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Performance Analysis of Electric Springs In Reducing the Power Drawn From 21-Bus System during Uncertainties


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Abstract:

In This Paper, We Discuss The Principles Of Operating The Electric Spring (ES) As A Reactive Power Compensator And As A Power Factor Corrector. The Theory On Electric Springs With Capacitors For Voltage Stabilization Is Reviewed To Present A General Idea On The Behavior Of ES. An Input Current Control Scheme Is Designed For ES With Batteries To Validate Its Capability In Power Factor Correction. A Low-Voltage Three-Phase Power System With Different Types Of Loads Has Been Built For Verifying The Feasibility Of Proposed Theory Of ES. MATLAB/SIMULINK Results Show That The ES Is Capable Of Performing The Different Operating Modes When Changing The Power Consumption Of The Non-Critical Load, And That With The Proposed Input Current Control, The ES Can Achieve Power Factor Correction For Both RL And RC Loads.

I. INTRODUCTION:

The impending energy crisis and environmental issues require that substantial renewable energy sources should be included in the future as either centralized power mills or distributed generators. Due to the dynamically changing nature of renewable energy sources, this foreseeable major change in power grid demands sophisticated control methodologies and a new discipline of management strategies.

Smart grids based on modern power electronics and telecommunication technologies have been proposed as a promising solution. To cope with the variability and uncertainty of renewable energy sources, new methods for load management are required. 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 [1]-[6] and energy storage solutions [7], [8] in that: I) it can control the load to reduce the fluctuation of the generator; ii) it can flatten the voltage fluctuation caused by unstable power generation in real time [9]. The first generation of ES is presented in [9].

Based on Hooke's law, the ES can handle reactive power to stabilize line voltage for critical loads. Research in [10] also shows that ES can reduce the capacity of energy storage by up to 50%. The potential of ES is further discovered in [11]. 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 favorable 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 [12]. 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 is introduced in [13]. 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 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 favorable 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.

II.ELECTRIC SPRING CONCEPT

Voltage control in LV and MV distribution networks and demand-side management (DSM) have traditionally been treated and tackled separately. Voltage control is usually achieved by control devices discussed in the previous section.

Demand-side management on the other hand is employed in a more distributed fashion (often at the appliance level) and is predicated on intelligence or communication facility in the appliance [10-12]. Alternatively, an integrated approach to voltage control and aggregated demand action could be achieved by separating the loads into critical loads requiring constant voltage and un-interrupted supply and non-critical, impedance-type loads. At times of generation shortfall or network constraint, the voltage of the non-critical loads is reduced while regulating the voltages across the critical loads. This addresses the generation shortfall or network constraint and also facilitates better voltage regulation of the critical loads through manipulation of the supply impedance voltage drop. V_{ES}-ref V_C Non-critical Load Critical Load V_{NC} Controller V_C Electric Spring V_{ES} LV/MV feeder or household supply mains Smart load

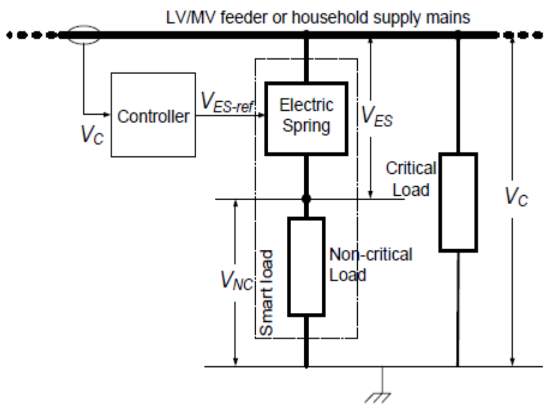


Fig.1.Electric spring set-up for Smart loads.

