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A Novel Approach to Regulate the Grid Voltage Based on Load with Electric Springs

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ABSTRACT:

Frequency-dependent loads inherently contribute to primary frequency response. This paper describes additional contribution to primary frequency control based on voltage-dependent noncritical (NC) loads that can tolerate a wide variation of supply voltage. By using a series of reactive compensators to decouple the NC load from the mains to form a smart load (SL), the voltage, and hence the active power of the NC load, can be controlled to regulate the mains frequency. The scope of this paper focuses primarily on reactive compensators for which only the magnitude of the injected voltage could be controlled while maintaining the quadrature relationship between the cur-rent and voltage. New control guidelines are suggested.

The effectiveness of the SLs in improving mains frequency regulation without considering frequency-dependent loads and with little relaxation in mains voltage tolerance is demonstrated in a case study on the IEEE 37 bus test distribution network. Sensitivity analysis is included to show the effectiveness and limitations of SLs for varying load power factors, proportion of SLs, and system strengths.

A fuzzy logic-based controller is developed to control the voltage of the DC Capacitor. This work presents and compares the performance of the fuzzy-adaptive controller with a conventional fuzzy and PI controller under constant load. The total Harmonic Distortion, Individual harmonic content with respect to % of fundamental in Supply current, source voltage have been analyzed.

Index Terms:

Demand response (DR), demand-side management (DSM), electric spring (ES), fuzzy controller .primary frequency control, reactive compensator, smart load (SL), voltage control.

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. 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.

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 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.

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 paper 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.

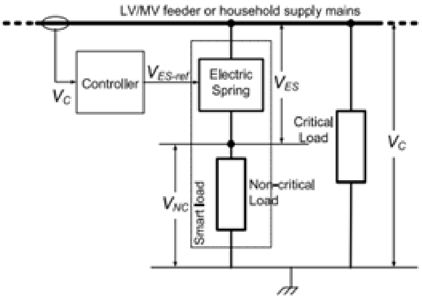

Fig: Electric spring set-up for smart loads.

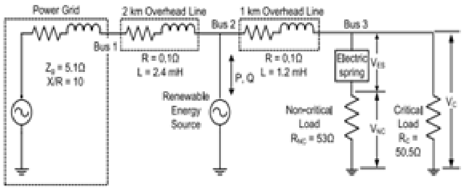

Fig: Simulation set-up with an intermittent source and an equivalent power grid.

2. ELECTRIC SPRING (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. 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.

2.1 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.

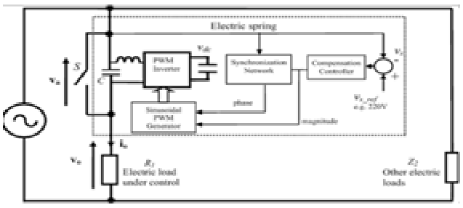

Fig: Electric spring design

Fig: Electric spring

2.2 Applications of Electric Springs:

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

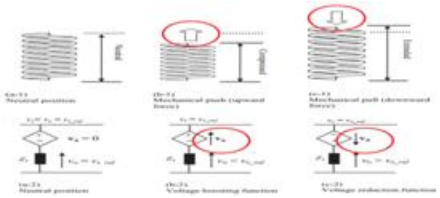

Fig: working of electrical spring

Fig.4 wind and solar power generation

3. ES VERSUS STATCOM:

3.1 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. 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.

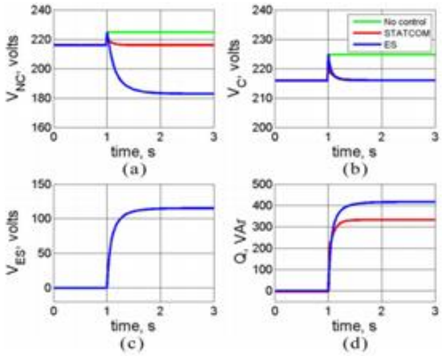

Fig: System response following decrease in reactive power consumption of the intermittent source from 467 to 110 VAR. (a) Non-critical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

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.

3.2.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.

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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 = 1.0s, the reactive power absorption by the intermittent renewable source is reduced from 467 VA 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. 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.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. 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.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. 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.

