop (PLL) is used to determine the phase angle of *IES*.From the output of a Fuzzy logic controller ,the magnitude of the modulation index (M) is determined which makes the difference between reference point of common coupling(PCC) voltage (VC-ref) and measured PCC voltage (VC) to zero.

A scale factor (K) is used to limit the output of the fuzzy controller within ±1.The control signal is drawn by multiplying the modulation index (M) and phase shifted sinusoidal signal by half of DC link voltage (*VDC-ref*).The STATCOM control circuit is also very similar to electric spring but the point is it connected in parallel with non critical load and critical load at the point of common coupling.

1.Voltage reduction mode -This mode is to test the capability of ES and STATCOM to reduce the voltage at the point of critical load to rated value when voltage is gone beyond the nominal level 216 Volts. First the intermittent renewable resource is adjusted in such a way that its consumption of reactive power is reduced.

Then the voltage across the load is increased more than the nominal rating. At t=1.0 seconds the reactive power absorption is decreased from 467 VAR to 110VAR.The voltage at the load point increased from 216 Volts to 224 Volts if the controller is not present which is shown in Fig.6(a) and (b). Either with ES or STATCOM the voltage across the critical load point has to be come back to rated value.

The ES injects 115Volts in series with NC loads, whose voltage is reduced to 185 Volts as shown in Fig.6 (a) and (c).In this case both ES and STATCOM will absorb reactive power from the system. From Fig 6(d) it is shown that reactive power injection of ES is 100 VAR more than the STATCOM. Here the active power consumption of non critical load reduces due to the reduced voltage across it which leads to demand side management.

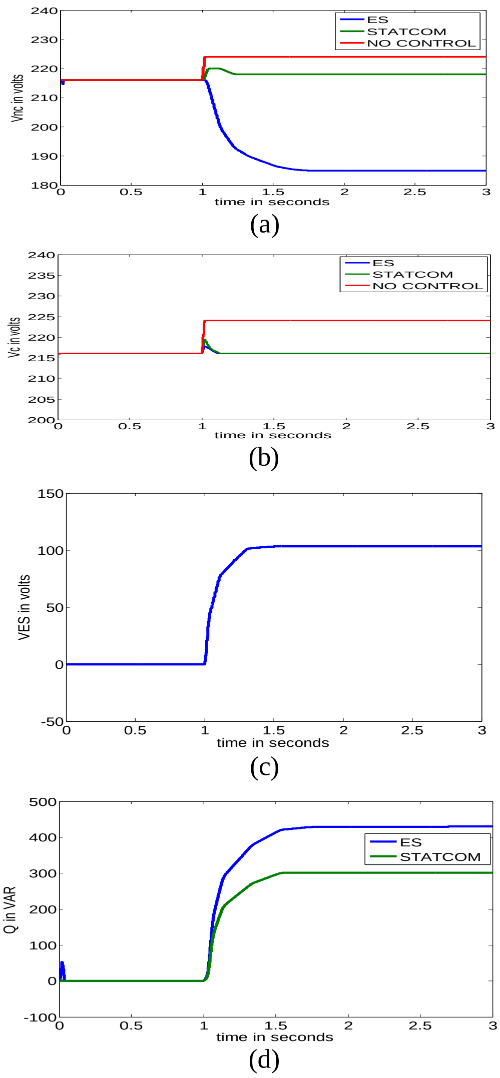

Fig.6 System responses with voltage reduction :(a) non critical mode load voltage(b) Critical load voltage (c) Electric spring voltage (d) Reactive power handling.

2. Voltage boosting mode

Just like the voltage reduction mode, This mode is to test the capability of ES and STATCOM to boost the voltage at the point of critical load to rated value when voltage is reduced below the nominal level 216 Volts. First with the increment in the reactive power absorption of intermittent renewable resource, the voltage across the load is reduced less than the nominal rating.

At t=1.0 seconds the reactive power absorption is increased from 467 VAR to 1100 VAR.The voltage at the load point decreased to 190 Volts if the controller is not present which is shown in Fig.7(a) and (b). Either with ES or STATCOM the voltage across the critical load point has to be come back to rated value.

