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Bulk Virtual Power Plant, a Novel Concept for Improving Frequency control and Stability in Presence of Large Scale RES

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Abstract

Frequency stability in power systems is essential to maintain supply quality and security. There are some challenges for maintaining frequency in its required limits with presence of Renewable Energy Sources (RES) in primary energy sources for electric power generation. This paper investigates a new control approach to consider bulk amounts of RES generation in frequency control and regulation of power systems when the RES power generation is the main generation of the system. In this regard the concept of Bulk Virtual Power Plant (BVPP) is introduced to cooperate with Transmission System Operators (TSO) and Distribution System Operators (DSO) under a new control approach to improve frequency characteristic of power system without increasing capacity of energy storage systems. The proposed control approach is applied to hybrid power generation systems. The effectiveness of these methods was verified using MATLAB/SIMULINK software. The simulation results indicate that the proposed control scheme works desirably and thereby large amounts of RES can effectively participate in Load Frequency Control (LFC).

Keywords: Bulk Virtual Power Plant, Frequency control, Transmission system operator

1. Introduction

The power-frequency droop method is widely used in interconnected power systems. The droop concept enables sharing of the total load between units proportionally. Also, since only the output parameters of the units are used, no communication between the units is necessary, but there are several issues that make this method inappropriate for future smart grid. First of

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all in this method units share real and reactive power according to pre-specified droop characteristics, that means since this is an offline and predetermined setting there is no awareness of generation units situation and all units are subject to a same stress and tension , besides in this method there is always need for additional restoration control action [1-4]. On the other hand power generation of RES[1] that are attracting great attention for future smart grid, mostly wind and solar energy, are not constant. Windmill output is proportional to the cube of wind speed, which causes the generated power of wind turbine generator (WTG) to fluctuate. The generated output power fluctuation increases relative to the increase in installation capacity of the WTGs. There is a same problem of power fluctuation for other kinds of RES like solar power that make the Load Frequency Control (LFC) more complicated in future smart grid with higher participation of RES[3-6] . There are ongoing researches to use BESS[2] to limit the effect of variability of these kinds of generation on power system frequency [7-8].

However, the capital and maintenance costs of large capacity BESS are a barrier to the large-scale installation of RES systems. Besides, these methods cannot control RES output power considering the power utility condition like load variation. Therefore, they are not into providing any frequency control. These methods usually tried to smooth the fluctuating PV power. However, none of them gave emphasis on controlling the PV power according to the load variation and frequency deviations. For handling mentioned issues, this paper presents a supervisory control strategy for load/frequency control problems with a new approach for cooperation between TSO[3] and DSO[4] in a smart power system in presence of RES and large scale energy storage systems. The aim here is to find supervisory strategies that are able to reconfigure, whenever necessary in response to unexpected load or renewable resource

[1] Renewable Energy Sources
[2] Battery Energy Storage System
[3] Transmission System Operator
[4] Distribution System Operator

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output generation changes, in hence new set-points on frequency and generated power of each area reached, so that viable evolutions would arise for the overall power system and a new sustainable equilibrium is reached. The focus is on the master/slaves scenario where the LFC master represents a supervisor in charge of taking main decisions. At the remote sides, the LFC slave units are those parts of the strategy which require only local information. Generally, the idea is that TSOs are working under supervision of master control center, while DSOs are working under supervision of slave control centers. Some low capacity RESs may work under the control of DSO while high penetrated ones (including the related energy storage) are supervised by the TSO. The master/slave scenario can be implemented in a power system with full observability and controllability which defines the future Smart grid.

All in all, this paper presents a new method for the coordination of large scale renewable energy resources in order to satisfy frequency regulation limits. A significant improves resulting from the participation of large scale RES in frequency control is the reduction in the need for energy storage systems. It must be noted that in this method there is no need for any further frequency restoration action like conventional frequency control system. Higher power frequency stability is another result of proposed method. A case study has been done with real data of Iran grid which confirms the robustness of proposed method.

The rest of this paper is organized as follows: Section2 provides brief explanations of frequency control problem in a smart grid, Section 3 is devoted to proposed methodology in this paper, and including presentation of a new concept; Bulk Virtual Power Plant (BVPP) and also the control structure, Section 4 presents modeling procedure and section 5 describes analysis and simulation results. Finally conclusions drawn from the analysis are presented in section 5.

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2. Frequency Control Problem In Future Smart Grid

In power systems operation, frequency control is always one of the main concerns of grid operators. Meanwhile, with major changes and developments in electric industry, it is becoming a bigger concern. Effect of future changes in power systems, known as smart grid, in frequency control are mainly due to presence of RES [9-12]. Increasing the share of RES in power system generation has many benefits for future grid like decreasing the environmental pollution. On the other hand, as the outputs from RES power generation fluctuate time to time and these resources are available only in specific areas, deterioration of the quality of utility's power supply has become an important issue to be solved [8],[13-15].

Other typical issues discussed recently in this subject are:

1. Tripping due to transmission system faults
2. Voltage fluctuation under varying RES conditions
3. Inability to control active power production
4. Lack of reactive power control and voltage regulation

It must be noted that beside all these issues the variability is a great concern, especially for frequency control purpose that is the main object of this paper. From this point of view there are two main topics that are needed to be discussed in more details.

2.1. Changes in Power System Frequency

As mentioned before, this paper focuses on inability of wind and solar power plants to dynamically participate in active power and frequency control of power systems. Many variable speed wind turbine generator systems use a doubly fed induction generator (DFIG), where the rotor is connected to the grid through a back-to-back ac/dc/ac converter. This results in the decoupling of the rotor speed from the grid frequency. With the increase in the number of these asynchronous generators the overall system inertia is decreased, which leads to higher frequency fluctuations [6].

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The latest wind turbines have robust designs for reliable performance and increased energy capture, as well as sophisticated control systems that support electric system requirements and enable cost-effective power system operation. But still corporation of these generations in frequency control needs sophisticated algorithms and controls in power grid. Beside internal control (pitch control, output control…) there is also a need for change the supervisory control [16, 17]. For the solar systems, the situation is even worth. Beside uncertainty of generation during the day, there is null generation in the nights or even cloudy days [18, 19].

To date, it has not been necessary for small PV generators to provide frequency-regulation services to the isolated utility. In the future, with an increasing penetration of PV generation, their impact upon the overall control of the power system will become significant. This will lead a situation, where the PV generators will be required to share some of the duties, such as frequency control [20-21]. This normally results in more investments and grid development to maintain grid stability, unless with the use of modern communication and control systems an smoother daily (even hourly) generation portfolio can be achieved.

2.2. Impacts of Energy Storage Systems

Load and Generation must be balanced on the Grid. Traditionally, Generation was controlled while the load was variable. With increasing renewable penetration, generation has also become variable. Measures to suppress the effects on the grid owing to the output change are being studied from various aspects, out of which utilizing the energy storage technology is available [20,21]. Between all different kinds of energy storage systems, Lithium Ion batteries and especially Lithium Iron Phosphate (LFP) batteries can be characterized by high power densities, relatively long life-time and no maintenance [21].A lot of research currently being done on increasing their performance. They are also considered as battery energy storage system (BESS) in this paper.

