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Distributed Voltage Control FLC Based With Electric Springs & Comparision with Statcom

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Abstract- *In this paper, a comparison is done between electric springs (ES) and static compensator (STATCOM). A comparison is made between distributed voltage control using ES against the traditional single point control with STATic COMpensator (STATCOM) by using fuzzy logic controller. For a given range of supply voltage variation, the total reactive capacity required for each option to produce the desired voltage regulation at the point of common coupling (PCC) connection is compared. In this paper, it turns out that a group of ESs achieves better total voltage regulation than STATCOM with less overall reactive power capacity. Dependence of the ES capability on proportion of critical and NC load is also shown. Here we are using fuzzy logic controller instead of using other controllers. Simulation was done by using MATLAB/Simulink software under various critical and NCloads.*

Index Terms— *Fuzzy logic controller, Demand response, electric springs (ES), STATic COMpensator (STATCOM), voltage control, voltage regulation.*

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I. INTRODUCTION

Control of voltage in medium voltage (MV) or low voltage (LV) distribution networks is typically exercised through transformer tap-changers and/or switched capacitors/reactors. Sometimes a STATic COMpensator (STATCOM) is used for fast and precise voltage regulation, especially for the sensitive/critical loads [1]. The novel concept of electric spring (ES) has been proposed as an effective means of distributed voltage control [2]. The idea is to regulate the voltage across the critical loads while allowing the noncritical (NC) impedance-type loads (e.g., water heaters) to vary their power consumption and thus contribute to demand-side response [3], [4] as well. This would allow and facilitate large penetration of intermittent renewable energy sources without requiring huge amounts of energy storage to act as a buffer between supply and demand [5]. In this paper, the focus is to compare the effectiveness of single point voltage control using STATCOM against distributed voltage control using a group of ESs. The basis for comparison is total voltage regulation [root mean square of the deviation of the actual voltages from the rated (1.0 p.u) values] achieved and the overall reactive capability required for each option in order to achieve that [8], [9].

A number of papers [2], [5]–[7] have been published recently on the ES concept and its control. However, none of those papers have focused on the collective performance of multiple of ESs considering realistic distribution networks. This paper demonstrates the effectiveness of multiple ESs working in unison through case studies on an IEEE test feeder network and also a part of a real distribution system in Hong Kong. The voltage regulation performance and total reactive power requirement of a group of ESs in case of distributed voltage control is compared against the single-point control using a STATCOM. In both cases, it turns out that a group of ESs achieves better total voltage regulation than STATCOM with less overall reactive power capacity.

II. ELECTRIC SPRINGCONCEPT

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 uninterrupted 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. Here for electric springs controller is needed, for that controller pulses are required to turn-on the converter switches. The pulses are provided by using PWM techniques along with using fuzzy logic controller.

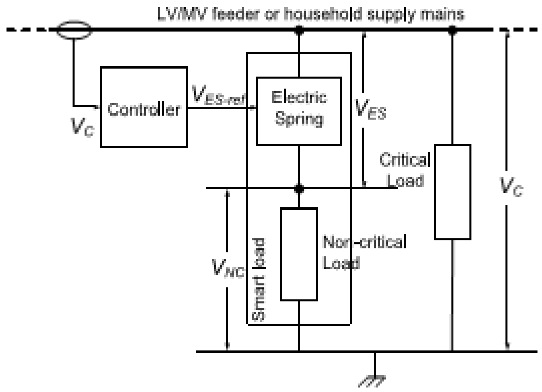


Fig. 1. Electric Spring set-up for Smart loads.

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 VES in series with each non- critical load to regulate the voltage VC across the critical load as shown in Fig. 1. The voltage VNC 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 noncritical 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 VES in quadrature with the current flowing through the ES ensures exchange of reactive power only like conventional voltage compensators including STATCOM. For further details about Electric Springs the readers can refer to [2,5].

