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Comparison of Electric Springs with STATCOM for UPQC Based Distributed Voltage Control

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ABSTRACT:

The concept of electric spring (ES) has been proposed recently as an effective means of distributed voltage control. The idea is to regulate the voltage across the critical (C) 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. In this paper, a comparison is made between distributed voltage control using ES against the traditional single point control with STATic Compensator (STATCOM) and UPQC. 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.

Index Terms:

Demand response, electric springs (ES), STATicCOM pensator (STATCOM), voltage control, voltage regulation.

I. INTRODUCTION:

VOLTAGE control 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]. The basic proof of concept of ES has already been demonstrated through hardware experimentation with the developed prototypes [2], [6]. Distributed voltage regulation through collective action of a cluster of ESs, each employing droop control has also been illustrated [7].

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. To validate the performance of the proposed Unified power quality conditioner(UPQC)an investigation is carried out for changes in input and output conditions. From the investigations the variations of voltage control, voltage gain, voltage regulation . ES has to compare to UPQC. a group of ESs acheives better voltage regulation than UPQC with less overall reactive capability. Finally the simulation results and theoretical concept of the proposed Unified power quality conditioner (UPQC) have been verified with experimental set up.

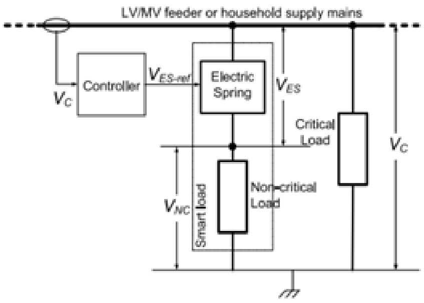

Fig. 1.Electric spring set-up for smart loads.

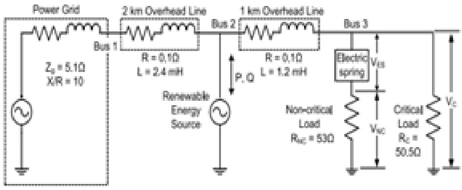

Fig. 2.Simulation set-up with an intermittent source and an equivalent power grid.

II. ELECTRIC S PRING (ES) 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. DSM, 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 (C) loads requiring constant voltage and uninterrupted supply and NC, impedance-type loads. At times of generation shortfall or network constraint, the voltage of the NC loads is reduced while regulating the voltages across the C loads. This addresses the generation shortfall or network. constraint and also facilitates better voltage regulation of the C loads through manipulation of the supply impedance voltage drop. One way to exercise this control is to use the so-called ESs which are power electronic compensators that inject a voltage with controllable magnitude VES in series with each NC load to regulate the voltage VC across the C load as shown in Fig. 1.

The voltage VNC across the NC loads is thus controlled (within allowable bounds) and the active power consumed by them modulated. The series combination of the ES and the NC load thus acts as a smart load which ensures tightly regulated voltage across the C 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 ESs the readers can refer to [2] and [5].

Electric Spring:

- An electric spring is a power electronics system.
- It can be embedded in an electric appliance such as electric water heater or refrigerator.
- Electric springs can therefore be ‘distributed” over the power grid to stabilize the mains voltage in the presence of a large % of intermittent renewable power generation.

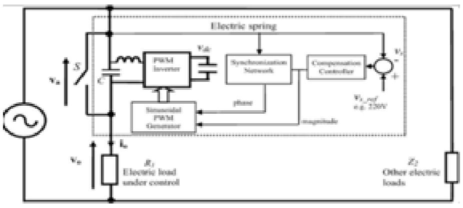

Fig. 3 (a) Electric spring design

Fig.3(b) Electric spring

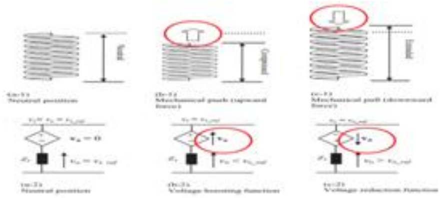

Fig. 3(c) working of electrical spring

Applications of Electric Springs:

- To stabilize future power grid with large-scale wind and solar power generation

Fig.4 wind and solar power generation

III. ES VERSUS STATCOM:

A. Test System:

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. 5 has 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.