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3. Proposed Frequency Control Algorithm

3.1. Developing the Concept of Bulk Virtual Power Plant (BVPP)

This section presents the proposed frequency control algorithm in this paper. A novel concept is introduced for the integration of bulk amounts of RES and energy storage systems. Then the collaboration of mentioned system with existing control operators (TSOs and DSOs) is described. The Virtual Power Plant (VPP) represents the aggregated capacity of RES under one single profile that is operated as unique entity from the point of view of any other power system actor hiding its inherent complexity. Therefore, the VPP is a flexible representation of RES commercializing energy at wholesale markets and/or ancillary services to any interested operator [22].

The VPP may be divided into two separated views: the Commercial VPP (CVPP) and the Technical VPP (TVPP). The CVPP does not take into consideration any network specific element, selling or buying energy from dispersed elements through bilateral contracts or into the wholesale market, providing balancing services or general ancillary services at system level. The CVPP role could typically be performed by a supplier, a balancing responsible, etc., that is, actors with market access.

The TVPP role is associated to the aggregation of resources from the same electrical location. Normally the electrical location will be linked to a similar geographical location but topology changes should be considered. The TVVP requires a deep knowledge of the network topology and its characteristics directing towards the DSO as the most suitable personification. For instance, for a given portfolio of RES units connected to the same distribution network, the aggregated capacity should be accounted for possible network constraints, reducing in consequence, the available response [23]. Also there is no definite description of virtual power plant, but most references [22-28] developed it as a concept to enhance the visibility and control of RES installed in distribution networks to system operators or market actors. Thus the capacity of generation usually doesn't exceed from

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hundred(s) of MW. As a result of increasing the share of RES, especially wind generation in power systems to almost 30%, deployments are needed to aggregate these high capacities for providing system support services like frequency control. Meanwhile, despite the benefits of RESs in VPP, high capacities of RESs, like large wind and solar farms are going to be installed in transmission levels instead of distribution. In aggregation of large scale RES; the most important problem is their variability. Since they have a noticeable share of generation, their participation in ancillary services like frequency control must be mandatory.

There are many ways to compensate the variable nature of wind generation, but all of them need large amount of investment. For large scale application, where geographically there is a simultaneous potential of solar radiation beside wind, these two are inherently capable of compensating each other's changes, thus reducing total cost for compensation. Fig.1. shows a daily pattern of wind and solar generation in Iran [29]. As shown in Fig. 1. in a typical day there is a good solar radiation between 9AM until 15PM, while highest amount of wind speed is in night hours. In this case, use of wind and solar generation, together as a hybrid generation system clearly results in significant reduction in the need for energy storage system. Rest of net generation changes usually compensated through the act of conventional power plants, which impose a high tension on power plants, especially in large amounts. Due to great advances in power electronics and Battery Energy Storage Systems (BESS) there is a possibility of compensating output power of RES with these techniques.

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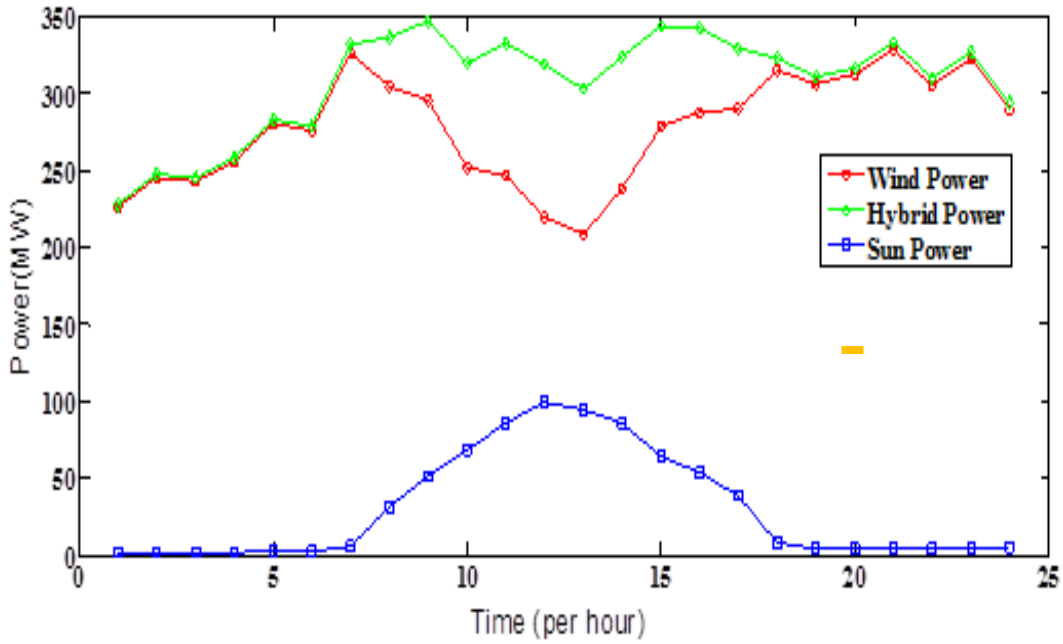

Figure 1: Semnan average wind and solar output

Emerging new technologies like large scale RES generations and distributed storage in transmission level requires a new control methodology to manage the cooperation between these technologies. For this reason the concept of Bulk Virtual Power Plant was presented in [30] by authors and discussed in more details in this paper. BVPP is a combination of large scale renewable energy generations together with large energy storage system in transmission system level which is capable of participating in different technical, commercial actions and ancillary services .the focus of this paper is the role of BVPP in improving effectiveness of participating of RES in frequency control procedure, while reducing the need for BESS. Important features of BVPP are:

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- Better Short Term Forecasting (Sub-Hourly) of Variable Generation Resources, with Finer Resolution (Minutes).
- Improve Supervisory Control and data Acquisition for RES.
- Possibility of short term Scheduling of All Resources due to issued commands.

3.2. Collaboration of TSO, BVPP and DSO Through Proposed Frequency Control Algorithm

As mentioned before, future projects; large wind farms and solar power plants may cause serious frequency deviations and frequency control problems. One of the major problems in controlling a large size wind farm from a central dispatching is that rated power of each turbine is normally around 1-5 MW, this turbines are not placed close together (they may be connected to different lines and transformers), and also, they may even be connected to several distribution systems, this is usually the case for large wind power plants with rated power of 500 MW and above. As a result, controlling such wind farm with more than 200 generation units through one control center is almost impossible.