The ES injects 150 Volts in series with NC loads, whose voltage is reduced to 150 Volts as shown in Fig.7 (a) and (c).In this case both ES and STATCOM will inject

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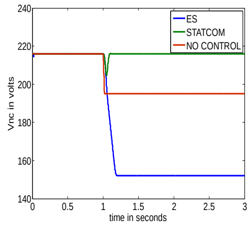
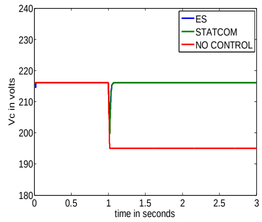
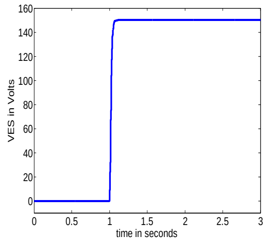
reactive power in to the system. From Fig 7(d) it is shown that reactive power injection of ES is 150 VAR less than the STATCOM. Here also the active power consumption of non critical load reduces due to the reduced voltage across it.



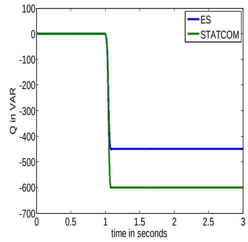
(a)



(b)



(C)



(d)

Fig.7 System responses with voltage boosting mode:(a) Non critical load voltage (b) Critical load voltage (c) Electric spring voltage (d) Reactive power handling.

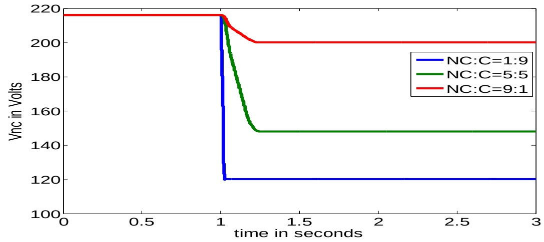
3. Proportion of critical and non critical loads

The proportion of C loads and NC loads are important to evaluate the effectiveness of ES.The reactive power capability of an ES is found by product of the series injected voltage and current flowing through the NC loads. If the series injected voltage increases the voltage across NC load decreases which in turn reduces current flowing through it.

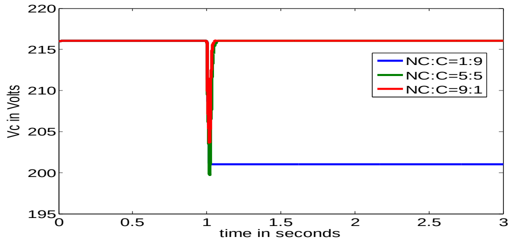
The reduction of current limits the reactive power handling capability of ES which leads to inability of ES to maintain constant voltage across C loads.The capacity of ES is increased with increase in NC load which is explained below.It is found that for high proportion of NC loads i.e. NC:C=9:1,With injection of only 80Volts by ES,the voltage across critical load is restored to original valuewhich is shown in Fig.8(b) and(c).

This results in a very little change in NC loads as shown in Fig.8(a).For equal proportion of NC loads and C loads i.e. NC:C=5:5,the voltage across NC load is lower than before because of large series injected voltage due to ES. However for low proportion of NC loads(NC:C=1:9),it is not possible to maintain the critical load voltage level at nominal value because of less current which again limits the reactive power capability of the system which is shown in Fig.8(b).

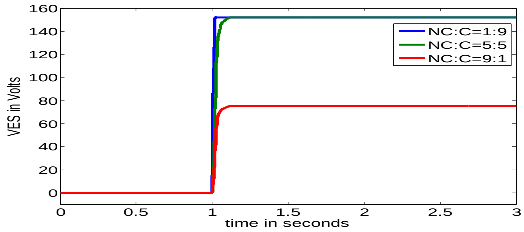
The reactive power exchange of with ES not only depends on the series injected voltage but also on the impedance of the NC load. For analyzing this, consider the network shown in Fig.3 but R-L load is considered in the place of NC load. The impedance of NC load is considered as ZNC∠θNC and the voltages VC, VNC,VES are represented on phasor diagram as shown in Fig.9.



