Power Frequency Balance in Multi-Generation Smart Grid Systems with V2G option.

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***Abstract*— In smart grid scenario, penetration of large scale renewable energy sources are increasing rapidly. This causes uncertainty among various power system parameters, mainly frequency in interconnected power system. When automatic generation control (AGC) is not sufficient to manage balance between demand and supply, battery energy storage is considered a viable option for short term active power support in order to bring frequency back to normal. In energy storage possibilities, super conducting magnetic energy storage, ultra-capacitor etc. are primarily discussed. This paper focuses on integrated model of vehicle to grid (V2G) and wind power as an alternative to supply instant power to regulate frequency when system is subjected to sudden perturbation. GA (Genetic algorithm) optimized fuzzy logic controller is used to intelligently suppress frequency and tie-line power oscillations. Results obtained are comprehensively presented and discussed in achieving power-frequency balance. MATLAB/Simulink is used for the simulation purpose.**

Keywords—Automatic Generation Control; Genetic Algorithm; Vehicle to Grid; Wind Power; Fuzzy Logic Controller

I. INTRODUCTION

Recently, there has been substantial increase in penetration of renewable sources of energy into electrical grid. Government of most of the countries worldwide are encouraging use of clean and green power in their countries by means of supporting various smart grid projects. This has given impetus to researchers across the globe to give a serious thought to implement a viable solution for reduction in greenhouse gases which are caused by emission of conventional thermal plants and existing vehicles. Policy makers are promoting the use of electric vehicles (EVs) with an option for user to sell electrical power to grid and get benefitted in different means.

According to statistics available, EVs are in idle situation in 90% of the time every day and have sufficient energy to cater to ancillary service requirements particularly frequency regulation in large power system [1-3]. There have been advanced battery technologies and charging infrastructure which is leading to more use of PHEVs (Plugged in hybrid electrical vehicle) and EVs in near future. Therefore, V2G is seen as potential source in frequency regulation [4-7]. Reference [8] has used EVs for secondary frequency modulation and results in decrease in area control error and tie-line deviations. In US, China and India, there are expectations of large number of EVs on the road as per their government plans [9-12]. Moreover, PHEVs are also being looked as a controllable load for future smart grid [13], [14]. PHEVs are basically charged in the night period as electricity price is cheap during that time [15]. An autonomous distributed V2G control of grid-connected PHEV and EV to the actual frequency measurements in Eastern 50 Hz system and western 60 Hz system of Japan is proposed in [16]. Reference [17] proposes the V2G control based on the average battery SOC deviation control applied to compensate the LFC capacity in the system. Reference [18] concentrates on the autonomous distributed V2G control considering the charging request and battery condition for suppressing the fluctuations of frequency and tie-line power flow in the two-area interconnected power system. The battery SOC is controlled by the SOC balance method. There has been various control strategies implemented in multi-area power system by researchers from conventional control to intelligent control [19-23].

This paper is mainly focusing on understanding different aspects of V2G and wind power inertial support mechanism (WISM) in restructured two area interconnected power system to overcome power-frequency imbalance. EVs are considered in this paper as a sufficiently large energy storage which will cater to power grid when there is need of power in case of sudden rise in demand. Wind power has gained sufficient popularity amongst power generating companies. Apart from supplying electrical power to grid, wind generators are also used to provide inertial support during large and sudden load perturbation. Modeling of V2G and WISM have been done in section II of paper. Controller design is another important aspect presented in the paper. Different intelligent techniques are used in literature for approaching this power system power-frequency balance issue. Fuzzy logic controller with genetic algorithm for optimization is used. The model and strategy are discussed in detail in section III. Section IV presents the simulation results and discussion on different conditions of V2G and Wind power connection in restructured power system. Conclusions are presented in Section V.

II. SYSTEM MODELING

A. Mathematical Modelling of Two Area Restructured Power System

The interconnected restructured power system considered has two control areas, each having two generation companies

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(GENCOs) and two distribution companies (DISCOs). There are two different models taken for study. In model 1, two reheat thermal units are connected in area-1 and two hydro-based generating units are in area-2 while the two identical thermal units are used in both areas in model 2. Both areas are connected via tie-line for exchange of power in model 1 and 2. DISCOs are operating on the basis of participation matrix [19], [20]. The system parameters are same as used in [20] for thermal and hydro units.