Another challenge is that droop control is not able to satisfy specified frequency margins in situation of high penetration of renewable energy resources. Thus a novel algorithm is proposed in this paper to cope with mentioned problems. Fig. 2 shows the flowchart of proposed structure in this paper. First of all, it must be calculated that how much of the difference in power (regarding to a contingency or load increase) can be compensated through droop control of conventional power plants, The difference must be supplied from available RES generation(that refers to wind and solar generation in this case) and BESS. It is worth mentioning that system awareness and availability of such information's (change in frequency, conventional units generation amounts, RES generation, wind speed, solar radiation, BESS charge/discharge/capacity state …) needs reliable and broadband communication platforms that will be provided by smart grid. With above mentioned

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information on such a power generation systems, this paper develops the concept of BVPP. It is actually an extension from VPP. VPP usually attributed to set of power generation with limited capacity connected to distribution system. But in the case of BVPP the assumption is a system of variant generation types (wind, solar, battery…) with large capacity connected to the grid through several points, either in transmission system or distribution system. Since the main concern of BVPP is to manage its generation in response to system regulators commands, effect of loads (active/passive) are not considered in this work.

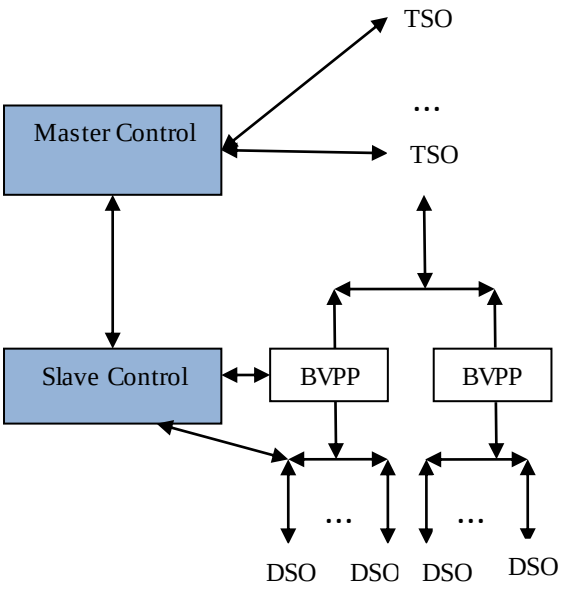

Figure 2: Flowchart of proposed algorithm in this paper

Fig. 2. shows the flowchart of proposed control structure in this paper.

Usually, Control devices in more than two power plants or substations are connected by communication equipments to form a regional stability control or large-scale power systems. Proposed control method is composed of a master station, several slave stations and executive stations. As it illustrated in Fig. 2. Based on smart grids infrastructure,

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communication links exist between all control centers, operation centers (DSO, TSO), large conventional generation centers and BVPPs. Thus the reliable real-time communication infrastructure is capable of handling required data and control signals between all different centers and units. With use of bilateral real-time communication structure, P-Q injection control method can be implemented in power system [31]. As mentioned before stability strategy based on N-1 or even N-2 contingency are existed in master and slaves tactic tables. Thus, after a contingency or a sudden change in load or generation that leads to a situation that needs a sudden change in power of BVPP, decision will be made in master control center and sent to related slave control center. Tactic table of master control center, consists of logic control chart with detailed and predicted calculation, analysis and strategies both offline and online. Slave control center make proper decision for providing issued generation change based on its subsets DSO and BVPP status. The BVPP itself, based on its situational awareness of generation units and predetermined algorithms, decides how to supply requested power. That means, based on real-time data, the situation of wind power plants, solar ones and batteries is clear, so correct decision can be made. Based on the decision of BVPP, DSO may regulate other existing generation units and batteries.

Fig. 3. shows the proposed algorithm for master control center. As it shown in Fig. 3, Δf is measured instantaneously through wide area monitoring system and phasor measurement units, until the Δf is out of the specified range. This range is usually determined by local grid codes. This situation means that droop control of conventional power plants was not able to maintain the frequency in desired limits. In this stage, it must be determined whether the frequency is out of emergency rate or not. If so, master control system uses determined commands in emergency tactic

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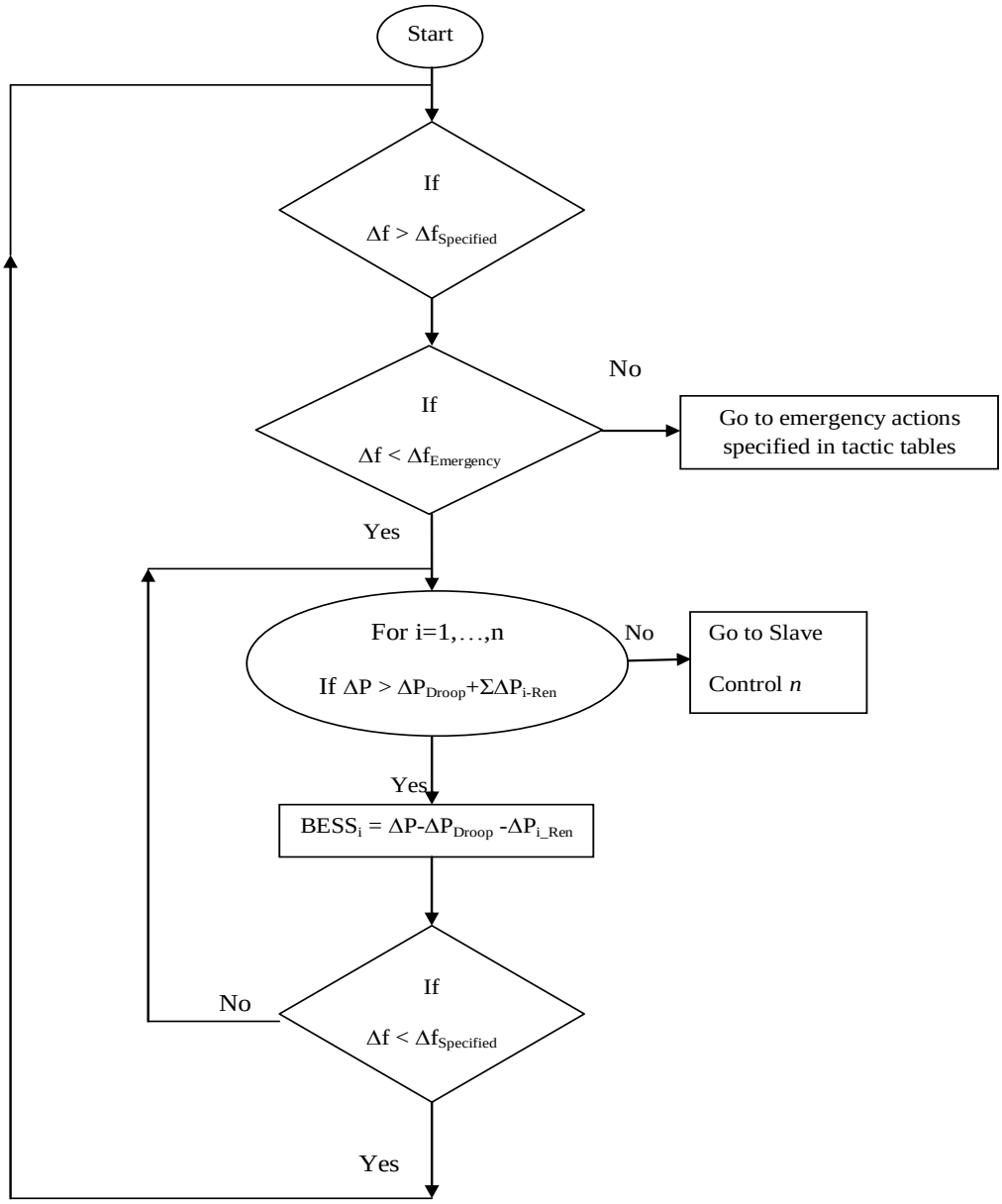

Figure 3: Proposed algorithm for of frequency regulation for master control center

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tables, otherwise appropriate commands are issued to slave control centers until the frequency is back to it s desired limits.