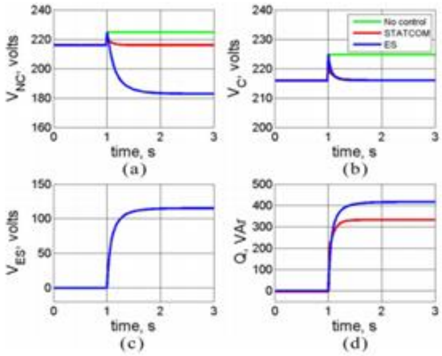

Fig. 5.System response following decrease in reactive power consumption of the intermittent source from 467 to 110 VAr. (a) Non-critical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

The controllable source is capable of 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 resistive. The parameters used for the system and the ES are the same as in [2] and are not repeated here due to space restriction. The above system is 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 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. The STATCOM is modeled by a controllable voltage source in series with impedance. Its control circuit is very similar to that of ES except for the adjustments due to its parallel connection to the C and NC load.

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 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 is 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. 5(a) and (b). Both STATCOM and ES are able to restore the voltage across the C load back to the nominal value as shown by the overlapping blue and red traces in Fig. 5(b).The ES achieves this by injecting about 115 V in series with the NC load the voltage across which drops to about 185 V as shown by the blue traces in Fig. 5(a) and (c). In order to suppress the voltage, both ES and STATCOM absorb reactive power (as indicated by positive sign of Q) from the system as shown in Fig. 5(d) with ES requiring to absorb about 100VAr more than the STATCOM.It is observed that the reactive power consumed by ES to restore the C load voltage to normal value is higher than the reactive power consumed by STATCOM to achieve the same voltage. This can be explained from Fig. 1. An increase in ES voltage will result in a decrease in NC load voltage. This causes a decrease in the active power consumption of the (resistive) NC load. In order to have a higher overall active/reactive power consumption for the smart load, ES has to consume more reactive power. Note that the X/R ratio is not large (about 2) in this case which is why both active and reactive power affect the voltage regulation.

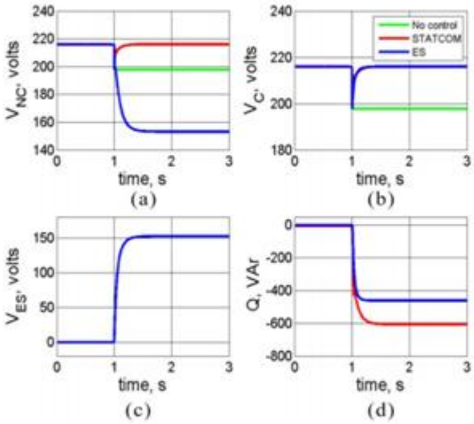

Fig. 6.System response following increase in reactive power consumption of the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

C. Voltage Support Mode:

To investigate the opposite effect of what was described in the previous subsection, the voltage across the loads is 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 is increased from 467 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. 5(a) and (b).As before, both STATCOM and ES are able to restore the voltage across the C load back to the nominal value as shown by the overlapping blue and red traces in Fig. 5(b). The ES achieves this by injecting about 150 V in series with the NC load the voltage across which drops to about 150 V as shown by the blue traces in Fig. 5(a) and (c). In order to suppress the voltage, both ES and STATCOM inject reactive power (as indicated by negative sign of Q) into the system as shown in Fig. 5(d) with ES requiring to inject about 150 VAr less

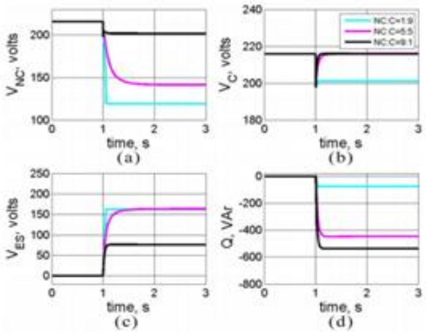

Fig. 7. System response for different distribution of noncritical and critical loads (NC:C). Disturbance is increase in reactive power consumption of the intermittentsourcefrom467to1100VAr.

