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Analysis and Performance Evaluation of Electric Springs and STATCOM for Compensating Voltage Fluctuations

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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). 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 connection is 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. Comparison between a STATCOM and ES is further substantiated through similar case studies on the IEEE 13-bus test feeder system and also on a part of the distribution network in Sha Lo Wan Bay, Hong Kong. In both cases, 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 the proportion of critical and NC load is also shown.

Keywords- STATic Compensator, electric spring, distributed voltage control, voltage regulation, reactive power.

1. 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 [1-3]. Sometimes a STATic Compensator (STATCOM) is used for fast and precise voltage regulation, especially for the sensitive/critical loads. The novel concept of electric spring (ES) has been proposed as an effective means of distributed voltage control. 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 as well [4,5]. 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. The basic proof of concept of ES has already been demonstrated through hardware experimentation with the developed prototypes.

Distributed voltage regulation through the collective action of a cluster of ESs, each employing droop control has also been illustrated. 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 [6-8]. 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. A number of papers 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 the case of distributed voltage control are 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.

2. Introduction To Electric Spring

Voltage control in LV and MV distribution networks and demand-side management (DSM) have traditionally been treated and tackled separately [9]. 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.

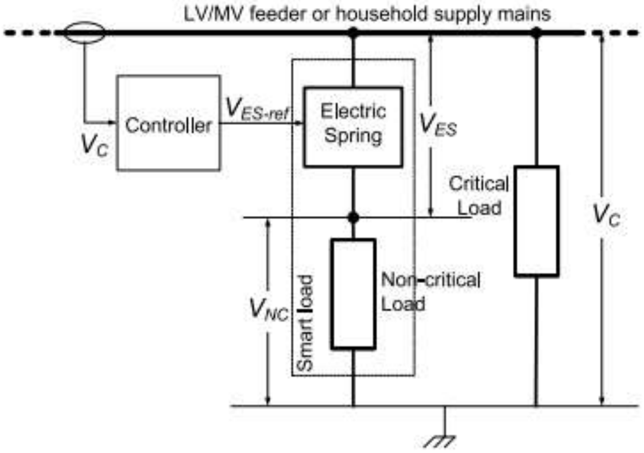

Figure 1. Electric spring set-up for smart loads.

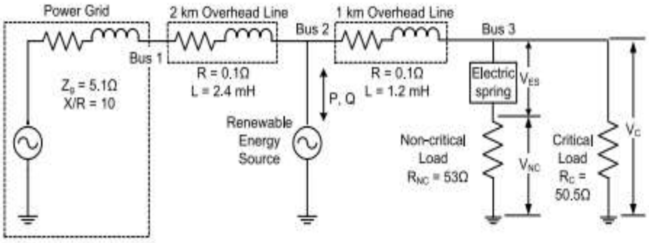

Figure 2. Simulation set-up with an intermittent source and an equivalent power grid.

Alternatively, an integrated approach to voltage control and aggregated demand action could be achieved by separating the loads into critical (C) loads requiring a 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 the 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.

2.1 Design and Operation Of Electrict 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.

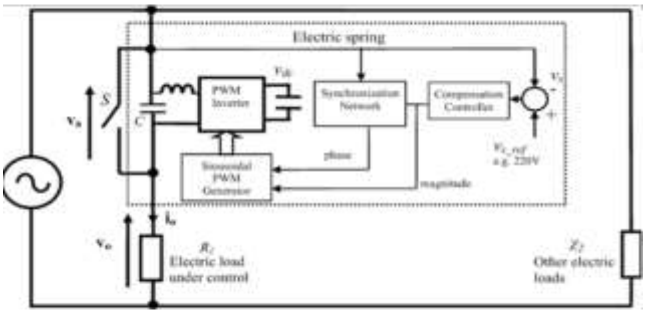

Figure 3. Electric spring design

Figure 4. Electric spring

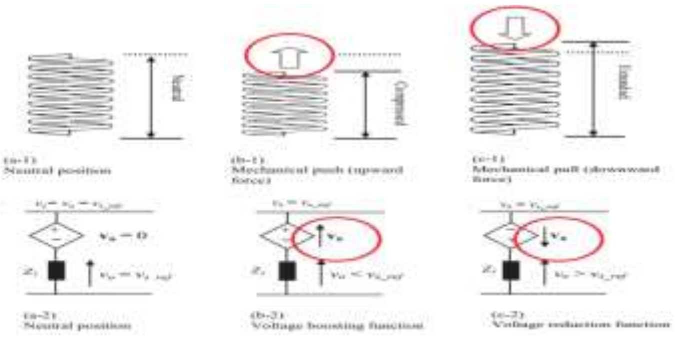

Figure 5. operation of Electric spring

3. Structure of Statcom

Basically, STATCOM is comprised of three main parts as shown in Fig. 6 a voltage source converter (VSC), a step-up coupling transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors [10-12]. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters.

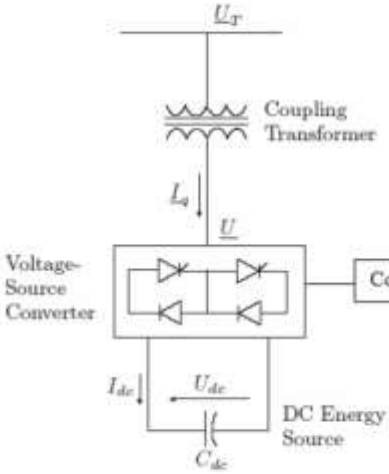

Figure 6. Reactive power generation by a STATCOM

3.1 BASIC OPERATING PRINCIPLES OF STATCOM

The STATCOM is connected to the power system at a PCC (point of common coupling), through a step-up coupling transformer, where the voltage-quality problem is a concern. The PCC is also known as the terminal for which the terminal voltage is U_T. All required voltages and currents are measured and are fed into the controller to be compared with the commands.