III. ELECTRIC SPRING (ES) VS.STATCOM

A. Test System

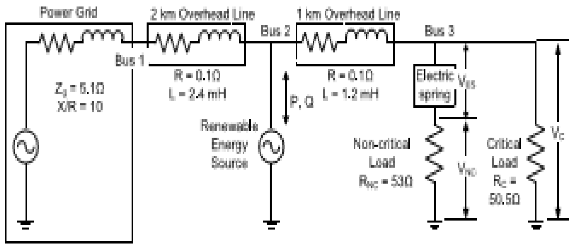


Fig. 2. Simulation set up with an intermittent source and an equivalent power grid.

In order to compare the voltage regulation performance of a single ES against that of a STATCOM, a simple test system as shown in Fig. 2 was 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 above system was modeled in Matlab/SIMULINK using a controllable voltage source representation for both ES and STATCOM. Modeling and control of ES is discussed in [13]. The magnitude of the controllable voltage representing the ES is controlled using a fuzzy logic controller to minimize the difference between the actual and reference values of the voltage across the criticalload.

B. Voltage Suppress Mode

The voltage across the loads was increased above the nominal value (216 V) by reducing the reactive power absorption of the renewable source. This is to test the ability of an ES and a STATCOM 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 was reduced from 467 VAr down to 110 VAr. Without any voltage control, the load voltage increases from the nominal value of 216 V up to 224 V as shown by Fig. 3(a) & (b). Both STATCOM and ES are able to restore the voltage across the critical load back to the nominal value as shown by the overlapping blue and red traces in Fig. 3(b). The ES achieves this by injecting about 115 V in series with the non-critical load the voltage across which drops to about 185 V as shown by the blue traces in Fig.3(c).

C. Voltage Support Mode

To investigate the opposite effect of what was described in the previous subsection, the voltage across the loads was reduced by increasing the reactive power absorption of the renewable source. This is to test the ability of an ES and a STATCOM to support the voltage and regulate it at the nominal value. At t=1.0 s, the reactive power absorption by the intermittent renewable source was increased from 467 VAr to 1100 VAr. Without any voltage control, the load voltage is seen to drop from the nominal value of 216 V to slightly below 190 V as shown by the green trace in Fig.4(a)&(b).

D. Proportion of Critical and Non-critical Loads

An ES injects a voltage is series with the non-critical load in order to regulate the voltage across the critical load. The proportion of the critical and non-critical load is therefore,quite important towards the effectiveness of an ES both in terms of its voltage regulation capability and also the amount of reactive power (and hence its rating) exchanged with the system. If the injected voltage increases, the voltage across the non-critical load and hence the current reduces which limits the reactive capability of an ES and thus its ability to regulate the voltage across the critical load.

The reactive power exchange with the ES depends on the injected voltage VES and also on the impedance of the noncritical load. Consider the circuitshowninFig.1.Foraresistive-inductive(R-L) type non-critical load with impedance ZNC ∠θ NC, the voltages VC, VES and VNC are shown on the phasor diagram in Fig. 6(a) when the ES is working in voltage support (i.e. capacitive) mode. From the phasor diagram we can write:

$$V_C^2 = (V_{NS} - V_{ES}\sin 8\,NC)^2 + (V_{ES}\cos 8NC)^2 \qquad (1)$$

$$V_{NC} = \pm\sqrt{V_C^2 - (V_{ES}\cos 8NC)^2} + V_{ES}\sin 8NC \qquad (2)$$

$$Q_{ES} = V_{ES} I_{NC}\sin(-90^\circ) = -V_{ES} I_{NC} = -\frac{V_{ES} I_{NC}}{Z_{NC}} \qquad (3)$$

$$Q_{NS} = VI_{ESNC}\sin 8\,NC = \frac{V_{NC}^2}{Z_{NC}}\sin 8NC \qquad (4)$$

Here, QES and QNC are the reactive powers of the ES and the non-critical load, respectively. For a purely resistive noncritical load, the reactive power of the ES and the smart load will be equal. However, they would be different if the the noncritical 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 QSL is given by:

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

$$Q_{SL} = \frac{-V_{EC}\left(\pm\sqrt{V_C^2-(V_{EC}\cos 8NC)^2}+V_{EC}\sin 8NC\right)}{Z_{NC}} + \frac{\left(V_{EC}\left(\pm\sqrt{V_C^2-(V_{EC}\cos 8NC)^2}+V_{EC}\sin 8NC\right)\right)^2}{Z_{NC}}\sin 8NC \qquad (6)$$

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

$$V_{NC} = \pm\sqrt{V_C^2-(V_{ES}\cos 8\,NC)^2} - V_{ES}\sin 8NC \qquad (7)$$

$$Q_{SL} = \frac{V_{ES}\left(\pm\sqrt{V_C^2-(V_{ES}\cos 8NC)^2}-V_{ES}\sin 8NC\right)}{Z_{NC}} + \frac{\left(\pm\sqrt{V_C^2-(V_{ES}\cos 8NC)^2}-V_{ES}\sin 8NC\right)^2}{Z_{NC}}\sin 8\,NC \qquad (8)$$

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 (ZNC). A decrease in the value of ZNC (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 anES.

E. Reactive Power Limit of Smart Load

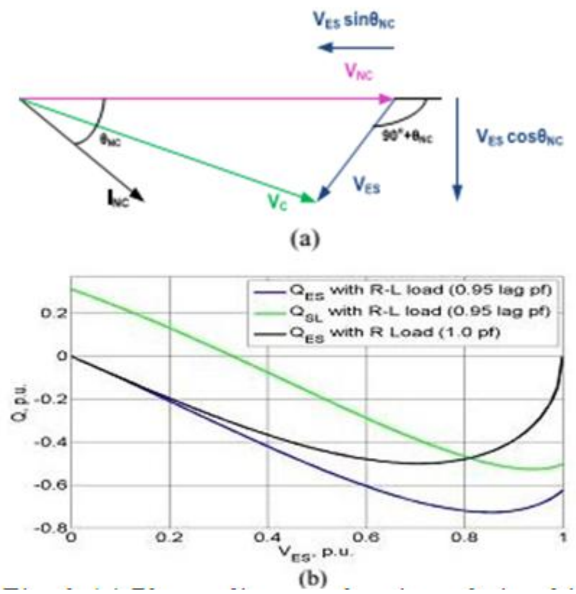


Fig. 6. (a) Phasor diagram showing relationship between voltages across non-critical load, critical load and ES, (b) Variation of reactive power of ES and smart load with respect to ES voltage for R-L and R non-critical loads.

For a fixed non-critical load impedance (ZNC∠ θNC)andatargetcriticalloadvoltage(VC= 1.0 p.u.), all the terms on the right hand side of (3), (6) and (8) are constant except the ES voltage (VES). Hence, QES and QSL can be expressed as functions of VES only. Fig. 6(b) shows the variation of QES and QSL versus VES for VC = 1.0 p.u., and ZNC =1.0 p.u. for two different power factor of thenon- critical load. In all cases the ES is considered to be in voltage support (i.e. capacitive) mode as indicated by the negative sign of QES. For a purely resistivenon- critical load, QES and QSL are equal and are shown by the black trace in Fig. 6(b).

It can be seen that beyond a certain point, increasing the ES voltage will result in a decrease in reactive power magnitude due to decrease of the current. Hence, it is essential to impose a limit on the output of the fuzzy logic controller which determines the ES voltage magnitude, so that the voltage injected by the ES does not go beyond the maximum reactive power (magnitude) point on the curves shown in Fig. 6(b).