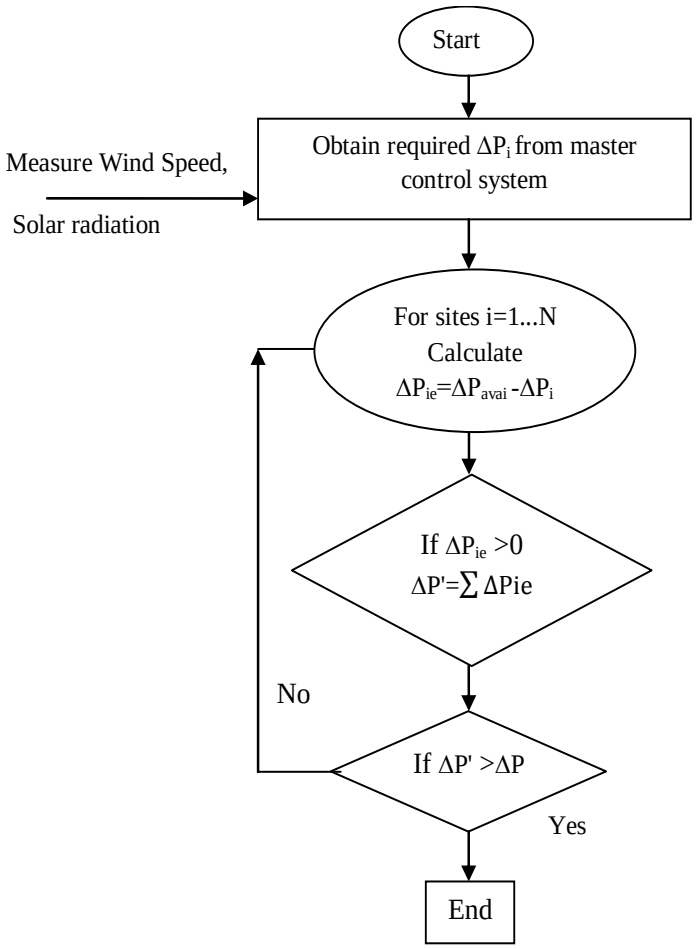

Figure 4: Proposed algorithm

Given the real-time input data, master control system determines required change in generation of each slave control system based on their status. In this regard master control system decides on whether the change in power demand should be supplied by all slave centers or few of them are sufficient. The benefit of this approach is that unlike conventional

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method (droop control) generations units are not impose to equal tension regarding sudden changes in their output. More than that, the required power mostly can be supplied by newer units or units with more proper situation or even higher technologies. Master control center can even consider power system loss, and market situation in dividing generation between slave control centers of different areas.

It is worth mentioning again that essential data of grid situation are provided in real-time for the master control system. Fig. 4. shows the proposed algorithm for slave control systems. In this procedure, a required change in power generation of area *n* (ΔPn that is under control of *nth* slave control system) is obtained from master control system. Each slave control system may consist of several DSO and BVPP. Based on real time data from each BVPP and DSO, slave control system decides on how to compensate generated power.

4. Modeling

This section describes modeling procedure of mentioned algorithms. At first conventional control procedure of a conventional control approach for frequency control of a VPP is presented [32]. Then the hybrid generation system is considered as a part of BVPP.

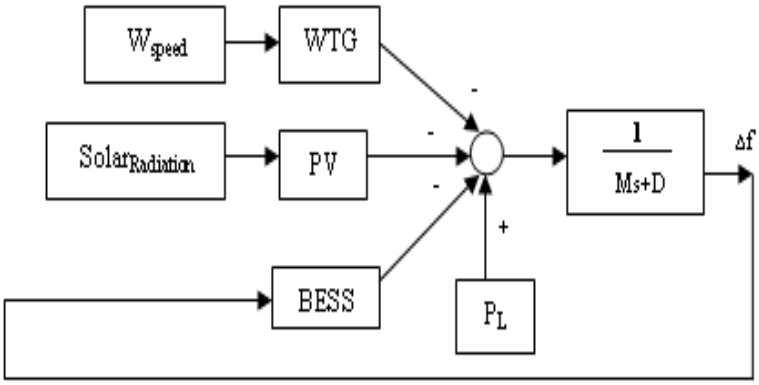

Figure 5: Block diagram of conventional control approach for VPP

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Fig. 5. shows the block diagram of conventioal control approach for a hybrid generation system (VPP). Based on this structure, through the feedback of changes in frequency, BESS compensates frequency deviations. As it illustrated in this figure, wind and solar generation units are not participating in frequency regulation in this method