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(a)Noncriticalloadvoltage. (b)Criticalload voltage. (c) Electric spring voltage. (d) Reactive power exchange.

Than the STATCOM. This is due to the fact that an increase in ES voltage will result in a reduction of NC load voltage which causes a decrease in active power consumption of the (resistive) NC load. Hence, the ES needs to produce less reactive power than an equivalent STATCOM to restore the system voltage due to the similar arguments about the X/R ratio as mentioned earlier for the voltage suppress case.

D. Proportion of C and NC Loads:

An ES injects a voltage is series with the NC load in order to regulate the voltage across the C load. The proportion of the C and NC load is therefore, quite important toward 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. The reactive capability of an ES is governed by the product of the voltage it injects and the current flowing through it (which is the same as the current through the NC load). If the injected voltage increases, the voltage across the NC load and hence the current reduces which limits the reactive capability of an ES and thus its ability to regulate the voltage across the C load. For low proportion of NC load, the fidelity of current is restricted which limits the capability of an ES compared to the case when the proportion of NC load is relatively high. To verify this, simulations have been conducted with different proportions of NC and C loads. The results are shown in Fig. 5.It can be seen that for high proportion of NC load (NC:C = 9:1) shown by the black traces, the C load voltage is restored back to its nominal value, with only 80 V injected by the ES. This results in little change (from 216 to 202 V) in voltage across the NC load. Voltage regulation is similar for equal proportion of C and NC (NC:C = 5:5) loads shown by magenta traces. However, the voltage across the NC load is lower (about 140 V) than before due to larger injected voltage (160 V) by the ES. Based on public statistics in Hong Kong [14], about 50% of loads (such as heaters, Air-conditioners, etc.) in domestics and commercial buildings can be considered as NC. For low proportion of NC load (NC:C = 1:9), it is not possible to restore the voltage across the C load back to its nominal value as shown by the cyan trace in Fig. 7(b). This is because of the low fidelity in current which restricts the reactive capability of the ES to less than 100 VAr [Fig. 7(d)] for a maximum possible ES voltage of 160 V. This demonstrates that the voltage regulation capability of an ES is dependent on the relative proportion of NC and C load. Lesser the proportion of NC load, lower is the voltage regulation capability of an ES. As the second generation of ES with embedded energy storage [15] has emerged, there would be more flexibility in control which would be demonstrated in a future paper. The reactive power exchange with the ES depends on the injected voltage VES and also on the impedance of the NC load. Consider the circuit shown in Fig. 1. For a resistive–inductive (R–L) type NC load with impedance ZNC∠θ NC, the voltages VC, VES, and VNC are shown on the phasor diagram in Fig. 8(a) when the ES is working in voltage support (i.e., capacitive) mode. From the phasor diagram, we can write,

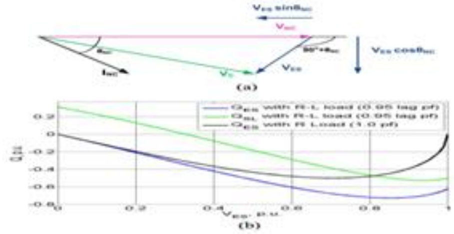

Fig. 8. (a) Phasor diagram showing relationship between voltages across noncritical load, critical load, and ES. (b) Variation of reactive power of ES And smart load with respect to ES voltage for R–L and R noncritical loads.

$$V_C^2 = (V_{NC} - V_{ES} \sin \theta NC)^2 + (V_{ES} \cos \theta NC)^2 \quad (1)$$

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

$$Q_{ES} = V_{ES} I_{NC} \sin(-90^0) = -V_{ES} I_{NC} = \frac{V_{ES} V_{NC}}{Z_{NC}} \quad (3)$$

$$Q_{NC} = V_{NC} I_{NC} \sin \theta NC = \frac{V_{NC}^2}{Z_{NC}} \sin \theta NC (4)$$