IV. FUZZY LOGICCONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.

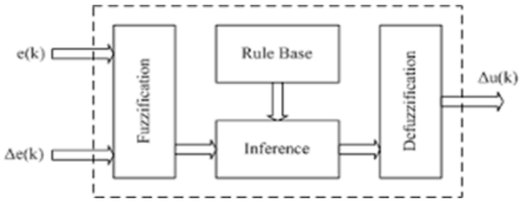


Fig.9.Fuzzy logic controller

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

TABLE I: Fuzzy Rules

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The Partition of fuzzy subsets and the shape of membership *CE(k) E(k)* function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular *E(k)* input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \qquad (18)$$

$$CE(k) = E(k) - E(k-1) \qquad (19)$$

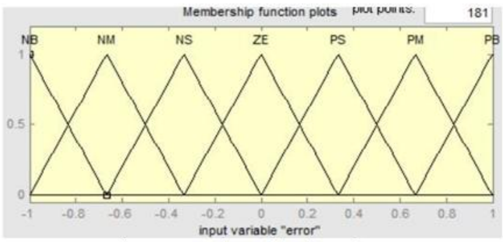


Fig.10.Membership functions

Inference Method: Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification: As a plant usually requires a non- fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error andoutput

The set of FC rules are derived from
u=-[α E+(1-α)*C] (20)

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error E indicates that the system is near to balanced state.

V. SIMULATIONRESULTS

WITH ES

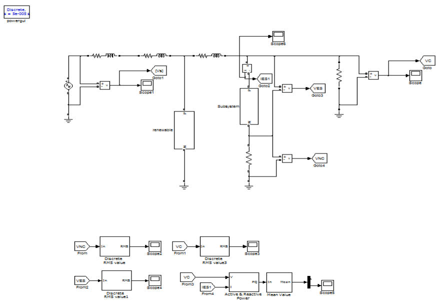


Fig.11. Matlab model of proposed system with ES

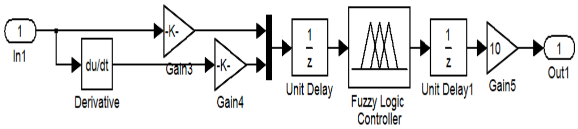
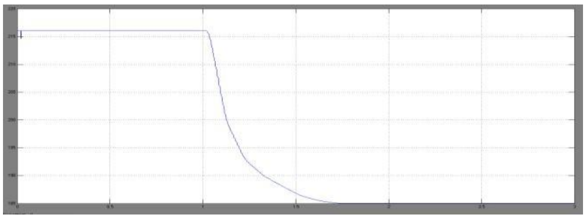
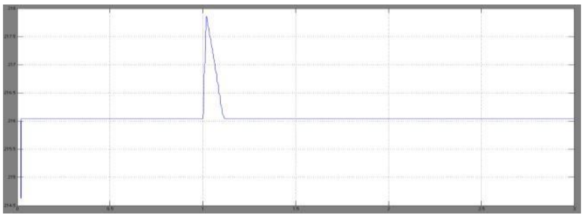


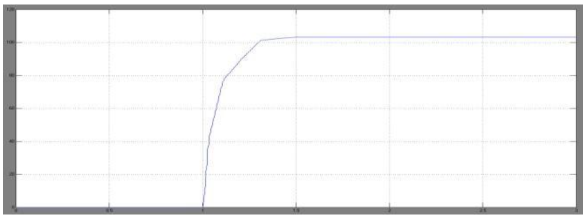
Fig.12. Fuzzy logic controller



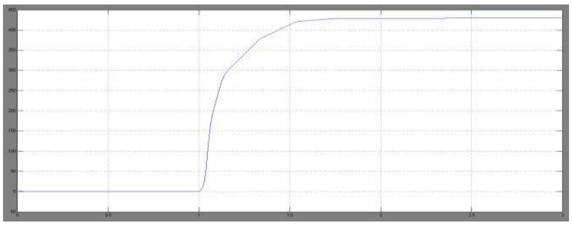
(a)



(b)

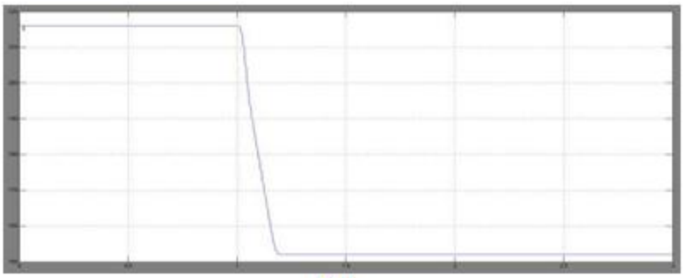


(c)

