EFFECT OF SELF-TUNING FUZZY FREQUENCY CONTROLLER TO AGC ON SMES CONTROL

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Abstract: *This paper presents a novel control method of Superconducting Magnetic Energy Storage (SMES) unit with a self-tuned Fuzzy Frequency Controller (FFC) associated with the Automatic Generation Control (AGC) for improving Load Frequency Control (LFC) in a single area power system. Boiler dynamics and nonlinearities such as governor dead band (DB) and generator rate constraints (GRC) are considered in the developed comprehensive mathematical model of a single area isolated power system. The effects of the self-tuning configuration of fuzzy frequency controller in AGC on SMES control is compared with that of optimized fixed gain PI controlled AGC. It is seen that with addition of self-tuned fuzzy frequency controller, SMES can perform a more effective primary frequency control for single area power system.*

Keywords: *Load frequency control, single area power system, automatic generation control, superconducting magnetic energy storage unit, fuzzy frequency controller.*

1. Introduction

Automatic generation control is a very important subject in power system operation for supplying sufficient and reliable electric power. This is achieved by AGC. In an interconnected power system, as the load demand varies randomly, the area frequency and tie-line power interchange also vary. The objective of the load frequency control (LFC) problem is to minimize the transient deviations in these variables and to ensure their zero steady state values. The solution to the LFC problem by a governor control alone imposes a limit on the degree to which the deviations in frequency and tie-power exchange can be minimized. However, as the LFC problem fundamentally being that of an instantaneous mismatch between the generation and demand of active power, the incorporation of a fast-acting energy storage device in the power system can improve the performance under such conditions. The superconducting magnetic energy storage (SMES) features highly efficient energy storage and high speed power control. At the same time, its operation and life are not influenced by the number of charge/discharge cycles unlike the classical batteries [1]. The estimated life of a typical SMES unit is more than 20 years. As a result of this, many attractive applications of SMES have been reported [1-6].

But fixed gain controller[3,6] for SMES and also for AGC [1, 7-9] cannot, however, perform optimally under different operating conditions in a power system and the suitable controllers for SMES are those with adaptive features [4]. Although the scheme presented in [4] is based on self-tuning type of adaptive control, it has some deficiencies. For example, the SMES model has been unnecessarily linearized, and the SMES control scheme is not purely adaptive. Also, in most of the already existing schemes, the converters used drain reactive power from the network and the SMES dynamics and control models used lack the practical implementation aspects related to SMES coil charging/discharging.

In this study, based on a simple SMES controller, a fuzzy frequency controller is designed in order to retain the frequency to the rated value after the load changes. The basic objective of the fuzzy frequency controller is to restore balance between the load and generation after the occurrence of a load disturbance. This is met when the control action maintains the frequency and the power interchange at the scheduled values. The on line adaptation of fuzzy frequency controller output makes the proposed intelligent controller more effective and suitable for different operating conditions. It is seen that with the addition of the proposed fuzzy frequency controller to AGC, a simple controller scheme for SMES is sufficient for load frequency control of single area power system.

2. Power System Model with SMES Unit

The single area power system model with the proposed configuration of SMES units is shown in Fig. 1. When there is a sudden rise in power demand in a control area, the stored energy is almost immediately released by the SMES through its power conversion system (PCS). As the governor control mechanism starts working to set the power system to the new equilibrium condition, the SMES coil stores back to its nominal energy. Similar is the action when there is a sudden decrease in load demand. Basically, the governor-turbine system is slow reacting compared with the excitation system, which is fast reacting. As a result, fluctuations in terminal voltage can be corrected by the excitation system very quickly. Fluctuations in generated power or frequency are corrected slowly. Since load frequency control is primarily concerned with the real power/frequency behavior,