The thermal and hydro unit components are characterized by standard transfer function [20]. In restructured environment, the concept of contract participation factor matrix (CPFM) makes the visualization of contracts. In CPFM, the number of rows indicates the number of GENCOs and the number of columns indicates the DISCOs [24] and sum of all *cpf*s is unity in a column of matrix.

The frequency regulation depends on the control signal composed of tie-line deviation and weighted frequency deviation. It is called area control error (*ACE*), as shown in (1).

$$\mathrm{ACE}_i = \Delta P_{\mathrm{tie},i} + \beta_i \Delta f_i, \tag{1}$$

Where β_i is the frequency bias constant.

$$\mathrm{APFM} = \begin{bmatrix} \mathrm{apf}_1 & 0 & 0 & 0 \\ 0 & \mathrm{apf}_2 & 0 & 0 \\ 0 & 0 & \mathrm{apf}_3 & 0 \\ 0 & 0 & 0 & \mathrm{apf}_4 \end{bmatrix}. \tag{2}$$

In deregulated environment, within a control area, ACE is again distributed among several GENCOs by coefficients are termed as ACE participation factors (*apf*s). The area participation factor matrix (APFM) is illustrated in (2).

The contracted scheduled loads in DISCOs in area-1 are ΔP_{Ld1_cont} and ΔP_{Ld2_cont} but in area-2 they are ΔP_{Ld3_cont} and ΔP_{Ld4_cont}, as shown in the ΔP_{LD_cont} matrix. The uncontracted local loads in DISCOs in area-1 are ΔP_{Ld1_uncont} and ΔP_{Ld2_uncont} but in area-2 they are ΔP_{Ld3_cont} and ΔP_{Ld4_cont}, as shown in the ΔP_{LD_uncont} matrix [9].

$$\Delta P_{\mathrm{LD\_cont}} = \begin{bmatrix} \Delta P_{\mathrm{Ld1\_cont}} \\ \Delta P_{\mathrm{Ld2\_cont}} \\ \Delta P_{\mathrm{Ld3\_cont}} \\ \Delta P_{\mathrm{Ld4\_cont}} \end{bmatrix}, \ \Delta P_{\mathrm{LD\_uncont}} = \begin{bmatrix} \Delta P_{\mathrm{Ld1\_uncont}} \\ \Delta P_{\mathrm{Ld2\_uncont}} \\ \Delta P_{\mathrm{Ld3\_uncont}} \\ \Delta P_{\mathrm{Ld4\_uncont}} \end{bmatrix}.$$

The total demanded load power ΔP_{LD} is represented by (3).

$$\Delta P_{\mathrm{LD}} = \Delta P_{\mathrm{LD\_cont}} + \Delta P_{\mathrm{LD\_uncont}}. \tag{3}$$

Similarly, the contracted generated powers in area-1 are ΔP_{g1_cont} & ΔP_{g2_cont}, but in area-2 they are ΔP_{g3_cont} & ΔP_{g4_cont}, as given in the ΔP_{G_cont} matrix. ΔP_{g1_uncont} & ΔP_{g2_uncont}, are uncontracted generated powers from area-1, but ΔP_{g3_cont} & ΔP_{g4_cont} are uncontracted generated powers from area-2, as given in the ΔP_{G_cont} matrix.

$$\Delta P_{\mathrm{G\_cont}} = \begin{bmatrix} \Delta P_{\mathrm{g1\_cont}} \\ \Delta P_{\mathrm{g2\_cont}} \\ \Delta P_{\mathrm{g3\_cont}} \\ \Delta P_{\mathrm{g4\_cont}} \end{bmatrix}, \ \Delta P_{\mathrm{G\_uncont}} = \begin{bmatrix} \Delta P_{\mathrm{g1\_uncont}} \\ \Delta P_{\mathrm{g2\_uncont}} \\ \Delta P_{\mathrm{g3\_uncont}} \\ \Delta P_{\mathrm{g4\_uncont}} \end{bmatrix}.$$

