FUZZY BASED SMART LOAD PRIMARY FREQUENCY CONTROL CONTRIBUTION USING REACTIVE COMPENSATION

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ABSTRACT: Increased level of usage of renewable energy resources might satisfy the increasing demand on the load end but puts the system into stressed conditions at the generation end in the form of reduced inertia of the system which is the key factor for maintaining synchronism. Frequency-dependent loads inherently contribute to primary frequency response. Primary frequency control is based on voltage dependent non-critical (NC) loads that may changes a large change of voltage is analyzed. A smart load (SL) includes of a voltage compensator connected in series between the mains and a voltage dependent load which may tolerate a wider variation in supply voltage. Such a load is henceforth referred to as NC load. By using a series of reactive compensators to decouple the NC load from the mains to create a SL, the voltage and hence the active power of the NC load can be controlled to control the mains frequency. A comparative study has been made between the normal load and smart load in regulating the primary frequency of the system by using fuzzy. The effectiveness of SL is presented by incorporating it in an IEEE 37 node test feeder. Simulation was done by using MATLAB/Simulink software.

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

With increasing environmental concerns over the use of conventional energy resources, the installed capacity of renewable energy sources (RES) is expected to increase even further. This projected increase of electric power coming from renewable energy sources will put an even higher stress to the already highly loaded power system. From a power system perspective, this dispersed renewable electricity generation behaves quite different from traditional, centralized generation facilities. Apart from their intermittent nature, most of these sources do not contribute to system reserves and to the total system inertia. This system inertia is often considered as one of the vital system parameters upon which the synchronized operation of current day power systems is based. When a frequency event occurs, the synchronous machines will inject or absorb kinetic energy into or from the grid to counteract the frequency deviation. The lower this system inertia, the more nervous the grid frequency reacts on abrupt changes in generation and load patterns. Wind turbines are generally equipped with back-to-back converters, which electrically decouple the generator from the grid. Therefore no inertial response is delivered during a frequency event, although a lot of kinetic energy is stored into the blades and the generator. Unlike wind turbines where there is actually some kinetic energy available, solar panels virtually do not possess inertia.

For the safe operation of power system there should be balance between generation and load. Frequency control plays important role in maintaining balance between generation and load. Frequency control maintains the frequency of power system tightly around its nominal value when demand or supply fluctuates. Three levels of frequency control (i.e. primary frequency control, secondary frequency control and tertiary frequency control) are generally used to maintain the balance between generation and load. . Three levels differ as per their time of response to a fluctuation and the methodology adopted to realize the fundamental operating philosophy of maintaining reliability and overall economy.

This paper deals with primary frequency control on demand side. Frequency control on demand side is generally done by switching off/on of loads which is known as demand side management (DSM) [1]-[3]. The loads supplied through adjustable speed drives have constant power characteristics over large voltage range. The voltage control with in allowable limits can be done based on optimization of reactive power consumption [4]-[6]. It is possible to control active power consumption by controlling supplying voltage for certain type of loads like electric heating, lighting, small motors with no stalling problems (e.g. Fans, ovens, dishwashers, and dryers). So, without interrupting such loads frequency control is done by implementing smart load (SL) configuration.

PI CONTROLLER

A proportional–integral controller (PI controller) could be a control loop feedback mechanism (controller) normally employed in industrial control systems. A PI controller continuously calculates an error value e(t), e(t) because the difference between a desired set point and a measured method variable and applies a correction supported proportional and integral terms (sometimes denoted P and i respectively) that provide their name to the controller kind.

A PI controller continuously calculates an error value e(t) , e(t) because the difference between a desired set point and a measured method variable and applies a correction supported proportional, integral, and derivative terms. The controller makes an attempt to reduce the error over time by adjustment of a control variable u(t), like the position of a control valve, a damper, or the ability equipped to a element, to a new value determined by a weighted sum:

$$U(t)=k_p e(t) + k_i\int_0^t e(t)dT \qquad (1)$$

The proportional term produces an output value that's proportional to the present error value. The proportional response will be adjusted by multiplying the error by a constant Kp, known as the proportional gain constant.

