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Participation of Renewable Energy Sources in Restructured Power System

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ABSTRACT

In the present paper, a frequency control method based on Genetic Algorithm (GA) has been presented. The proposed scheme has been successfully tested on well known IEEE 39- bus test system. A deregulated electricity market scenario has been assumed in the test system. It has been assumed that both the generators and the consumers are participating in the frequency regulation market. Simulation results show that the proposed GAPID Controller along with HVDC link improves the system frequency. The performance studies have been carried out by using the MATLAB SIMULINK for transactions within and across the control area boundaries.

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1. INTRODUCTION

Currently, in the electricity industry for power generation by conventional generator are being not completely replaced by the Renewable Energy Resources (RES) technology, but it is significantly added to balance the demand power requirement in the power system. In connection to this, RES technology such as Photo-voltaic (PV) system and Wind Turbine Generator (WTG) are the two most attractive technologies [1]. The photovoltaic (PV) plants, on the cost point of view, have some disadvantages over other conventional energy resources. The thermal conventional technologies are actually more expensive in term of social costs, but customers no directly pay this social cost that is in charge on the society [2]. The influence of PV system on power system frequency control is discussed in [3].

A wind farm is a group of wind turbines in the same location used for production of electric power. A large wind farm may consist of several hundred individual wind turbines, and cover an extended area of hundreds of square miles. A wind farm may also be located offshore. In addition to this, there are two alternative methods for connecting a remote wind farms to grid either through a high-voltage direct current (HVDC) link with thyristor-based line commutated converters (LCC) or high-voltage alternating current (HVAC) line. For distances less than 50-75 km, HVAC line considered be the best economical alternative for power transmission [4]. The main advantages of the dc link with respect to the ac link are as follows: there is no charging current in the cable at dc, Losses and voltage drop in the dc link are very low and the dc link provides fast control of active and reactive power, whereas the ac link provides no or slow control [5].

The role of integrating renewable energy in a hybrid plants is primarily to utilize the benefit of different forms of RES. The objective of synergy or hybridization has been to overcome the weakness in one technology during its application, with the strengths of the other by appropriately integrating them.

A control method for a wind farm with the Line Commutated Converter (LCC) based HVDC delivery participates in load frequency control (LFC) has been discussed in ref. [6]. For extracting maximum power from a wind farm in coordination with HVDC wind farm side converter has been discussed in [7]-[8]. Power transferred through the HVDC link is controlled by firing angle of the rectifier converter. For performing some important functions like, storing and releasing energy in a hybrid system, Energy Storage System (ESS) plays an important role. Flywheel Energy Storage System (FESS) stores energy in the form of the kinetic energy stored in the rotating flywheel and can be retrieved later as an electrical output. The advantages of FESS are higher power density, insensitivity to environmental conditions, no hazardous chemicals etc [9].

Combining the above mentioned RES with energy storage unit FESS in a multi-area AGC scheme, the generated electric energy can be effectively controlled the frequency deviation and meet the demand of control area. In the same time the coordination of a wind farm with HVDC link suppressed the system frequency deviation adequately.

In the present paper, a frequency control method based on Genetic Algorithm (GA) has been presented. Merits of GA in PID controller design for the proposed multi-area AGC scheme are given in as: Genetic algorithms are more likely to converge to global optima than other conventional Techniques: since they search from a population of points and are based on probabilistic transition rules. This minimization technique is ordinarily based on gradient descent methods, which, by definition, will only find local optima. Genetic algorithms can also tolerate discontinuities and noisy function evaluations.

The main contribution of the present paper is that a novel GA based PID (GAPID) controller has been design for a restructured power system with RES to meet the demand of the control area of the system. In addition to this, the proposed scheme has also been compared an interconnected power system with and without HVDC Link. As the electrical power generated by WTG has been transmitted to grid through HVDC link.The proposed scheme has been successfully tested on well known IEEE 39- bus test system. A deregulated electricity market scenario has been assumed in the test system. It has been assumed that both the generators and the consumers are participating in the frequency regulation market. Simulation results show that the proposed GAPID Controller along with HVDC link improves the system frequency. The performance studies have been carried out by using the MATLAB SIMULINK for transactions within and across the control area boundaries.

2. SYSTEM MODELING

In order to maintain the frequency at nominal value, a physical balance between the power produced and power consumed is required. System operator maintains this balance through the frequency regulation market. This market is an hourly-based market. In a frequency regulation market following transactions can take place.

i. Poolco based transactions
ii. Bilateral transactions

In the present paper, only Poolco based transactions has been considered. In Poolco based transaction [10],[11], the Discos and Gencos of the same area participate in the frequency regulation through system operator. System operator (SO) accepts bids (volume and price) from power producers (Gencos) who are willing to quickly (with in about 10-15 minutes) increase or decrease their level of production. Consumers (Discos) also can submit bids to SO for increasing or decreasing their level of consumption. In each hour of operation, the SO activates the most favorable bid.

2.1 Calculation of Area Control Error (ACE)

In a practical multi area power system, a control area is interconnected to its neighboring areas with tie lines, all forming part of the overall power pool. If P_{ij} is the tie line real power flow from an area-i to another area- j and m is the total number of areas, the net tie line power flow from area-i will be

$$P_{tie-i} = \sum_{\substack{j=1 \\ j \neq i}}^{m} P_{ij} \tag{1}$$

In a conventional AGC formulation P_{ij} is generally maintained at a fixed value. However, in a deregulated electricity market, a Disco may have contracts with the Gencos in the same area as well as with the Gencos in other areas, too. Hence, the scheduled tie-line power of any area may change as the demand of the Disco changes.