One way to exercise this control is to use the so called Electric Springs (ESs) which are power electronic compensators that inject a voltage with controllable magnitude V_{ES} in series with each non-critical load to regulate the voltage V_C across the critical load as shown in Fig. 1. The voltage V_{NC} across the non-critical loads is thus controlled (within allowable bounds) and the active power consumed by them modulated. The series combination of the ES and the non-critical load thus acts as a 'Smart Load' which ensures tightly regulated voltage across the critical load while allowing its own power consumption to vary and thereby, participate in demand side response. Adding the voltage V_{ES} in quadrature with the current flowing through the ES ensures exchange of reactive power only like conventional voltage compensators including STATCOM.

A. Test System

In order to regulate the voltage regulation performance of a single Electric Spring . Simple test system as shown in fig.1 haa been considered. It comprises of a power source acting as the main power grid and a separate controllable power source to emulate an intermittent renewable energy source. The controllable source is capable injecting variable active and/or reactive power which causes the voltage across the C load to fluctuate. For simplicity both C and NC loads are represented by resistors although they do not have to be necessarily resistivity. The magnitude of controllable voltage representing the ES is controlled using a PI controller to minimize the difference between the actual and reference values of the voltage across the C load. Phase angle of the voltage source is locked in quadrature to the phase angle of series current to ensure there is no active power transfer.

B .Voltage suppress Mode

The voltage across the loads is increased above the nominal value (216 V) by reducing the reactive power absorption of the renewable source. This test is ability of an ES to suppress the voltage and regulate it at the nominal value. At t=1.0 s, the reactive power absorption by the intermittent renewable source is reduced from 467 VAr down to 110VAr. Without any voltage control, the load voltage increases from the nominal value 216 V up to 224 V as shown in fig 2(a). The ES are able to restore the voltage across the critical load back to the nominal value as shown by the overlapping the traces. The ES achieves this by injecting about 115 V in series with the NC load the voltage across which drop to about 185 V as shown in fig 2(c) . In order to suppress the voltage, the ES absorb reactive power from the system.

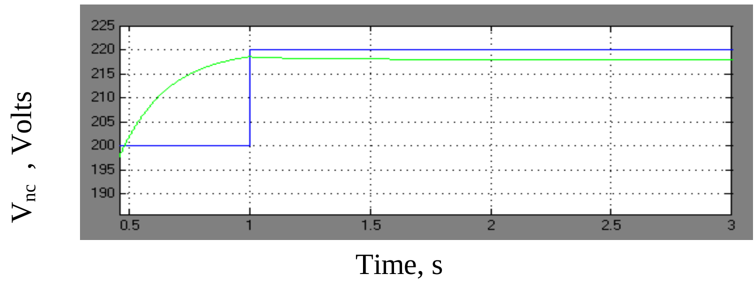
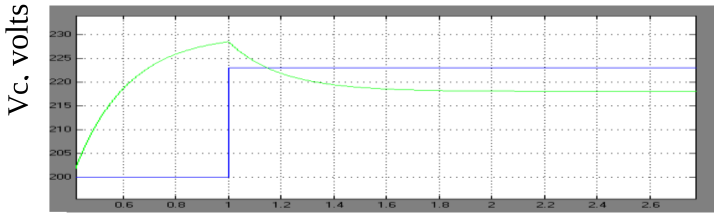