Contracted generated power by GENCOs, ΔP_{G_cont} is calculated by (4).

$$\Delta P_{\mathrm{G\_cont}} = \mathrm{CPFM} \cdot \Delta P_{\mathrm{LD\_cont}}. \tag{4}$$

Uncontracted generated power by GENCOs, ΔP_{G_uncont} is calculated by (5).

$$\Delta P_{\mathrm{G\_uncont}} = \mathrm{APFM} \cdot \Delta P_{\mathrm{LD\_uncont}}. \tag{5}$$

Therefore, the total generation power by each GENCO at steady state is visualized in the ΔP_G matrix, as expressed in (6).

$$\Delta P_{\mathrm{G}} = \Delta P_{\mathrm{G\_cont}} + \Delta P_{\mathrm{G\_uncont}}. \tag{6}$$

The scheduled tie-line power flow between area-*i* and area-*j* can be represented in (7) and (8).

$$\Delta P_{\mathrm{L},Ai \to Aj} = \sum_{m=1}^{M} \sum_{n=1}^{N} \left(\mathrm{cpf}_{mn} * \Delta P_{\mathrm{Ld}(n)\_\mathrm{cont}} \right) \tag{7}$$

$$\Delta P_{\mathrm{tie}ij,\mathrm{sch}} = \Delta P_{\mathrm{L},Ai \to Aj} - \Delta P_{\mathrm{L},Aj \to Ai}. \tag{8}$$

B. Mathematical Modeling of Wind power generating system with inertial support mechanism

All areas in developed restructured power system model are connected with a wind power generating unit separately. DFIG model [25] is used for the inertial support to have short term active power supply. The model is simplified with controller is shown in Fig. 1. A one-mass model for the mechanical drive of the turbine is considered. The mechanical power developed by the turbine is given as:

$$P_M = \tfrac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v^3 \tag{9}$$

where R is the rotor radius, v is the wind speed, ρ is the air density, and $C_p$is the power coefficient of the turbine which depends on the pitch angle, β, and the tip-speed ratio, λ, which is defined by:

$$\lambda = \frac{R\,\omega_e}{v} \tag{10}$$

where ω_e is the rotor speed. The power coefficient is a characteristic of the wind turbine, and for our case, it can be approximated by

$$C_p(\lambda,\beta) = \sum_{i=0}^{4}\sum_{j=0}^{4} \alpha_{i,j}\beta^i\lambda^j \quad (11)$$

The rotor speed, as well as the pitch angle must be controlled to optimize the amount of power captured by the wind turbine. Thus, a reference speed, ω^*, is generated based on the electric power,P_e, for maximum power tracking and given by (12):

$$\omega^* = -0.67\,{P_e}^2 + 1.42\,P_e + 0.51 \quad (12)$$

Then, the generator speed is controlled by a PI controller that has as output the value P_ω^*, given by:

$$P_\omega^* = K_P(\omega^* - \omega_e) + K_I\int(\omega^* - \omega_e)\,dt \quad (13)$$

To support the frequency variation in the grid, the so-called inertial control must be added to system. This controller adds to the power reference output signal given by:

$$P_f^* = -K_{df}\frac{d\Delta f}{dt} - K_{pf}\Delta f \quad (14)$$

where K_{df} and K_{pf} are constants and must be chosen as weights to the frequency deviation derivative and frequency deviation respectively. This signal can increment the system inertia, supporting the frequency variation indirectly.
Thus, the total active power reference for our turbine must be calculates as follows:

$$P_{f\omega}^* = P_\omega^* + P_f^* \quad (15)$$

The penetration level is possible to change for study and variation is studied extensively in [20] but it is considered to be 30% for all simulation purpose in this paper.