Thus, the net change in the scheduled steady-state power flow on the tie line from an area- i can be expressed as

$$P_{tie-i-new} = \Delta P_{tie-i} + \sum_{\substack{j=1 \\ j\neq i}}^{m} D_{ij} - \sum_{\substack{j=1 \\ j\neq i}}^{m} D_{ji} \tag{2}$$

Where ΔP_{tie-i} is the change in the scheduled tie-line power due to change in the demand, D_{ij} is the demand of Discos in area-j from Gencos in area-i , and D_{ji} is the demand of Discos in area- i from Gencos in area-j.

Generally, ΔP_{tie-i} (Conventional AGC). During the transient period, at any given time, the tie-line power error is given as [12]:

$$\Delta P_{tie-i-error} = (\Delta P_{tie-i-actual} - \Delta P_{tie-i-new}) + (\Delta P_{RES-actual} - \Delta P_{RES-scheduled}) \tag{3}$$

Where $\Delta P_{RES-actual}$ and $\Delta P_{RES-scheduled}$ are actual and estimated power of RESs. This error signal can be used to generate the Area Control Error (ACE) signal as:

$$ACE_i = B_i \Delta f_i + \Delta P_{tie-i-error} \tag{4}$$

Where, B_i is the frequency bias factor and Δf_i is the frequency deviation in area-i.

2.2 Modeling of a PV generator

In Photovoltaic technology, there is a direct conversion of sunlight into electricity through the use of photovoltaic array. The incoming solar radiation or sunlight is measured in units W/m^2.

There are some assumptions made in the mathematical modeling of PV generators and they are, all the energy losses in a PV generator, including connection losses, wiring losses and other losses are assumed to be zero. Second, is the PV generator has a maximum power point tracker i.e. η=1.

The output power of the PV system can be expressed as follows [4],

$$E_{pvg}(t) = \eta_{pvg} \times s \times \phi \times \left(1 - 0.005(T_a + 25)\right) \tag{5}$$

Where E_{pvg} is the output power from PV, ϕ is the solar irradiation, s is the surface area of the PV modules in m^2, T_a is the ambient temperature and η_{pvg} is the conversion efficiency of PV generator. From (1), it is clear that the output power of PV system mainly depends on four factors, conversion efficiency of PV array η_{pvg} , ambient temperature (T_a), solar radiation (ϕ) and 's' surface area of PV array. The transfer function of PV is represented by a simple first order system and described in [4]:

$$G_{PV} = \frac{\Delta \phi}{\Delta E_{PVG}} = \frac{1}{1 + sT_{PVG}} \tag{6}$$

Where T_{pvg} is called time constant of PV system.

2.3 Modeling of Wind Turbine Generator (WTG)

The generated power of the wind turbine generator depends on the wind speed V_w. The mechanical power output of the wind turbine is expressed as [4]:

$$\mathrm{P_W} = \frac{1}{2} \rho A_r C_p V_w \tag{7}$$

Where, ρ is the air density in Kg/m^3, A_r is the swept are of blade in m^3, C_p is the power coefficient which is a function of tip speed ratio (λ) and blade pitch angle (β). The transfer function of WTGs is given by simple linear first order lag by neglecting all the non-linearity

$$G_{WTG} = \frac{\Delta E_{WTG}}{\Delta P_W} = \frac{1}{1 + sT_{WTG}} \tag{8}$$

Where, T_{WTG} is called time constant of wind generator, and taken as 1.5 sec.

2.4 Modeling of HVDC Link

The power through the dc link is given by [6],

$$P_{dc} = 3V_{ac}I_{ac}\cos\alpha \tag{9}$$

Where, V_{ac} is the rms value of the bus voltage, I_{ac} is the rms value of bus current and α is the firing angle of the rectifier. It is clear from the above equation, that the larger the firing angle, the lower will be the delivered power. Therefore, in order to get maximum power from the wind turbine generator through HVDC link, the firing angle should be reduced. In order to have improved frequency response the wind farm should operate with reserves. The most important feature of the wind farm to participate in power sharing when the system frequency deviates from the nominal value is that the pitch controllers of wind farm increases or decreases the captured wind power [6].

In case when the hybrid plants are connected to grid, variable-speed wind turbine used, the rotational speed is decoupled from grid frequency by power converter. Thus, this energy does not contribute to the inertia of the grid. Therefore, the equivalent inertia of the overall system mainly consists of conventional generator units. Depending on the type of generator units, typical inertia constants for the grid power generators are in the range of 2-9 sec [12].

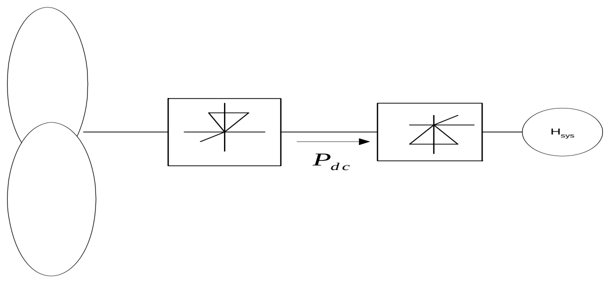


Fig.1 WTG system with HVDC Link connected to a system with aggregated inertia H_{sys}

Therefore, the transfer function of the HVDC link can be represented by a first-order lag as given in [4],

$$G_{HVDC}(s) = \frac{\Delta P_{dc}}{\Delta P_W} = \frac{K_{HVDC}}{1 + sT_{HVDC}} \tag{10}$$

Where, T_{HVDC} is called time constant of wind generator, and taken as 0.7 sec [4].