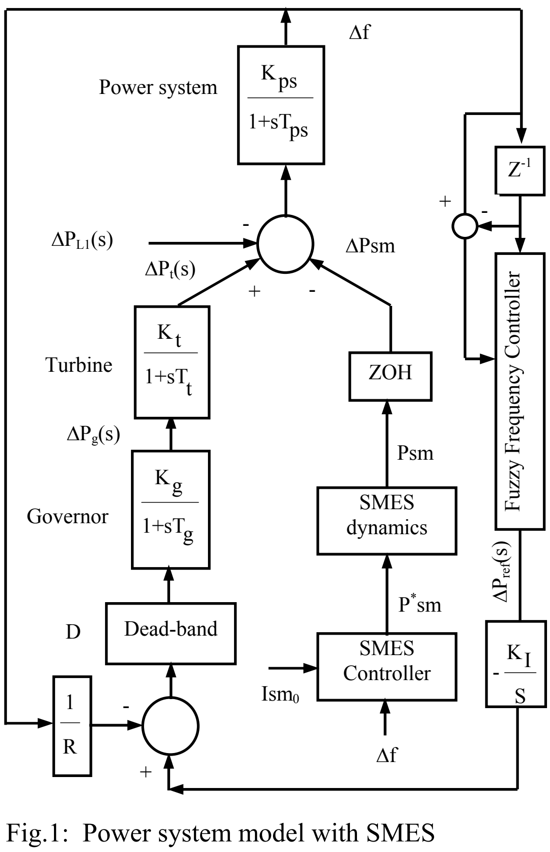


Fig.1: Power system model with SMES

the excitation system model will not be required in the approximated analysis [1]. This important simplification paves the way for constructing the simulation model shown in Fig. 1. The presence of zero-hold (ZOH) device in Fig.1 implies the discrete mode control character for SMES.

All of the governors have dead band, which has significant effect on the dynamic performance of the power system [9]. So effects of governor dead-band are studied in relation to AGC. The limiting value of dead-band is specified as 0.06%. The governor dead band is defined, as the total magnitude of a sustained speed change within which there is no change in valve position. The nonlinearity of hysteresis is expressed as [9]:

$$y = F(x, dx/dt) \tag{1}$$

For a basic assumption, the variable x is taken as a sinusoidal oscillation

$$x \approx A\sin\omega_0 t \tag{2}$$

where A is the amplitude of oscillation, ω_0 is the frequency of oscillation. It has been known that the backlash nonlinearity tends to give continuous sinusoidal oscillation with a natural period of about two seconds [10]. F(x, dx/dt) function can be evaluated as a Fourier series as follows [9]:

$$F(x,\dot{x}) = F^0 + N_1 x + \frac{N_2}{\omega_0}\dot{x} + \ldots \tag{3}$$

Since the backlash nonlinearity is a symmetrical about the origin, the constant term F^0 in the Fourier series is zero [11]. So from (3)

$$F(x,\dot{x}) = N_1 x + \frac{N_2}{\omega_0}\dot{x} = Dx \tag{4}$$

where D denotes the dead band [10,11]. Therefore, the describing function incorporating the governor dead band nonlinearity for single area power system is expressed as nonlinear differential equations [12].

Also in practical steam turbine, due to thermodynamic and mathematical constraints, there is a limit to the rate at which its output power (dP_t/dt) can be changed. This limit is referred to as generation rate constraint (GRC). In practice, there exists a maximum limit on the rate of change in the generating power of a steam plant. In the presence of GRC, the dynamic responses of the system experience larger overshoots and longer settling time compared to the case without considering the GRC. Hence, if the load changes are too fast under transient conditions, then system nonlinearities will prevent its achievement. Moreover, if the parameters of the controller are not chosen properly, the system may become unstable. Thus, the GRC is taken into account by adding a limiter to the turbine as shown in Fig. 2, with a value of 0.17 p.u. MW/min [11]. This is a typical value up to 3.4 MW/second. All parameters are shown in Table 1.

$$\Delta \dot{P}_{generation} = 0.1 \text{ p.u.MW/min} = 0.0017 \text{p.u.MW/sec} = \delta$$