C. *Mathematical Modeling of Vehicle to Grid (V2G) System for frequency regulation*

The EVs participation in AGC is from a broader perspective is used in developing mathematical model of EVs. Secondary frequency regulation is primarily accomplished by control action with area control error as input to controller. EVs for vehicle to grid process need to be modeled by keeping in view of change in frequency and AGC control signal. Communication channels between AGC and EVs is simplified and designed as an aggregated EVs model for secondary frequency control. The State of charge (SOC) of electrical vehicle is noted at every instant to have the correct accumulated capacity of all available EVs for frequency regulation. Therefore, EVs are basically used as reserve capacity to cater at the time of sudden demand in power system and this would be case in peak hours during a load cycle. The inputs are controller output and change in frequency to aggregated model of EVs for V2G which is represented by a first order transfer function. K_{EV} and T_{EV} are frequency characteristic of aggregated EVs and V2G time constant respectively. There values are calculated by power capacity of area and maximum change in frequency. The values of these parameters are considered as 10 and 0.1 respectively for all

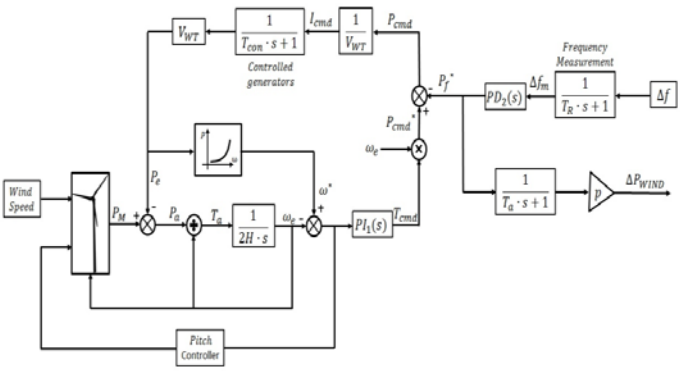

Fig. 1: Simplified block diagram of wind turbine

simulation purpose. The other parameters are same as given in [20].

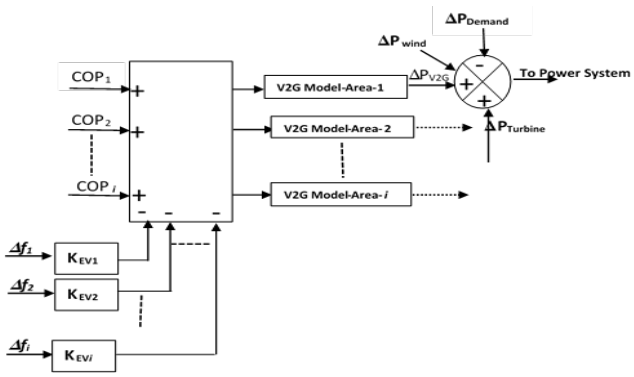

Fig 2: An integrated model with V2G for AGC in multi-generating system

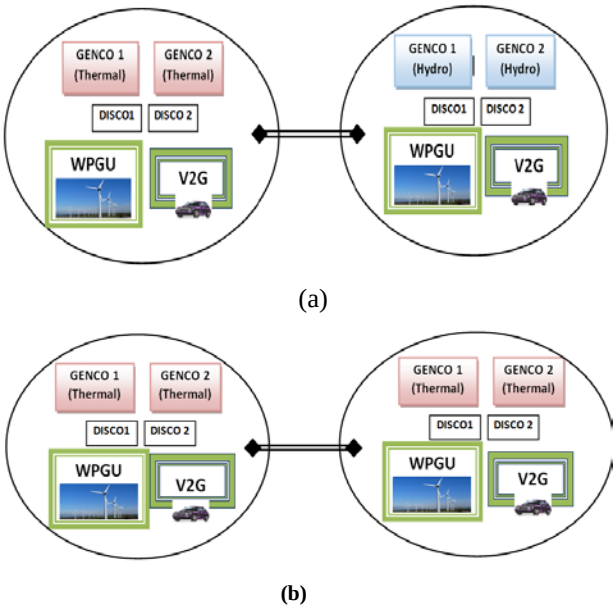

Fig. 3: (a) Model 1 with Thermal and Hydro Units in area-1 and area-2 respectively (b) Model 2 with Thermal Units in area-1 and area-2

The integrated model for AGC in multi-area interconnected power system is shown in Fig. 2, where COP_1, COP_2 ….COP_i and Δf_1, Δf_2…Δf_i are controlled input for conventional AGC and change in frequency from area-1, area-2 and i^{th} area

respectively. Transfer function representing V2G model is given by (16),

$$\Delta P_{EV} = \frac{1}{T_{EV}s+1} \qquad (16)$$

An aggregated model of EVs represented by a single transfer function for a particular area is used and has a simplified communication process between AGC and EVs. The prime purpose of having EVs grouped together that they represent a virtual large energy storage plant with a sufficient capacity to support AGC at the time of peak demand or sudden demand during the course of power supply at any other time.