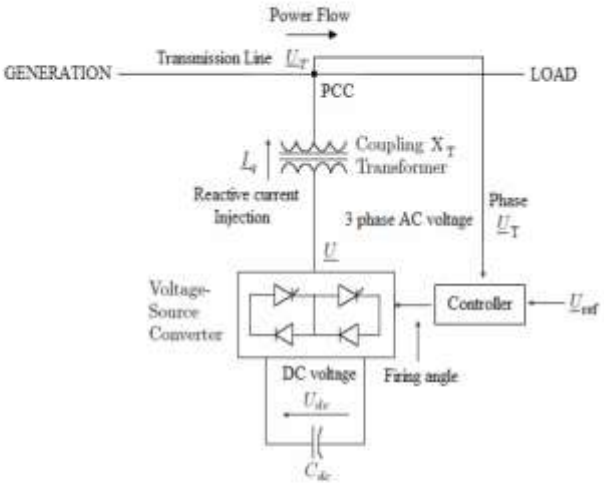

Figure 7. STATCOM operation in a power system

The controller then performs feedback control and outputs a set of switching signals (firing angle) to drive the main semiconductor switches of the power converter accordingly to either increase the voltage or to decrease it accordingly [13]. A STATCOM is a controlled reactive-power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks. Using the controller, the VSC and the coupling transformer, the STATCOM operation is illustrated in Fig. 7.

The charged capacitor C_{dc} provides a DC voltage, U_{dc} to the converter, which produces a set of controllable three-phase output voltages, U in synchronism with the AC system. The synchronism of the three-phase output voltage with the transmission line voltage has to be performed by an external controller [14]. The amount of desired voltage across STATCOM, which is the voltage reference, Uref, is set manually to the controller. The voltage control is thereby to match U_T with Uref which has been elaborated. This matching of voltages is done by varying the amplitude of the output voltage U, which is done by the firing angle set by the controller. The controller thus sets U_T equivalent to the Uref. The reactive power exchange between the converter and the AC system can also be controlled. This reactive power exchange is the reactive current injected by the STATCOM, which is the current from the capacitor produced by absorbing real power from the AC system.

$$I_q = \frac{U_T - U_{eq}}{X_{eq}} \qquad (1)$$

where I_q is the reactive current injected by the STATCOM

U_T is the STATCOM terminal voltage

U_{eq} is the equivalent Thevenin voltage seen by the STATCOM

X_{eq} is the equivalent Thevenin reactance of the power system seen by the STATCOM

If the amplitude of the output voltage U is increased above that of the AC system voltage, U_T, a leading current is produced, i.e. the STATCOM is seen as a conductor by the AC system and reactive power is generated. Decreasing the amplitude of the output voltage below that of the AC system, lagging current results and the STATCOM is seen as an inductor. In this case, reactive power is absorbed. If the amplitudes are equal no power exchange takes place. A practical converter is not lossless. In the case of the DC capacitor, the energy stored in this capacitor would be consumed by the internal losses of the converter. By making the output voltages of the converter lag the AC system voltages by a small angle, δ, the converter absorbs a small amount of active power from the AC system to balance the losses in the converter. The diagram in Fig. 8 below

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illustrates the phasor diagrams of the voltage at the terminal, the converter output current and voltage in all four quadrants of the PQ plane.

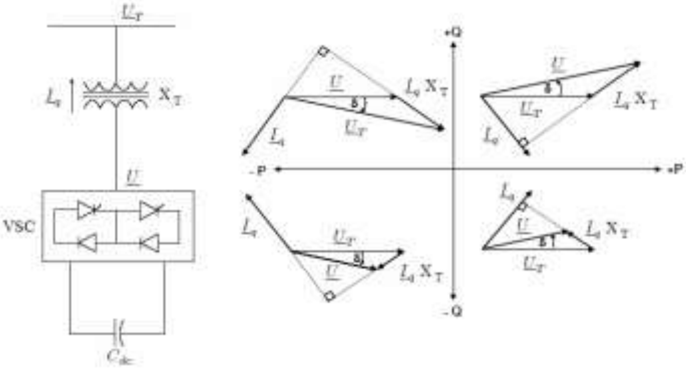

Figure 8. Pharos diagrams for STATCOM applications

The mechanism of phase angle adjustment, angle δ, can also be used to control the reactive power generation or absorption by increasing or decreasing the capacitor voltage U_{dc}, with reference with the output voltage U. Instead of a capacitor a battery can also be used as DC energy. In this case, the converter can control both reactive and active power exchange with the AC system. The capability of controlling active, as well as reactive power exchange, is a significant feature which can be used effectively in applications requiring power oscillation damping, to level peak power demand, and to provide uninterrupted power for critical load

4. Electric Springs 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. 2 has been considered. It comprises a power source acting as the main power grid and a separately controllable power source to emulate an intermittent renewable energy source.

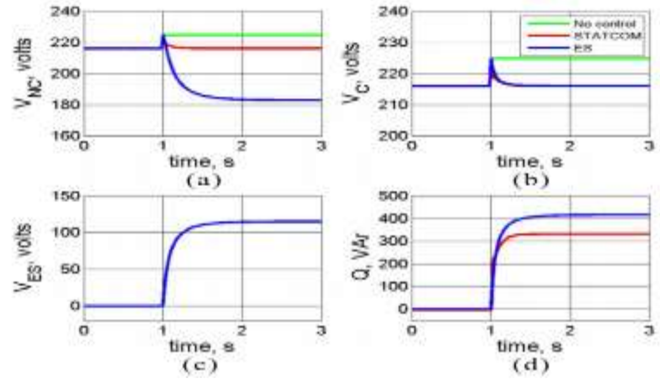

Figure 9. System response following a decrease in reactive power consumption of the intermittent source from 467 to 110 VAr. (a) Non-critical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

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 above system is modeled in MATLAB/SIMULINK using a controllable voltage source representation for both ES and STATCOM. 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. The 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 in Fig. 9(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. 9(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. 9(a) and (c). In order to suppress the voltage, both ES and STATCOM absorb reactive power (as indicated by the positive sign of Q) from the system as shown in Fig. 9(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.