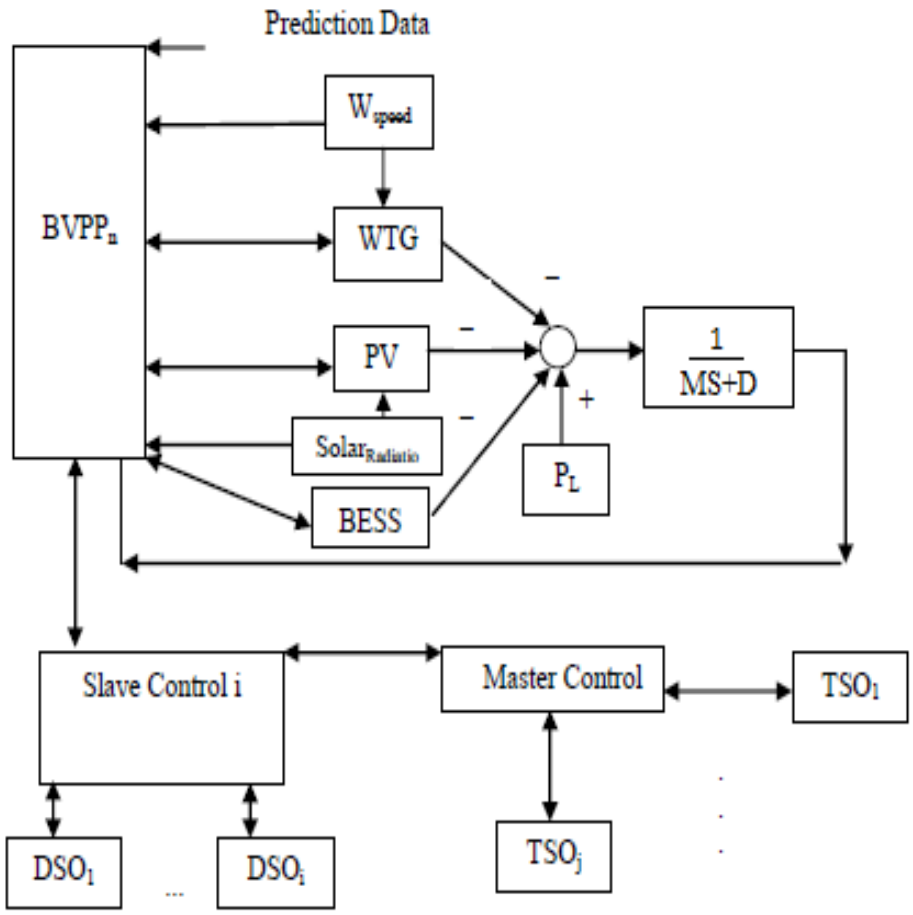

Figure 6: Block diagram of proposed control approach for BVPP

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Fig. 6. Shows the block diagram of proposed control approach for BVPP. As shown in Fig.6 BVPP gathers essential data of its subsystems like changes in frequency, BESS status, wind speed, solar radiation, load demand… Based on this data, available net power generation of BVPP is calculated and sent to slave control center. Slave control center estimates its available net power generation based on received data from different DSOs and BVPPs and sent it to the master control center. Slave control center may or may not include a TSO, either way important data of TSO is sent to the master control center too.

In normal conditions, slave centers are capable of power management and maintain frequency and voltage stability within their area. In case of a contingency or a sudden change in load or generation, master control center decides on how to compensate the power deviation and proper commands and control signals sent to slave control centers. For the wind generation, the generated mechanical power is a complex function of wind speed (ω_s), rotor speed ($\omega_{\omega t}$) and pitch angle (β) [17]. The power coefficient (C_p) values of the turbine are fit with a fourth order polynomial on λ (tip speed ratio) and β to obtain the mathematical representation of the C_p curves, which is

$$C_p(\lambda,\beta)=\sum_{i=0}^{4}\sum_{j=0}^{4}\alpha_{i,j}\beta^i\lambda^j \tag{1}$$

The values of the coefficient $\alpha_{i,j}$ are given in Appendix A. The expression for λ is

$$\lambda=\omega_0 R\frac{\omega_{\omega t}}{\omega_s} \tag{2}$$

Where ω_0 is the rotor base speed in rad/s and R is the rotor radius in meter.

The transfer functions of the WTG shown in Figure (6) is represented by a first order lag as

$$\frac{\Delta P_{Wind}}{\Delta P_{WTG}}=\frac{1}{1+sT_{WTG}} \tag{3}$$

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For the solar generation, the output power of the studied PV system is determined by [32]:

$$P_{PV}=\eta S\Phi\{1-0.005\ (Ta+25)\} \tag{4}$$

Where η ranging from 9% to 12% is the conversion efficiency of the PV array, S (= 4084 m^2) is the measured area of the PV array, Φ (= 1 kW/m^2) is the solar radiation, and Ta is ambient temperature in degree Celsius. The value of P_{PV} depends on Ta and Φ because η and S are constant. In this paper, Ta is kept at 25 ◦C and P_{PV} is linearly varied with Φ only.

$$\frac{\Delta\Phi}{\Delta P_{PV}}=\frac{1}{1+sT_{PV}} \tag{5}$$

The transfer function model of battery energy storage system expressed by first order [32] as

$$G_{BESS}=\frac{K_{BESS}}{1+T_{BESS}} \tag{6}$$

The net power generation is comprised by power of WTG, PV, FC and BESS system. The expression for P_{Net} given by

$$P_{Net}=P_{PV}+P_{WTG}\pm P_{BESS} \tag{7}$$

The total power generation must be effectively controlled and properly dispatched to maintain a stable operation of an autonomous system to satisfy power demand by proper control of different power generation and components. The power balance is expressed as follow:

$$\Delta P=P_{NET}-P_{Load} \tag{8}$$

The fluctuation in the frequency profile Δf is expressed by the equation:

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$$\Delta f = \frac{\Delta P}{K_{\mathrm{SYS}}} \tag{9}$$

Where K_{sys} is called system frequency characteristic constant of the hybrid power system. The transfer function for system frequency variation to per unit power deviation can be expressed by

$$\frac{\Delta P}{\Delta f} = \frac{1}{\mathrm{D+sM}} \tag{10}$$

Where M and D are the equivalent inertia constant and damping constant of the hybrid power system, respectively.

5. Simulation Results

One of the main wind energy resources is located around Semnan (central region of Iran). The interesting point for this region is that there is also a very high radiation of solar energy in this region. Because of mentioned reasons, there is a plan for constructing bulk wind and solar power plant in Semnan. The wind power plant estimated to be around 500MW with DFIG turbines, and PV arrays are going to be used for solar power plants with estimated capacity of 100 MW. Simulation analyses were performed with a wind/PV/BESS hybrid power system model. Simulation tests considering both conventional and proposed control approach in this paper were conducted with MATLAB/SIMULINK software.

Fig.7. illustrates local load and output power of PV and wind systems under conventional control approach. As it shown in Fig.7. , PV and wind generations don't show any change in response to changes in load, the only variation of wind and PV generation are due to the change of their primary supply (wind speed and solar radiation that are shown in Fig. 8.

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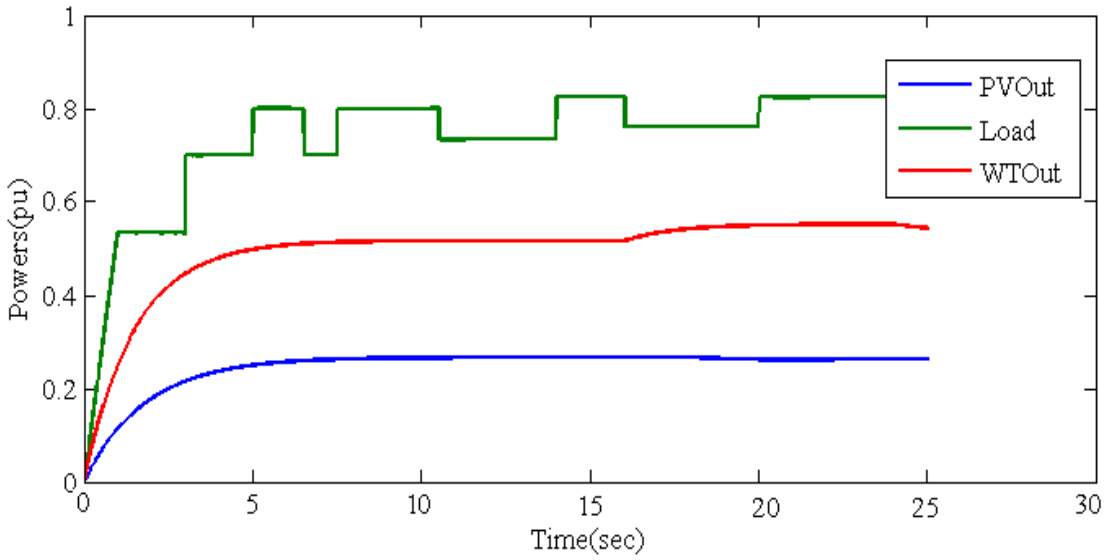