TABLE I RULE BASE FOR FLC

	ΔACE							
ACE		***VVL***	***VL***	***L***	***Z***	***H***	***VH***	***VVH***
	VVL	VVL	VVL	VL	VL	L	L	Z
	VL	VVL	VL	VL	L	L	Z	H
	L	VL	VL	L	L	Z	H	H
	Z	VL	L	L	Z	H	H	VH
	H	L	L	Z	H	H	VH	VH
	VH	L	Z	H	H	VH	VH	VVH
	VVH	Z	H	H	VH	VH	VVH	VVH

VVH: Very Very High, VH: Very High, H: High, Z: Zero, L: Low, VL: Very Low, VVL: Very Very Low

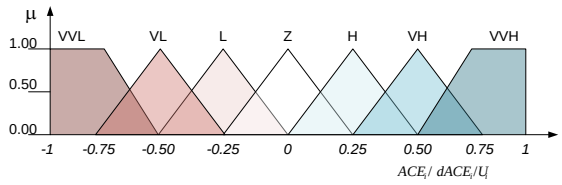

Fig. 4: MF's Distribution within defined variable range

III. PROPOSED CONTROL STRATEGY

In this paper, an optimized control strategy has been implemented. First model which is shown in Fig. 3 (a), and model 2 in Fig. 3 (b) are used for simulations. A fuzzy logic controller, where PI controller parameters as well as range of variables are optimized using GA. The perturbations are represented by the demand raised from DISCOs and basically it is step signal of 0.05 pu. In the recent times, fuzzy logic controller (FLC) has gained popularity in control system applications in uncertain and nonlinear systems. In complex and multi-variable power system, conventional control methods may not give satisfactory solutions. On the other hand, FLCs are more robust and more reliable in solving a wide range of control problems Fuzzy logic is a systematic and easier way to implement control algorithm for uncertain and indefinite models in engineering. The FLC modeling consists of three step as fuzzification, formation of fuzzy control rule base and defuzzification [23]. The control actions of a FLC are described by some set of linguistic rules and these are obtained from experience or trial and error, but this way does not lead towards optimum results. In order to achieve optimized results, FLC is done using powerful optimization tool i.e. GA in a systematic way.

Seven membership function (MF) have been used to explore best performance as shown in Fig.4. The FLC is designed based on MISO type. The first input is ACE_i and other one is derivative of ACE_i $(dACE_i/dt)$ which justifies of PI controller implementation. In Fig. 5, K_e and K_{ce} are scaling factors for both input variable respectively and K_p and K_i are the proportional and integral gains. Whereas, U_i is a crisp value and u_i is a control signal for the system.

$$u_i = -K_p U_i - K_i \int U_i \, dt \qquad (17)$$

Initially for each variable, MF's distribution are kept same. MF specifies the degree to which a given input belongs to set or a function that defines how each point in the input space is mapped to a degree of membership between 0 and 1. MF's distribution for ACE_1 is within [-0.5 0.5], $dACE_1$ is within [-0.1 0.1] and U_1 is within [-0.5 0.5] for FLC controller for area-1and for area-2 MF's distribution for ACE_2 is within [-0.5 0.5], $dACE_2$ is within [-0.1 0.1] and U_2 is within [-0.1 0.1] for FLC controller for area-2.

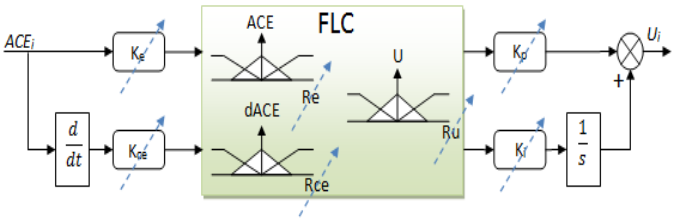

Fig. 5: MISO Fuzzy Logic controller

Table I presents the rules for FLC used in designing the controller. In rule base 49 rules are designed to get the response.

