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Improving the dynamic performance in Automatic generation control of restructured power system by using Superconducting magnetic energy storage and novel controller

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Abstract: *In this paper, coordinated control of superconducting magnetic energy storage (SMES) in automatic generation control (AGC) of an interconnected two area multi-source (hydro-thermal-gas) power generation system in restructured environment is presented. The proposed method can improve the dynamic performance of AGC after the sudden load perturbation. The integral (I) and proportional–integral–derivative (PID) controller gain of AGC is obtained by tuning the quadratic performance index using integral square error (ISE) technique. After deregulation, each area contains three GENCOS and three DISCOS. For describe bilateral contract for two areas AGC, DISCO participation matrix is used. Simulation result reveals that combination of SMES and PID controller reduces frequency deviation and gives faster settling time than without any energy storage devices.*

Keywords: *AGC, ISE, LFC, SMES, Deregulation, Bilateral contracts.*

I. Introduction

Automatic generation control (AGC) is very important issue in modern power system operation and control for supplying enough power with good quality. The traditional AGC is well discussed in [1] .Controlling the frequency has always been a major subject in electrical power system.

The engineering aspects of planning and operation have been reformulated in a restructured power system in recent years although essential ideas remain the same. These major changes into the structure of electric power utilities have been introduced to improve efficiency in the operation of the power system by means of deregulating the industry and opening it up to private competition. With the emergence of the distinct of GENCOs, TRANSCOs, DISCOs and the ISO, many of the ancillary services of a Vertically Integrated Utility (VIU) will have a different role to play and hence have to be modeled differently [12]. The AGC in restructured electricity market should be designed to consider different types of possible transactions such as Poolco based transactions, bilateral transaction and contract violation transaction. In this modern system, a DISCO can contract individually with a GENCO for power and these transaction are done under independent systemoperator (ISO) .The values of GENCOs participation and tie-line power exchanges are computed by some equations [16] .

In the available literature analyses the use of superconducting magnetic energy storage (SMES) for improvement of the dynamic performance of power system [3-20]. A time domain simulations used to study the performance of the power system dynamics are analyzed.

The objectives of the proposed works are:

1. To obtain the transient performance of the coordination action of two areas AGC loop with various contract between GENCOS and DISCOS.
2. To investigate the further impact of SMES on the same transient performance.
3. Finally comparing analysis has been carried between system action of the transient performance of optimized gain by ISE technique based AGC with SMES and without SMES with use of I and PID controller.

II. Super conducting magnetic energy storage (SMES)

The schematic diagram in Fig. 2 shows the thyristor controlled SMES unit configuration. In the SMES unit, a dc magnetic coil is connected to the ac grid through a Power Conversion System(PCS) which includes an inverter/rectifier. The energy exchange between the super conducting coil and the electric power system is controlled by a line commutated converter .To reduce the harmonics produced on ac bus in the output voltage to coil,12-pulse converter is preferred which are connected to grid through a Y-Δ/Y-Y transformer. The superconducting coil can be charged to a set value from the utility grid during steady state operation of the power system. The DC magnetic coil is connected to grid via inverter/ rectifier arrangement. The charged superconducting coil conducts current which is immersed in a tank containing helium. When there is a sudden rise in the load demand, the stored energy is almost released through the converter to the power system as alternating current. As the governor and other control mechanisms start working to set the power system to the new equilibrium the coil current changes back to its initial value and are similar for sudden release of load [6-13].

