PRIMARY FREQUENCY CONTROL CONTRIBUTION FROM SMART LOADS USING REACTIVE COMPENSATION

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Abstract—This paper describes using fuzzy logic controller the additional contribution to primary frequency control based on voltage dependent noncritical (NC) loads that can tolerate a wide variation of supply voltage. Frequency-dependent loads inherently contribute to primary frequency response. 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 quadrature relationship between the current and voltage should maintaining the magnitude of the injected voltage could be controlled. 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.

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

I INTRODUCTION

The renewable energy generation with growing penetration of asynchronous inverter interfaced the effective inertia of future power systems is expected to reduce drastically. The rates of change of the system frequencies (RoCoF) following a loss of in feed which would threaten the system security and this would cause unacceptably large excursions [1]. Moreover, loss-of-in feeds larger than the reserve capacity of the system could be more likely for example, due to a cable fault within a dc grid.

Several papers have been published on contribution of wind farms on frequency control [2]–[4]. To overcome the problem, asynchronous generators like the wind farms and even some selected categories of loads (demand) would be required to contribute to frequency control alongside the conventional synchronous plants with fast ramp rates and natural response of the frequency-dependant loads. On the demand/load end, the focus has primarily been on load scheduling [5] and grid frequency control [6] through on/off control of loads which has been collectively referred to as “demand response” or “demand-side management (DSM)” [7]–[9]. The easiest way to exercise any sizeable variation in their average power consumption is to operate as the loads are connected in parallel across the supply/mains in on/off mode. Frequency control using variation in average power consumption of the loads is achieved by switching those on/off with appropriate duty cycles [10], [11]. This is also predicated on the fact that the potential candidate loads for DSM e.g., air conditioners, especially, the ones supplied through adjustable speed drives exhibit a constant power characteristics over a wide voltage range [12] which rules out any possibility of continuous control.

Controlling voltage at different system nodes based on optimization of reactive power compensation have been proposed different methods [13]–[15]. The system voltage within an allowable limit rather than controlling the frequency by manipulation of load this is basic aim in all these methods is to be control. However, it is neither straightforward (given the stiffness of even moderately weak systems) nor recommendable (as there are sensitive loads connected to the mains which require tightly regulated voltage) to vary the supply/mains voltage. Therefore, these loads would have to be decoupled from the supply/mains through a voltage compensator.

Using electric springs (ES) the concept of smart load (SL) was proposed in [20] as a mean of exercising continuous control of both voltage and frequency in an unified framework by using fuzzy logic controller. A SL comprises of a voltage compensator (ES) connected in series between the supply/mains and a voltage-dependant load which can tolerate a wider variation in supply voltage. Such a load is henceforth referred to as NC load. By using
fuzzy controlling the voltage injected by the compensator, the mains voltage can be regulated while allowing the voltage (and hence the power) across the NC load to be controlled. Thus, a SL ensures a tightly regulated voltage across the other sensitive loads connected to the mains, while varying its own power consumption and thus, contribute to system frequency control. However, injection of voltage at any arbitrary phase angle other than ±90° would require exchange of active power and hence an additional storage element or a back-to-back converter arrangement.

The change of voltage control paradigm from a centralized one using STATCOM to a distributed one based on SLs deserves more investigation, especially on the aspects of better control and total reactive power requirements. In particular, the results in [27] suggest that the use of SLs has the potential of using only a fraction of the total reactive power required by a STATCOM to achieve similar or better voltage regulation than a STATCOM in the distribution network.

The contribution of the SLs with reactive compensation to primary frequency control is illustrated for the first time presents in this paper. In [21]–[27] the active and/or reactive power of the SL has been fuzzy controlled implicitly by controlling the active and/or reactive power of the series connected compensator using appropriate limits [27] which is not necessarily the best strategy. Ultimately, it is the net change in active and/or reactive power of the overall SL which affects the voltage or frequency regulation. Therefore, in this paper an improved control philosophy is reported to directly modify the active power consumption of the SL. Fuzzy logic controller used for control of active power will either provide reactive or active or both active and reactive compensations. The latter two would require an energy storage or a back-to-back converter arrangement. In this paper Reactive only compensation is preferable from that point of view and was therefore, considered as a first option.