Figure 7: Output powers of PV and WT units and load

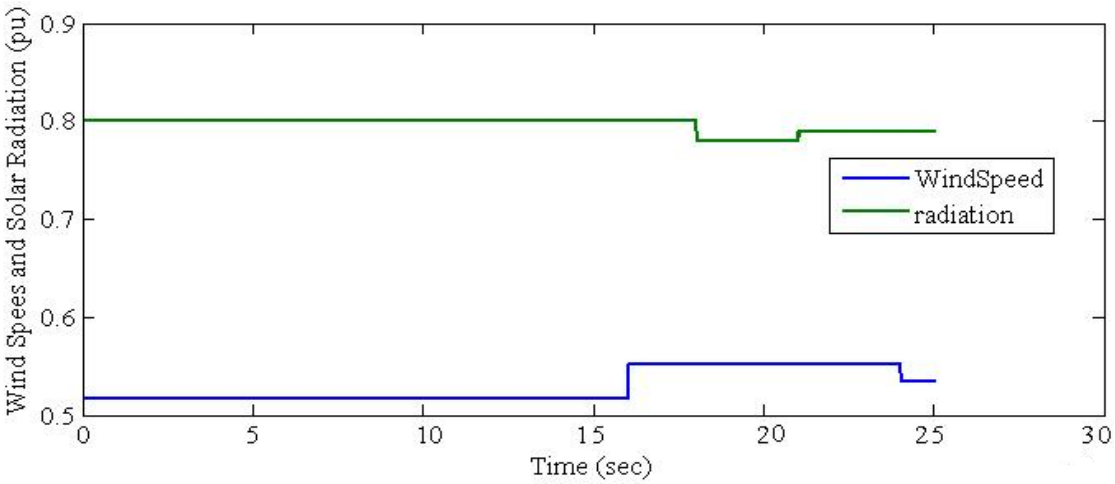

Figure 8: changes in solar radiations and wind speed

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It is worth mentioning again that load data, solar radiation and wind speed are taken from real data of a part of Iran electrical grid in Semnan. Frequency deviation is shown in Fig. 9.. Fig. 10. illustrates battery output power and its charge/discharge states.

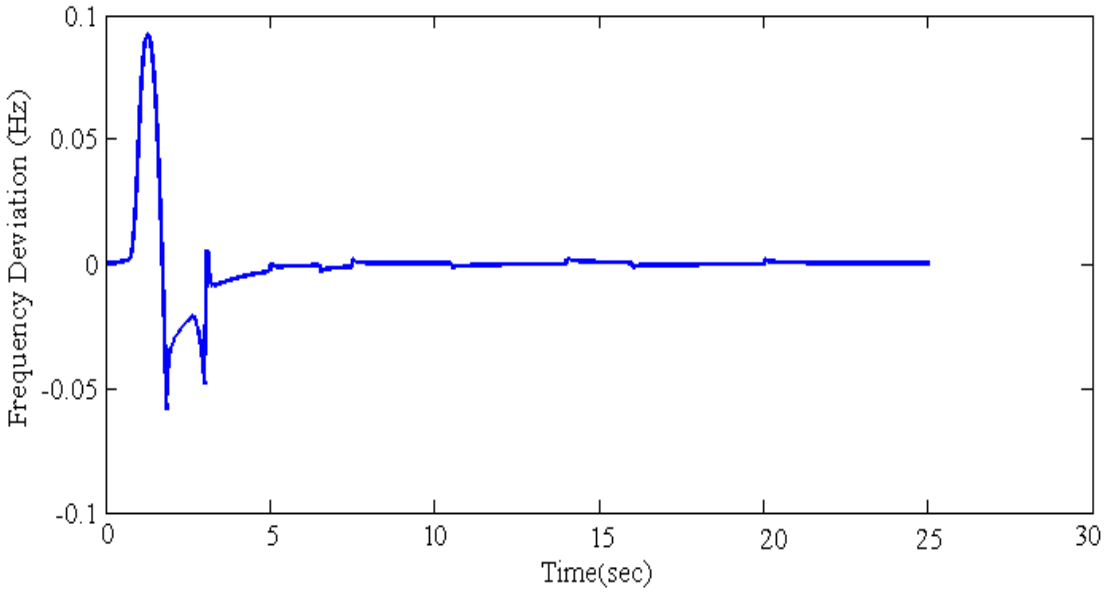

Fig. 9. Frequency deviation of study system with conventional frequency control approach

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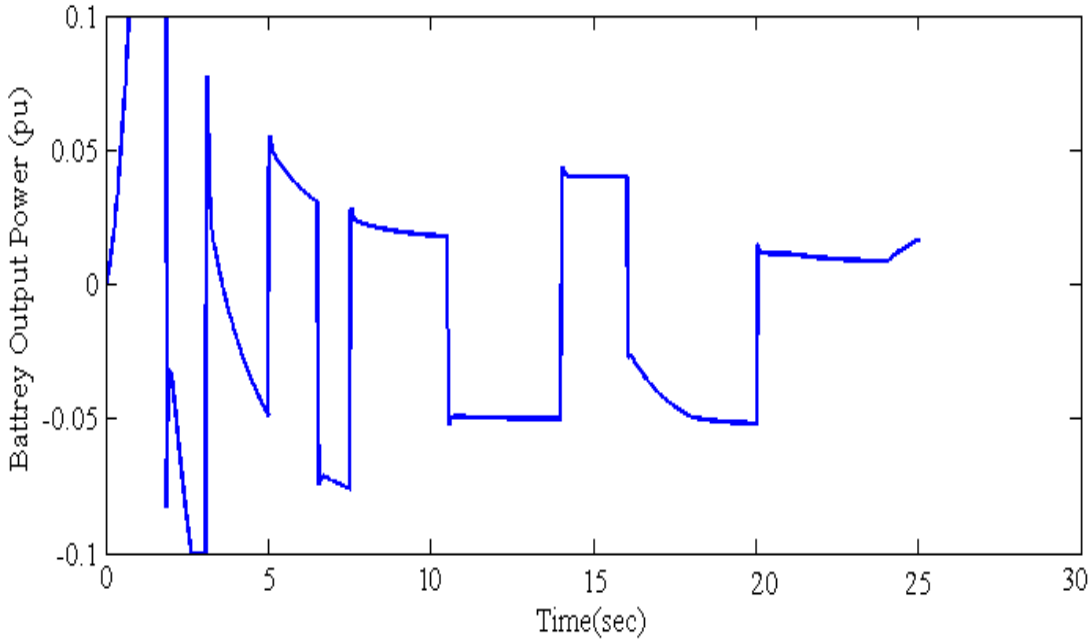

Figure 10: BESS output power with conventional frequency control approach

Figures (11, 12) show output power of wind and solar generation. In cases of conventional control approach and proposed control approach in this paper. In latter, RES participation in frequency control assumed to be maximum ± %5 of available capacity. As it illustrated in Fig 11, 12, wind and solar generation output changed in response to frequency deviation.