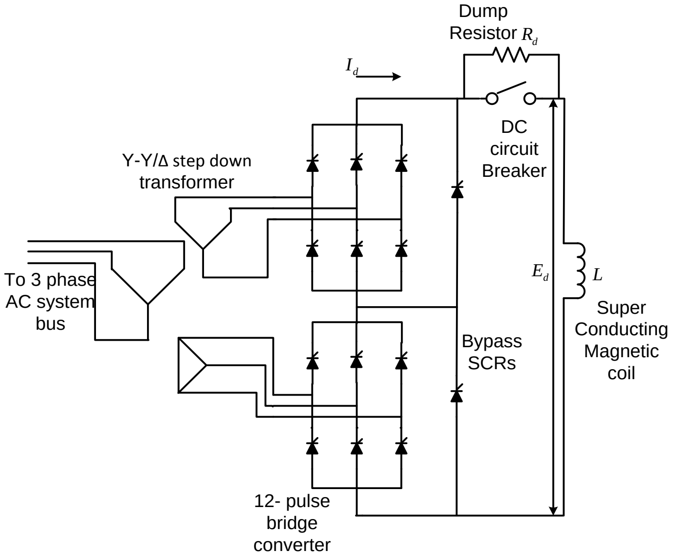

Fig 1. SMES Circuit Diagram

A. CONTROL OF SMES UNIT

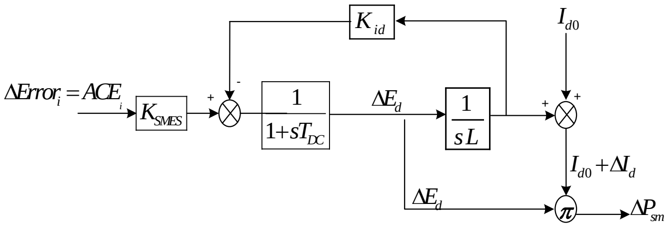

Fig 2. Block diagram of SMES

When the power is to be pumped back into the grid in the case of a fall in frequency due to sudden loading in the area, the control voltage E_d is to be negative since the current through the inductor and the thyristors not change its direction. The incremental change in the voltage applied to the inductor is expressed as:

$$\Delta E_d = \left[\frac{K_{SMES}}{1+sT_{DC}}\right]\Delta Error_i \tag{1}$$

Where, T_{DC} is the converter time delay, K_{SMES} is the gain of the control loop the inductor current deviation is given by

$$\Delta I_d = \frac{\Delta E_d}{sL} \tag{2}$$

In this paper, Area Control Error (ACE) is used as error signal ($\Delta Error_i$) to SMES unit.

$$ACE_i = B_i \Delta f_i + \Delta P_{tieij}$$

Where i,j is area Δf_i is change in frequency of area i and ΔP_{tieij} is change in tie line power flow out of area i- j .

III. System under investigation

In the restructured system having several GENCOs and DISCOs, any DISCO may contract with any GENCO in another control area independently. This case is calls as ‘bilateral transaction’. The transactions have to be implemented through an ISO. The neutral body ISO has to control many of ancillary services, one of AGC. In deregulated environment, any DISCO has the liberty to buy power at competitive prices from different GENCOs, which may or may not have contract in the same area as the DISCO. For work, GENCO-DISCO contract is proposed in [12-15] with ‘DISCO participation matrix’ (DPM). Basically, DPM gives the participation of a DISCO in contract with a GENCO. In DPM, the number of row has to be equal to the number of GENCOs and number of columns has to be equal to the number of DISCOs in the system. Here, The i-j entry corresponds to the fraction of the total load power contracted by DISCO j from a GENCO i. As a result, total of entries of column belong to DISCO1 of DPM is $\sum \mathrm{C}_{\mathrm{pij}} = 1$. The corresponding DPM to the considered power system having two equal areas and each of them including three DISCOs and three GENCOs is given as follows:

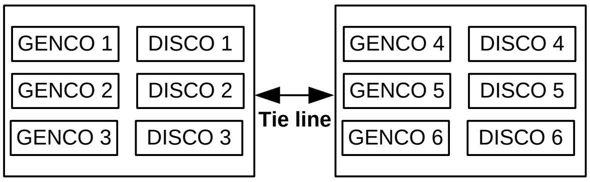

Fig.3. Configuration of the power system

Participation factor of different GENCOS:

$$DPM = \begin{bmatrix} cpf11 & cpf12 & cpf13 & \vdots & cpf14 & cpf15 & cpf16 \\ cpf21 & cpf22 & cpf23 & \vdots & cpf24 & cpf25 & cpf26 \\ cpf31 & cpf32 & cpf33 & \vdots & cpf34 & cpf35 & cpf36 \\ \cdots & \cdots & \cdots & \vdots & \cdots & \cdots & \cdots \\ cpf41 & cpf42 & cpf43 & \vdots & cpf44 & cpf45 & cpf46 \\ cpf51 & cpf52 & cpf53 & \vdots & cpf54 & cpf55 & cpf56 \\ cpf61 & cpf62 & cpf63 & \vdots & cpf64 & cpf65 & cpf66 \end{bmatrix}$$