2.5 Modeling of Flywheel Energy Storage System (FESS)

Integrating an Energy Storage System (ESS) into the hybrid system can suppress the fluctuations in wind velocity (speed) and the deviations in solar power and have adverse impacts on power quality, such as local voltage and system frequency. In the literature many storage technologies proposed include Flywheel Energy Storage System (FESS) [13],[14], battery storage energy storage (BESS) [15], advanced capacitor [16], and superconducting magnetic energy storage (SMES) [17],[18].

Flywheel Energy Storage System (FESS) stores energy in the form of the kinetic energy stored in the rotating flywheel and can be retrieved later as an electrical output. There are some advantages of FESS over Battery Energy Storage System (BESS), and they are higher power density, insensitivity to environmental conditions, no hazardous chemicals etc. The kinetic energy stored in the rotating flywheel is given by

$$E = \frac{1}{2}J\omega^2 \tag{9}$$

Where, E is the Energy stored in the flywheel in N-m, J is the flywheel moment of inertia in N-m-sec^2, and ω is the rotational velocity in rad/sec.

The transfer function of the storage systems FESS can be taken as first order lag [4],

$$\frac{\Delta P_{FEES}}{\Delta f} = \frac{K_{FEES}}{1 + sT_{FEES}} \tag{10}$$

Where, K_{FEES} is the gain constant and T_{FEES} is the time constant.

The overall block diagram of Multi-area AGC scheme for an ith area of m-area power system is shown in Fig.2.The power system block represents the power system dynamics given by, $\frac{K_{pi}}{1+sT_{pi}}$ where K_{pi} is the system gain and is equivalent to $1/D_i$, where D_i is the rate of change of load demand ΔP_D to the change in frequency Δf and is expressed in Hz/pu MW and T_{pi} is the time constant and is equivalent to $2H_i/(f^*D_i)$ where, the parameter H_i is the per –unit inertia constant.

In Fig.2 ΔP_D is the total demand of area-i. The area demand is fulfilled by the system operator through Poolco-based contracts.

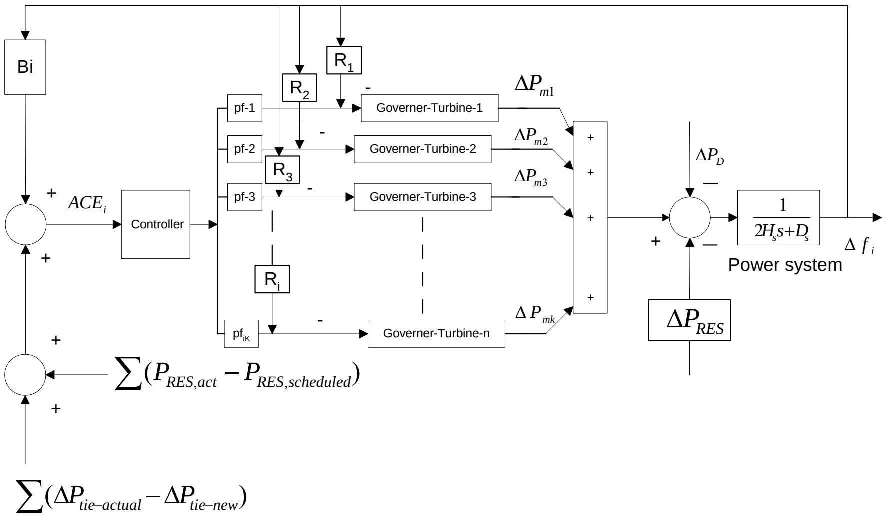


Fig.2 AGC Block diagram for area-i.

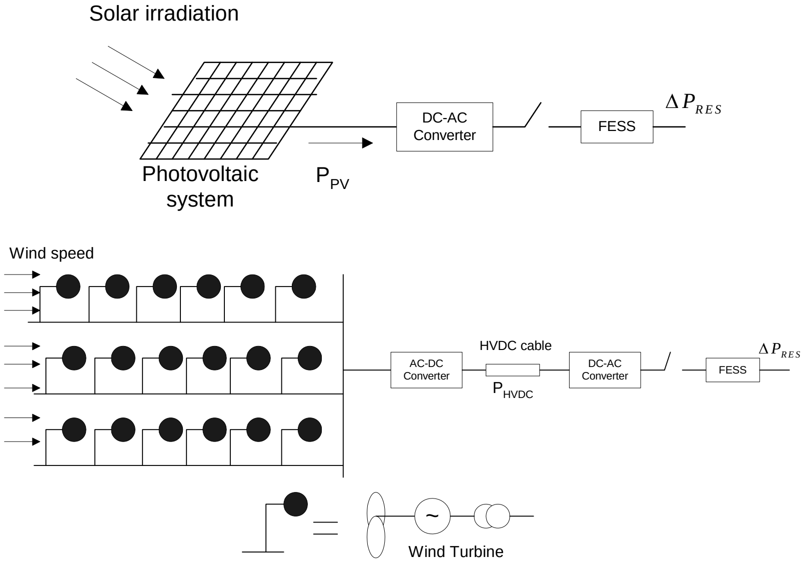


Fig.3 Configuration of RES components in the proposed scheme

3. PID Controller tuning using Genetic Algorithm

The form of a PID controller can be expressed as the sum of three terms, proportional, integral, and derivative control. The transfer function of such a PID controller can be expressed as:

$$G_C(s) = K_P + \frac{K_I}{s} + K_D s \tag{11}$$

Where, K_P, K_I, K_D are the proportional, integral and derivative gain constant of the controller. Optimal values of K_P, K_I, K_D can be determined by many ways, one of them, is suggested by the Donde et al. A Genetic Algorithm based minimization approach to determine the values of K_P, K_I, K_D has been developed in this work.