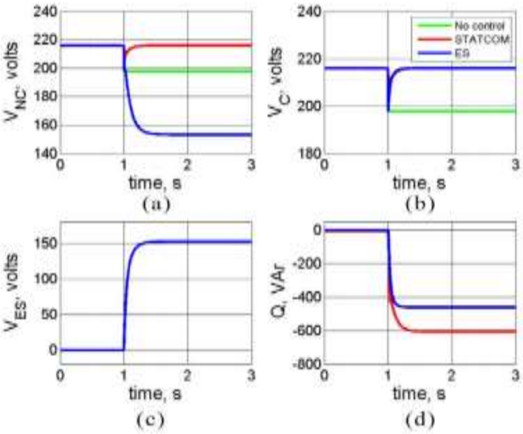

Figure 10. System response following an increase in reactive power consumption of the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

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 affects the voltage regulation.

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. 10(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. 10(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. 10(a) and (c). In order to suppress the voltage, both ES and STATCOM inject reactive power (as indicated by the negative sign of Q) into the system as shown in Fig. 10(d) with ES requiring to inject about 150 VAr less 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.

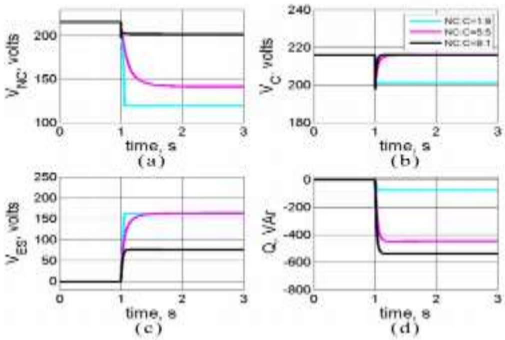

Figure 11. System response for a different distribution of noncritical and critical loads (NC:C). The disturbance is an increase in reactive power consumption of the intermittentsourcefrom467to1100VAr. (a) Noncritical load voltage.(b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

D. Proportion of C and NC Loads

An ES injects a voltage is a 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 it's 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 the 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.

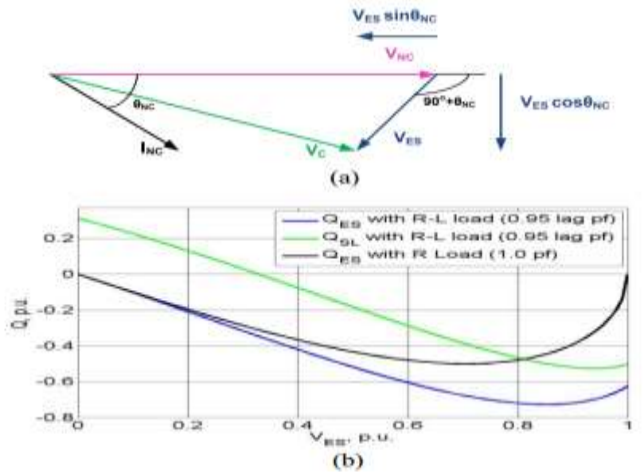

Figure 12. (a) Phasor diagram showing the relationship between voltages across the noncritical load, critical load, and ES. (b) Variation of reactive power of ES and smart load with respect to ES voltage for *R*–*L* and *R* noncritical loads.

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. 12(a) when the ES is working in voltage support (i.e., capacitive) mode. From the phasor diagram, we can write,

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

$$V_{NC} = \pm\sqrt{V_C^2 - (V_{ES}\cos\theta NC)^2} + V_{ES}\sin\theta NC \quad (3)$$

$$Q_{ES} = V_{ES}I_{NC}\sin(-90^0) = -V_{ES}I_{NC} = \frac{V_{ES}V_{NC}}{Z_{NC}} \quad (4)$$

$$Q_{NC} = V_{NC}I_{NC}\sin\theta NC = \frac{V_{NC}^2}{Z_{NC}}\sin\theta NC \quad (5)$$

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

$$Q_{SL} = Q_{ES} + Q_{NS} \quad (6)$$

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

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

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

And

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

From (4), (7), and (9) 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.

E. Reactive Power Limit of Smart Load

For a fixed NC load impedance (*ZNC ∠θ NC*) and a target C load voltage (*VC* = 1.0 p.u.), all the terms on the right hand side of (4), (7), and (9) are constant except the ES voltage (*VES*). Hence, *QES* and *QSL* can be expressed as functions of *VES* only. Fig. 12(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 factors of the NC 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 resistive NC load, *QES* and *QSL* are equal and are shown by the black trace in Fig. 12(b). *QES* and *QSL* for an *R*–*L* NC load with 0.95 power factor are shown by blue and green traces, respectively. The figure is drawn only for nonnegative values of *VNC* phasor represented by (2).

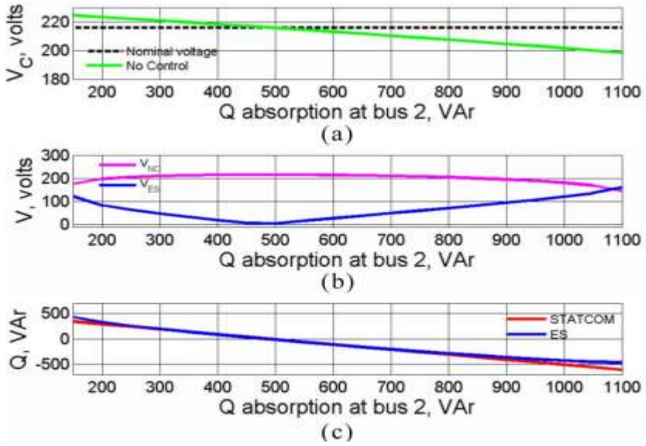

Figure 13. Variations of the (a) voltage across the critical load, (b) voltages across the noncritical load and the ES, and (c) reactive power of the ES and STATCOM