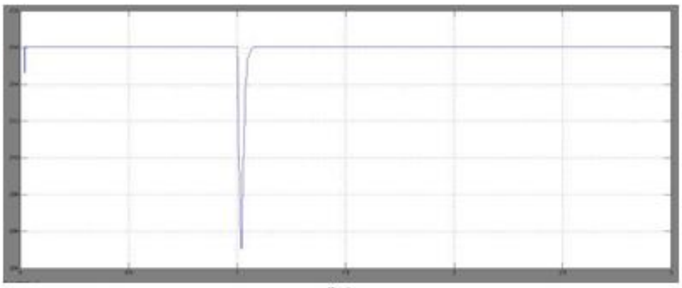


(d)

Fig. 13. System response following decrease in reactive power consumption of the intermittent source from 467 to 110 VAr. (a) Non-critical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.



(a)



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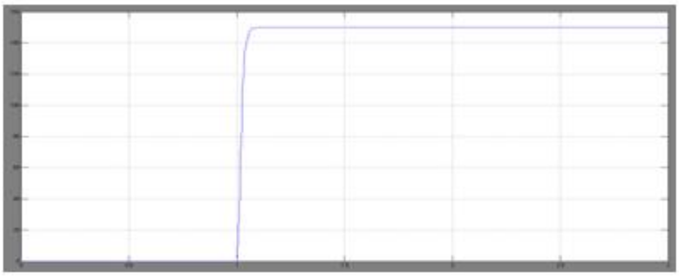

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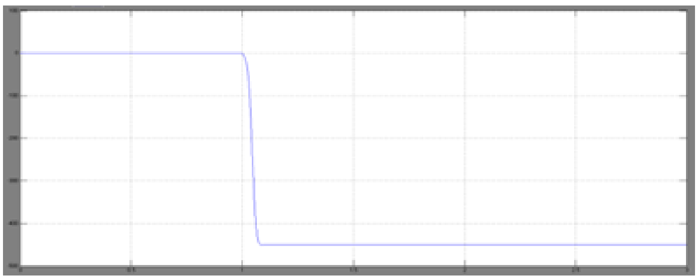
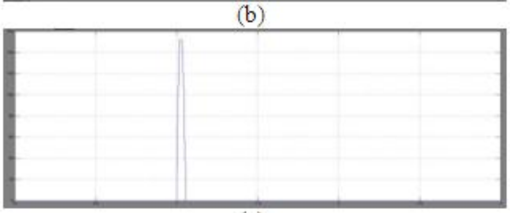


(d)

Fig. 14. System response following increase in reactive power consumption of the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.


(a)


(b)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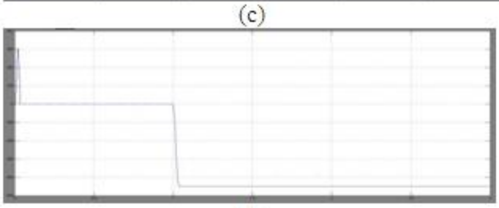
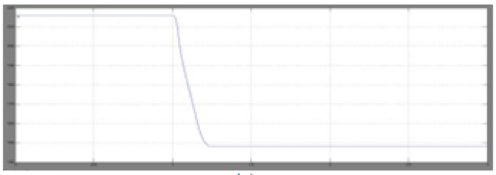