Genetic Algorithms are based on Darwin's theory of natural selection and survival of the fittest. It is a heuristic optimization technique for the most optimal solution (fittest individual) from a global perspective but more importantly, it provides a mechanism by which solutions can be found to complex optimization problems fairly quickly and reliably. Following are the important terminology in connection with the genetic algorithm as given in [20]:

Individual - An individual is any point to which objective function can be applied. It is basically the set of values of all the variables for which function is going to be optimized. The value of the objective function for an individual is called its *score*. An individual is sometimes referred to as a *genome* and the vector entries of it as *genes*.

Population – It is an array of individuals. For example, if the size of the population is 100 and the number of variables in the objective function is 3, population can be represented by a 100-by-3 matrix in which each row correspond to an individual.

Generation - at each iteration, the genetic algorithm performs a series of computations on the current population to produce a new population by applying genetic operators. Each successive population is called a new generation.

Parents and children - To create the next generation, the genetic algorithm selects certain individuals in the current population, called parents, and uses them to create individuals in the next generation, called children. Following three genetic operators are applied on parents to form children for next generation:

1. *Reproduction* - Selects the fittest individuals in the current population to be used in generating the next population. The children are called *Elite children.*
2. *Cross-over* - Causes pairs of individuals to exchange genetic information with one another. The children are called *Crossover children.*
3. *Mutation* - Causes individual genetic representations to be changed according to some probabilistic rule. The children in this case are called *Mutation* children.

In GA's the value of fitness represents the performance which is used to rank 0 and the ranking is then used to determine how to allocate reproductive opportunities. This means that individual with a higher fitness value will have a higher opportunity of being selected as a parent. The fitness function is essentially the objective function for the problem.

Interconnected power system model as shown in Fig.2 has been created in MATLAB Simulink. Area Control Error (ACE) for each area is calculated by running this model with PID controller. Initially, parameters (K_P, K_I, K_D) of PID controller area selected using Least Square Minimization method, which gives stable results. ACE is further minimized using the GA optimization toolbox GAOT in MATLAB proposed by C. R. Houck [21] to obtain the optimal PID parameters.

The complete algorithm is described below:

Minimize (Integral of square of the Area Control Error)

$$ISACE = \int \sum_{i=1}^{m} (ACE_i)^2 \tag{12}$$

Where, m is the number of area in the system.

Subjected to

$$K_{P,i}^{\min} \le K_{P,i} \le K_{P,i}^{\max}$$

$$K_{I,i}^{\min} \le K_{I,i} \le K_{I,i}^{\max}$$

$$K_{D,i}^{\min} \le K_{D,i} \le K_{D,i}^{\max}$$

Where, $K_{P,i}$, $K_{I,i}$, $K_{D,i}$ are the proportional, integral and derivative gains of the PID controller of *i*th area, $K_{P,i}^{\min}$, $K_{I,i}^{\min}$, $K_{D,i}^{\min}$ and $K_{P,i}^{\max}$, $K_{I,i}^{\max}$, $K_{D,i}^{\max}$ are the lower bounds and upper bounds of the PID controller.

With the above description, the procedure of applied genetic algorithm for the tested system in this work is given below:

a) Generate randomly a population of parameter strings to form parameter vector.
b) Calculate the fitness function as given in the equation (12) for each *Individual* in the population.

c) Create *Parents.*
d) Evaluate the *children* and calculate the fitness function for each *Parent.*
e) If the fitness function of the *Parents* is reached to the maximum value, stop and return; else go to step (c).

Genetic algorithm parameters are taken as given below
The number of population = 50
The number of generation = 100
The probability of crossover is 0.8
The mutation function taken is Gaussian
The fitness scaling function is Rank.

4. Test System

The proposed GAPID controller for a multi-area power system, described in the previous section, has been tested on a 39-bus New England system [12]. The 39-bus system has been divided into two control areas. For the system, three Discos and at least one Genco, having the Poolco based contract, have been considered in each area. The number of Gencos and Discos in the 39-bus system is given in Tables I. A general purpose Governor- Turbine model has been used [22].

Here, the 39-bus system is updated by one WTG system in area-1 and one PV system in area-2. The total generation includes 881 MW conventional power, 2000 kW solar power and 17 MW wind power.

Table 1. Control Areas in 39-bus power system

Control Area	Area Rating(MW)	Market Participants
Area-1	400	Genco 1,2,3,4,5 Disco-1,2,3, WTG
Area-2	500	Genco 6,7,8,9,10 Disco4,5,6, PV

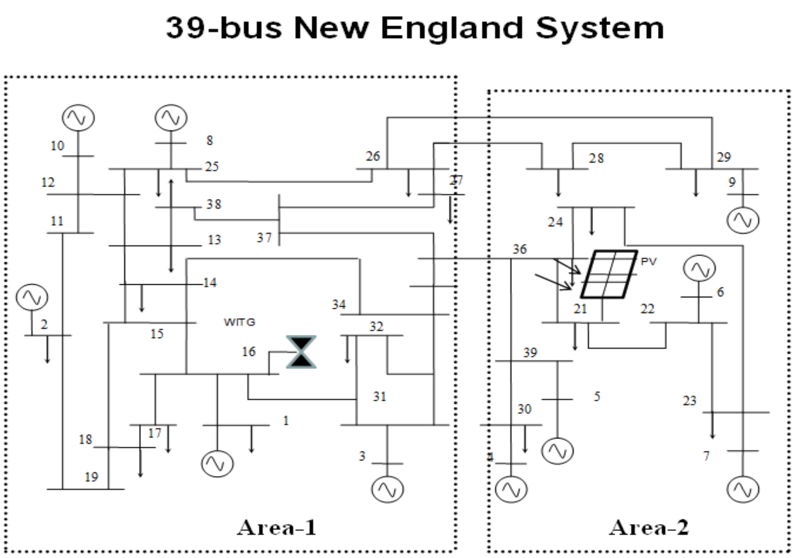


Fig.4 Single-line diagram of 39-bus test.