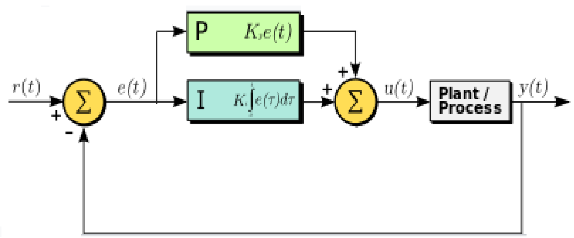


Fig.1. PI controller

The contribution from the integral term is proportional to each the magnitude of the error and therefore the duration of the error. The integral during a PID controller is that the adding of the instantaneous error over time and provides the accumulated offset that ought to are corrected previously. The accumulated error is then multiplied by the integral gain (Ki) and added to the controller output. Here , we are using PI controller in current reference generator , when filtering the error voltage by using low pass filter we are applying it to the PI controller it provides the ability reference signal.

II. CONCEPT OF SMART LOAD

Generally the frequency control with respect to demand is done by changing speed governor, which is known as secondary control which takes 30 seconds to 15 minutes to restore the frequency. Primary frequency control gives quick restoration of the frequency which takes 0 to 30seconds after disturbance of balance between generation and demand. Thus, a smart load configuration is introduced to get quick control of frequency. A smart load consists of a voltage compensator, critical load, non-critical (NC)load and controller as shown in Fig. 2. This system can be connected at the distribution level. That is low voltage (LV)/medium voltage (MV) feeders.

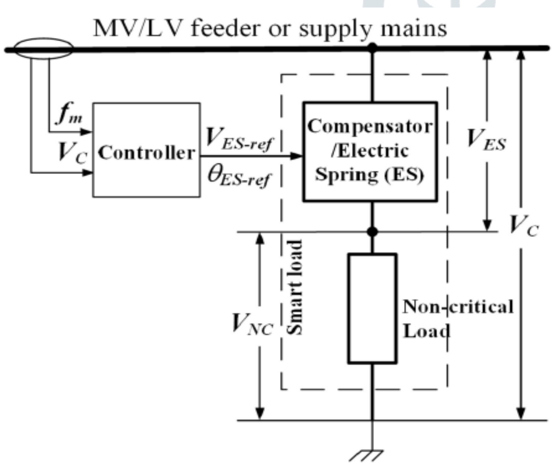


Fig.2. SL configuration

The compensator used in smart load is a STATCOM (Static Synchronous Compensator) [7]. The effect of smart load on frequency control is explained in section 3.

III. MODELLING OF SMART LOAD

By controlling the compensator injected voltage (V_{ES}) and the voltage across the non-critical load (V_{NC}), power consumption of total load at the point of connection, is controlled. In this paper, the type of loads used is of resistive-inductive (R-L) nature. The compensator used here is a STATCOM which has two compensating modes i.e. capacitive and inductive compensations where the phase angle is $\pm 90^{\circ}$. The phasor diagrams for the smart load with the compensations are shown in Fig. 3.

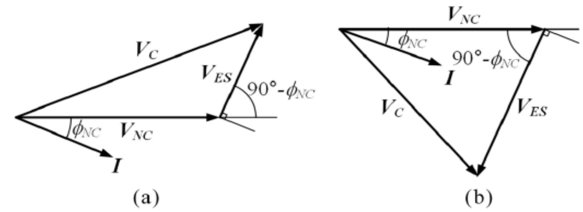


Fig.3. Phasor schematic for SLQ. (a) For inductive compensation mode. (b) For capacitive compensation mode

From the phasor diagrams, the relation between compensator voltage, non-critical load voltage and mains voltage can be expressed as Eq. 2

$$V_C \angle \theta_C = V_{NC} \angle \emptyset_{NC} \pm V_{ES} \angle \theta_{ES} \qquad (2)$$

The positive and negative corresponds inductive and capacitive modes respectively. Since one can need to provide voltage support from the compensator, VES in terms of mains current and voltage is expressed as Eq. 3 and Eq. 4 for inductive and capacitive compensation modes respectively.

$$V_{ES} = -IZ_{NC} \sin \emptyset_{NC} \pm \sqrt{V_C^2 - (IZ_{NC} \cos \emptyset_{NC})} \qquad (3)$$

$$V_{ES} = +IZ_{NC} \sin \emptyset_{NC} \pm \sqrt{V_C^2 - (IZ_{NC} \cos \emptyset_{NC})} \qquad (4)$$

Compensation modes used depending upon the change in frequency. Frequency is directly related with active power consumption. The capacitive compensation ($\theta_{ES} = -90$) reduces active power consumption of smart load PSL while inductive compensation increases PSL. The control architecture of compensator connected in smart load is as shown in Fig. 4.