If where CPF is ‘contract participation factor’ For example, the fraction of the total load power contracted by DISCO1 from GENCO2 is respected by CPF21 entry. The coefficients, which represent this sharing, are called as ‘‘ACE participation factors (APF)’’ and $\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{ap}_{\mathrm{j}} = 1$ where n is the number of GENCOs in each area. As different from conventional AGC systems, any DISCO can demand power from all of the GENCOs. These demands are determined by cps, which are contract participation factors, as load of the DISCO. In the case of two-area power system, the mutual scheduled tie-line power flows among the areas can be represented by the following formula:

$$\Delta P_{tie1-2,scheduled} = \sum_{i=1}^{3}\sum_{j=4}^{6} cpfij \Delta P_{Lj} - \sum_{i=4}^{6}\sum_{j=1}^{3} cpfij \Delta P_{Li} \tag{3}$$

Total generation required of individual GENCOs can be calculated as:

$$\Delta P_{Mi} = \sum_{j} cpfij \Delta P_{Lj} \tag{4}$$

Equations of the considered power system including two areas are given in steady state from as follows:

$$\dot{X} = \mathrm{AX} + \mathrm{BU}$$

Where X is the state vector and, U is the total demand of DICOs as Follows:

$$X = [\ \Delta f_1\ \ \Delta P_{G1}\ \ \Delta P_{TR1}\ \ \Delta P_{T1}\ \ \Delta P_{G2}\ \ \Delta P_{RH1}\ \ \Delta P_{GH1}$$
$$\Delta P_{G3}\ \ \Delta P_{F1}\ \ \Delta P_{YG1}\ \Delta P_{bg1}\ \ \Delta f_2\ \ \Delta P_{G4}\ \ \Delta P_{TR2}$$
$$\Delta P_{T2}\ \ \Delta P_{G5}\ \ \Delta P_{RH2}\ \ \Delta P_{GH2}\ \ \Delta P_{G6}\ \Delta P_{F2}\ \ \Delta P_{YG2}$$
$$\Delta P_{bg2}\ \ \Delta P_{tie12}\ \ \Delta I_d\ \Delta E_d]^T$$
$$U = [\Delta PD_1\ \Delta PD_2$$

Where $\Delta \mathrm{PD}_1$ is total demand of area 1 DISCOs and $\Delta \mathrm{PD}_2$ is total demand of area 2 DISCOs.
Fig 4 the linearzed transfer function model of the inter connected power system of two area multisource power generation with SMES at area 1 in restructured environment is presnted.apf11,apf12 and apf13 are the participation factors in area-1 and apf21,apf22 and apf23are the participation factors in area-2.it may noted that apf11+apf12+apf13=1 and apf21+apf22+apf23=1.Simulation is carried out for different test cases of the possible contracts under large load demands and disturbances.

IV. Simulation test systems

Case A: Poolco based transactions

In this case GENCOs participate in automatic generation control of their own areas only. It is assumed that large step contracted loads are simultaneously demanded by DISCOs of area 1 and 2. A case of Poolco based contracts between DISCOs and available GENCOs is simulated based on the following contract participation factor matrix (DPM1).

$$DPM1 = \begin{bmatrix} 0.4 & 0.4 & 0.2 & \vdots & 0 & 0 & 0 \\ 0.4 & 0.2 & 0.4 & \vdots & 0 & 0 & 0 \\ 0.2 & 0.4 & 0.4 & \vdots & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & \vdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \vdots & 0.4 & 0.3 & 0.3 \\ 0 & 0 & 0 & \vdots & 0.3 & 0.4 & 0.3 \\ 0 & 0 & 0 & \vdots & 0.3 & 0.3 & 0.4 \end{bmatrix}$$

The load is demanded only by all the DISCOs on own GENCOs area. Let the value of this load demand be 0.1 pu MW for each of them.