Fig. 2(a) Non critical load voltage v_s time



Critical voltage v_s time Time, s

Fig. 2(b) critical load voltage

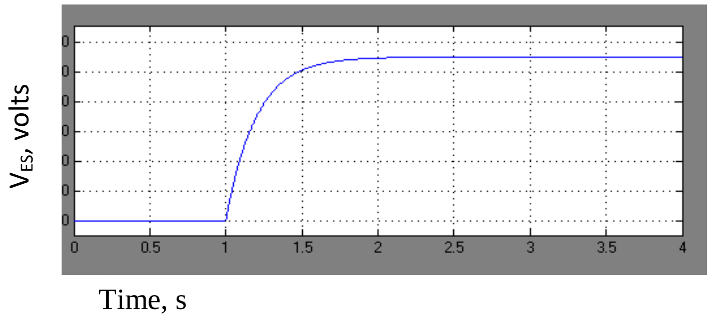


Fig.2(c) electric spring voltage v_s time

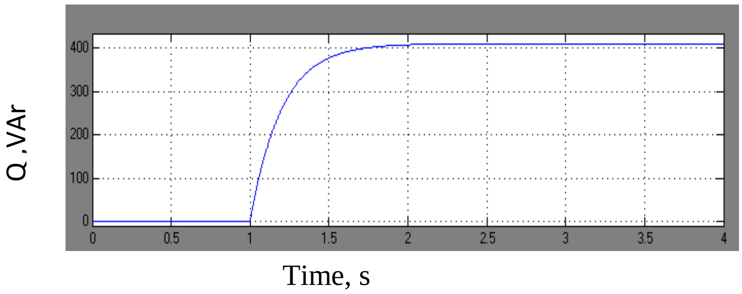


Fig 2(d) Reactive power exchange v_s time

C. Voltage Support Mode

To investigate the opposite effect of what was described in the previous subsection, the voltage across the loads reduced by increasing the reactive power absorption of the renewable source. This is to test ability of an ES to support voltage and regulate it at nominal value .

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At t= 1.0 s, the reactive power absorption by the intermittent renewable source is increased from 467 VAr to 1100 VAr. Without any voltage control, the load voltage seen drop from nominal value of 216 V to slightly below 190 V . ES are able to restore the voltage across the C load back to nominal value as shown in fig 3(a). The ES achieves this by injecting about 150 V shown in fig 3(c). In order to suppress the voltage, ES inject reactive power into the system.