It can be seen that beyond a certain point, increasing the ES voltage will result in a decrease in reactive power magnitude due to a decrease in the current. Hence, it is essential to impose a limit on the output of the PI 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. 12(b). It may also be noted that the maximum values of the two reactive powers will occur at different values of *VES* if the NC load is not purely resistive. In such cases, the limits of the PI controller should be based on the maximum value of *QSL*. Also, it can also be seen that the as the reactive power absorption by the renewable source (at bus 2, Fig. 2) is changed from 150 to 1100 VAr. the reactive power output of the smart loads would be maximum at different values of *VES* depending on the power factor of the NC loads

F. Variable Active and Reactive Power

In this subsection, the result of varying the reactive power absorbed and the active power generated by the renewable energy source connected to bus 2 (see Fig. 2) is shown. First, the reactive power absorbed is varied between 150 and 1100 VAr keeping the active power generation fixed at zero. Without any voltage control, the voltage across the loads reduces as the reactive power absorption increases. This is shown by the green trace in Fig. 13(a) about the nominal voltage of 216 V. For $Q <$ 467 VAr, the actual voltage is higher than nominal requiring voltage suppression while for $Q >$ 467 VAr, the actual voltage is less than the nominal requiring voltage support. Voltage injected by the ES and the voltage across-then load are shown in Fig. 7(b). For Q = 467 VAr, the voltage injected by the ES is almost zero while the voltage across the NC load is equal to the nominal value of 216 V. On either side of Q = 467 VAr, the ES injects a positive voltage, resulting in a reduced voltage across the NC load such that the vector sum of the two equals the nominal voltage (i.e., 216 V) which is maintained across the critical load. The reactive power exchanged by the ES is compared against that of a STATCOM to regulate the C load voltage at 216 V. It can be seen that for voltage suppression ($Q <$ 467 VAr), both of the ES and STATCOM absorbs VAr from the system (as indicated by the positive sign) while for voltage support ($Q >$ 467 VAr) they inject VAr into the system. It should be noted that over the range of variation of Q absorption shown in Fig. 13 (c), the reactive power exchanged by the ES and the STATCOM is very similar. For higher levels of voltage support ($Q >$ 900 VAr),a STATCOM requires more reactive power than an ES with the difference between the two growing for larger Q absorption. For higher levels of as the active power generation by the renewable source (at bus 2, Fig. 2) is changed from 0 to 900 W.

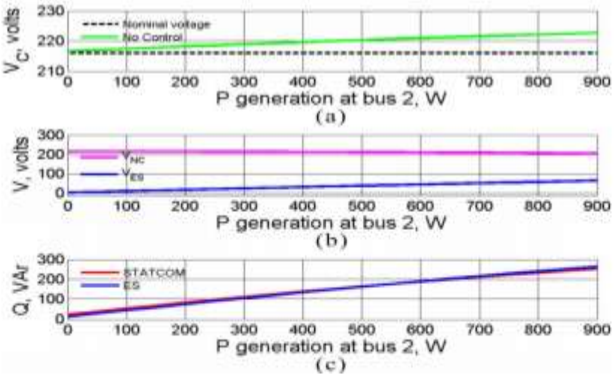

Figure 14. Variations of the (a) voltage across the critical load, (b) voltages across the noncritical load and the ES, and (c) reactive power of the ES and STATCOM

4.1. CASE STUDY 1: IEEE 13-NODE TEST FEEDER

A. Test Network

After comparing the performance of a single ES against a STATCOM, the focus is on the collective action of a group of distributed ESs and how that compares against a single STATCOM. To investigate this, the IEEE 13-bus test feeder system shown in Fig. 15 is considered [16]. The network has two voltage levels 4.16 kV and 480 V with a distribution a transformer connected between node 633 and 634.In the original IEEE 13-node test feeder, the LV side is represented by an aggregated load at bus 634. For the purpose of this paper, the LV side has been 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 634 is split equally among these four new nodes. The ratio of C to NC loads is assumed to be 50:50. The LV distribution line conductor dimensions are chosen based on the current ratings of the loads and the conductor data and the distance between the LV bus bars are provided in the Appendix. All other circuit parameters are exactly the same as the feeder is set up to study unbalanced operation. For this paper, we consider only one phase of the system as the unbalanced operation is not the focus here.

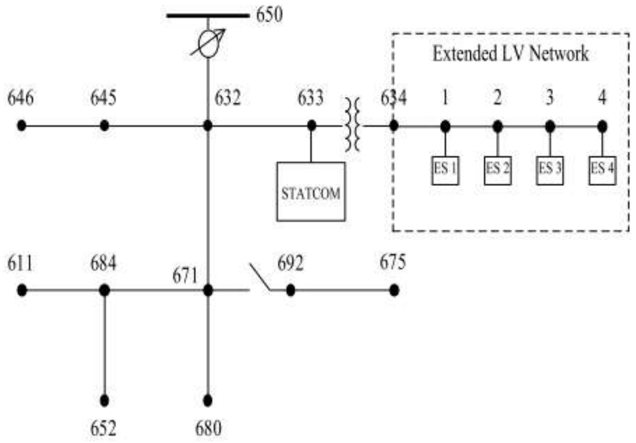

Figure 15. IEEE 13-node test feeder network with distributed representation of the LV side.

B. Voltage Support Mode

The collective action of the distributed ESs has been compared with a STATCOM installed on the MV side at bus 633.A 5% step reduction in the source voltage at bus 650 is considered. The comparison is based on the total reactive power required by the four ESs in order to achieve an acceptable voltage regulation at the LV buses. Voltage regulation at a the particular bus is defined in (10) as the normalized difference between the rated voltage (1.0 p.u.) and the actual voltage in the event of a voltage disturbance

$$\text{Voltage Regulation}=\frac{|V_{rated}-V_{actual}|}{V_{rated}}\times 100\% \qquad (10)$$

The voltage regulation achieved at different LV buses is shown in Fig. 16. Without any voltage compensation, the voltage regulation becomes progressively poorer away from the MV bus (bus 633) due to the voltage drop in the LV feeder.In this case, the voltage regulation turns out to be unacceptably high (>5%). With a STATCOM providing perfect (0) voltage regulation at bus 633, the voltages at the LV bus bars are regulated within the acceptable limit (5%). Nonetheless, the regulation gets poorer away from the STATCOM location.