The restricted to SLs based on reactive (Q) compensation (SLQ) and impedance-type loads only be focus on this paper. This implies that the compensator in series with the impedance-type NC load can inject a voltage of controllable (within acceptable bounds) magnitude but only in quadrature (either leading or lagging) with respect to the current. As there is only fuzzy is control variable, the magnitude of the voltage, such as SLQ can be controlled either to control the mains voltage or the frequency, but not both at the same time. Frequency regulation is achieved at the expense of slight deterioration in supply voltage regulation which still remains well within the acceptable limits for a range of system strengths. The effectiveness of a SLQ is demonstrated through a case study on the IEEE 37 bus test system. The frequency and voltage regulation and the total reactive capacity of the compensators required for different load power factors, proportion of SLs, and system strength are also compared through a rigorous sensitivity study. By using fuzzy logic controller the limitations of the SLQ are explained highlighting the possible need for a SL based on active (P) and reactive (Q) compensation (SLPQ) [22] to achieve both distributed voltage and primary frequency control simultaneously.

Fig. 1. SL configuration.

II. SMART LOAD (SL) WITH REACTIVE COMPENSATION (SLQ)

A. Basic Principle

There are two types of categories should be in Demand or loads could: 1) critical; or 2) sensitive loads, which require a tightly regulated supply voltage and NC loads which can tolerate a wider fluctuation in supply voltage without causing perceivable disruption to the consumers. Some of these NC loads, e.g., air-conditioners draw a constant power from the supply over a wide range of voltage. As shown in Fig. 1 a SL is formed by inserting a voltage compensator (or ES) in series between the supply/mains and the load itself.

In fuzzy system controlling the voltage across the NC load (VNC) the injected voltage (VES) and, hence, its power consumption can be controlled. Collective action of many such SLs could contribute to regulating the frequency of the mains. At times of generation shortfall (excess), the voltage across the
NC loads is reduced (increased). The fuzzy logic controller block is described later in Section II-C.

![Phasor schematic for SLQ](image)

Fig. 2. Phasor schematic for SLQ. (a) For inductive compensation mode. (b) For capacitive compensation mode.

The scope of this paper is restricted to SLQ only. Depending on the type of compensation used, there could be two types of SLs. For a SLQ, the compensator has been injected the voltage to be in phase quadrature with the current. This implies only the magnitude of the injected voltage can be controlled while maintaining the phase angle at ±90°. On the other hand, a SL does not have any restriction on the phase angle with both active and reactive compensation (SLPQ). Hence, both the magnitude and phase angle of the voltage injected by the compensator can be controlled fuzzy. This allows control of both active and reactive power of the SL, enabling voltage, and frequency regulation at the same time. However, energy storage (e.g., battery or super-capacitor) or a back-to-back converter arrangement is required by the compensator to support the active power exchanged. Henceforth, the term SL would represent a SLQ unless otherwise specified.

This is similar to the power losses incurred in any power electronic interface (e.g., drive circuit) of the loads. Power losses will be incurred due to the flow of load current through the converter even under normal condition when the ES is not producing any compensation. Notably, a typical drive circuit with back-to-back converters then the ES with only one converter will incur less loss. Alternatively, special arrangements could be made to bypass the converter or leave it under a floating state under normal condition through use of hybrid (mechanical/electronic) switching.

Frequency dependance of the loads is neglected to isolate the contribution to primary frequency response from voltage dependance alone. In this paper, simple impedance-type load representation is used for the NC loads. As most impedancetype loads (including those in the study system used later in this paper) are of resistive-inductive (R-L) nature, the discussion throughout the rest of this paper assumes R-L-type loads only. However, the inferences are general and are applicable to resistive-capacitive loads as well.

Fig. 2 shows the R-L-type SLQ, the phasor diagrams are (a) inductive and (b) capacitive compensation modes. The relationship between the voltages across the compensator/ES (VES), the NC load (VNC) and the mains (VC) from the phasor diagrams, can be expressed as

\[ V_C^2 = V_{NC}^2 + V_{ES}^2 + 2V_{NC}V_{ES} \sin \phi_{NC}. \]

The positive is inductive compensation mode and negative sign corresponds to the capacitive compensation mode, respectively. Using VNC = I × ZNC, the compensator voltage (VES) in inductive compensation mode can be expressed in terms of the current (I) and supply/mains voltage (VC) as

\[ V_{ES} = -IZ_{NC} \sin \phi_{NC} \pm \sqrt{V_C^2 - (IZ_{NC} \cos \phi_{NC})^2} \]

While in capacitive compensation mode, VES can be expressed in terms of the current (I) and supply/mains voltage (VC) as

\[ V_{ES} = +IZ_{NC} \sin \phi_{NC} \pm \sqrt{V_C^2 - (IZ_{NC} \cos \phi_{NC})^2} \]