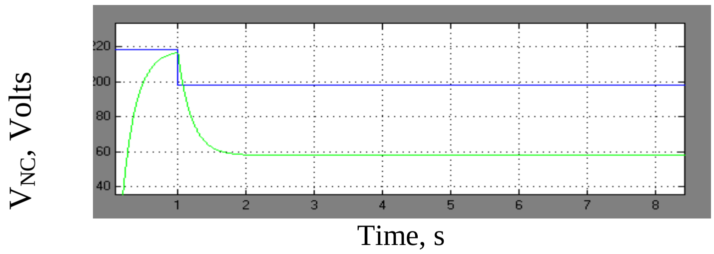

Fig. 3(a) Non critical load voltage v_s time

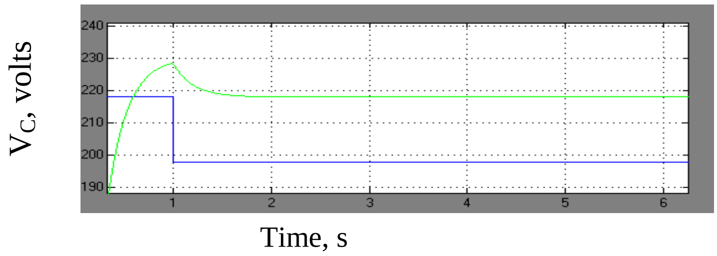

Fig.3(b). Critical load voltage v_s time

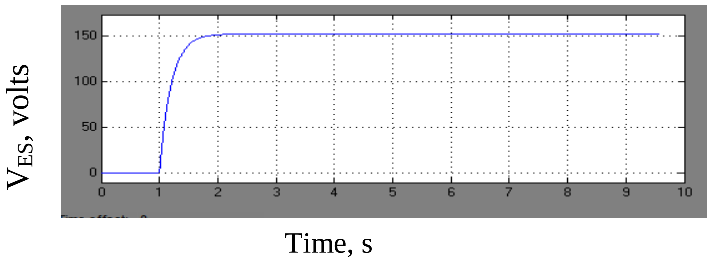

Fig.3(c). Electric spring voltage v_s time

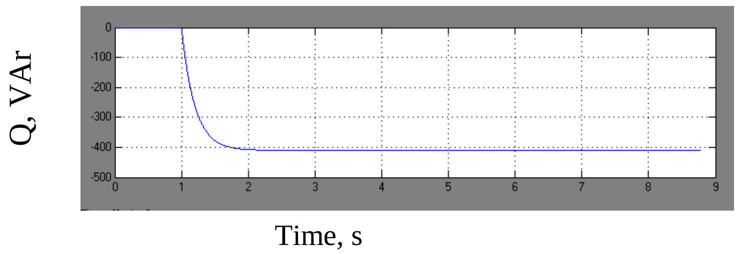

Fig. 3(d). Reactive power exchange v_s time

D. Proportion of C and NC loads

The portion of the critical and non critical load is therefore, quite important towards the effectiveness of its voltage regulation capability and also the amount of reactive power exchanged with the system. The reactive power capability of an ES is governed by the product of the voltage it injects and the current flowing through it. If injected voltage increases, the voltage across the non-critical load and hence the current reduces which limits the reactive power capability of an ES and thus its ability to regulate the voltage across the critical load. System response for different distributions of non-critical and critical loads (NC:C) as shown in below tabular column fig 4.

	Noncritical : critical loads(NC:C)		
	1:9	5:5	9:1
Critical voltage	204V	216V	216V
Non critical voltage	201V	150V	125V
Reactive power	-50 VAr	-450 VAr	-560 VAr
Spring voltage	150V	150V	50V

Fig. 4. System response for different portion of non-critical and critical loads.

The reactive power exchange with the ES depends on the injected voltage V_{ES} and also on the impedance of the non-critical load. Consider the circuit shown in Fig. 1. For a resistive-inductive (R-L) type non-critical load with impedance $Z_{NC}\angle\theta_{NC}$ the voltages V_C, V_{ES} and V_{NC} are shown on the phasor diagram. When the ES is working in voltage support (i.e. capacitive) mode. From the phasor diagram we can write:

$$V^2{}_C = (V_{NC} - V_{ES}sin\theta_{NC})^2 + (V_{ES}cos\theta_{NC})^2 \quad (1)$$

$$V_{NC} = \pm\sqrt{V^2{}_C - (V_{ES}cos\theta_{NC})^2} + V_{ES}sin\theta_{NC} \quad (2)$$

$$Q_{ES} = V_{ES}I_{NC}\sin(-90°) = -V_{ES}I_{NC} = -\frac{V_{ES}V_{NC}}{Z_{NC}} \quad (3)$$

$$Q_{NC} = V_{NC}I_{NC}sin\theta_{NC} = \frac{V^2{}_{NC}}{Z_{NC}}sin\theta_{NC}. \quad (4)$$

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Here, Q_{ES} and Q_{NC} are the reactive powers of the ES and the non-critical load, respectively. For a purely resistive non-critical load, the reactive power of the ES and the smart load will be equal. However, they would be different if the the non-critical is not purely resistive. If the ES is working in voltage support (i.e. capacitive) mode with a non-critical load of R-L type, the total reactive power of the smart load Q_{SL} is given by:

$$Q_{SL=}\ Q_{ES}+Q_{NC} \qquad (5)$$

$$Q_{SL} = \frac{-V_{ES}(\pm\sqrt{V^2{}_C-(V_{ES}\cos\theta NC)^2}+V_{ES}\sin\theta_{NC}}{Z_{NC}}$$

$$+\frac{(\pm\sqrt{V^2{}_C-(V_{ES}\cos\theta_{NC})^2}+V_{ES}\sin\theta_{NC})^2}{Z_{NC}} \qquad (6)$$

Similarly, voltage suppress mode we can write

$$V_{NC} = \pm\sqrt{V^2{}_C-(V_{ES}\cos\theta_{NC})^2}+V_{ES}\sin\theta_{NC}$$
(7)

and

$$Q_{SL} = \frac{-V_{ES}(\pm\sqrt{V^2{}_C-(V_{ES}\cos\theta NC)^2}-V_{ES}\sin\theta_{NC}}{Z_{NC}}$$

$$+\frac{(\pm\sqrt{V^2{}_C-(V_{ES}\cos\theta_{NC})^2}-V_{ES}\sin\theta_{NC})^2}{Z_{NC}}\sin\theta_{Nc} \qquad (8)$$

From (3), (6) and (8) it is clear that the reactive power of the ES and the smart load are both dependent on non-critical load impedance (Z_{NC}). A decrease in the value of Z_{NC} (increase in the non-critical load) will result in an increase in reactive power. Hence, a higher proportion of non-critical load will increase the effectiveness of an ES.