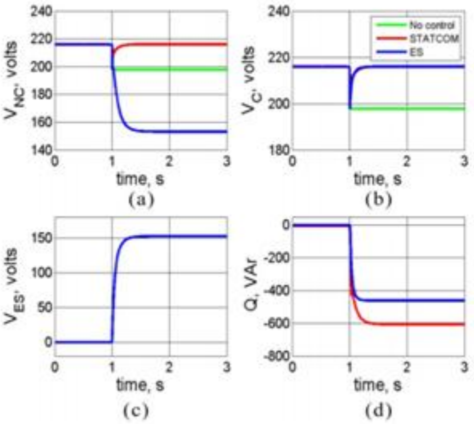


Fig: System response following increase in reactive power consumptionof the intermittent source from 467 to 1100 VAr. (a) Noncritical load voltage. (b) Critical load voltage. (c) Electric spring voltage. (d) Reactive power exchange.

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.

3.3 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..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. 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. 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 with ES requiring to inject about 150 VAR less

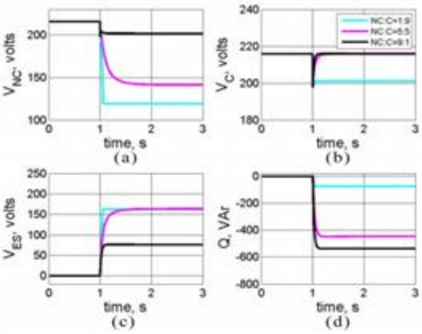


Fig: System response for different distribution of noncritical and critical loads (NC:C). Disturbance is increase in reactive power consumption of the intermittentsourcefrom467to1100VAr.(a)Noncriticalloadvoltage.(b)Criticalload voltage. (c) Electric spring voltage. (d) Reactive power exchange.

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.

3.4 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. 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 80V 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, about 50% of loads (such as heaters,

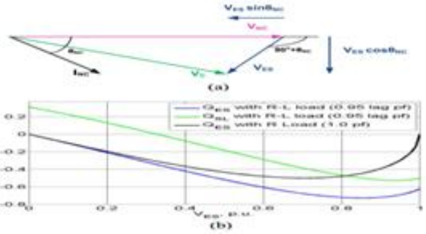


Fig.Phasor diagram showing relationship between voltages across noncritical load, critical load, and ES.(b) Variation of reactive power of ES

And smart load with respect to ES voltage for R–L and R noncritical loads. 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 This is because of the low fidelity in current which restricts the reactive capability of the ES to less than 100 VAR 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 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.when the ES is working in voltage support (i.e., capacitive) mode. From the phasor diagram, we can write,

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

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

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

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

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

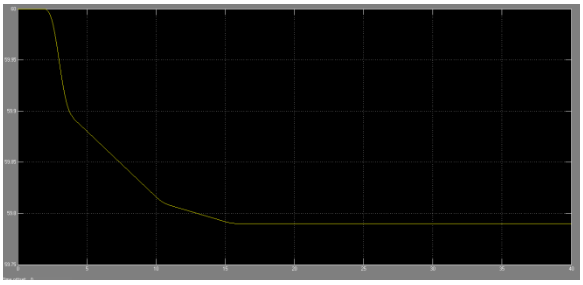
$$Q_{SL} = \frac{V_{ES}\left(\pm\sqrt{V_C^2 - (V_{ES}\cos\theta NC)^2} - V_{ES}\sin\theta NC\right)}{Z_{NC}} + \frac{\left(\pm\sqrt{V_C^2 - (V_{ES}\cos\theta NC)^2} - V_{ES}\sin\theta NC\right)^2}{Z_{NC}}\sin\theta NC(8)$$

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.