The relationship between I and VES is used later in Section II-C in the control loop for a SLQ. It can be seen that in inductive compensation mode, there is only one possible value for VES corresponding to a value of I and VC as the second root of (2) will always be fictitious (negative). However, it is possible to have two values of VES corresponding to a value of I and VC in capacitive compensation mode (4).

b. Analysis of Active and Reactive Power Capabilities

This section provides new information about such capabilities related to primary frequency control and the boundaries of operation under different power factors. It is important to estimate active and reactive power capabilities of the SL to evaluate its effectiveness in frequency and voltage control. The analysis leads to new guidance for the use of the SLs
for fuzzy logic control. It can be used to calculate the change in active and reactive power of the SL for different values of VES considering both phase angles (±90°). For a constant supply voltage VC, the voltage across the NC load VNC can be written as a function of the compensator voltage VES (1). The corresponding values of the reactive compensation required (QES) and the NC load voltage (VNC) can also be determined.

As shown in Fig. 3 The reactive compensation QES required to change the active and reactive power of a SLQ rated at 1 p.u. is for three different power factors of the NC load. The range of 0.8–1.2 p.u the dotted lines represent the original curves without any restriction on the magnitude of VNC, while the solid lines represent the region in which VNC which is limited. The supply voltage (VC) is considered to be tightly regulated at 1 p.u. The unity power factor (green trace) there are no positive values of PSL It can be seen from Fig. 3(b) that the voltage across the NC load cannot exceed 1.0 p.u. Decreasing PSL will result in some nonzero value of QSL which would impact the supply voltage depending on the system strength.

The change in SL reactive power \( _Q_{SL} \) is negative when PSL > 0. This would increase the supply voltage and hence, the active power consumption of other voltage-dependent loads connected to the mains resulting in an improved frequency regulation. The maximum positive value of \( _P_{SL} \) occur at the point when the inductive reactive power of the NC load is exactly matched by the capacitive reactive power of the ES. The current flowing though the SLQ is maximum at this point. PSL cannot be increased beyond this point as any increase in VES will result in a decrease in the SL current.

However, the QES required in inductive mode is lower than that required in the capacitive mode for the same value of PSL. In case of an under-frequency event, with a 0.9 lagging power factor load, the compensator can either be in inductive or capacitive mode [Fig. 3(b) and (c)]. Hence, the phase angle of the fuzzy controller is set at −90° for an over-frequency event in case of a R-L-type NC load. There can be two possible values of VES to achieve the same value of PSL. The smaller value should be considered to ensure minimum rating of the compensator.
angle of the compensator is set at +90°. This would reduce the supply voltage and hence, the positive power consumed by other voltage-dependant loads connected to the supply/mains. If there is no restriction on VNC, the current flowing through the SL can be reduced to zero by injecting a voltage VES equal to VC. Hence, the minimum possible value of PSL will be equal to negative of the nominal value of active power consumed by the SL under normal conditions. However, the minimum allowed value of VNC will determine the minimum value of PSL that can be achieved.

The voltage across the NC load required to change the active and reactive power of the SLQ (1 p.u.) shows in Fig. 4. It is clear that VNC can not be greater than 1.0 p.u. for a unity power factor load. A simple way of enforcing that is to limit the minimum and maximum current for a given NC load impedance as shown later in Section II-C.

A. Control of SLs

The capability of the SLQ in order to regulate the supply frequency control then the objective is to vary the active power consumption of the SL. Variation in active power is achieved by controlling the magnitude of the voltage injected by the compensator (or ES) which causes the voltage across the NC load to vary within the acceptable limits. The control loop is shown in Fig. 5.

By using fuzzy logic, any difference between the reference (fref) and measured (fm) frequency is filtered through a dead band (±0.01 Hz) and multiplied by a droop gain D = (0.215/PSL0) to calculate the required change in active power consumed by the SL about its nominal value (PSL0). The value of PSL is limited based on the maximum and minimum possible values calculated from the supply voltage (VC), and the NC load impedance (ZNC ZφNC). An ideal phase-lock-loop (PLL) was assumed for frequency measurement. The active power to be consumed by the SL at a given instant (PSL) is obtained by adding up the nominal power (PSL0) and the desired change.

As the compensator exchanges only reactive power, the current (I) through the SL is obtained by calculating square root of PSL divided by RNC. The current magnitude is limited based on the acceptable limits (VNC−max − VNC−min) on the voltage across the NC load using its impedance (ZNC).