$$\Delta P_{Mi} = 0.1 puMW$$

Case B: Combination of Poolco and bilateral based transactions

In this case, any DISCO has the freedom to have a contract with any GENCO in its own and other areas. Consider that all the DISCOs contract with the available GENCOs for power as per the following:

$$DPM2 = \begin{bmatrix} 0.3 & 0.35 & 0.25 & \vdots & 0.2 & 0.1 & 0.1 \\ 0.3 & 0.3 & 0.3 & \vdots & 0.1 & 0.2 & 0.1 \\ 0.2 & 0.15 & 0.25 & \vdots & 0.1 & 0.1 & 0.2 \\ \cdots & \cdots & \cdots & \vdots & \cdots & \cdots & \cdots \\ 0.05 & 0.05 & 0.1 & \vdots & 0.25 & 0.25 & 0.25 \\ 0.1 & 0.05 & 0.05 & \vdots & 0.25 & 0.2 & 0.2 \\ 0.05 & 0.1 & 0.05 & \vdots & 0.1 & 0.15 & 0.15 \end{bmatrix}$$

The scheduled power on the tie line in the direction from area I to area II is calculate by using Eq 3.

$$\Delta P_{\text{tie 12,scheduled}} = -0.2700 \text{ pu MW}$$

As given in Eq. 4, in the steady state, the GENCOs must generate:

$$\Delta P_{M1} = 0.13 puMW, \Delta P_{M2} = 0.13 puMW, \Delta P_{M3} = 0.1 puMW,$$
$$\Delta P_{M4} = 0.095 puMW, \Delta P_{M5} = 0.085 puMW, \Delta P_{M6} = 0.06 puMW$$

Case C: Contract Violation

In this case, DISCO violates a contract by demanding more power than that specified in the contract. This excess power is not contracted out to any GENCO. This unconstructed power must be supplied by the GENCOs in the same area as the DISCO. It must be reflected as a local load of the area but not as the contract demand. Consider case 2 again with a modification that DISCOs of area one demands 0.2 pu MW and area two 0.05 pu MW of excess power.

Total of all DISCOs contracted loads and the un-contracted load of the area are taken up by the GENCOs in the same area, the scheduled incremental tie-line powers remain the same as in Test Case B in the steady state. Un-contracted load of the area is taken up by the GENCOs of its own area according to ACE participation factors of GENCOs in the steady state.

V. Tuning the controller gain setting

The ultimate objective of AGC is to maintain the frequency and inter area power flow within their respective scheduled values with minimum settling time following a sudden load disturbance. The integral and PID gain are optimally tuned to obtain better control performance. The integral gains of the area are tuned over the range from 0.01 to 1 for the PID set the limit up to 0.01 to 1.5. Integral Squared Error (ISE) criterion weighs large errors heavily and small errors lightly, ISE technique is used to formulate the objective function [5]. A quadratic performance index defined by,

$$J=\sum_{0}^{t}(\ \Delta f_1^2+\Delta f_1^2+\Delta P_{tie\,12}^2)dt \qquad (5)$$

is minimized for 1% step load perturbation in either of the areas to obtain the minimum values of integral gain Ki and PID gain Kp ,Ki And Kd. The minimum gain values are obtained for with and without SMES are tabulated in table 1.