Here, QES and QNC are the reactive powers of the ES and the NC load, respectively. For a purely resistive NC load, the reactive power of the ES and the smart load will be equal. However, they would be different if the NC is not purely resistive. If the ES is working in voltage support. (i.e., capacitive) mode with a NC load of R–L type, the total reactive power of the smart load QSL is given by

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

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

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

$$V_{NC} = \pm\sqrt{V_C^2 - (V_{ES}\cos\theta NC)^2} + V_{ES}\sin\theta NC (7)$$

And

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

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

Unified power quality conditioner (UPQC):

Unified power quality conditioner (UPQC), which aims at the integration of series active and shunt-active power filters. The main purpose of a UPQC is to compensate for voltage imbalance, reactive power, negative-sequence current and harmonics.

The UPQC is a combination of series and shunt active filters connected in cascade via a common DC link capacitor. The main purpose of a UPQC is to compensate for supply voltage power quality issues such as, sags, swells, unbalance, flicker, harmonics, and for load current power quality problems such as, harmonics, unbalance, reactive current and neutral current .

BASIC CONFIGURATION OF UPQC:

- UPQC is the integration of series and shunt active power filters connected back to back on the dc side sharing on common DC capacitor.
- The series component of the UPQC is responsible for mitigation of the supply side disturbances.
- The shunt component is responsible for mitigating the current quality problems caused by the consumer.

The series APF inserts a voltage, which is added at the point of common coupling (PCC) such that the load end voltage remains unaffected by any voltage disturbance, whereas, the shunt APF is most suitable to compensate for load reactive power demand and unbalance, to eliminate the harmonics from supply current, and to regulate the common DC link voltage[2].

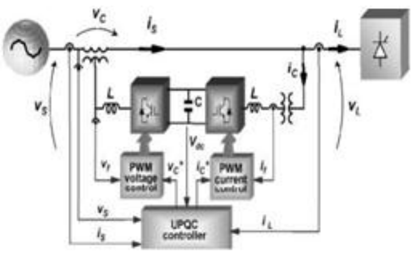

Figure 5.1: Basic configuration of the UPQC

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SIMULATION RESULTS:

ELECTRIC SPRING RESULTS:

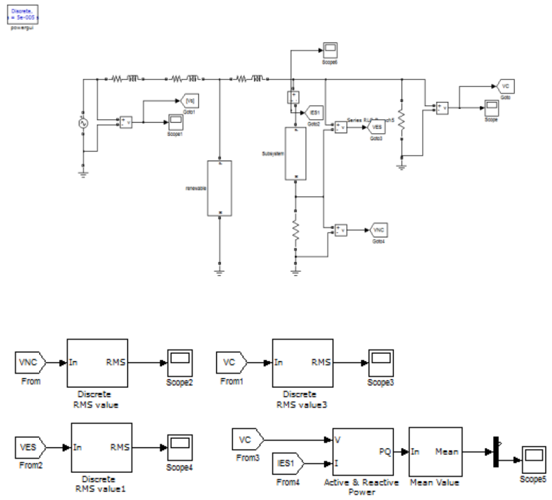

Figure 6.1: Matlab model of proposed system with ES1

WAVEFORMS:

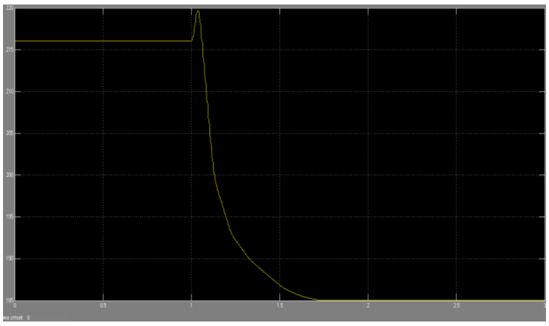

Figure 6.2 : System response following decrease in reactive power consumptionof the intermittent source from 467 to 110 VAr. (a) Non-critical load voltage.