The Fig. 5 shows the phase angle of the injected voltage (θES) would be set according to the sign of f. From I, the magnitude of the injected voltage (VES) can be derived using (3) and (5). Capacitive compensation (θES = −90°) reduces PSL while an inductive compensation (θES = +90°) is more effective in increasing PSL as explained earlier in Section II-B. An additional benefit is that inductive (capacitive) compensation decreases (increases) the supply/mains voltage slightly which would result in decrease (increase) in power consumption of other voltage-dependent loads connected to the mains which helps the frequency regulation further.

The fuzzy output is reference values of the voltage magnitude (VES) and the phase angle (θES) are provided to the standard control system of the inverter. To determine the magnitude of VES, the corresponding positive and real solution(s) of (3) and (5) are considered. If there are multiple positive real solutions, the minimum value of VES is selected to ensure minimum reactive capacity (QES = VES × I) of the compensator/ES. An ideal tracking response is assumed for the inverters so that the reference values of the compensator voltage (VES−ref, θES−ref) are the same as their actual (VES, θES) values. For a practical inverter, we will have to consider the nonideal behavior of the PLL, the time delay for the inverter control, and dynamics of the dc link which might cause the phase angle to change a little from the reference angle (±90°) in transient state to account for the losses in the inverter.

III. CASE STUDY

The supply frequency is a global variable which is influenced by the combined action of several generators and loads connected at the bulk power transmission and distribution networks, respectively. A case study is set up based on the following considerations: It is not straightforward to conduct
simulation studies with detailed representation of both bulk power transmission network and low- or medium-voltage (LV/MV) distribution network. Hence, aggregated representation of the LV/MV networks as lumped loads is commonly used for frequency control studies. Therefore, the Fig. 6 shows a two-part bottom-up and top-down approach has been adopted for this research.

Fig. 6. Top-down and bottom-up approaches for system modeling.

Results of the simulation studies with detailed representation of a distribution network is presented with an equivalent model of the upstream system (bottom-up approach) with same capacity as the load capacity in this paper. In a follow-up paper, similar results with a detailed representation of the bulk power transmission network (including dynamic models of generators, etc.) and aggregated loads would be presented to complement the results presented in this paper (top-down approach).

Fig. 7. IEEE 37-bus test system with equivalent dynamic representation of the upstream system at bus 799.

As a standard distribution system, the IEEE 37-bus test system, shown in Fig. 7 is considered for this paper. It is a three-phase medium voltage radial distribution system with both single phase and unbalanced three phase loads. There are 32 static loads with a mix of constant impedance (Z), constant current (I), and constant power (P) i.e., ZIP characteristics. About 50% of these loads are considered as noncritical [27] and assumed to be of purely impedance type while the other loads (connected to the supply/mains) are represented by the ZIP model. The location of SLs is the same as the location of original loads in the standard system. The actual percentage of the voltage dependent NC load is the key to the effectiveness of SLs. Also, the limits of voltage variations allowable across different loads would differ widely which affects the above percentage. The results of the sensitivity analysis in Section V show the effect of larger (and smaller) percentage of NC loads.

V. FUZZY LOGIC CONTROLLER

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

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

TABLE I: Fuzzy Rules

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

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

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

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

The set of FC rules are derived from

$$u=\alpha E + (1-\alpha)*C$$

(15)

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

IV. SIMULATION RESULTS

Time domain simulations have been carried out in MATLAB SIMULINK using a time step of 20 $\mu$s. Frequency disturbances were created by applying 15% step changes in the equivalent source power reference. Simulation results at bus 738 are shown here separately for under- (Figs. 8 and 9) and over-frequency (Figs. 10 and 11) events. It is a bus close to the far end of the distribution system. So the voltage regulation at this bus is relatively poor compared to the buses close to the upstream system. A small increase in voltage is observed for a reduction in the supply frequency. This is due to decrease in network reactance with a decrease in the frequency. Similarly, an increase in frequency results in a slight decrease in voltage due to an increase in network reactance. There are no frequency dependant loads in the standard IEEE 37 test feeder.

In both cases (Figs. 8 and 10), the SL ensures much improved frequency regulation compared to a normal load (i.e., a NC load without a series compensator/ES). The mains voltage regulation turns out to be slightly worse but still staying well within the acceptable (5%) limits. In this case, the compensator is required to inject about 10% of the rated voltage while the variation in voltage across the NC load is limited to $\pm10\%$.

This transient voltage variation will not cause perceivable change in the performance of NC loads like heating [16], lighting (especially, LED lighting [17]), and small motors with no stalling problems (e.g., fans, ovens, dish washers, dryers) [18]. With
normal loads (red traces), the mains voltage would increase (decrease) in the under- (over-) frequency case which aggravates the situation resulting in the poor frequency regulation.