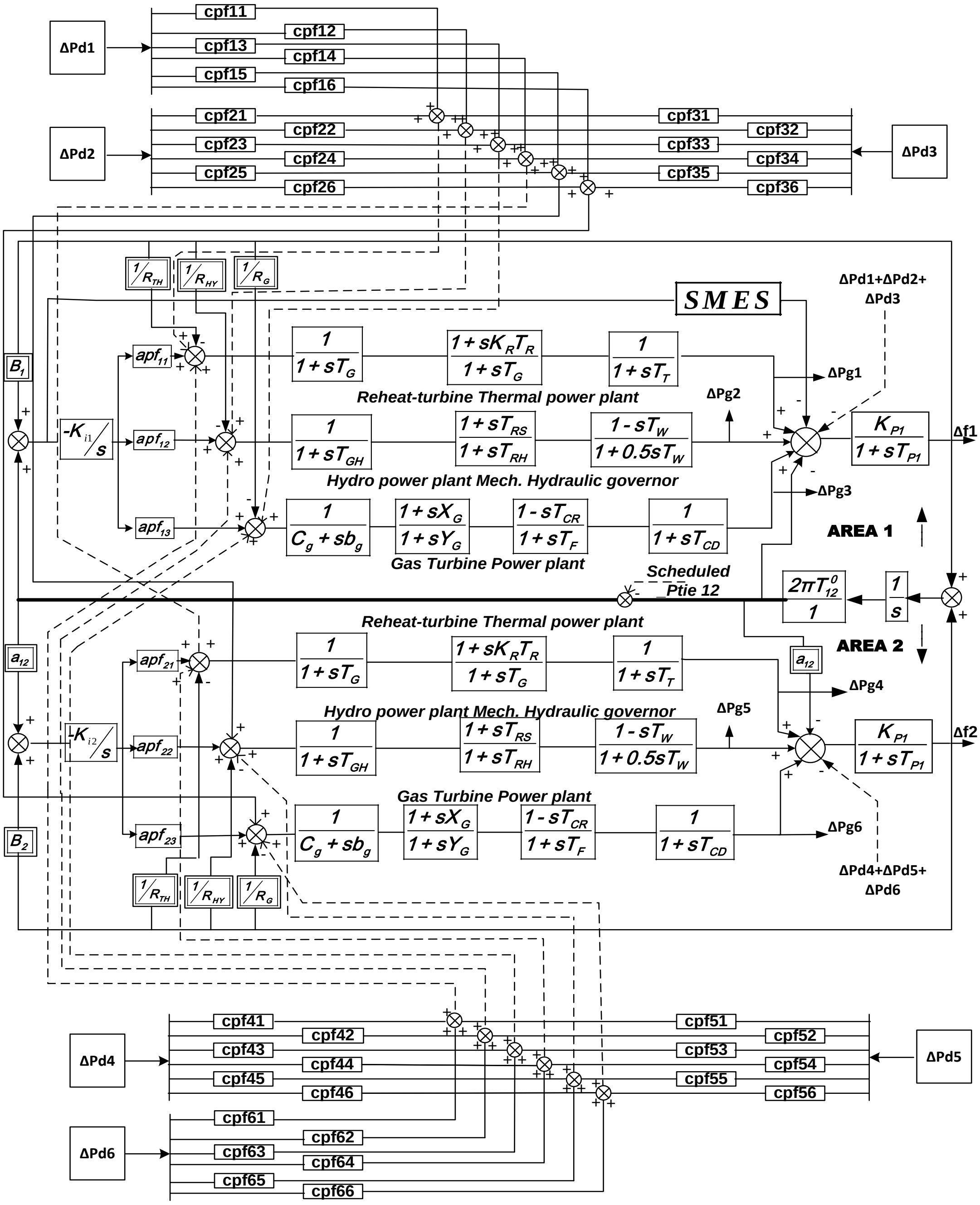

Fig 4. Two area AGC block diagram in restructured power system with SMES

VI. Simulation results and discussion

Time domain simulation are carried out on a sample two are restructured power system. Simulations are performed for three different cases of possible contract under market condition and large load demands. Values of Δf1, Δf2, ΔPtie and ΔPg (GENCO power change) are obtained using MATLAB software (simulink) for all three case without SMES and with SMES in area one with using integral and PID controller.

Table 1. Optimum integral and PID gain setting

Controller	Gain	Without SMES		SMES in area 1	
I		Area 1	Area 2	Area 1	Area 2
	Ki	0.18	0.18	0.86	0.256
PID	Kp	1.3	1.3	0.31	1.20
	Ki	0.28	0.28	0.72	0.5
	Kd	1.5	1.5	0.81	1.35