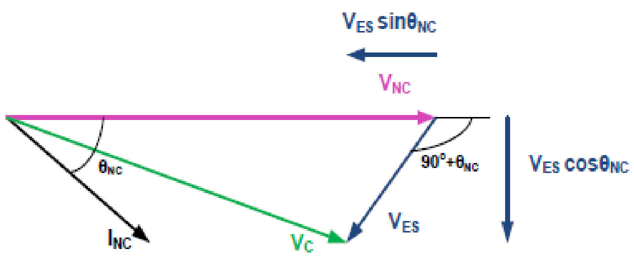

Fig5. Phasor diagram showing relationship between voltages across non-critical load, critical load and ES

III. 21 NODE TEST FEEDER:

A. Test Network

The focus was on collective action of a group of distributed ESs. To investigate this, the IEEE 21-bus test feeder system shown in Fig.5 was considered. The network has two voltage levels 4.16 kV and 480 V with a distribution transformer connected between node 1 and 21.In the original IEEE 21-node test feeder, the LV side is represented by an aggregated load at bus 21. For the purpose of this study, the LV side was modified to distribute the total load (160 kW with 0.825 lagging power factor) among four newly introduced LV bus bars labeled as 1, 2, 3 and 4. The aggregated load (160 kW) connected at node 21 was split equally among these four new nodes. The ratio of critical to non-critical loads was assumed to be 50:50. The LV distribution line conductor dimensions were chosen based on the current ratings of the loads and the conductor data and the distance between the LV bus bars. All other circuit parameters are exactly the same as feeder is set up to study unbalanced operation. For this study we considered only one phase of the system as unbalance operation is not the focus here.

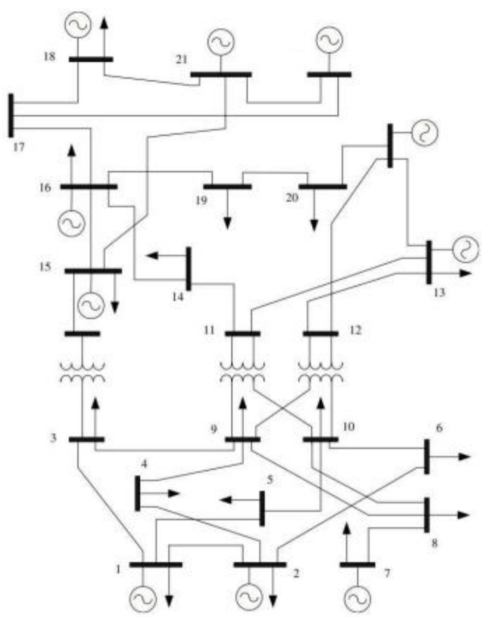

Fig 6. 21 node test feeder network with distributed representation of the LV side.

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SIMULATION DIAGRAM OF 21 NODE TEST FEEDER