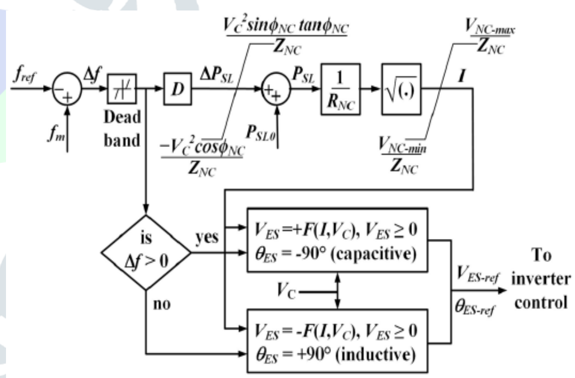


Fig.4. Control architecture of smart load

The reference frequency (f_{ref}) and measured frequency (f_m) are compared. The change in frequency (Δf) is sent through dead band (±0.01). According to the change in frequency, compensation modes are applied. To give appropriate compensation modes, current I and voltage of compensator (V_{ES}) are required. A change in power of smart load (ΔP_{SL}) is obtained by sending Δf into droop gain ($0.215/P_{SL}$). ΔP_{SL} is limited between ΔP_{SLmax} expressed in Eq. 5 and ΔP_{SLmin} expressed in Eq. 6 .

$$\Delta P_{SLmax} = \frac{V_C^2 \sin \emptyset_{NC} \tan \emptyset_{NC}}{Z_{NC}} \qquad (5)$$

$$\Delta P_{SLmin} = -\frac{V_C^2 \cos \emptyset_{NC}}{Z_{NC}} \qquad (6)$$

The change in power is added with nominal smart load power (P_{SL0}) to get the total power of smart load. The maximum and minimum currents can be obtained by Eq. 7 and Eq. 8 respectively as shown in Fig. 4.

$$I_{max} = \frac{V_{NC\,max}}{Z_{NC}} \qquad (7)$$

$$I_{min} = \frac{V_{NC\,min}}{Z_{NC}} \quad (8)$$

The current and compensator voltage (V_{ES}) are compared to give particular type of compensation.

IV. FUZZY INFERENCE SYSTEM

Fuzzy logic block is prepared using FIS file in Matlab 7.8.0.347(R2009a) and the basic structure of this FIS editor file as shown in Fig. 5. This is implemented using following FIS (Fuzzy Inference System) properties:

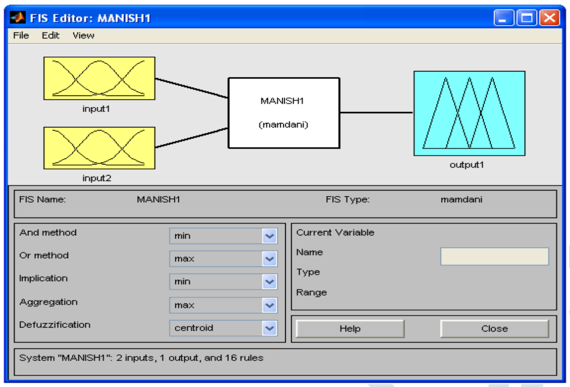


Fig.5. Fuzzy Inference System

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.

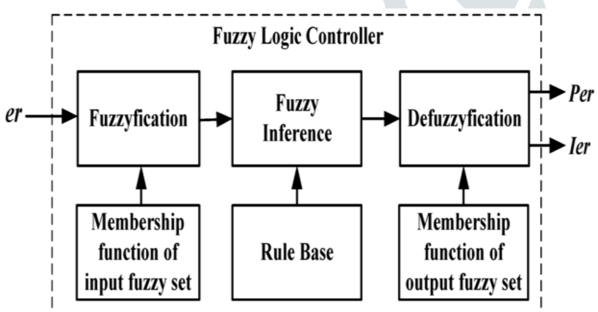


Fig.6. Fuzzy logic controller

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.

Table 1: Fuzzy Rules

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

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

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \quad (11)$$

$$CE(k) = E(k) - E(k\text{-}1) \quad (12)$$

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.