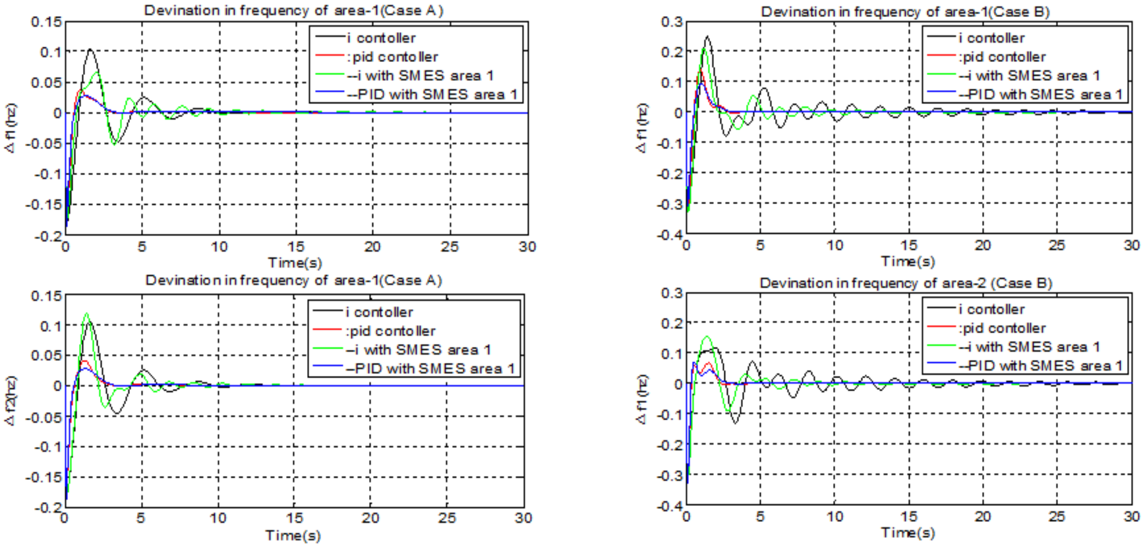

Fig 4:- Variation in area frequency Δf_1 and Δf_2 for case A and B

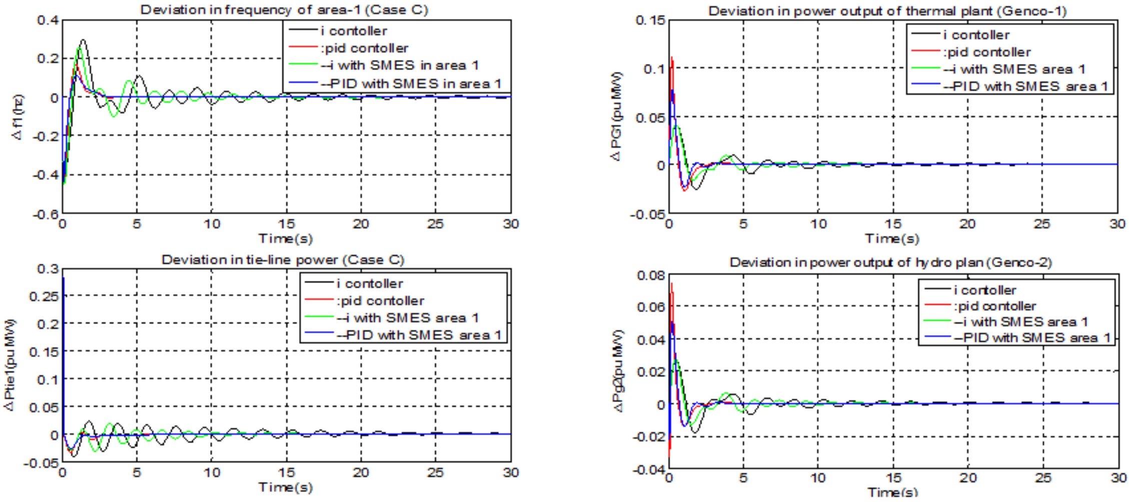

Fig 5:- Variation in area frequency Δf_1 ,Tie line Power flow $\Delta Ptie_{12,}$ and power output GENCOSs $\left(\Delta PG_{1,}\Delta PG_2 and \Delta PG_3\right)$ for case C.

By using DPM coordination action AGC loop under various contract conditions between GENCOs and DISOCs are presented. It is clear that addition of SMES in the restructured power system improves the dynamic performance of AGC. It is clear the fig 5 and result table that SMES with PID controller give better performance over single handed integral, PID or SMES with integral controller for all the case. Similar conclusion can be obtained from fig 5, and Case C result in table 2, where the contract violates (Case C) even in that condition SMES with PID controller give better performance. From fig 5-6, we conclude that SMES with PID controller is helpful to decrease settling time over shoot and undershoot of area frequency (Δf), tie-line power (ΔPtie) and GENCO power output (ΔPG) even in worst condition of AGC.