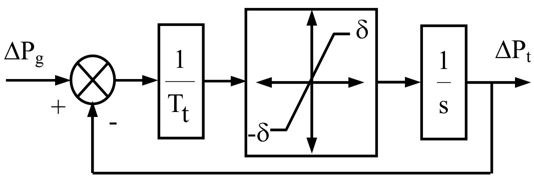


Fig. 2: A non-linear turbine model with GRC

Table 1: Nominal parameters of single-area power system

Area capacity=P_R= 2000 MW

K_P = 120 Hz/p.u. MW, T_P = 20 sec

K_G = 1 Hz/p.u. MW, T_G = 0.08 sec

K_T =1 Hz/p.u. MW, T_T = 0.3 sec

R =2.4 Hz/p.u. MW

K_I^0 = 0.27 & 0.29 with and without DB & GRC respectively

D = 0.0083 pu. MW/ Hz

3. Optimization of the Integral Gain, K_I for Fixed gain PI controller

The tuning of the value of K_I at Kp=0 was achieved using a systematic exhaustive search according to the IAET criterion shown in (5).

$$J_{fre} = \int_0^T |\Delta f(t)| t \, dt \qquad (5)$$

Considering this performance index (J_{fre}) for the fixed load disturbance, the optimal value of fixed gain K_I is determined for the fixed gain controller. It is found that in the absence of generation rate constraints (GRC) the best-tuned integral gain value is K_I = 0.29 & K_P =0 at J_{fre} = 0.1871, which is also called the critical value. In the presence of governor dead-band and GRC the gain values of the conventional PI controller are K_I = 0.27 & K_P = 0 at J_{fre} = 0.2696, which is shown in Fig. 3.

4. Conventional PI Control System

The general practice in the design of a LFC is to utilize a PI structure. A typical conventional PI control system is shown in Fig. 4. This gives adequate system response considering the stability requirements and the

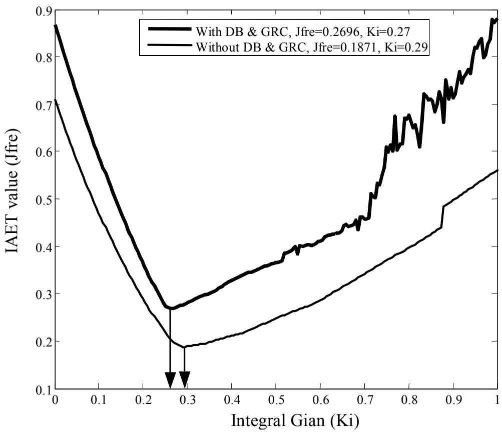


Fig.3: The optimal K_I setting with and without considering DB and GRC

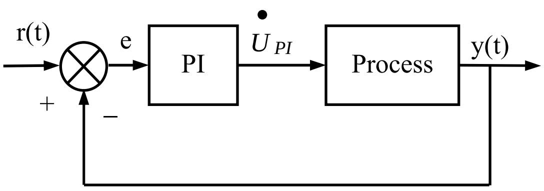


Fig. 4: A typical conventional PI controller

performance of its regulating units. In this case the response of the PI controller is not satisfactory enough and large oscillations may occur in the system [13-14]. For that reason, a fuzzy frequency controller is designed and implemented in this study.

4.1 Basic Fuzzy Frequency Controller (FFC)

For the fuzzy frequency controller implementation shown in Fig. 5, it will be taken into account the error (difference of the reference frequency and the sampled frequency) and the rate of change of error as the input of the controller. From theses variables, it will be deducted the control signal's variation.

The error signal:

$$e^*(k) = r^*(k) - y^*(k) \qquad (6)$$

And the rate of change of error signal:

$$v^*(k)=\frac{\left[e^*(k)-e^*(k-1)\right]}{T_S} \qquad (7)$$

where, T_s is the sampling period.