5. Simulation Results

To simulate the 39-bus system, it is assumed that the generators and the loads are participating in the frequency regulation market, To simulate the proposed AGC scheme, the change in demand of area-1 &2 was assumed to be 0.2 p.u. (80 MW) and 0.2 p.u. (100 MW). The Gencos and Discos bids for area-1 and area-2 were assumed as given in Table 2 and 3.

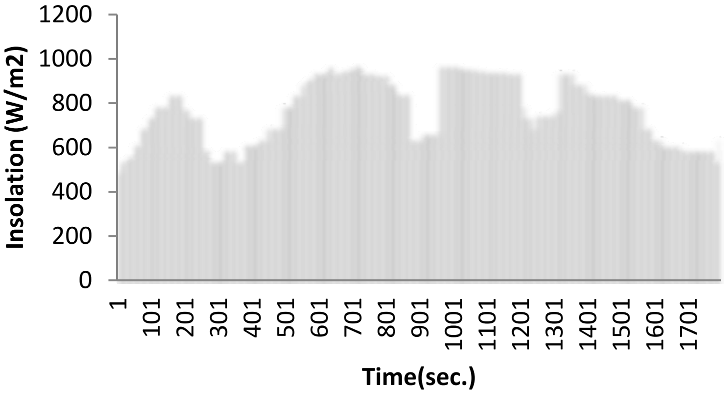


Fig.5 Real irradiance data used for proposed scheme for 30 min.

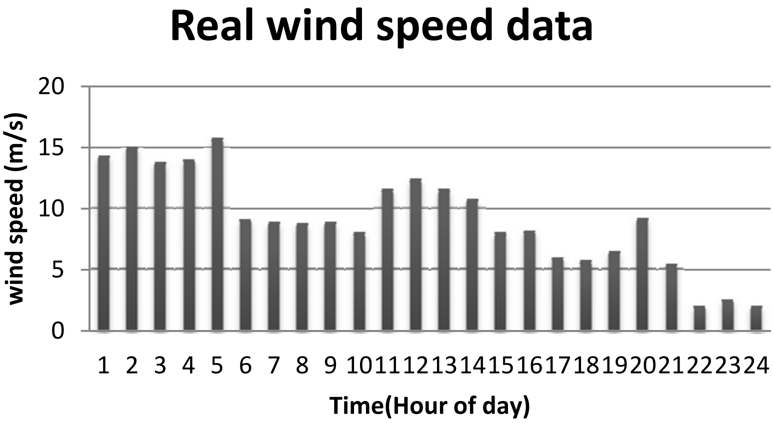


Fig.6 Real wind speed data used for proposed scheme

Table 2. GENCOS AND DISCOS BIDS IN AREA-1 OF 39-BUS SYSTEM

Gencos	Price(Rs./KWh)	Capacity(MW)
Genco-1	4.9	30.0
Genco-2	5.5	15.0
Genco-3	5.8	15.0
Genco-4	5.1	25.0
Genco-5	6.1	25.0
Disco-1	4.9	8.0
Disco-2	5.5	8.0
Disco-3	5.7	8.0

Table 3. GENCOS AND DISCOS BIDS IN AREA-2 OF 39-BUS SYSTEM

Gencos	Price(Rs./KWh)	Capacity(MW)
Genco-6	5.9	25.0
Genco-7	6.5	45.0
Genco-8	4.8	60.0
Genco-9	5.7	30.0
Genco-10	5.0	30.0
Disco-4	6.7	8.0
Disco-5	6.1	8.0
Disco-6	5.2	8.0

To implement the Poolco transaction, Gencos of the same area participate in the frequency regulation service. In area-1, to meet the load demand of 80 MW, Genco-1 and Genco-4 increases its output by 30 MW, 25 MW and Disco-1 of area-1 curtail its load by 8 MW. And the remaining demand i.e. (80-63) = 17 MW, provided by WTG connected in area-1. This is shown in the following Fig. 7 (b) to Fig. 7 (d).

The results of frequency deviations for area-1 and area-2 for 30 min with and without HVDC Link are shown in Fig. 7 (a) and Fig. 8 (a). From this result, it is clear that the oscillations are more in the system without HVDC Link as compared to a system with HVDC Link. Therefore, it gives evidence of improving the frequency deviation using HVDC Link.

In area-2, to meet the load demand of 100 MW, Genco-8 and Genco-10 increases its output by 60 MW, 30 MW and Disco-6 of area-2 curtail its load by 8 MW. And the remaining demand i.e. (100-98) = 2 MW, provided by PV system connected in area-1. This is shown in the following Fig. 8 (c) to Fig. 8 (d).

The average change in the power output of PV system and other Genocs of area-1 and WTG system and other Gencos of area-2 are given in Table 4 and 5 respectively.