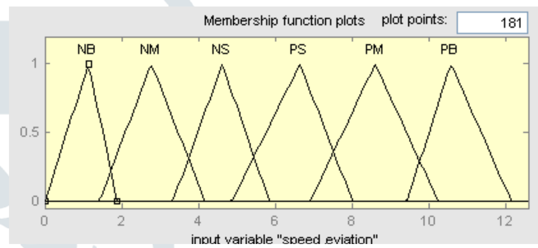


Fig.7. Membership functions for error

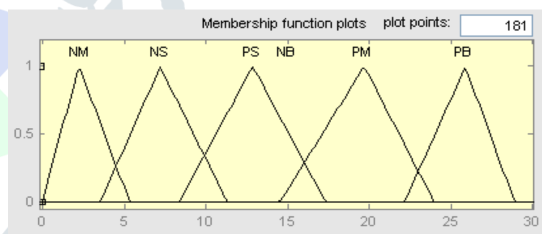


Fig.8. Membership functions for change In error

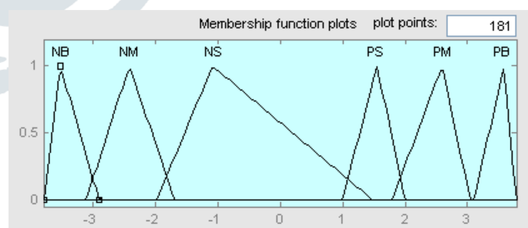


Fig.9. Membership functions for output

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

$$u = -[\alpha E + (1-\alpha)^* C] \quad (13)$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable.

V. SIMULATION AND RESULTS

The practical evaluation of smart load is evaluated by incorporating it in an IEEE 37 node test feeder. This feeder is an actual feeder in California, with a 4.8 kV operating voltage. It is characterized by delta configured, all line segments are underground, substation voltage regulation is two single-phase open-delta regulators, spot loads, and very unbalanced. This circuit configuration is fairly uncommon. Simulation of the IEEE 37 node test feeder with smart load is done in MATLAB (Matrix Laboratory)/Simulink platform. The equivalent single line diagram of the total system is shown in Fig. 10.

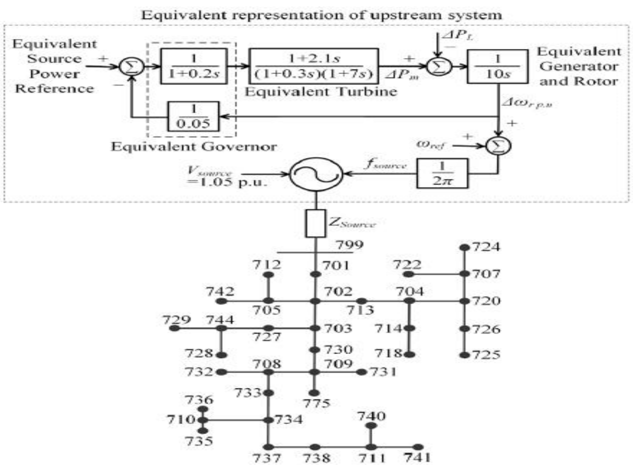


Fig. 10.Single line diagram of IEEE 37 node test feeder

When change in frequency (Δf) is greater than zero then capacitive compensation modes is applied. Inductive compensation is applied change in frequency (Δf) is less than zero.