(d)
(i) NCC=1.9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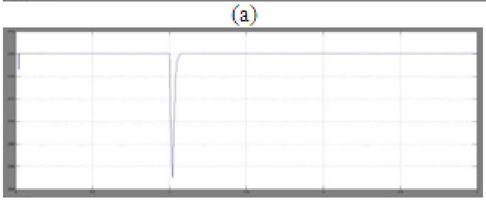
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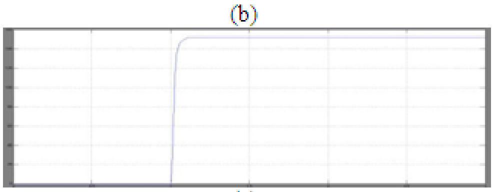
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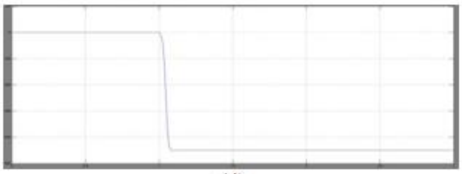
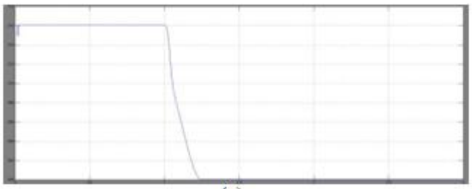

(d)
(ii) NCC=5.5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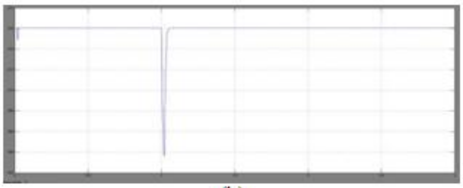
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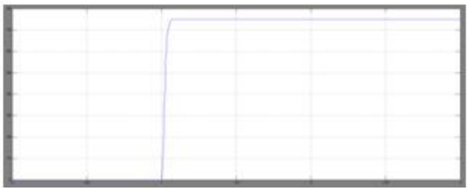
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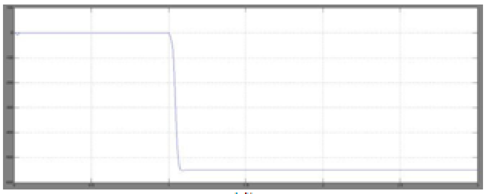

(d)
(iii) NCC=9.1

Fig. 15. System response for different distribution of noncritical and critical loads (NC:C). Disturbance is increase in reactive power consumption of the intermittent source from467 to 1100 VAr.(a) Noncritical load voltage.(b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

WITH STATCOM

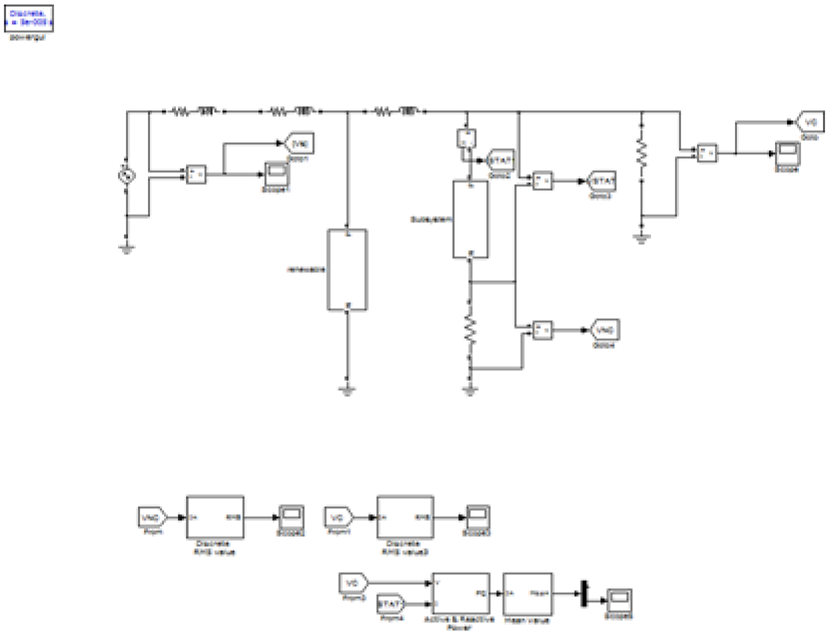
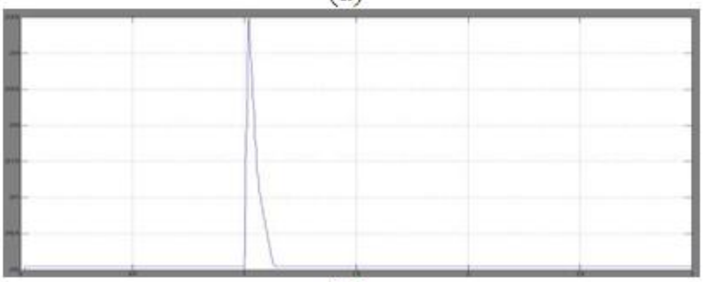
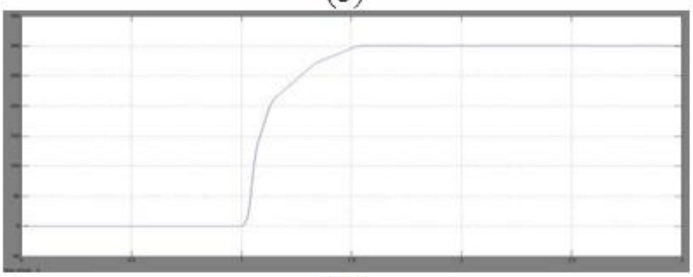