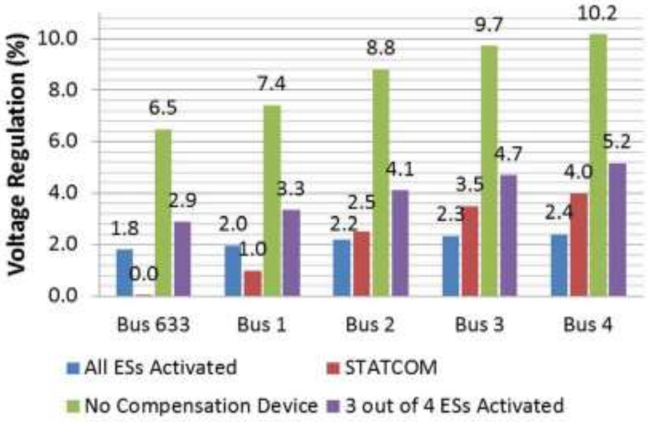

Figure 16. Voltage regulation with distributed ESs and STATCOM following 5% reduction of the source voltage at bus 650.

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

$$=\sqrt{\frac{\sum_{i=1}^{Nb}(V_{rated\_(p.u)}-V_{actual\_(p.u)})^2}{Nb}} \qquad (11)$$

where *Nb* is the total number of buses where voltage regulation is considered. The results are shown in Fig. 17 for both voltage support and voltage suppress (discussed in next subsection) modes. It can be seen that the group of ESs achieves better voltage regulation than a STATCOM at bus 633 [Fig. 17(b)]. Moreover, the total reactive capacity required for the ESs is about six times less than that required by the STATCOM [Fig. 17(a)].

C. Voltage Suppress Mode

A 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. The voltage regulations with ESs and a STATCOM are shown in Fig. 18. As before, voltage regulation with a STATCOM gets worse away from its connection point. 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 which results in less than half of the total voltage regulation achieved with a STATCOM as shown in Fig. 17(b).

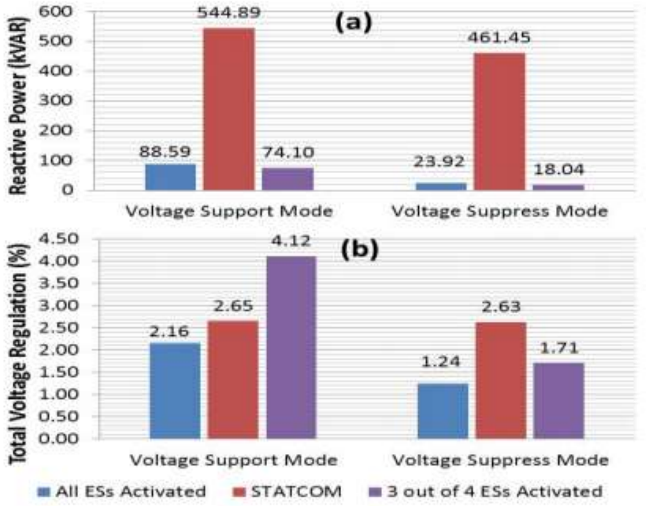

Figure 17. (a) Reactive power required. (b) Total voltage regulation achieved collectively by all the

distributed ESs and STATCOM under voltage support and suppress condition.

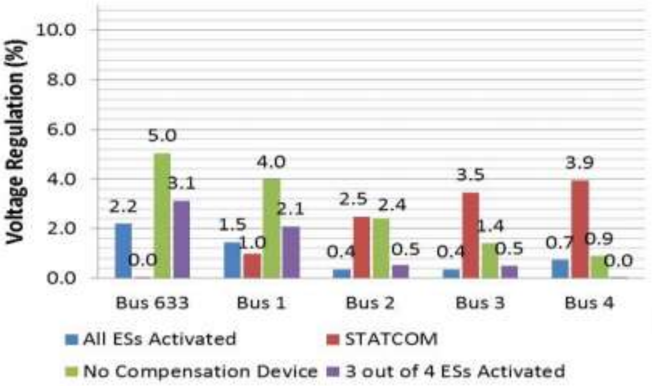

Figure 18. Voltage regulation with distributed ESs and STATCOM following 5% increase in source voltage at bus 650.

Moreover, the total reactive power consumption by the ESs is less than 20 times that of a STATCOM. Thus, for both under-voltage and over-voltage conditions, a group of distributed ESs is shown to achieve better total voltage regulation than a STATCOM with a total reactive capacity much less than that of a STATCOM [Fig. 17(a)]. The study on the modified IEEE 13-node test feeder network confirms the following. 1) Better total voltage regulation is achieved with a group of distributed ESs compared to a STATCOM although both are able to ensure acceptable regulation. 2) Total reactive capacity required by the group of ESs is significantly less than that of the STATCOM

4.2 CASE STUDY 2: DISTRIBUTION NETWORK IN S HA LO WAN BAY, LANTAU ISLAND, HONG KONG

A. Test Network

Another case study has been performed on a part of the distribution network at Sha Lo Wan Bay in Lantau Island of Hong Kong. The objective is to compare the voltage regulation the performance of a group of ESs against a STATCOM. The 11 kV substations and a part of the 220 V feeder network as shown in Fig. 19 is considered for this paper.