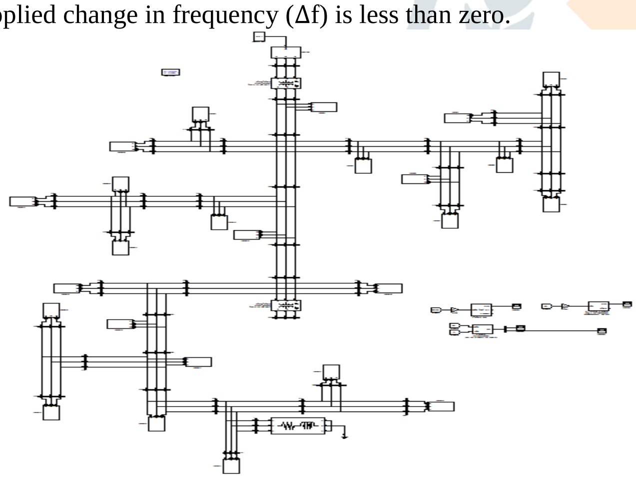


Fig.11.Matlab model for test feeder with normal load

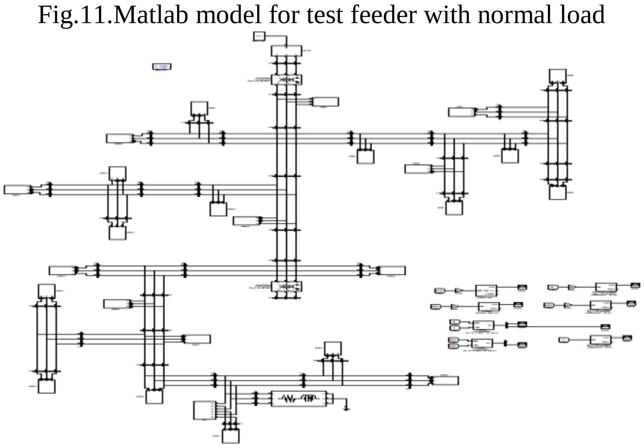


Fig.12.Matlab model for test feeder with smart load

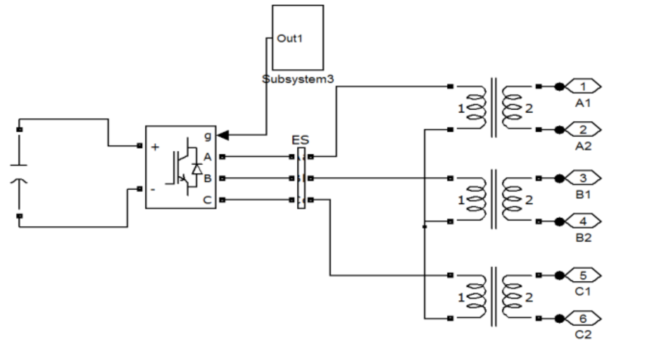


Fig. 13.SL configuration Matlab model

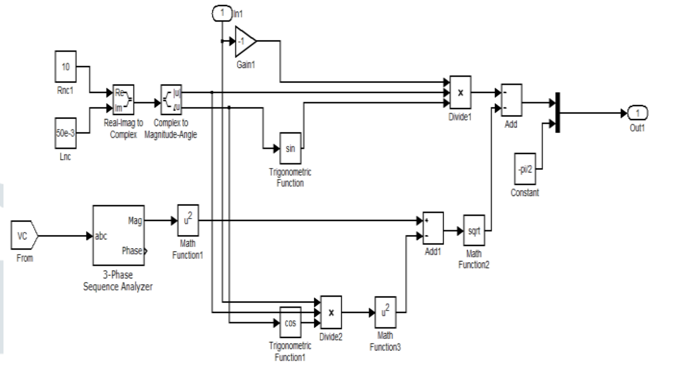


Fig. 14.Simulink model of capacitive compensation mode

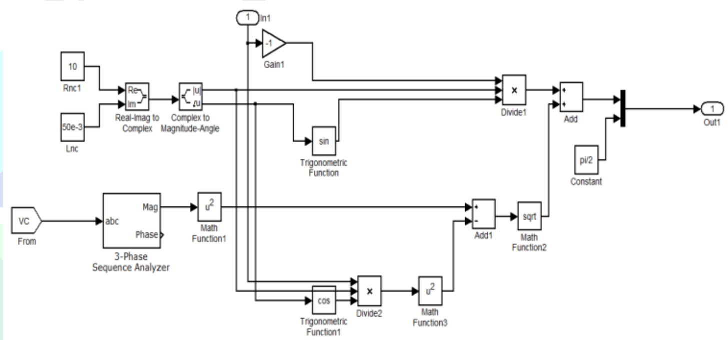
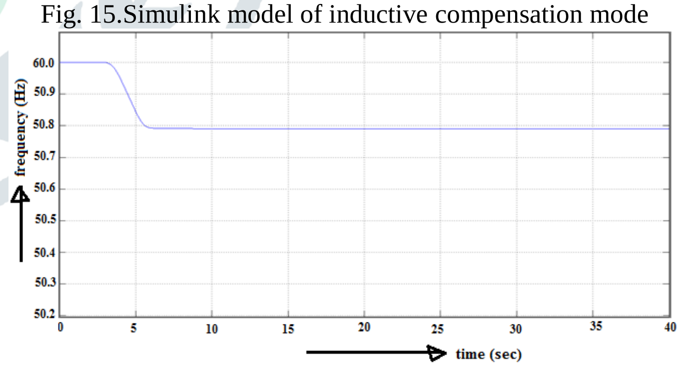