IV. SIMULATIONS AND DISCUSSION

Simulations are performed on two different models as discussed earlier. Results obtained are using MATLAB/Simulink. The dynamic parameters of frequency response have been critically analyzed to justify the controller actions on different case studies. There have been four cases with each model type which makes total 16 simulation graphs of change in frequency in area-1 and area-2 respectively.

A. Case 1(No Wind Power and V2G Power Penetration):

The disturbance is subjected in both areas and results obtained are given in Fig. 6 and 7. Oscillatory response is observed in model 1 with high setting time and peak overshoot. The main reason of having such response is interconnection of thermal and hydro units. There is difference in their time constants which results in sustained oscillations for sufficiently longer time. On the other hand, when model 2 is considered, there is stable response as both the areas are similar and acting simultaneously to perturbation. All responses in model 2 will have same peak overshoot and settling time for this reason.

B. *Case 2 (With Wind Power and No V2G Power Penetration):*

In second case, wind power inertial support is connected in all areas along with conventional AGC system. Since both areas are equipped with wind power generating units (WPGU), this is leading to short term active power support to some extent and managing to minimize oscillatory behavior of frequencies in both areas in model 1 particularly. Model 2 already has smooth responses but immediate power demand is met by WPGU leading to lesser overshoot as compared to previous case. Graphical results are shown in Fig. 6 and 7 for both models.

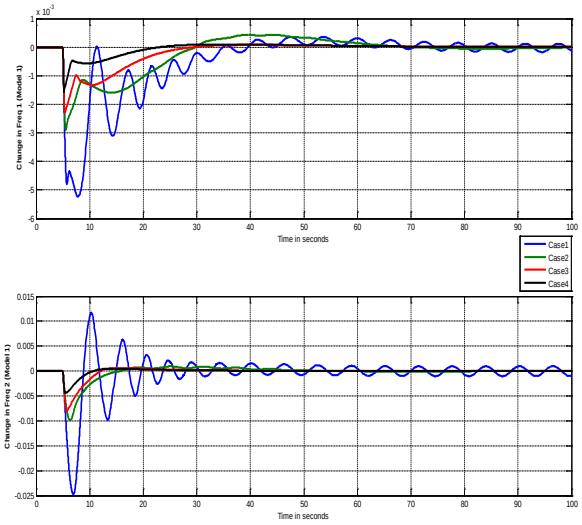

Fig. 6: Frequency deviations in area-1 and area-2 for model 1 in all cases

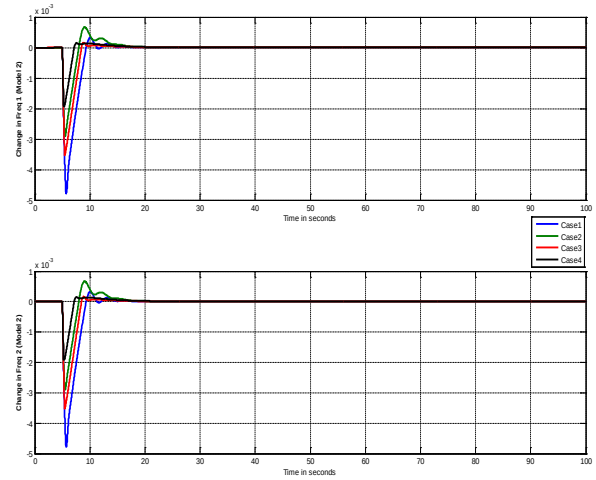

Fig. 7: Frequency deviations in area-1 and area-2 for model 2 in all cases

C. *Case 3 (Without Wind Power and With V2G Power Penetration):*

In smart grid era, where possibilities of micro grids are being discussed amongst researchers with V2G power penetration. These results in an interconnected power system with V2G effect should be considered encouraging in terms of frequency regulations. In this particular case, only V2G is incorporated in both areas of power systems under study. The responses shown in Fig. 6 and 7 are justifying the presence of having bulk vehicle power storage in new power system age. This is alone capable enough to have substantial improvement in dynamic parameters of response as clearly visible in graphs. The major reason here is fast acting converters and a small response time of overall model of V2G support system.