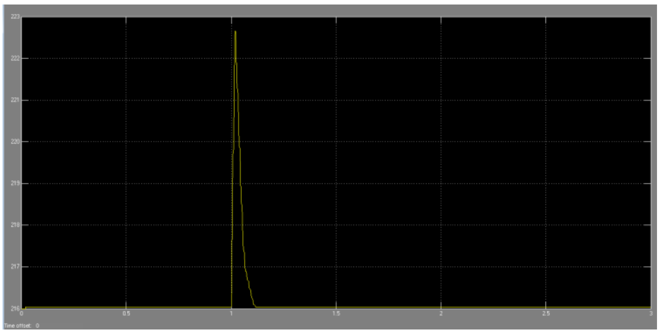

Figure 6.3: (b) Critical load voltage.

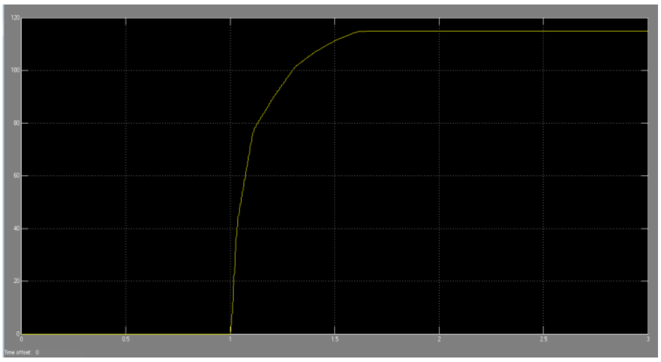

Figure 6.4: (c) Electric spring voltage

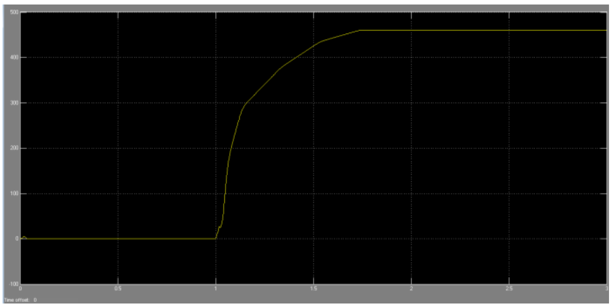

Figure 6.5: (d) Reactive power exchange.

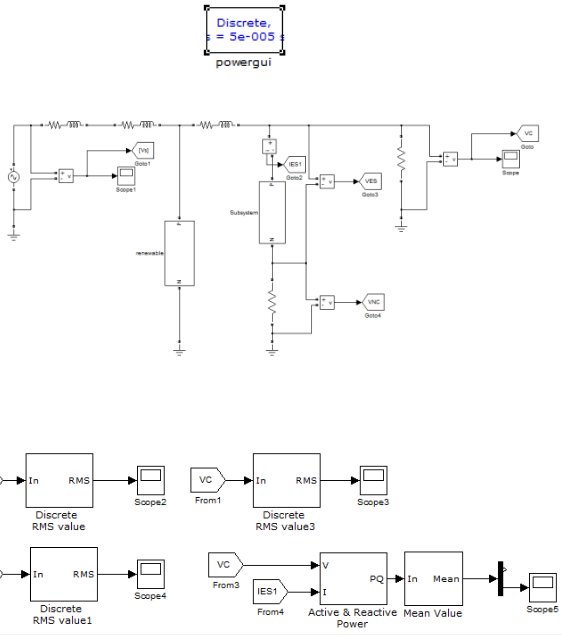

Figure 6.7: Matlab model of proposed system with ES2

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WAVEFORMS:

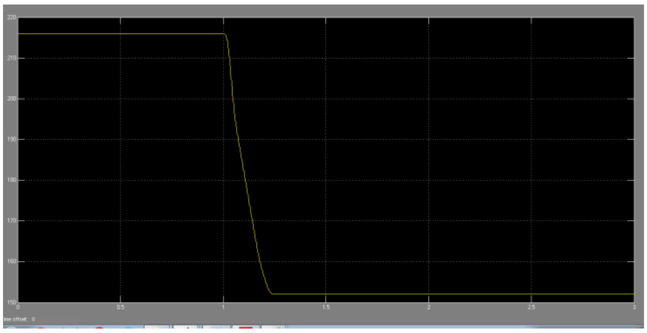


Figure 6.8: System response following increase in reactive power consumptionof the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage.