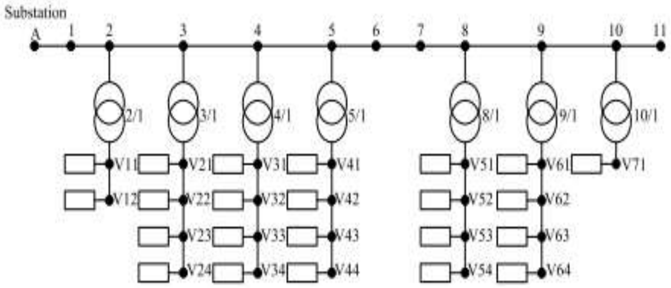

Figure 19. Single line diagram of a part of the distribution network from Sha Lo Wan Bay, Lantau Island, Hong Kong

The network data are provided in the Appendix. The parameters of the distribution lines are practical values, but the loads are arbitrarily set because the actual load data are confidential due to the privacy policy. There are 23 purely resistive loads connected to the 220 V network. Each load has a rating of 30 kW which is assumed to have a 50:50 split between C and NC load. An ES is connected in series with each of the 23 NC loads.

B. Voltage Support Mode

To validate the collective performance of the ESs and compare it with the voltage control of a STATCOM, a 5% step reduction in the 11 kV substation (substation A) voltage has been simulated. Voltages at all the load connection points across the distribution network at Sha Lo Wan Bay (shown in Fig. 19) are monitored. The three subplots in Fig. 20 correspond to the cases with no voltage compensation, with a STATCOM regulating the voltage at the 11 kV substation (substation A) and ESs connected in series with all the NC loads at 220 V level. The distribution of voltage is shown in Fig. 20 along the 11 kV feeder (*x*-axis) and also along each of the 220 V feeders (*y*-axis). Without, any voltage compensation [Fig. 20(a)] the voltage regulation , is poor (>5%) getting worse as we move further away along the 11 kV feeder and also the 220 V feeders due to natural voltage drop in the lines. The STATCOM regulates the voltage at substation A which results in very good regulation at bus 1 [Fig. 20(b)]. However, the voltage regulation is poorer (but much better than the case without voltage, compensation) further away along the 11 kV and 220 V feeders. In the case with ESs, the voltage regulation turns out to be better, especially at the loads which are at the far ends of the 220 V feeder. As the ES regulates the voltage by manipulating the voltage drop across the supply impedance, larger impedance (for distant loads) improves the effectiveness of ESs which is apparent from Fig. 20(c). The distribution of the voltage across all the load buses of Sha Lo Wan Bay distribution system is captured in terms of their mean and standard deviation in Fig. 21 for voltage support and voltage suppress modes (discussed in the next subsection). For voltage support mode, the distributed ESs provide much better (lower average) and tighter (lower standard deviation) voltage regulation than a STATCOM [Fig. 21(a)]. This is further substantiated by the total voltage regulation shown in Fig. 22(b) which shows ESs achieve three times better total regulation than a STATCOM. Moreover, the total reactive power capability required for the group of ESs is about 14 times less than that of the STATCOM as shown in Fig. 22(a).

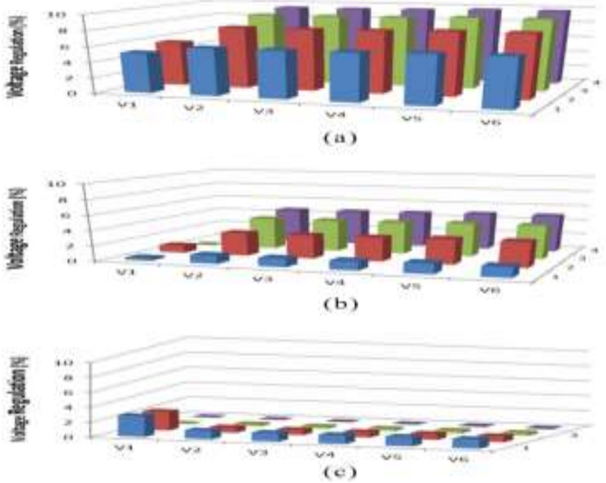

Figure 20. Voltage regulation with distributed ESs and STATCOM following 5% reduction in source voltage at substation A. (a) No compensation device. (b) STATCOM. (c) ESs.

C. Voltage Suppress Mode

Similar exercise as above has been conducted to compare the collective performance of the ESs and a STATCOM under voltage suppress mode. A 5% step increase in the 11kVs substation voltage has been simulated. The voltage regulation performance is shown in Fig. 21(b) in terms of the mean and standard deviation of the voltages at all the load buses. It can be seen that voltage regulation without any voltage compensation is within the acceptable (5%) limits. In this case, the voltage regulation actually gets better away from the 11 kV bus (substation A) due to the natural voltage drop across the 11 kV and 220 V feeders. Similar to the voltage support mode, ESs provide much better (lower average) and tighter (lower standard deviation) voltage regulation than a STATCOM. The total voltage regulation shown in Fig. 22(b) depicts that the group of ESs achieves about two times better total regulation than a STATCOM. The total reactive power capability required for the group of ESs [Fig. 22(a)] is about 30 times less than that of the STATCOM. The above case study on the Sha Lo Wan Bay distribution network in Hong Kong demonstrates the effectiveness of distributed voltage control through a group of ESs under both voltage support and suppresses modes. A group of distributed ESs achieves much better total voltage regulation compared to a STATCOM with much less reactive capability.