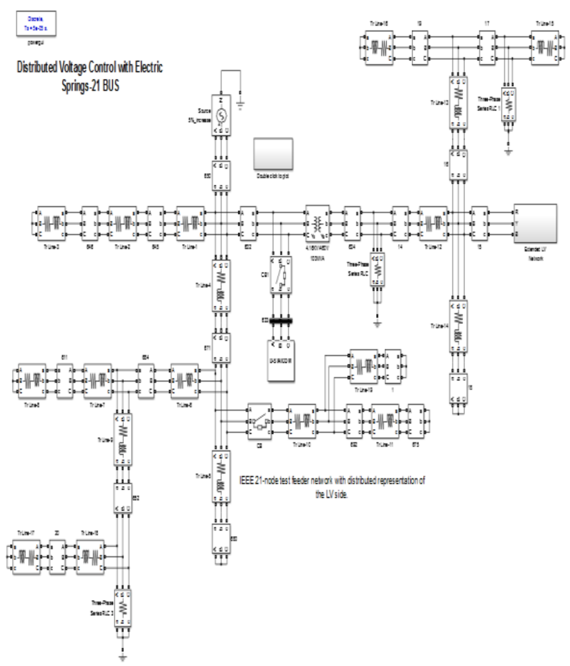

Fig. 7. Simulation setup for 21 node test feeder

B. Voltage Support Mode

The collective action of the distributed ESs was installed on the MV side at bus 633. A 5% step reduction in the source voltage at the bus 650 was considered. The comparison is based on the total reactive power required by the 4 ESs in order to achieve an acceptable voltage regulation at the LV buses. Voltage regulation at a particular bus is defined in [22] as the normalized difference between the rated voltage (1.0 p.u) and the actual voltage in the event of a voltage disturbance.

$$\text{Voltage Regulation} = \frac{|V_{rated} - V_{actual}|}{V_{actual}} \times 100\%$$

The voltage regulation achieved at different LV buses is shown in fig .2.Wth out any voltage compensation the voltage regulation becomes progressively poorer away from the MV bus(bus 633) due to voltage drop in the LV feeder. In this case the voltage regulation turns out to be un acceptably high (>5%). With ESs the voltage regulation is more uniform across the LV feeder. A degree of voltage regulation can still be ensured even if one or more ESs are out of operation. In order to demonstrate this qualitatively, the ES connected with bus 4 was deactivated. It can be seen that the voltage regulation is still better than having no control at all. There are only four ESs in the system. In a larger system, we can have multiple ESs deactivated without making the system prone to voltage changes.

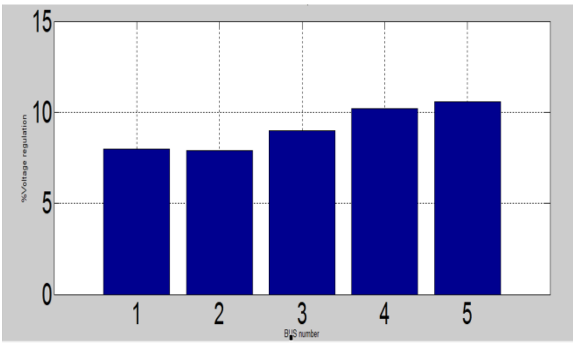

Fig. 8(a). No Compensation

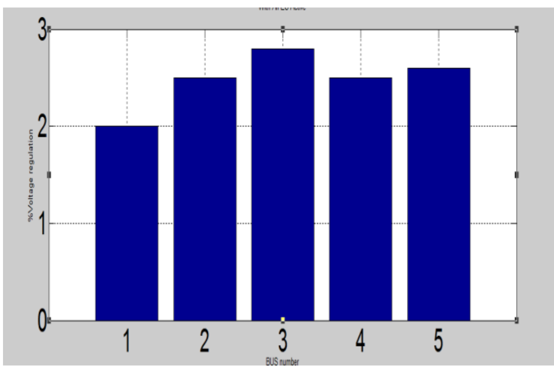

Fig. 8(b). All ESs activated

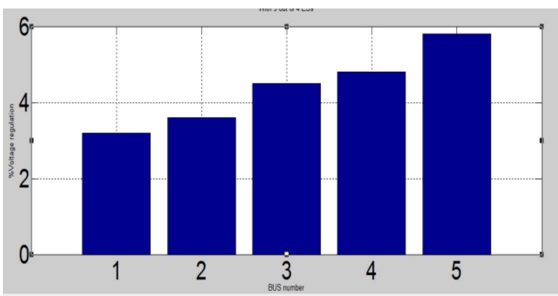

Fig.8(c). 3 out of 4 springs activated

Reactive power with All ES: 89 KVAR

Reactive power with 3 out of 4 ES: 104 KVAR

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The overall voltage regulation achieved in each case is compared in terms of root mean square of the deviation of the actual voltages from the rated (1.0 p.u) values which is termed as total voltage regulation and defined in [5].

$$\text{The voltage regulation} = \sqrt{\frac{\sum_{i=1}^{Nb}\left(V_{rated\_(p.u)} - V_{actual\_(p.u)}\right)^2}{Nb}}$$

The results are shown in for both voltage support and voltages suppress modes. It can be seen that the group of ESs achieves better voltage regulation at bus 633. Moreover the total reactive capacity required for the ESs is less.