Fig. 15.Simulink model of inductive compensation mode



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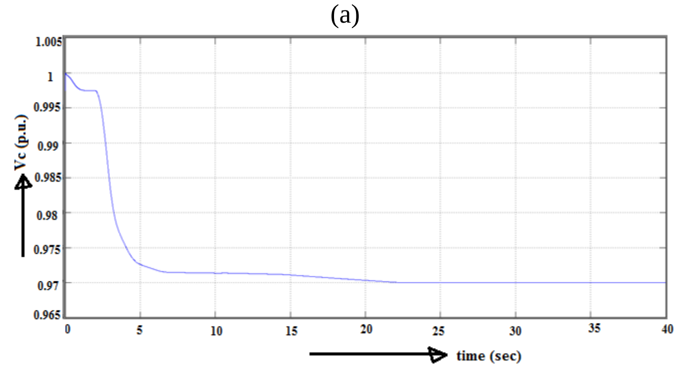

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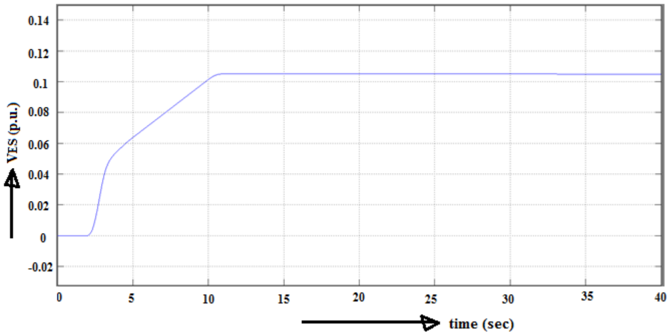

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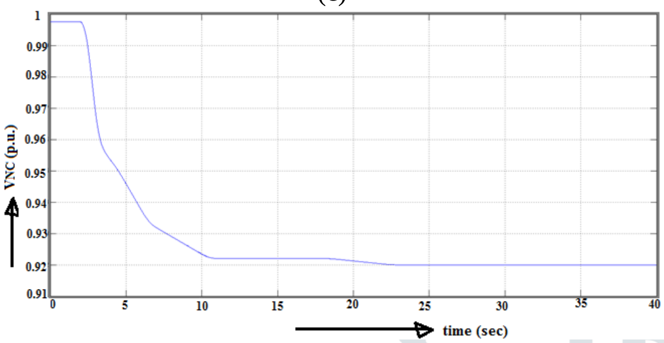
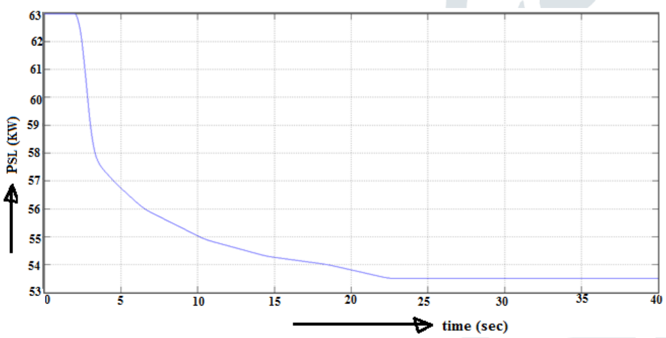


(d)

Fig. 16.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 under-frequency event at t = 2.0 s.



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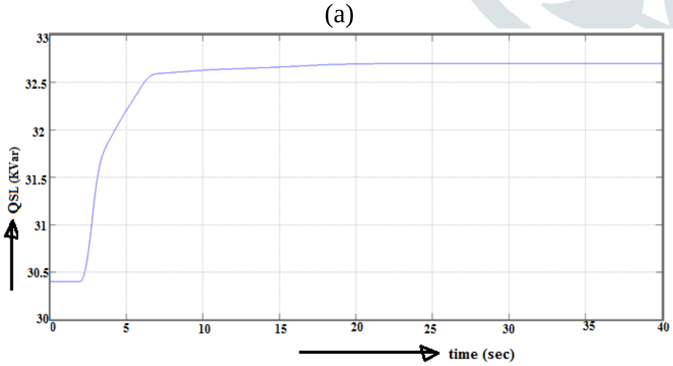

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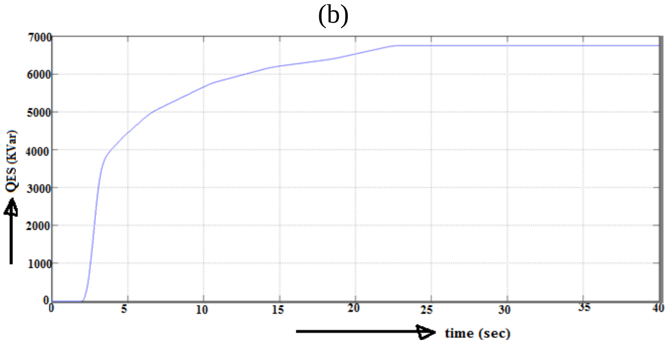