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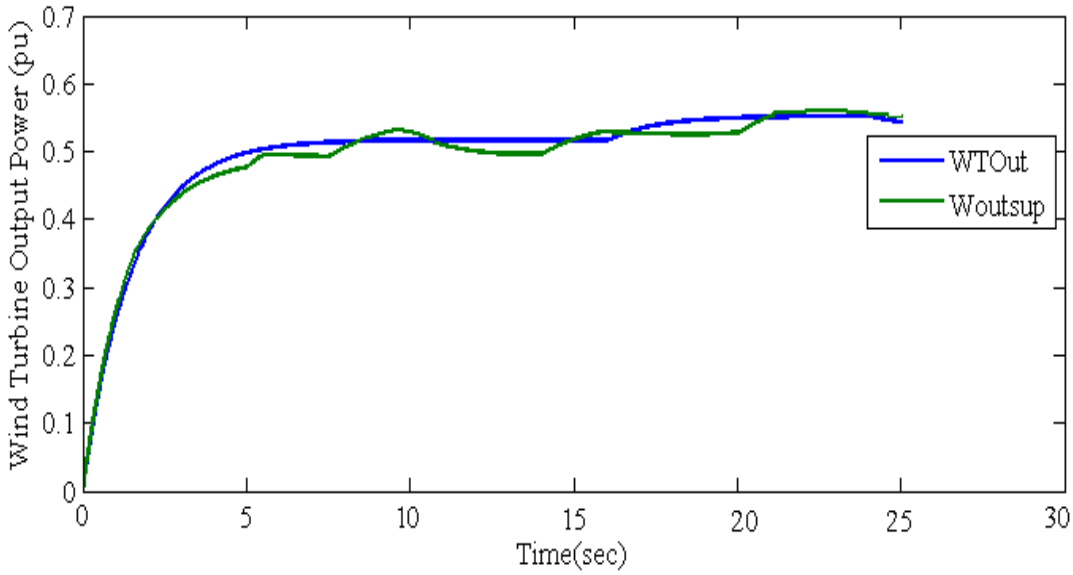

Figure 11: Output power of wind generation with (Woutsup) and without (WTOUT) frequency support

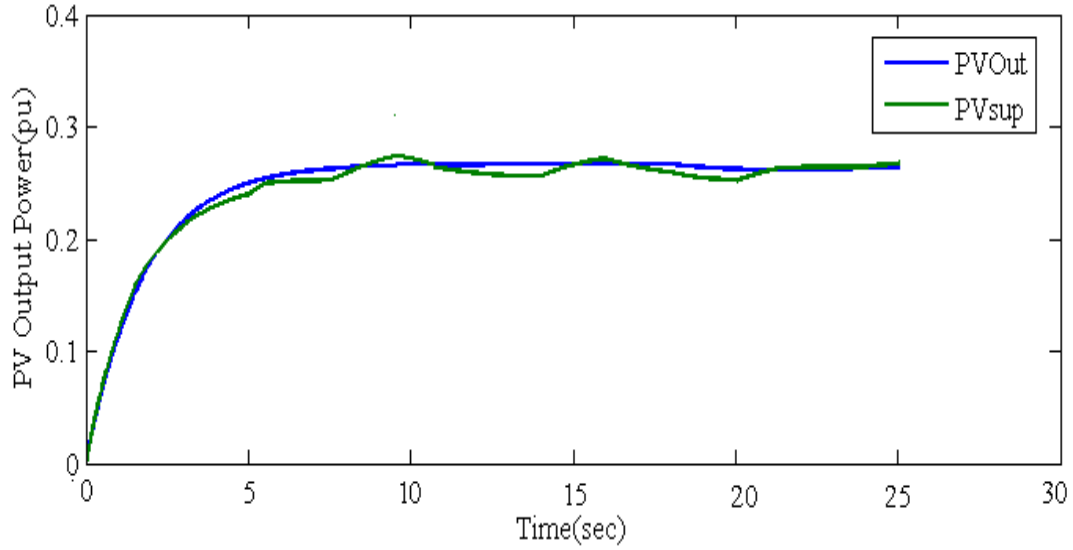

Figure 12: Output power of solar generation with (PVsup) and without (PVOUT) frequency support

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Fig.13. Shows BESS output power in cases of conventional and proposed frequency control approach in this paper. As it can be concluded, from Fig.13. in case of participation of RES in frequency control, less capacity of BESS is used. Due high investment for installation of BESS, reducing capacity is an important challenge.

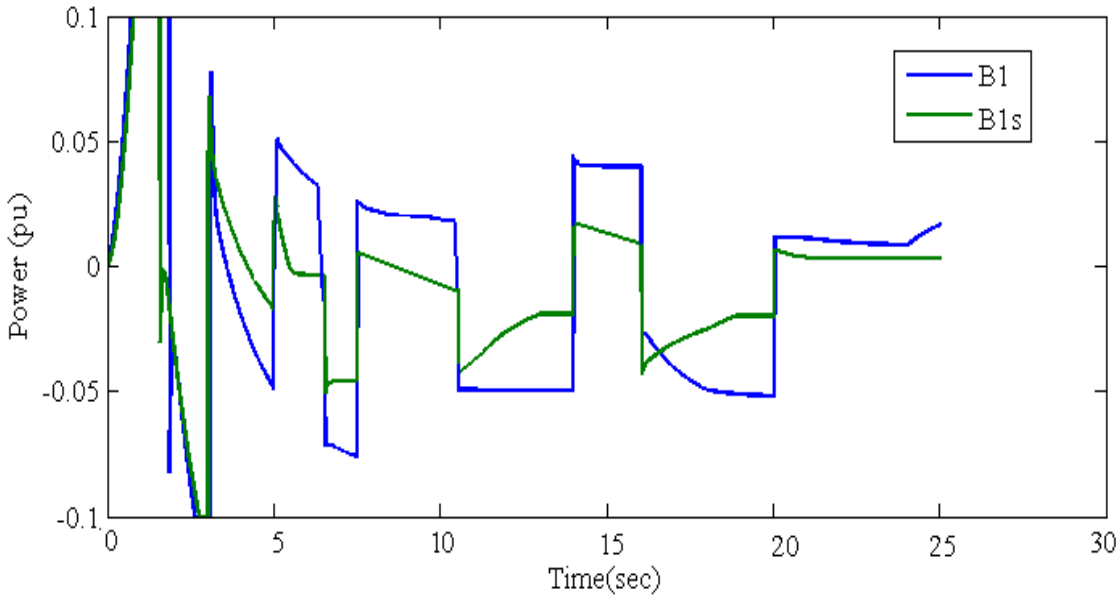

Figure 13: BESS output power with conventional (B1) and proposed (B1s) frequency control approach

Finally, Fig. 14. Shows frequency deviation of study system with conventional and proposed frequency control approach. As it shown, frequency deviation is considerably reduced.