Fig.16. Matlab model of proposed system with STATCOM

(a)

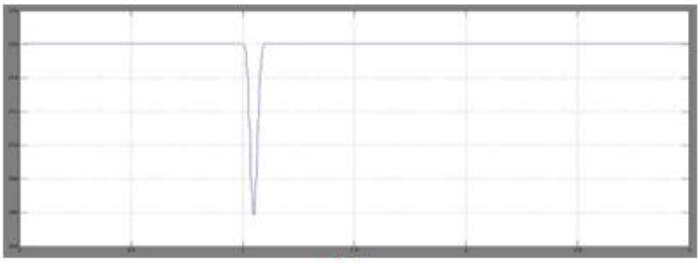


(b)

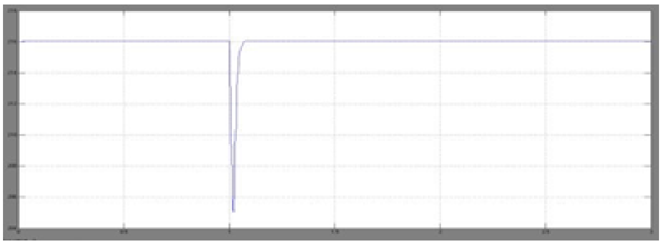


(c)

Fig. 17. System response following decrease in reactive power consumption of the intermittent source from 467 to 110 VAr. (a) Non-critical load voltage. (b) Critical load voltage. (c) Reactive power exchange.



(a)



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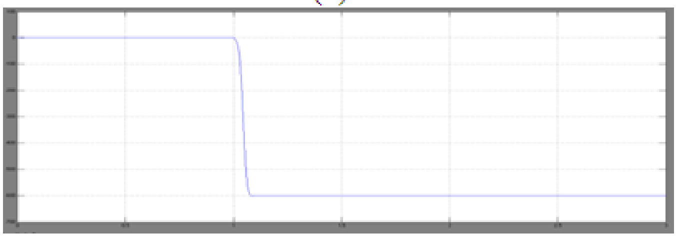


(c)

Fig. 18. System response following increase in reactive power consumption of the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage. (b) Critical load voltage (c) Reactivepower exchange.