Table 4. Average change in the power output of WTG system and other Gencos in area-1

No. of Gencos/Disco	Output power in p.u.	Gencos output power in MW
Genco-1	0.0625	25
Genco-4	0.075	30
WTG-1	0.0425	17
Disco-1	0.02 (load Curtailment)	8 (load curtailment)

Table 5. Average change in the power output of PV and other Gencos in area-2

No. of Gencos/Disco	Output power in p.u.	Gencos output power in MW
Genco-8	0.12	60
Genco-10	0.06	30
PV-Genco	0.004	2
Disco-5	0.016(load Curtailment)	8 (load curtailment)

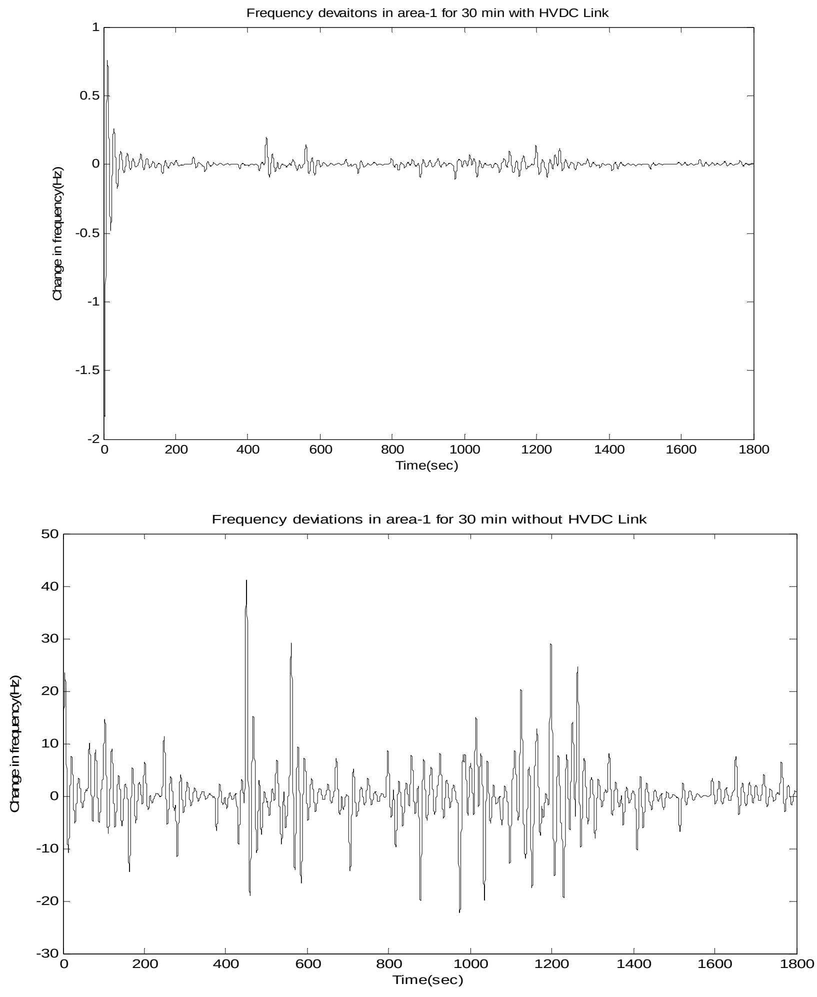
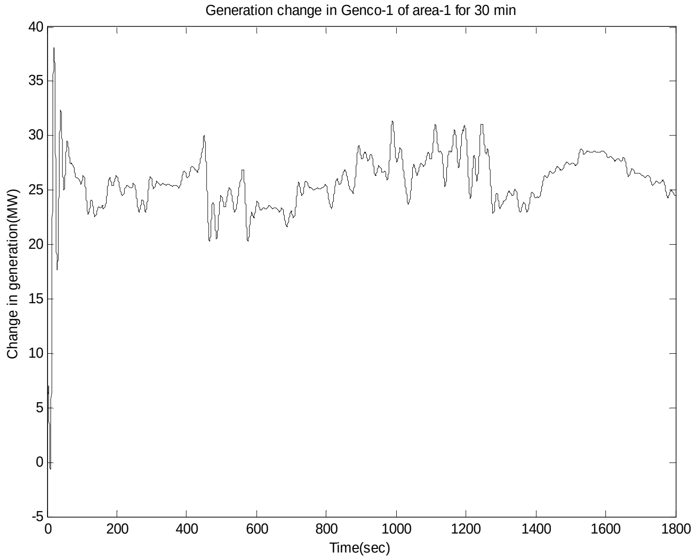