4.2 Design Steps for FFC Scheme

Fig. 6 shows a schematic representation of a typical closed loop fuzzy control system. For implementation of fuzzy frequency

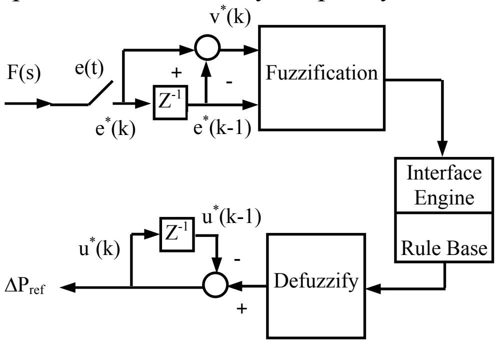


Fig. 5: A typical fuzzy frequency controller (FFC) for an AGC

controller, the precise numerical values obtained by measurements are converted to membership values of the various linguistic variables. The fuzzy frequency controller has the two inputs, which are defined as:

Input 1: error $= e_t = \Delta f = f_{norm} - f_t$ (8)

Input 2: rate of change of error =

$$c\dot{e}_t = \Delta\dot{f} = \dot{f}_{nominal} - \dot{f}_t \qquad (9)$$

The approach taken here is to exploit fuzzy rules and reasoning to generate controller parameters. The triangular membership functions for the proposed FFC of the three variables (e_t, $c\dot{e}_t$, P_{ref}) are shown in Fig. 6, where error (e_t) and change of error ($c\dot{e}_t$) are used as the inputs of the fuzzy logic controller. Considering these two inputs, the output of FFC (ΔP_{ref}) is determined. The use of two input and single output variable makes the design of the controller very straightforward. A membership value for the various linguistic variables is calculated by the rule given by

$$\mu\left(e_t, c\dot{e}_t\right)=\min\left[\mu\left(e_t\right),\mu\left(c\dot{e}_t\right)\right] \qquad (10)$$

The equation of the triangular membership function used to determine the grade of membership values in this work is as follows:

$$A\left(x\right)=\frac{\left(b-2\left|x-a\right|\right)}{b} \qquad (11)$$

where A(x) is the value of grade of membership, 'b' is the width and 'a' is the coordinate of the point at which the grade of membership is 1 and x is the value of the input variables. The control rules for the proposed strategy are very straightforward and have been developed from the viewpoint of practical system operation and by trial and error methods. The fuzzy rule base for the FFC scheme is shown in Table II.

The membership functions, knowledge base and method of defuzzification determine the performance of the fuzzy frequency controller in a single area power system as shown in (12).

$$\Delta P_{ref}=\frac{\sum_{j=1}^{n}\mu_j u_j}{\sum_{j=1}^{n}\mu_j} \qquad (12)$$