WITHOUT CONTROL

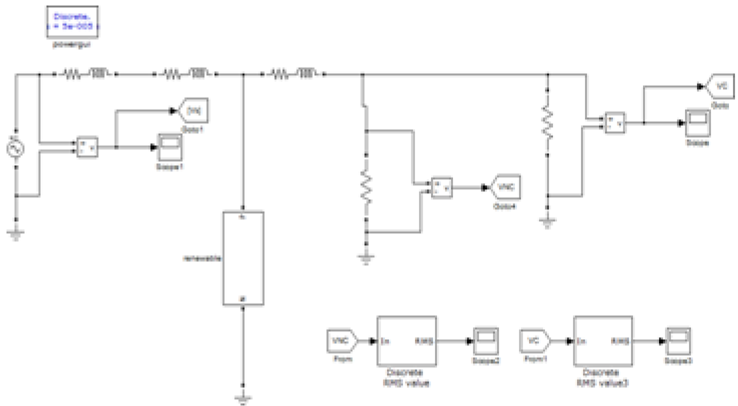
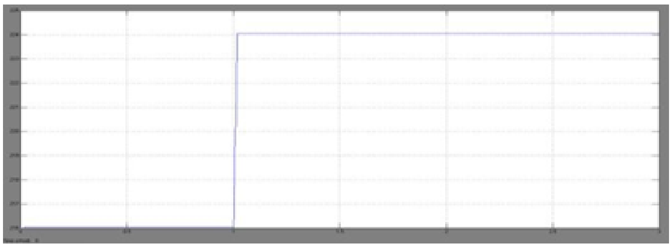
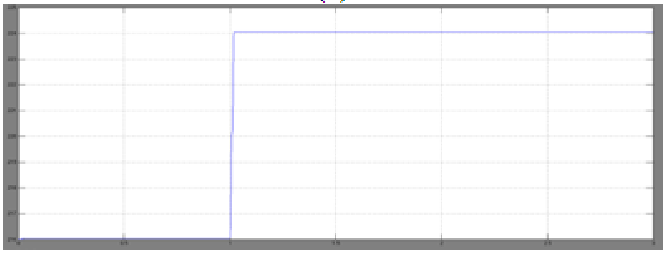


Fig.19. Matlab model of proposed system without any control

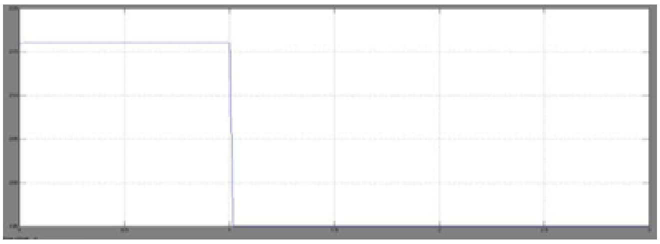


(a)



(b)

Fig. 20. System response following increase in reactive power consumption of the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage. (b) Critical load voltage



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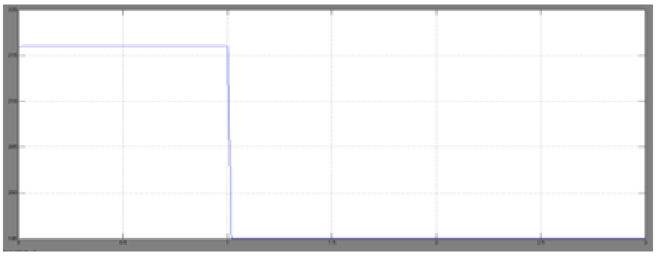

(b)

Fig. 21. System response for different distribution of noncritical and critical loads (NC:C). Disturbance is increase in reactive power consumption of the intermittent source from467 to 1100 VAr.(a) Noncritical load voltage.(b) Critical load voltage.

VI. CONCLUSION

In this paper a comparison is made between distributed voltage control using ES against the traditional single point control with STATCOM by using fuzzy logic controller. For a given range of supply voltage variation, the total voltage regulation and the total reactive capacity required for each option to produce the desired voltage regulation at the point of connection are compared. In this paper, it turns out that the ESs requires less overall reactive power capacity than STATCOM and yields better total voltage regulation. This makes electric springs (ESs) a promising technology for future smart grids where selective voltage regulation for sensitive loads would be necessary alongside demand side response. The simulation was done using MATLAB/Simulink software. The comparison was done between electric springs (ES) and static compensator(STATCOM).

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