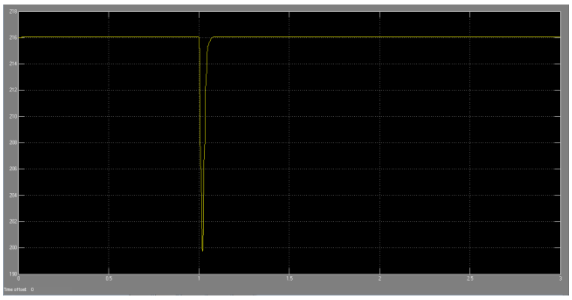


Figure 6.9: (b) Critical load voltage.

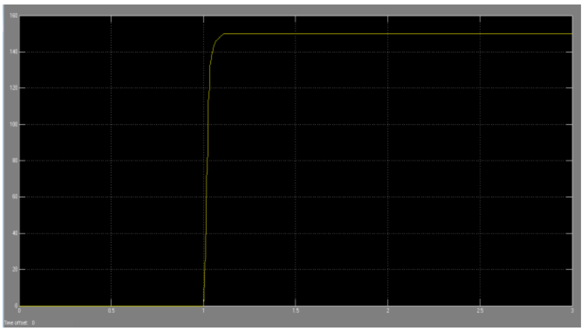


Figure 6.10: (c) Electric spring voltage.

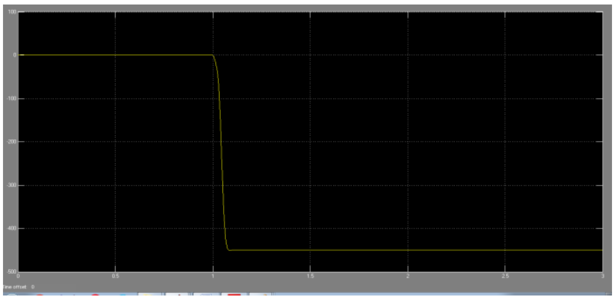


Figure 6.11: (d) Reactive power exchange.

SIMULATION OF STATCOM:

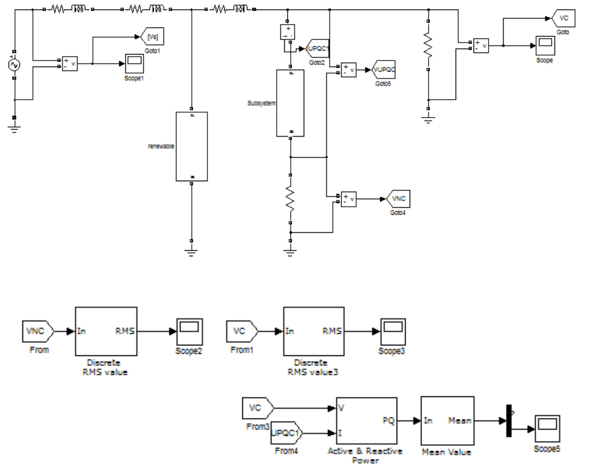


Figure 6.12:Matlab model of proposed system with STATCOM1

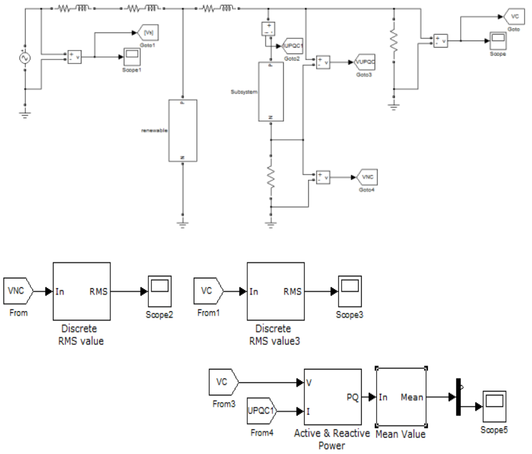
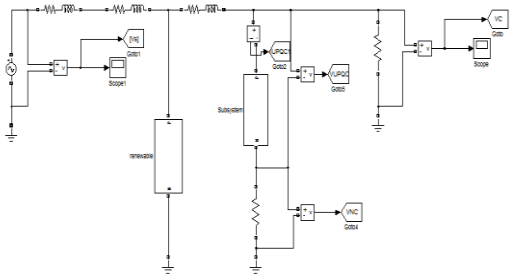


Figure 6.13:Matlab model of proposed system with STATCOM2

UPQC RESULTS:



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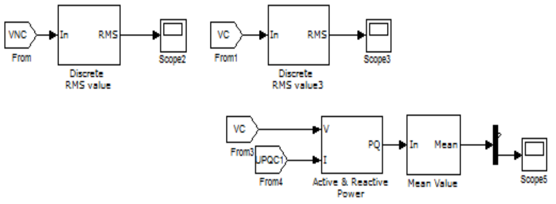

Figure 6.1: Matlab model of proposed system with UPQC1

WAVE FORMS:

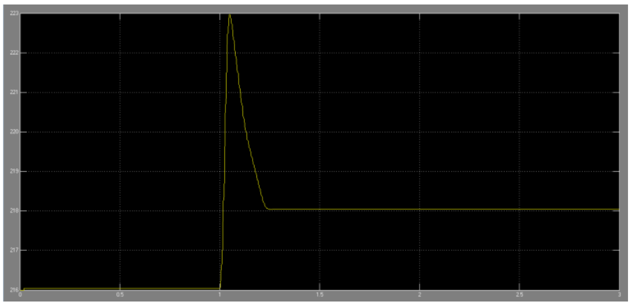

Figure 6.2: System response following decrease in reactive power consumption of the intermittent source from 467 to 110VAr .(a) Non-critical load voltage.

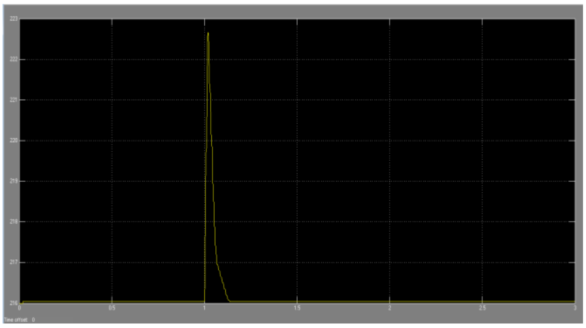

Figure 6.3: System response following decrese in reactive power consumption of the intermittent source from 467 to 110VAr (b)Critical load voltage.

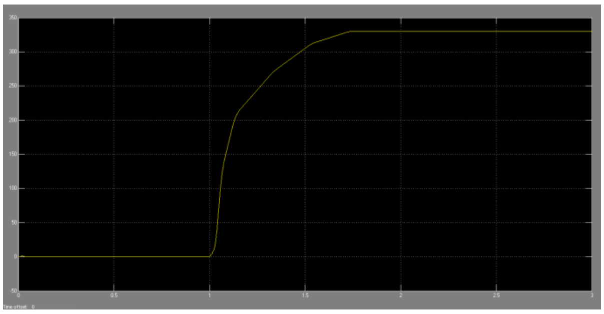

Figure 6.4: System response following decrease in reactive power consumptionof the intermittent source from 467 to 110 VAr. (d)Reactive power exchange.