Table2. Response $\Delta f_1 \Delta f_2$ and $\Delta Ptie_{12}$ under various possible contract between GENCOs and DISCOs

Case	Variation in	Controller	Condition	Settling time (sec)	Max over shoot	Under shoot
A	Δf_1	I	Without SMES	10	0.11	-0.049
			SMES in Area-1	8.5	0.07	-0.05
		PID	Without SMES	9	0.03	-
			SMES in Area-1	4	0.03	-
	Δf_2	I	Without SMES	8.5	0.11	-0.042
			SMES in Area-1	6	0.12	-0.036
		PID	Without SMES	4	0.042	-
			SMES in Area-1	2.5	0.029	-
	$\Delta Ptie_{12}$	I	Without SMES	9	.00005	-0.002
			SMES in Area-1	9	0.008	-0.015
		PID	Without SMES	7	0.00025	-
			SMES in Area-1	5	0.00025	-
B	Δf_1	I	Without SMES	19	0.24	-0.077
			SMES in Area-1	10	0.21	-0.056
		PID	Without SMES	4	0.14	-
			SMES in Area-1	4	0.09	-
	Δf_2	I	Without SMES	20	0.15	-0.13
			SMES in Area-1	9	0.13	-0.09
		PID	Without SMES	3	0.071	-
			SMES in Area-1	3	0.067	-
	$\Delta Ptie_{12}$	I	Without SMES	10	0.017	-0.031
			SMES in Area-1	4	0.009	-0.02
		PID	Without SMES	4	0.0005	-0.027
			SMES in Area-1	4	-0.0025	-0.022
C	Δf_1	I	Without SMES	23	0.3	-0.08
			SMES in Area-1	14	0.25	-0.1
		PID	Without SMES	3	0.058	-
			SMES in Area-1	3	0.0112	-
	Δf_2	I	Without SMES	23	0.196	-0.165
			SMES in Area-1	10	0.205	-0.12
		PID	Without SMES	4	0.058	-
			SMES in Area-1	3	0.012	-
	$\Delta Ptie_{12}$	I	Without SMES	14	0.024	-0.04
			SMES in Area-1	6	0.019	-0.028
		PID	Without SMES	4	0.004	-0.04
			SMES in Area-1	2	-0.002	-0.026

Low frequency oscillation in area frequencies and tie-line power deviations pertaining to sudden change in contract can be possible to damp out effectively by SMES with PID controller over other possible combination conclude from table no 2. It can be see that SMES with PID controller, settling time has been considerably reduced and responses are almost ripple free.

VII. Conclusion

The simulation results show that the SMES and PID controller combination is give better performance over Integral controller with SMES and single approach of both controllers. In other word SMES with PID controller effectively stabilize the system and notable improves the transient response of area frequency and tie line power exchange as well as also reduce settling time, maximum over shoot and undershoot under different contract variation in restructured electric market.

Appendix [17]

$$P_{rt} = 2000MW, P_L = 1640MW, f = 60Hz, H = 5MW - s/MVA, D = \frac{\partial P_L}{\partial f}\frac{1}{P_{rt}} puMW/Hz, K_p = \frac{1}{D} Hz/puMW$$

$$T_P = \frac{2.H}{f.D} s, T_G = 0.08s, T_T = 0.3s, R_{TH} = R_{HY} = R_G = R = 2.4Hz/puMW$$

$$K_R = 0.3, T_R = 10s, T_W = 1s, T_{RS} = 5s, T_{RH} = 28.75s, T_{GH} = 0.2s,$$

$$X_G = 0.6s, Y_G = 1s, C_g = 1, b_g = 0.05s, T_F = 1.0s, T_{CR} = 0.01s, T_{CD} = 0.2s$$

$$apf_{11} = apf_{21} = 0.543478, apf_{12} = apf_{22} = 0.326084, apf_{13} = apf_{23} = 0.130433$$

SMES data [13]
$L = 2.65H, T_{DC} = 0.03s, K_{SMES} = 100kV/kA, I_{d0} = 4.5kA$

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