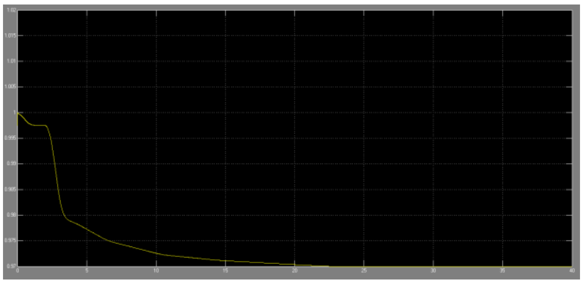
4. EXPERIMENTAL RESULTS:

4.1Smart load:

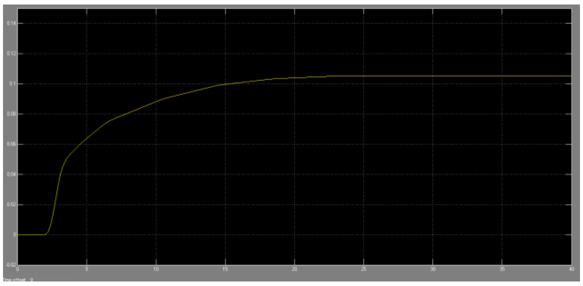
Dynamic variation of supply frequency



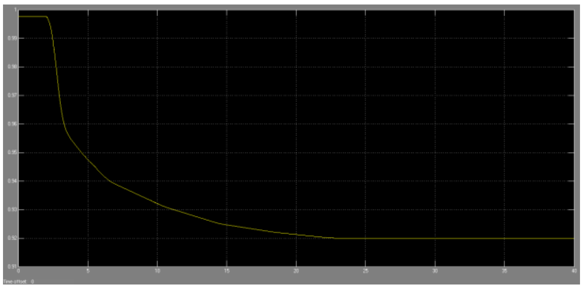
Supply voltage at bus 738



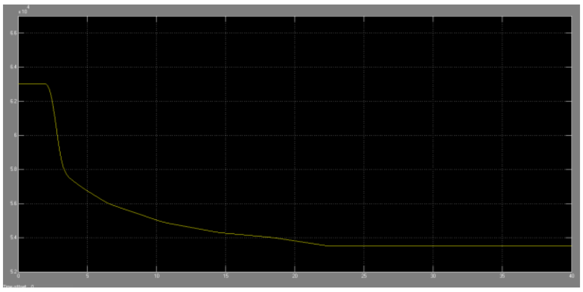
Voltage across NC load



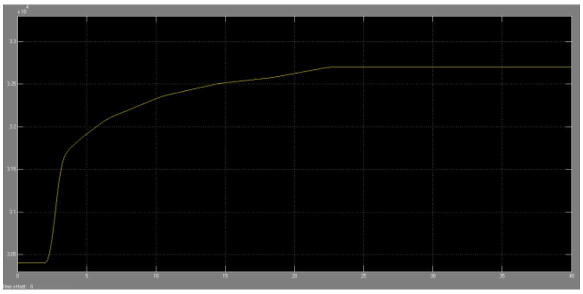
Voltage injected by compensator /ES
Following an under-frequency event at t = 2.0 s.



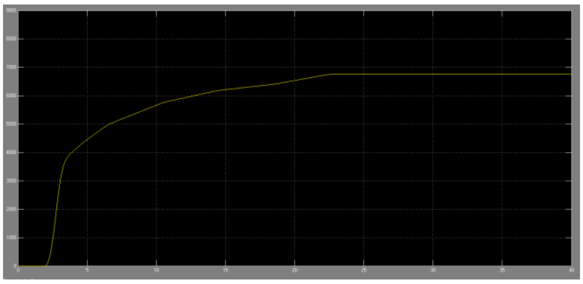
Dynamic variation of active power



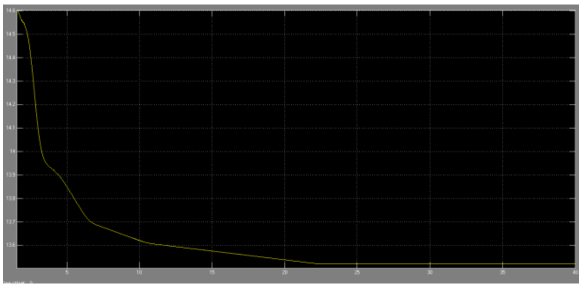
Reactive power consumed by the SL



Reactive compensation

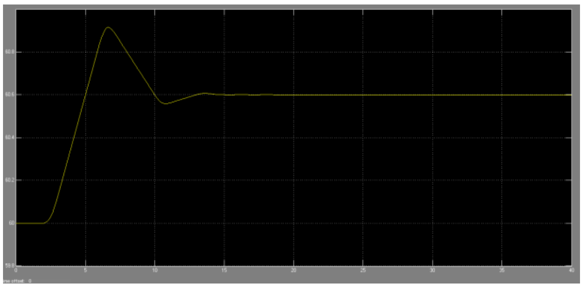


Current following an under frequency event at t = 2.0 s.