6.2 SIMULATION OF OF UPQC2:

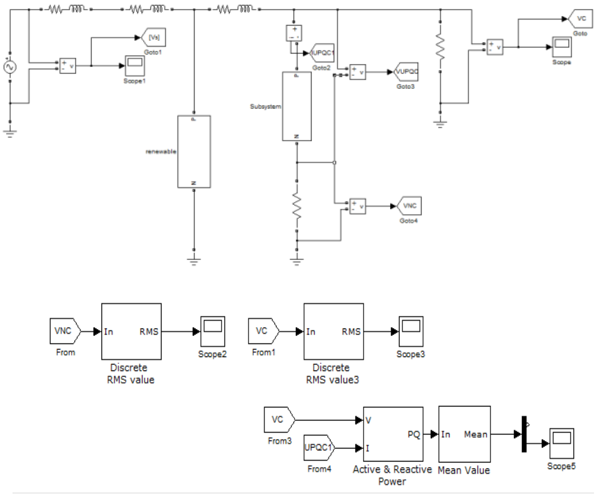

figure 6.5: Matlab model of proposed system with UPQC2

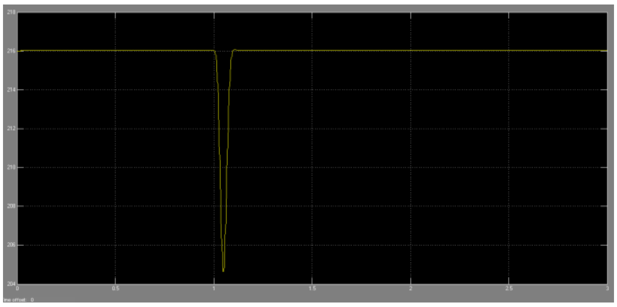

Figure 6.6: System response following increase in reactive power consumptionof the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage.

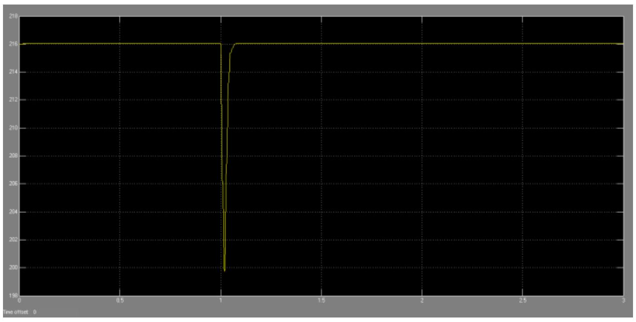

Figure6.7: System response following increase in reactive power consumptionof the intermittent source from 467 to 1100 VAr (b)Critical load voltage..

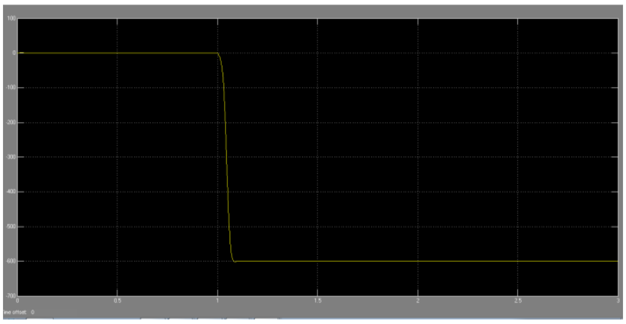

Figure 6.8: System response following increase in reactive power consumptionof the intermittent source from 467 to 1100 VAr.(c)reactive power exange.

CONCLUSION:

In this paper, a comparison is made between distributed voltage control using ES against the traditional single point control with STATCOM. 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. A simple case study with a single ES and STATCOM is presented first to show that the ES and STATCOM require comparable reactive power to achieve similar voltage regulation. it turns out that a group of distributed ESs requires less overall reactive power capacity than STATCOM and yields better total voltage regulation.

This makes ESs a promising technology for future smart grids where selective voltage regulation for sensitive loads would benecessary alongside demand-side response. The Proposed distributed voltage control with electric spring compare to UPQC.UPQC better than electric spring acheives better voltage regulation. The Electric spring and UPQC require comparable reactive power to achieves similar voltage regulation.

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