Fig. 7 (a) Frequency deviations in area-1 with and without HVDC Link for 30 min



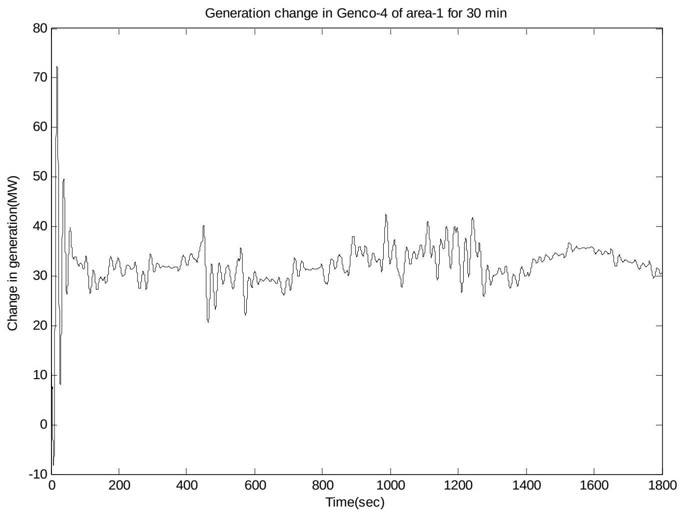


Fig.7 (b) Generation change in Genco-1 and Genco-4 for 30 min

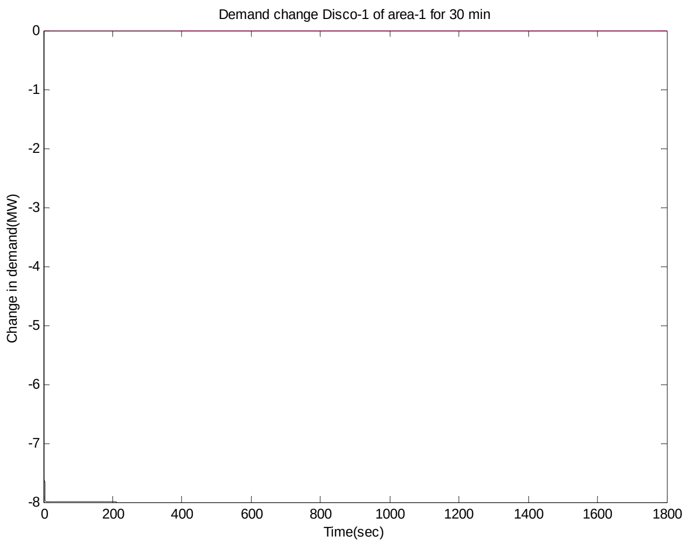


Fig.7 (c) Demand change in Disco-1 for 30 min

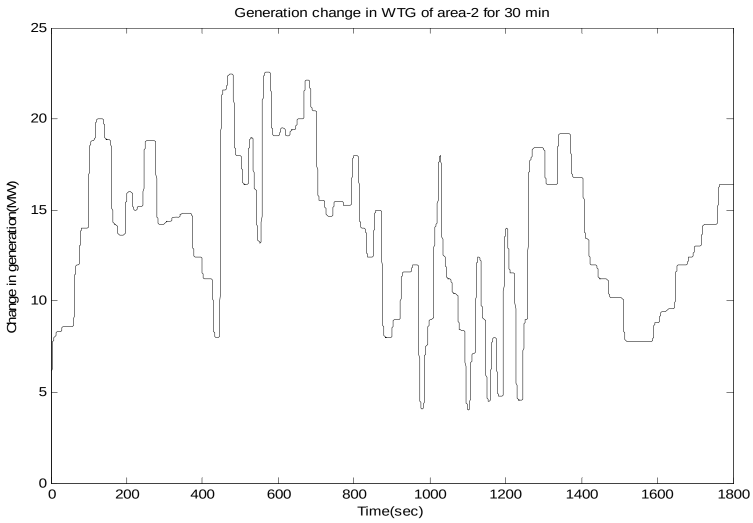
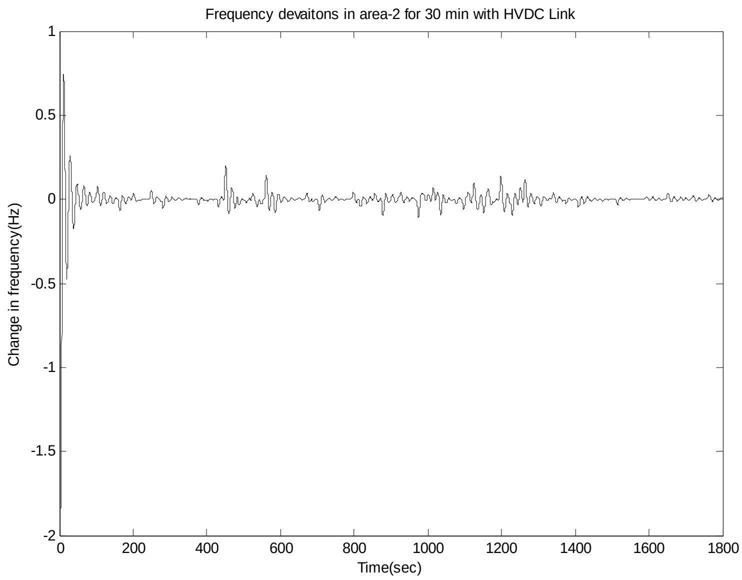