(a)



(b)



(c)

Fig.8 System response for different proportions of NC loads: (a) Non critical load voltage (b) Critical load voltage (c) Electric spring voltage

From phasor diagram we can write equations

$$V_C^2 = (V_{NS} - V_{ES}\sin\theta\, NC)^2 + (V_{ES}\cos\theta\, NC)^2 \quad (4)$$

$$V_{NC} = \pm\sqrt{V_C^2 - (V_{ES}\cos\theta\, NC)^2} + V_{ES}\sin\theta\, NC \quad (5)$$

$$Q_{ES} = V_{ES}I_{NC}\sin(-90^\circ) = -V_{ES}I_{NC} = -\frac{V_{ES}I_{NC}}{Z_{NC}} \quad (6)$$

$$Q_{NS} = V_{ES}I_{NC}\sin\theta\, NC = \frac{V_{NC}^2}{Z_{NC}}\sin\theta\, NC \quad (7)$$

Here QES and QNC are the reactive power absorption of ES and NC load. For pure resistive load the reactive power absorption of NC load and ES are same but if ES

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is working in voltage boosting mode(i.e. capacitive type) then the total reactive power of smart load is

$$Q_{SL} = Q_{ES} + Q_{NC} \quad (8)$$

$$Q_{SL} = \frac{-V_{ES}\left(\pm\sqrt{V_C^2-(V_{ES}\cos\theta\,NC)^2}+V_{ES}\sin\theta\,NC\right)}{Z_{NC}} + \frac{V_{ES}\left(\pm\sqrt{V_C^2-(V_{ES}\cos\theta\,NC)^2}+V_{ES}\sin\theta\,NC\right)^2}{Z_{NC}}\sin\theta\,NC \quad (9)$$

Similarly, for the ES in voltage reduction (i.e. inductive) mode, we can write:

$$V_{NC} = = \pm\sqrt{V_C^2-(V_{ES}\cos\theta\,NC)^2} - V_{ES}\sin\theta\,NC \quad (10)$$

$$Q_{SL} = \frac{V_{ES}\left(\pm\sqrt{V_C^2-(V_{ES}\cos\theta\,NC)^2}-V_{ES}\sin\theta\,NC\right)}{Z_{NC}} + \frac{\left(\pm\sqrt{V_C^2-(V_{ES}\cos\theta\,NC)^2}-V_{ES}\sin\theta\,NC\right)^2}{Z_{NC}}\sin\theta\,NC \quad (11)$$

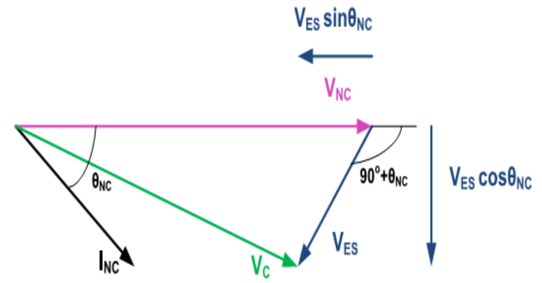

Fig.9 Phasor diagram showing the relation between NC load and ES voltages.

It is evident from equations (6), (9) & (11) the reactive power absorption depends upon the impedance of NC loads. Hence the decrease in value of ZNC will increase the reactive power capability of ES.S o higher proportion of NC loads will increase the effectiveness of electric spring (ES).

IV.CONCLUSION

In this paper the realization of Electric Spring from mechanical spring and the modeling of control circuit for ES using fuzzy logic is discussed. The concept of distributed voltage control using ES is explained well and comparison is made with single point controller with STATCOM.The total voltage regulation, the total reactive power handling capability for voltage boosting mode and voltage regulation mode is compared for given supply range and effect of proportionality of NC load with C load for better control is described.

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