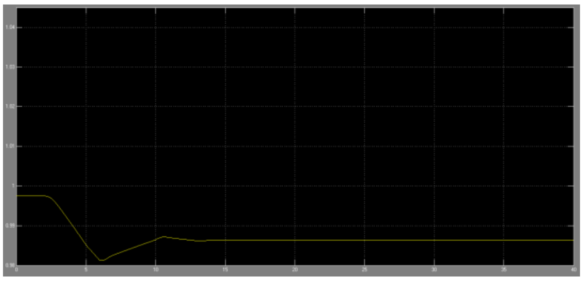


4.2 Normal load

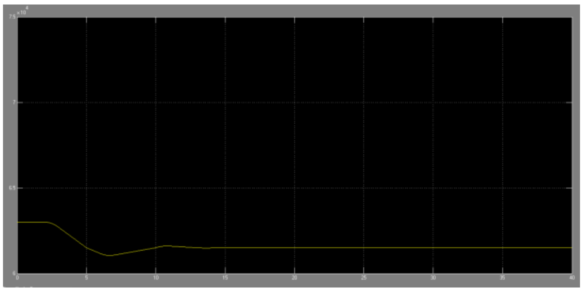
Dynamic variation of supply frequency



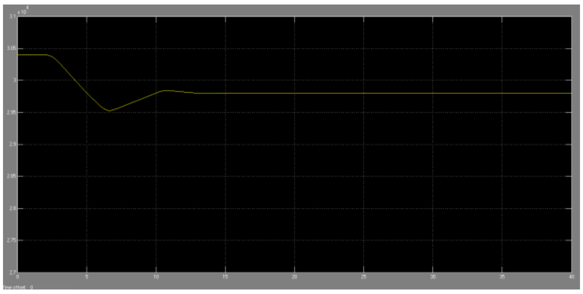
Supply voltage at bus 738



Dynamic variation of active power



Reactive power consumed by the SL



CONCLUSION:

The effectiveness and limitations of SLs in terms of their contribution to primary frequency control is presented in this paper. Without considering any primary frequency response contribution from frequency dependence of loads, the SLs on their own are shown to achieve much improved frequency regulation with little relaxation in voltage tolerance for the NC loads and a small (fraction of the load rating) reactive compensation. With SL using reactive compensation only (SLQ), the mains voltage regulation got slightly worse (still staying well within acceptable limits). If tighter voltage regulation is a requirement due to presence of sensitive loads, then SLs with both active and reactive compensation (SLPQ) would have to be used to enable simultaneous control of both frequency and voltage—this would be reported in a follow-on paper. Sensitivity analysis is presented to show the effectiveness of the SLQs under varying load power factors, proportion of SLs and system strengths.

Two important practical considerations toward realizing SLs are: 1) the rating (which dictates the cost and size) of the reactive compensator and 2) the range of variation in voltage across the NC load connected in series with the compensator. This paper shows that the rating of the reactive compensator is limited to less than 10% of the load rating. The range of volt-age variation can be limited to 10% without any perceivable impact on the consumers. Control of load power consumption through voltage variation using a shunt reactive compensation device like STATCOM will require more reactive power as it will be more difficult to change the system voltage compared to the voltage across the NC load. Also it will result in a poor voltage profile for all other loads including the critical loads. In this paper, simple impedance-type representation is assumed for the SLs while a mix of constant current, constant power, and impedance-type characteristics is used for the other loads connected to the mains. Frequency dependence of loads are neglected to isolate the impact on primary frequency response from the voltage-dependant part alone which leads to pessimistic results. Frequency dependence of loads and typical P-V, Q-V sensitivities of specific types of candidate SLs would have to be incorporated in future for more realistic results.

Future Scope:

Our future concept, a novel approach to regulate thegrid voltage based on load with electric springs is used to compensate reactive power simultaneously for both non critical as well as smart loads.

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