D. *Case 4 (With Wind Power and V2G Power Penetration):*

This case represents an integrated approach to handle power system frequency regulation challenge. The integration of WPGUs and V2G support system is connected in both areas. Keeping the same perturbation for obtaining comparative analysis, this case results in finest form. In both models, not only peak overshoot and settling time are reduced but also a smooth and oscillation free responses are achieved. This integration has its justification in smart grid system because smart grid focuses on mainly clean power inputs into the grid. Both of them (WPGUs and V2G) are indeed foremost choices for power engineers. There are always issues associated with both of them because of their technical complexity in design for practical purpose, but nevertheless, this suits best for frequency regulations aspect. Results with integrated model in place are shown in Fig. 6 and 7 for model 1 and 2 respectively.

All results are also presented in Table II. Observing all results for model 1, it may be concluded that by simply putting V2G into system, there is 47% decrease in peak overshoot and 62% in settling time from case 1 to case 4 in area-1 only while if area-2 is considered, new values are 33% and 20% of their earlier values. Integrated model of V2G and WPGUs leads to highly encouraging results i.e. peak overshoot and settling time in area-1 are 30% and 39 % of their initial values.

If model 2 is considered where both areas are similar, all results of different cases are same for area-1 and area-2. Peak overshoot and settling time are considerably reduced i.e. new values are 38% and 7% of their earlier values. Finally, it is recommended that V2G should be considered as a viable and suitable option for critical aspect of modern day power system i.e. frequency regulation. This is obvious to say that the practical power plants will have slightly higher dynamic parameters with such controller as there will be more non-linearties into the electro-mechanical system.

Table II COMPARATIVE ANALYSIS

Case	Area	Model 1 (Thermal-Hydro)		Model 2 (Thermal-Thermal)	
		Peak Overshoot (Hz)	***Settling Time (s)***	***Peak Overshoot (Hz)***	***Settling Time (s)***
1	***1***	-0.005313	28.83	-0.004925	8.99
	2	-0.024734	97.40	-0.004925	8.99
2	***1***	-0.003022	24.41	-0.002987	9.73
	2	-0.009908	39.02	-0.002987	9.73
3	***1***	-0.002573	18.73	-0.003569	8.07
	2	-0.008089	19.50	-0.003569	8.07
4	***1***	-0.001616	11.72	-0.001913	6.68
	2	-0.004345	9.52	-0.001913	6.68

V. CONCLUSION

An integrated V2G and WPGUs model is presented in paper for automatic generation control in restructured power system. A newly developed V2G model represents an aggregated V2G where vehicles are assumed to be available for bulk power supply for short term. This is justified and validated with simulation results presented. Power system engineers come across the situations of sudden rise in demand quite often. This solution is a win-win situation for both customers and power companies. Two different models of power system are used for a comprehensive analysis of effect of wind power and V2G power. Wind power generating units are modeled with inertial support which is crucial at the time of sudden load requirement in power system because thermal and hydro generators lose their kinetic energy to support additional demand which is undesirable. Despite the fact that associated power management system will have to be quick in transferring information through a secured and robust communication channels, V2G has capability of changing power scene in days to come.

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APPENDIX:

A. Parameters of Hydro Thermal System Investigated:

P_{r1}= P_{r2}=2000MW; K_{p1}= K_{p2}=120; $T_{p1=}$ $T_{p2=}$20; R_1=R_2=2.4; T_{12}= 0.545; T_w=1;T_t=0.3; T_{g1}= 0.08;T_{g2}=0.02; T_r=5;R_t=0.38; R_p=0.05; β=0.425;a_{12}=1;

B. Parameters of Wind Turbine Investigated:

H=4.64; pAr=2*0.00159; Kb=56.6; Tr=0.1; Ta=0.2; Tc=0.2; Kp=1.5; Ki=0.15;

C. Parameters of V2GSystem Investigated:

Te=1; u_e=0.025; del_e=0.01; Emax=0.95; Emin=0.80; E=0.90; Pmax=200/1000;