Fig.7 (d) Power produced by WTG system for 30 min



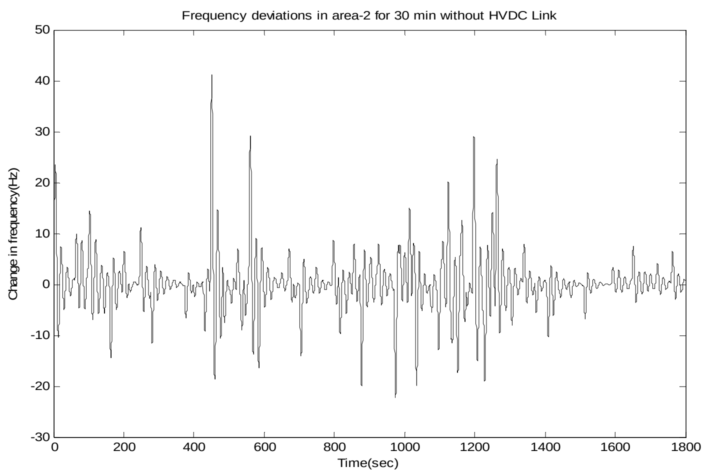


Fig. 8 (a) Frequency deviations in area-2 with and without HVDC Link for 30 min

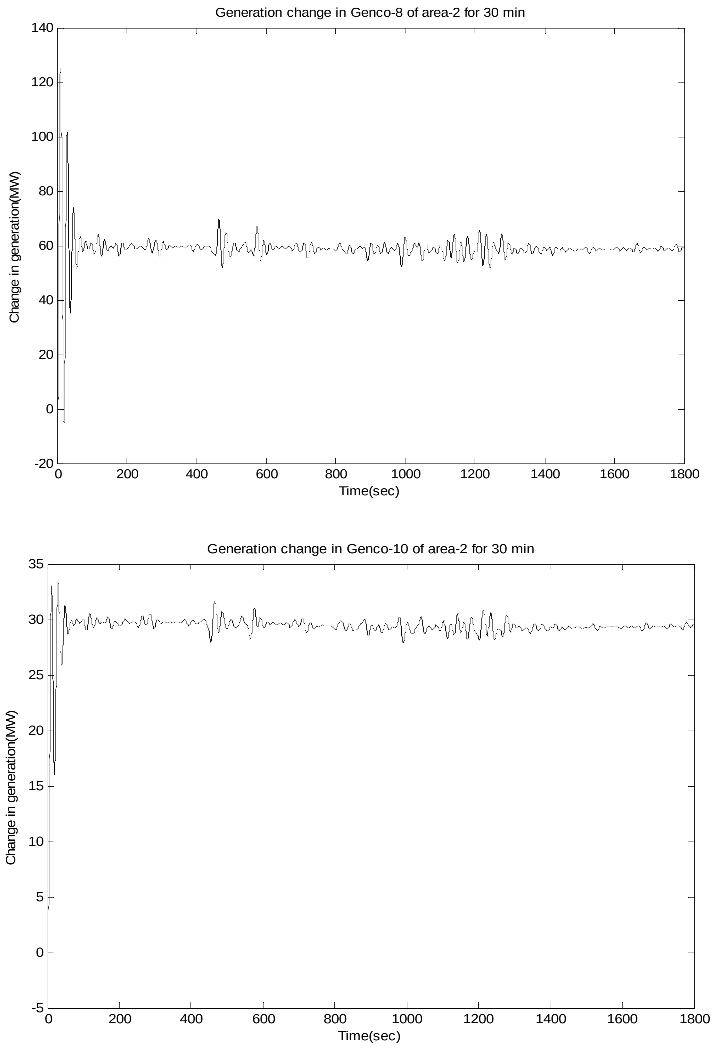


Fig.8 (b) Generation change in Genco-8 and Genco-10 for 30 min

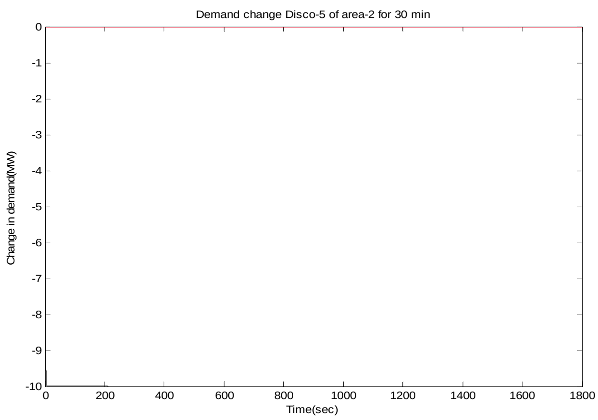


Fig.8 (c) Demand change in Disco-4 for 30 min

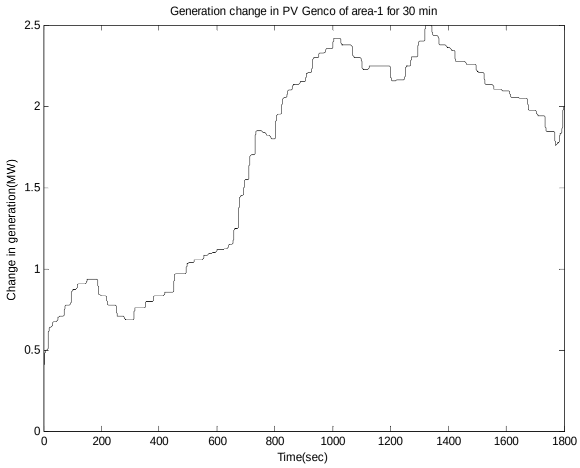


Fig.8 (d) PV Power generated for 30 min

6. CONCLUSION

A Genetic Algorithm based PID (GAPID) controller for a Multi-area AGC scheme with hybrid PV/ wind system suitable in competitive electricity market in introduced. This paper presents a multi-area AGC scheme to improve RES technology based power generation in restructured power system. The proposed AGC scheme has been successfully implemented on IEEE 39-bus system. With the proposed GAPID controller, the deviations in the system frequency reduces during transient period and steady state and meet out the load demand by different conventional generators according to their participation factor. The mathematical models for the WTG, PV system, FESS, and HVDC Link are represented by first-order transfer functions to simplify for the system simulation. From the simulations results, it can be concluded that the power generation from the WTG, PV system, as well as the energy stored in or released from FESS can effectively meet the load power demand. More fluctuations in system frequency have been observed without HVDC link. Therefore, it is suggested that for transmitting the power from WTG system to meet the power demand HVDC link may preferred.

An important feature of RES units is the fast active power injection in the system, which causes power imbalance and this, results the slowdown of the response of conventional generators in multi-area AGC scheme. The proposed GAPID controller has avoided this undesirable effect to certain extent and it is shown in the simulation results.

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