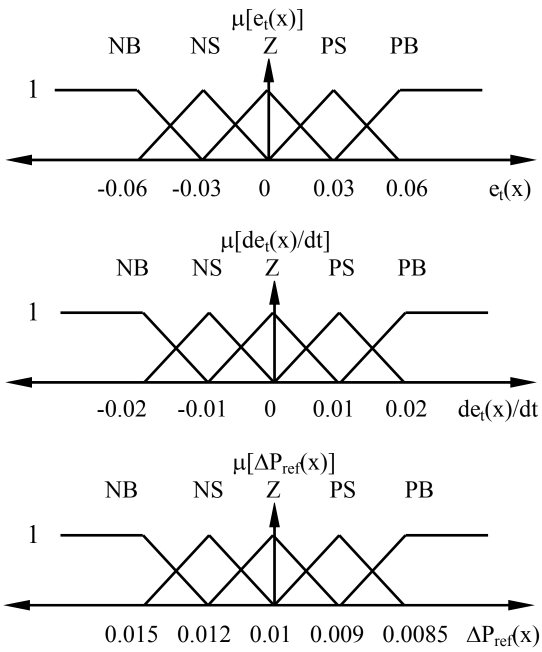


Fig. 6: Membership functions for the fuzzy variables

Table 2: Fuzzy Rule Base for FFC

ce \ e	NB	NS	Z	PS	PB
NB	PB	PB	PS	PS	Z
NS	PB	PS	PS	Z	NS
Z	PB	PS	Z	NB	NS
PS	PS	Z	NS	NS	NB
PB	Z	NS	NS	NB	NB

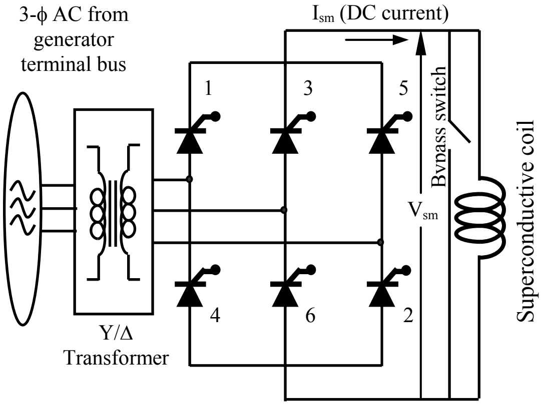


Fig. 7: SMES unit with 6-pulse bridge AC/DC thyristor controlled converter

5. The SMES Unit and It's Control Strategy

The schematic diagram in Fig. 7 shows the configuration of a thyristor controlled SMES unit, which is incorporated in the power system for LFC. The converter impresses positive or negative voltage on the superconducting coil by using a cryogenic system and the power conversion/ conditioning system with control and protection functions [15-16]. Charge and discharge are easily controlled by simply changing the delay angle α, which controls the sequential firing of the thyristors. If α is less than 90°, the converter operates in the rectifier mode (charging) and if α is greater than 90°, the converter operates in the inverter mode (discharging). As a result, power can be absorbed from or released to the power system according to the system requirement. At steady state SMES should not consume any real or reactive power.

Fig. 8 outlines the proposed simple control scheme for SMES, which was designed to reduce the instantaneous mismatch between demand and generation. For operating point change due to load changes, fuzzy frequency controlled AGC including SMES unit is proposed. Firstly, ΔP_{ref} is determined using fuzzy frequency controller to obtain frequency deviation, Δf, and finally this Δf is used as the input to the SMES controller.

It is desirable to restore the inductor current to its rated value as quickly as possible after a system disturbance, so that the SMES unit can respond properly to any subsequent disturbance. So inductor current deviation is sensed and used as negative feedback signal in the SMES control loop to achieve quick restoration of current and SMES energy level. The parameters of the SMES controller are shown in Table III.

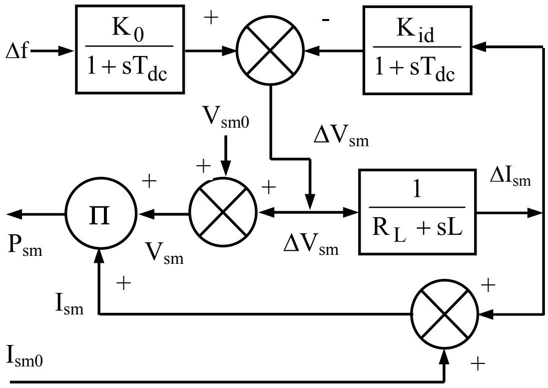


Fig. 8: SMES control system

TABLE 3: Parameters of Smes Controller

K_0=400 kV/p.u. MW, K_{id} = 2.5 kV/p.u. kA
$I_{sm,max}$= 6.760482 kA, $I_{sm,min}$= 1.46967 kA
L_{sm}= 0.5 Henry
I_{sm0}= 4.8989 kA, V_{sm0}= 0 kV
T_{dc}=0.026 sec, R_L=0.0 Ω, R_c=0.0 Ω
W_{sm} = 6 MJ

6. Digital Simulation Results

To demonstrate the usefulness of the proposed controller, computer simulations were performed using the MATLAB environment under different operating conditions. The system performances with fuzzy frequency controlled AGC including SMES and optimized fixed gain PI controlled AGC including SMES are shown in Fig. 9 through Fig. 12. Two cases studies are conducted.