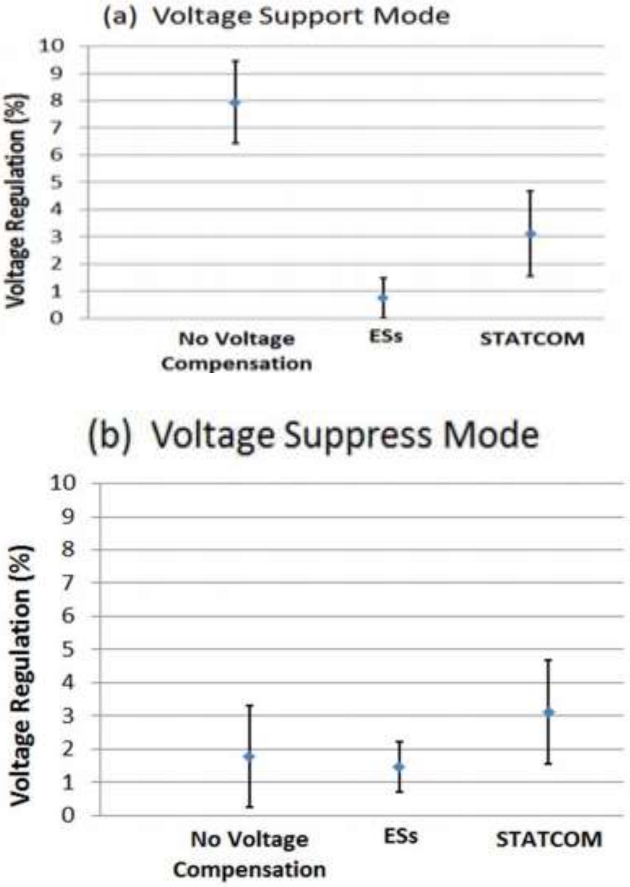

Figure 21. Voltage distribution at different parts of the Sha Lo Wan distribution network under. (a) Voltage support. (b) Voltage suppress modes.

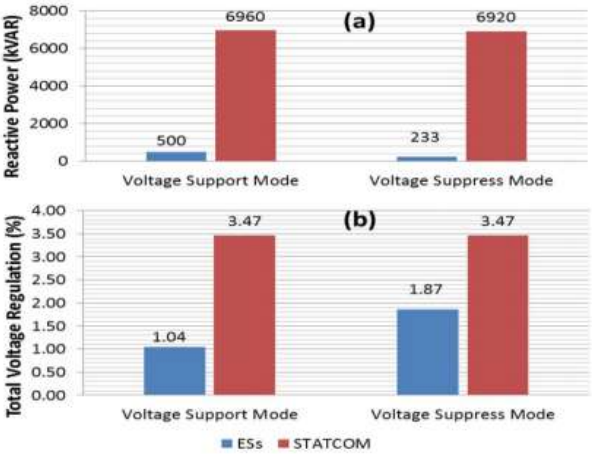

Figure 22. (a) Reactive power required. (b) Total voltage regulation achieved collectively by all the distributed ESs and the STATCOM under voltage support and suppress condition.

5. DISCUSSION

The case studies presented in this paper confirm the following.

1) A group of distributed ESs is able to achieve better voltage regulation than a STATCOM. The reactive power capacity of a STATCOM is not limited until the current limits are violated. In

principle, a STATCOM can inject any amount of current (within its rated capacity) and thus, any amount of reactive power. On the contrary, the reactive power capacity of an ES is limited.

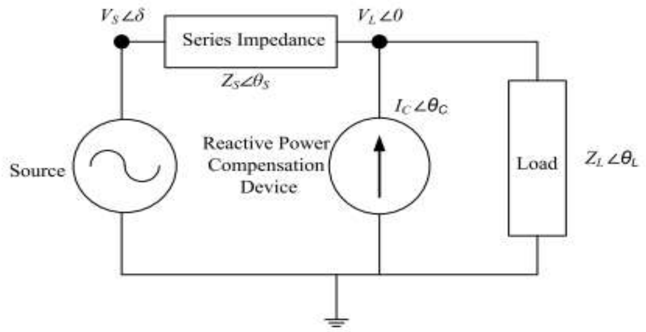

Figure 23. Simple circuit showing an ideal source connected with a fixed impedance load through some series impedance and a voltage compensation device in parallel to the load.

As the voltage injected by an ES increases the voltage across the NC load and hence the current through the ES (as they are in series) decreases. At some point their product, which is the reactive power reaches the maximum beyond which the ES cannot inject/absorb more reactive power. Hence, its voltage regulation capability is limited. However, if there are multiple ESs distributed in the system, they can share the burden and this would not necessarily be a problem. The capability of ESs to regulate the voltage also depends on the relative proportion of C and NC loads. Higher proportion of NC loads allows larger fidelity on the current and hence improves the voltage regulation capability.

2) In general, it is easier to regulate the voltage at locations which are electrically farther away from a stiff voltage source which in this case would be the upstream MV/HV network. As the ESs are located farther away from the upstream MV network than a STATCOM, there is less burden on the ESs and collectively, they require less reactive power than a STATCOM installed upstream. This can be explained analytically by considering a simple circuit shown in Fig. 23. An inductive load (*ZL ∠θ L*) is supplied from an ideal voltage source though a series impedance (*ZS ∠θ S*) representing a feeder. A reactive power compensation device is connected in parallel to regulate the load voltage (*VL∠0*) to the nominal value in case fluctuations in the source voltage (*VS*). If *IC ∠θ C* is the current injected by the compensation device, the load voltage (considered as the reference) can be expressed as follows:

$$\mathrm{V_L} < 0 = \mathrm{V_S} < \delta\,\frac{\mathrm{Z_L} < \theta_\mathrm{L}}{\mathrm{Z_L} < \theta_\mathrm{L} + \mathrm{Z_S} < \theta_\mathrm{S}} + \mathrm{I_C} < \theta_\mathrm{C}(\mathrm{Z_L} < \theta_\mathrm{L} \| \mathrm{Z_S} < \theta_\mathrm{S}) \qquad (12)$$

In power systems, the series impedance is typically much lower compared to the load impedance (*ZL* >> *ZS*). Under normal operation, the voltage across the load impedance is between 0.95 and 1.05 p.u. while the voltage drop across the series impedance varies in the range of ±0.05–0.10 p.u. Hence, the following Approximation is valid without introducing much error:

$$(\mathrm{Z_L} < \theta_\mathrm{L} + \mathrm{Z_S} < \theta_\mathrm{S}) \approx \mathrm{Z_L} < \theta_\mathrm{S} \qquad (13)$$