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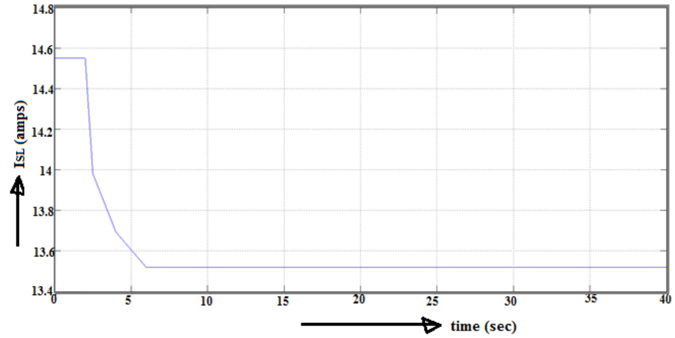
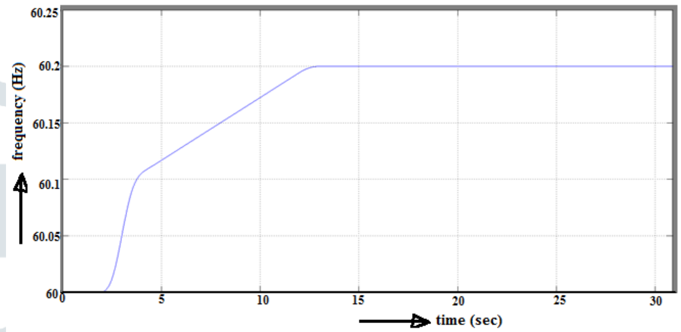


(d)

Fig. 17.Dynamic variation of (a) active power, (b) reactive power consumed by the SL, (c) reactive compensation, and (d) current following an under frequency event at t = 2.0 s.



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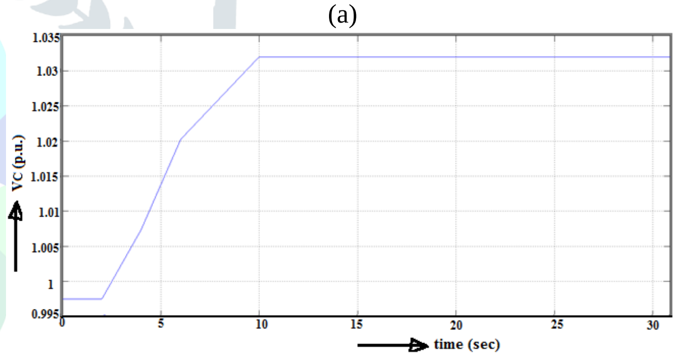

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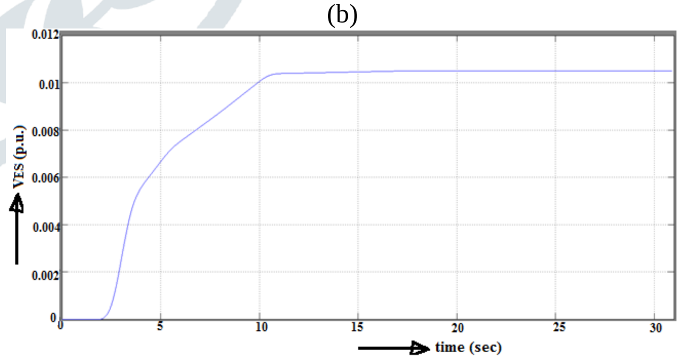