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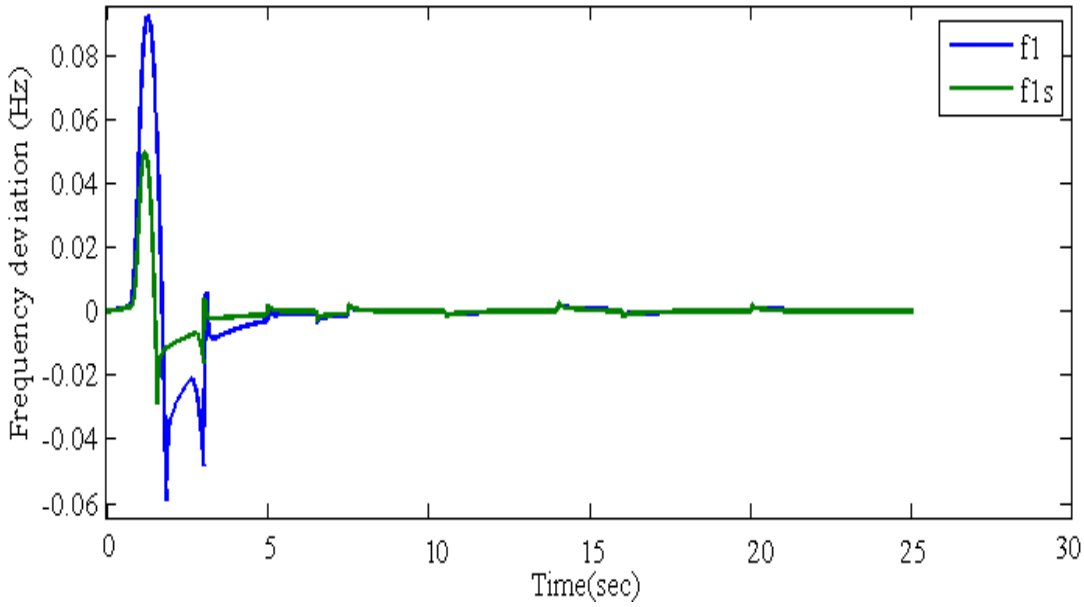

Figure 14: Frequency deviation of study system with conventional (f1) and proposed (f1s) frequency control approach

Fig. 15. Is a magnified version of Fig. 14. To provide a cleare view of improvement in frequency control.

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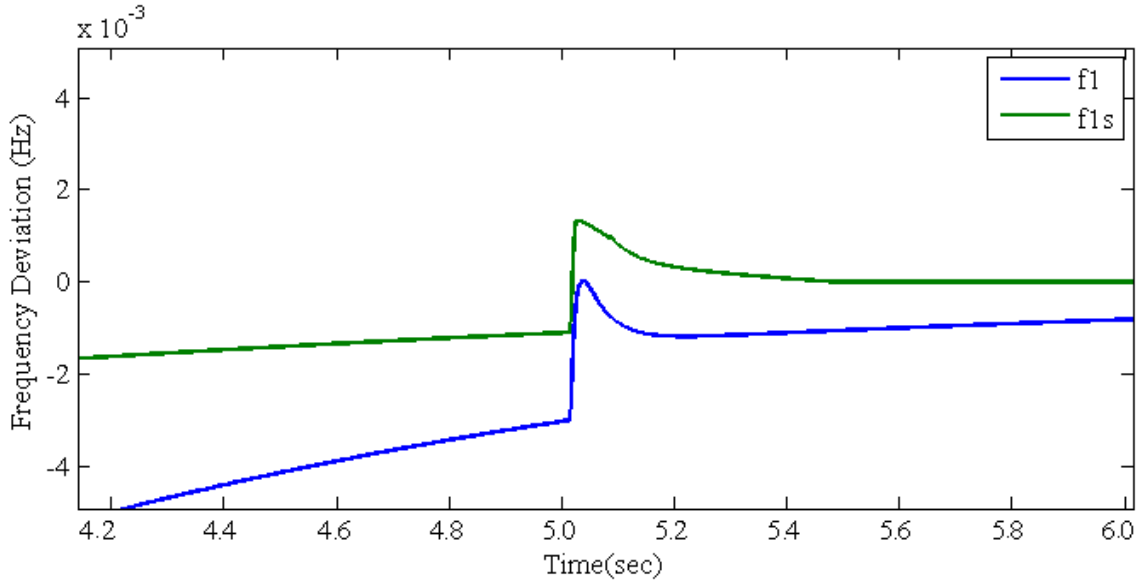

Figure 15: closer view of the frequency deviation of study system with conventional (f1) and proposed (f1s) frequency control

Conclusions

The disadvantage of PV and wind power generation especially in bulk amounts is their unstable power output, which can impact negatively on utility operations. One means of solving this problem is to develop new control strategies to integrate PV, WP and BESS in a way that they can effectively participate in frequency regulation and smoothing the output fluctuation. For this purpose, presented paper introduced a new concept, BVPP, in power dispatch control structure. New algorithms are developed to identify required coordination of control actors including master/slave control centers, TSOs, DSOs and BVPPs. Analysis and simulation results demonstrate the effectiveness of the proposed method in enlarging the stability margin of the power system frequency and reducing the capacity of required BESS.

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Appendix

A

C_p Coefficients α_{ij}: α_{00}=-4.1909e-1, α_{01}=2.1808e-1
α_{02}=-1.2406e-2, α_{03}=-1.3365e-4, α_{04}=1.1524e-5
α_{10}=-6.7606e-2 , α_{11}= 6.0405e-2, α_{12}=-1.3934e-2 ,α_{13}=1.0683e-3 , α_{14}=-2.3895e-5
α_{20}=1.5727e-2 , α_{21}=-1.0966e-2 , α_{22}=2.1495e-3 ,
α_{23}=-1.4855e-4 , α_{24}= 2.7937e-6
α_{30}=-8.6018e-4 , α_{31}=5.7051e-4 , α_{32}=-1.0479e-4 ,α_{33}=5.9924e-6 , α_{34}= -8.9194e-8
α_{40}=1.4787e-5 , α_{41}=-9.4839e-6 , α_{42}=1.6167e-6 ,
α_{43}=-7.1535e-8 , α_{44}=4.9686e-10

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