![Fig. 9. Dynamic variation of (a) active power, (b) reactive power consumed by the SL, (c) reactive compensation, and (d) current following an underfrequency event at t = 2.0 s.](image)

The change in active/reactive power of the SL and the reactive compensation required is shown in Figs. 9 and 11 for under- and over-frequency events, respectively. A change of 10 kW in active power consumption of the SL could be achieved with less than 8 kvar reactive compensation.

![Fig. 10. Dynamic variation of (a) supply frequency, (b) supply voltage at bus 738, (c) voltage across NC load, and (d) voltage injected by compensator/ES following an over-frequency event at t = 2.0 s.](image)

After presenting the time-domain responses at a particular bus (bus 738), the collective performance of all the SLs is captured through system-wide averaged measures like voltage regulation index (VRI) and frequency regulation index (FRI). VRI is defined as

\[
VRI(in\%) = \frac{\sum_{i=1}^{N_{bus}} [\max_t |V_i(t) - V_{ref}| \times W_{Vi}]}{N_{bus}}
\]  

(6)

Where

\[W_{Vi} = \begin{cases} 
1 & \text{if } \max_t |V_i(t) - V_{ref}| \leq 0.05 \text{ p.u.} \\
2 & \text{if } 0.05 \text{ p.u.} < \max_t |V_i(t) - V_{ref}| \leq 0.1 \text{ p.u.} \\
10 & \text{if } \max_t |V_i(t) - V_{ref}| > 0.1 \text{ p.u.}
\end{cases}
\]

![Fig. 11. Dynamic variation of (a) active power, (b) reactive power consumed by the SL, (c) reactive compensation, and (d) current following an over-frequency event at t = 2.0 s.](image)

In the above expression, \(V_i(t)\) is the p.u. value of voltage at the ith bus as a function of time, \(V_{ref}\) is the reference voltage in p.u., \(N_{bus}\) is the total number of buses, and \(W_{Vi}\) is a weighted penalty factor to impose extra penalty if the voltage variation is outside the allowed range. The maximum deviation from reference value over time for each bus is considered. Similarly, FRI is defined as

\[
FRI(in\%) = \frac{\sum_{i=1}^{N_{bus}} [\max_t |f_i(t) - f_{ref}| \times W_{fi}]}{N_{bus}}
\]  

(7)

where

\[W_{fi} = \begin{cases} 
1 & \text{if } \max_t |f_i(t) - f_{ref}| \leq 0.5 \text{ Hz} \\
10 & \text{if } \max_t |f_i(t) - f_{ref}| > 0.5 \text{ Hz}
\end{cases}
\]

where \(f_i(t)\) is the p.u. value of frequency at the ith bus as a function of time, \(f_{ref}\) is the reference frequency in p.u., \(N_{bus}\) is the total number of buses, and \(W_{fi}\) is a weighted penalty factor.
The RoCoF is also very important for normal operation of sensitive loads. It is defined as the maximum value calculated over a moving window of 500 ms.

It can be seen from Fig. 12 that both FRI and RoCoF have improved significantly with the SLs for both under- and over-frequency events. A similar performance in terms of frequency control is achieved by using STATCOMs.

Fig. 13(a) shows that the VRI for the mains has got worse with SLs. All the node voltages remained within the allowable (5%) limits. Improvement in frequency regulation is achieved through a wider variation in voltage (and hence power) across the NC load as shown in Fig. 13(b). Nonetheless, this variation was limited to less than 10% which can be tolerated in short-term by most NC loads. The VRI for STATCOMs is very large compared to that for SLs. STATCOMs achieve frequency regulation by varying the supply voltage. Most node voltages violated the allowable (5%) limits which would affect the critical loads. As the STATCOMs change the supply voltage, the value of VRI for NC loads is same as that for supply voltage [Fig. 13(b)]. However, it can be seen that VRI for NC loads is higher in case of SLs compared to STATCOMs. This is due to the fact that the NC loads share larger burden of voltage variation to safeguard the critical loads.

VI. CONCLUSION

This paper presents by using fuzzy logic controller the effectiveness and limitations of SLs in terms of their contribution to primary frequency control. With SL using reactive compensation only (SLQ), the mains voltage regulation got slightly worse (still staying well within acceptable limits). If 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 voltage variation can be limited to 10% without any perceivable impact on the consumers. Also it will result in a poor voltage profile for all other loads including the critical loads.

In this paper, by using fuzzy logic controller 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 dependance of loads are neglected to isolate the impact on primary frequency response from the voltage-dependant part alone which leads to pessimistic results.

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