Case I: a step load increase in ΔP_L=0.01 pu MW is applied in the control area.

Case II: a step load increase in ΔP_L=0.02 pu MW is applied in the control area.

Form the simulation results it is found that with the addition of SMES unit not only make the system stable but also the settling time decreases substantially. It is seen from Figs 9-12 that the system has more impact when considering DB and GRC compared to the system when it is not considered. When the power system demands the extra power during the first few seconds following the disturbance, energy is supplied from SMES coil by sensing Δf signal. The ($K_{id}.\Delta I_{sm}$) term becomes effective only when the inductor current has deviated by a considerable amount. Consequently, the reduction in total energy discharge from the SMES unit does not bring any appreciable deterioration in the frequency and power deviations of the power system. It is interesting to observe that P_{sm} becomes zero and inductor current (I_{sm}) return back to the rated value quickly after providing appropriate compensation. This enables the SMES unit to respond to a subsequent load disturbance in the power

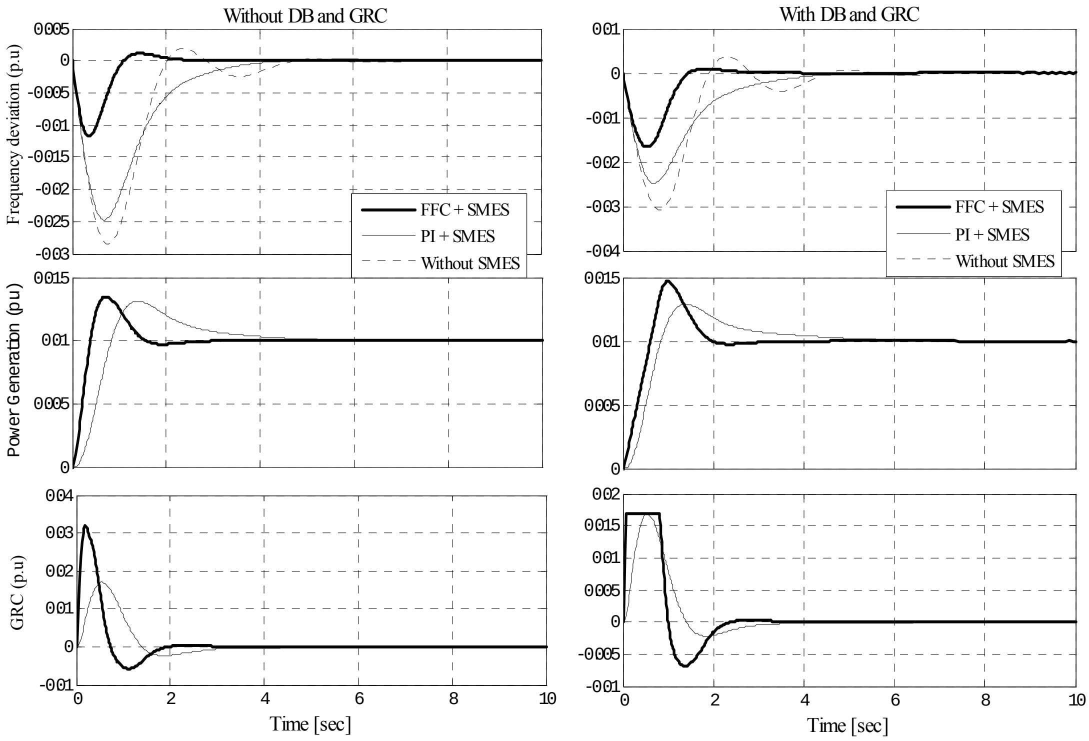


Fig. 9: System performances for a step load change of ΔP_L= 0.01 p.u MW [Case

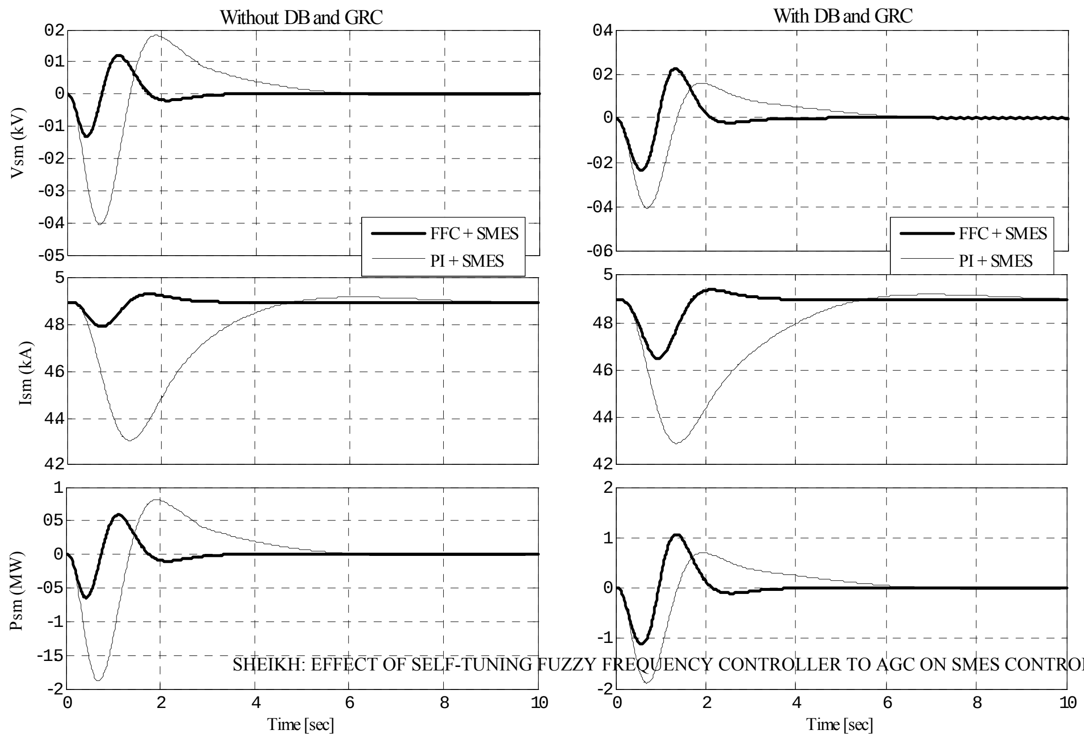
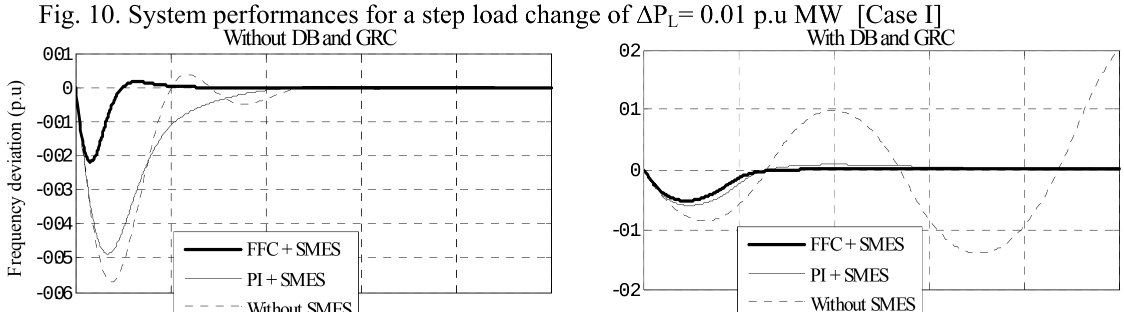


Fig. 10. System performances for a step load change of ΔP_L= 0.01 p.u MW [Case I]