C. VOLTAGE SUPPRESS MODE

Similar exercise, as in the previous subsection, has been repeated for over-voltage (voltage suppress) condition. A 5% step increase in the source voltage at bus 650 is simulated.

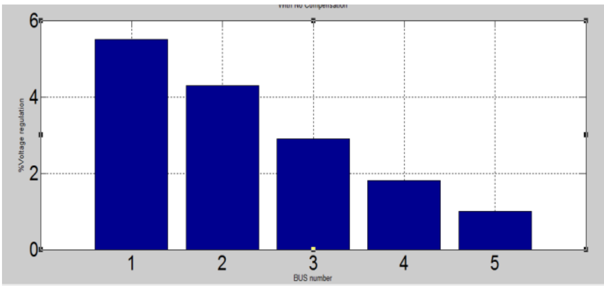

Fig. 9(a). No compensation

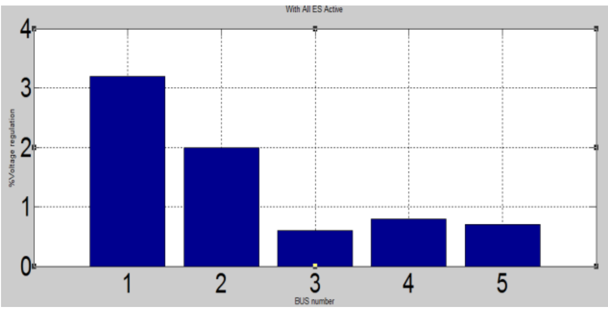

Fig. 9(b). All ESs activated

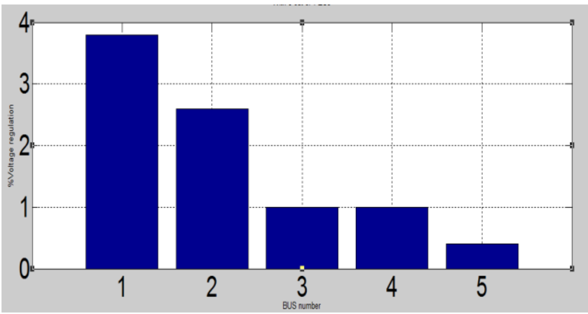

Fig.9(c). 3 out of 4 springs activated

Reactive power with All ES: 32 KVAR

Reactive power with 3 out of 4 ES: 48 KVAR

Without any voltage compensation, the voltage regulation is better away from the MV bus (bus 633) due to the natural voltage drop across the LV feeder .With a group of ESs, the voltage regulation is more uniform. Moreover, the reactive power consumption by the ESs is less. Thus, for both under-voltage and over-voltage conditions, the group of distributed ESs is to achieve better voltage regulation. The study on the modified IEEE 21 node test feeder network confirms the following:

1. Better total voltage regulation is achieved with a group of distributed ESs.
2. Total reactive capacity required by the group of ESs is significantly less.

IV. CONCLUSIONS:

The principles and operations of the electric springs (ES) with DC-link capacitors and with batteries are investigated. The original proposal of the ES with capacitors provides reactive power compensation for mains voltage stabilization and automatic non-critical load power variation for balancing power supply and load demand. By replacing the DC-link capacitors with batteries (or connecting the battery across the dc link capacitor of the inverter), the ES can operate in eight operating modes, which enable the ES to provide power factor correction. A detailed discussion into this aspect is provided in this paper.

It is shown theoretically that the ES with batteries is capable of performing line current regulation as well as power factor correction. A design of an input current controller allowing the ES to operate like a power factor corrector is presented and practically verified.

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