From (11) and (12), we can write,

$$\mathrm{V_L} < 0 \approx \mathrm{V_S} < \delta + \mathrm{I_C} < \theta_\mathrm{C}(\mathrm{Z_S} < \theta_\mathrm{S}) \qquad (14)$$

$$\mathrm{I_C} < \theta_\mathrm{C} \approx \frac{\mathrm{V_L} < 0 - \mathrm{V_S} < \delta}{(\mathrm{Z_S} < \theta_\mathrm{S})} \qquad (15)$$

The phase angle *θ C* will be either 90o or -90o depending on the type of reactive power compensation required (inductive or capacitive). The phase angle *θS* is constant for a given *X*/*R* ratio of the feeder. From (14), it is evident that the magnitude of the compensation current (*IC*) required to restore the load voltage (*VL*) back to the nominal value, in case of a change in source voltage magnitude (*VS*), is inversely proportional to the source impedance (*ZS*). For a given change in source voltage, a higher series impedance magnitude (for longer distance away from the source) will require a smaller compensation current (which implies less reactive power) to restore the critical load voltage. Therefore, the farther the load is from the voltage source, the easier it is to regulate the voltage with a less reactive power exchange.

3) A STATCOM regulates the voltage at the point of connection but the load buses downstream will still have a natural voltage profile where the voltage at far end could still be low even if the voltage at STATCOM bus is regulated at 1.0 p.u. On the contrary, a group of distributed ESs with droop control also improves the voltages at the far end resulting in a better total voltage regulation.

4) STATCOMs do central voltage control typically at the point of coupling with the MV/LV feeders. So the entire downstream feeders are vulnerable to voltage problems if the STATCOM is out of operation. The ESs provide distributed voltage control, and failure of one/two does not make the entire feeder system susceptible to voltage problems.

5) For an *R*–*L* type NC load, better voltage regulation could be achieved in voltage suppress mode as both ES (working in inductive mode) and the NC load consume inductive reactive power and thereby, aid each

other. Same is true for voltage support mode (ES in capacitive mode) in case of an *R–C* type NC load. In voltage support mode with an *R–L* type NC load, the total reactive power of the smart load is equal to the difference between the reactive power produced by the ES and that consumed by the load which reduces the voltage regulation capability compared to the case of a purely resistive load.

6. Conclusions

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. Comparison between a STATCOM and ES is further substantiated through similar case studies on the IEEE 13-bus test feeder system and also on a part of the distribution network in Sha Lo Wan Bay, Hong Kong. In both cases, 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 be necessary alongside demand-side response

7. References

[1] Lee, Chi Kwan, Balarko Chaudhuri, and Shu Yuen Hui. "Hardware and control implementation of electric springs for stabilizing future smart grid with intermittent renewable energy sources." IEEE Journal of Emerging and Selected Topics in Power Electronics 1.1 (2013): 18-27.

[2] Rajasekharachari, K., G. Balasundaram, and K. Kumar. Implementation of A Battery Storage System of An Individual Active Power Control Based on A Cascaded Multilevel PWM Converter. Int J Inno Res Sci Eng Technol. 2013; 2(7).

[3] Kumar K, S.V. Sivanagaraju, Rajasekharacharik. Single Stage AC-DC Step Up Converter using Boost And Buck-Boost Converters. Int J Adv Res Electric Electron Instru Eng. 2013; 2(9): 4245-4252.

[4] Goel, Naveen, R. N. Patel, and Saji T. Chacko. "Genetically Tuned STATCOM for Voltage Controland Reactive Power Compensation." International Journal of Computer Theory and Engineering 2.3 (2010): 345.

[5] Hassan, A. K., et al. "Electric spring enhanced decoupled dual function operation: bus voltage controller and renewable energy grid integration." (2016): 8-8.

[6] Yan, Shuo, et al. "Simultaneous voltage and current compensation of the 3-phase electric spring with decomposed voltage control." Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE. IEEE, 2016.

[7] Wang, Qingsong, Ming Cheng, and Yunlei Jiang. "Harmonics Suppression for Critical Loads Using Electric Springs With Current-Source Inverters." IEEE Journal of Emerging and Selected Topics in Power Electronics 4.4 (2016): 1362-1369.

[8] Kumar, K., N. Ramesh Babu, and K. R. Prabhu. "Design and Analysis of an Integrated Cuk-SEPIC Converter with MPPT for Standalone Wind/PV Hybrid System." International Journal of Renewable Energy Research (IJRER) 7.1 (2017): 96-106.

[9] Yan, Shuo, et al. "Electric springs for reducing power imbalance in three-phase power systems." IEEE Transactions on Power Electronics 30.7 (2015): 3601-3609.

[10] S. V. Sivanagaraju , K. Kumar , K. Rajasekharachari. Performance Comparison Of Variable Speed Induction Machine Wind Generation System With And Without Fuzzy Logic Controller. Int J Innov R Devel. 2013; 2(7).

[11] Wang, Li, and Chia-Tien Hsiung. "Dynamic stability improvement of an integrated grid-connected offshore wind farm and marine-current farm using a STATCOM." IEEE Transactions on power systems 26.2 (2011): 690-698.

[12] Rajasekharachari, K., and K. Shalini, Kumar. K and SR Divya. Advanced Five Level-Five Phase Cascaded Multilevel Inverter with SVPWM Algorithm. Int J Electric Engi & Technol. 2013; 4(4): 144-158.

[13] Mok, Kwan-Tat, et al. "A Comprehensive Analysis and Control Strategy for Nullifying Negative-and Zero-Sequence Currents in an Unbalanced Three-Phase Power System Using Electric Springs." IEEE Transactions on Power Electronics 32.10 (2017): 7635-7650.

[14] Yang, Yun, Siew-chong Tan, and Shu Yuen Ron Hui. "Mitigating Distribution Power Loss of DC Microgrids with DC Electric Springs." IEEE Transactions on Smart Grid (2017).