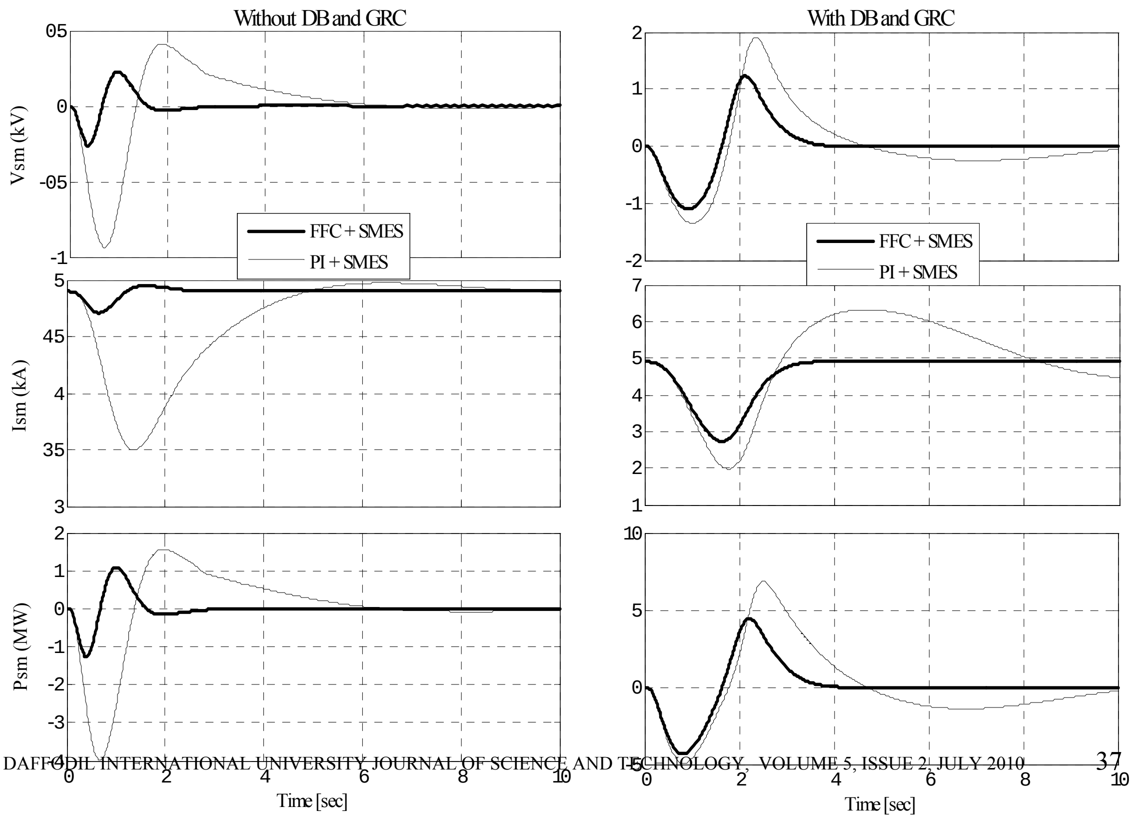


Fig. 12. System performances for a step load change of ΔP_L= 0.02 p.u MW [Case II]

system. It is also observed that the deviation of I_{sm} is less in both the cases when the proposed control system is used. A matter of good satisfaction is that the size of SMES energy capacity is also reduced significantly with the effectively controlled proposed system. Finally, it is seen that the damping of the system frequency is not satisfactory for the fixed gain controller. But proposed controlled SMES associated with the fuzzy frequency controller of AGC significantly improves the system performances.

7. Conclusions

The simulation studies are carried out on a single-area power system considering DB and GRC to investigate the impact of the proposed intelligently controlled SMES for dynamic improvement of LFC. The fuzzy frequency control approach yields automatic, self-adjusting outputs irrespective of widely varying, imprecise, uncertain off-nominal conditions. The results show that the proposed control scheme for SMES is very powerful in reducing the frequency deviations, in the case when fuzzy frequency controlled AGC including SMES unit is used compared to optimized fixed gain PI controlled AGC including SMES unit. On line adaptation of fuzzy frequency controller output makes the proposed intelligent controller more effective and suitable for different operating conditions.

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