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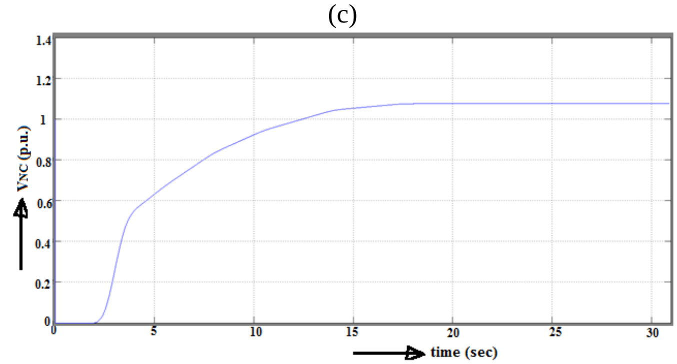
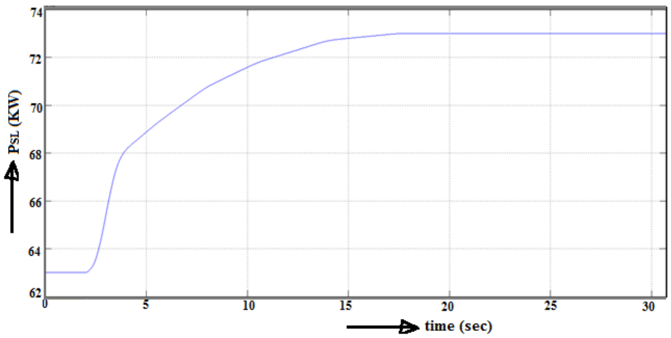


(d)

Fig. 18.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



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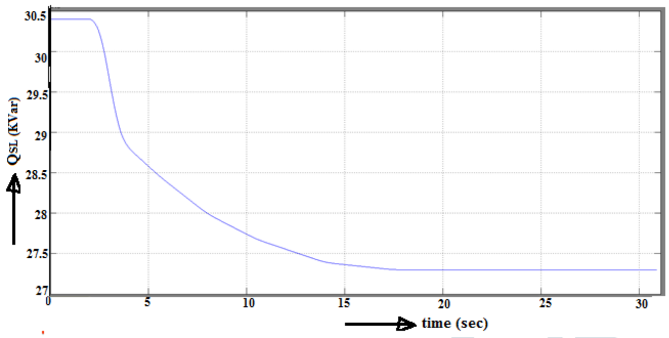

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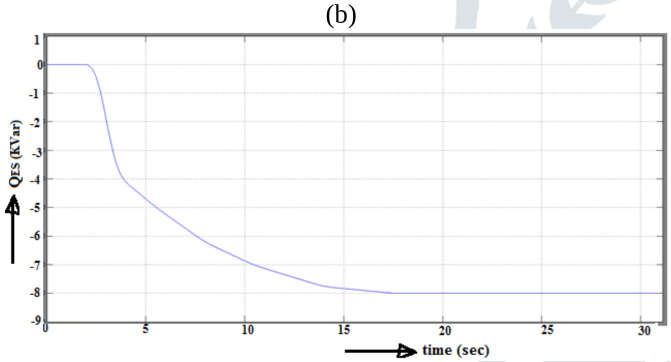

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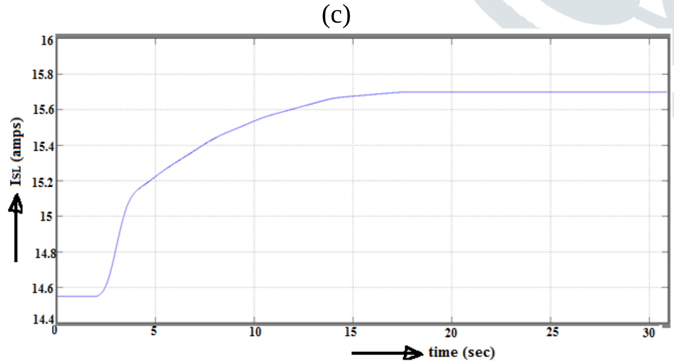

(d)

Fig. 19.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

CONCLUSION

A robust fuzzy control method was presented in this paper to mitigate the impact of integrating renewable energy sources on primary frequency control. The proposed method was examined on a IEEE 37 bus test system network which consists of non-critical loads. The simulation results demonstrated that the proposed fuzzy based smart load provides desirable performance against disturbances and effective in controlling the primary frequency of the system. A better performance is achieved when compared with the normal load on the system. Without considering any primary frequency response contribution from frequency dependence of loads, the fuzzy based SLs are shown to achieve much improved frequency regulation with little relaxation in voltage tolerance for the NC loads and a small reactive compensation which is a fraction of the load rating. With SL using reactive compensation only (SLQ), the mains voltage regulation deviated slightly but still lies within the limits. The range of voltage variation can be limited to 10% without any perceivable impact on the consumers. The effect of smart load on frequency regulation of mains is evaluated by simulating IEEE 37 node test feeder using MATLAB/Simulink. The results shows that the frequency variation is less for both capacitive as well as inductive compensation using smart load configuration compared to a normal load.

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