Frequency Regulation of Micro-grid Connected Hybrid Power System with SMES

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Abstract This paper presents the frequency regulation analysis of a micro-grid connected hybrid power system based on solar Photovoltaic (PV), Wind and Diesel-Engine Generator (DEG) with Superconducting Magnetic Energy Storage system (SMES) unit. Abrupt change in load demand and power fluctuations from PV and wind power source causes frequency variability in the system. In order to mitigate this issue, the hybrid power system incorporates along with the energy storage devices. A case study of the impact of SMES operations on the performance of frequency stability of hybrid system has been carried out. Simulation of a Hybrid Power System (HPS) model has been carried out in two different scenarios with the two phases. First is the steady state investigation of HPS using PI controller with step load change response. Second is the dynamic performance study throughout a typical day with arbitrary variation in load demands. Controller parameters are tuned with Genetic Algorithm based optimization approach. The limits on the inductor (coil) current due to the possibilities of discontinuous conduction in the presence of large disturbances and limited storage capacity have also been incorporated. HPS has analyzed in the Matlab Simulink environment. Simulation results indicate that SMES system

can contribute towards the frequency stability in both cases for variable power generations from renewable sources and irregular demand loads.

Keywords Renewable power · Photovoltaic · Energy storage · SMES · Micro-grid · Frequency stability · Hybrid power system

Introduction

The adverse effect of the greenhouse gases on atmosphere and decreasing fossil fuel reserves drags attentions towards clean and pollution free energy. In modern era, the leading clean energy sources are hydro energy, solar energy, wind energy and biogas mainly [1, 2]. Moreover, generations from the wind and solar have enhanced their contribution in most of the world's electricity generation [3]. The primary application of solar power system is to provide power to the off-grid area where the extension of the grid is not possible. However, wind power is more commonly used for grid integrations. Solar PV arrays have more installation flexibility and can be easily mounted on domestic locations [4]. In the current scenario, the wind, and solar PV power plants are widely deployed for distributed generations and microgrids (MGs). Generated power from PV and wind sources is variable in nature; it can be used to compensate the load demand locally and/or injected into local grids [5]. Renewable technology is also facing a lot of technical, economic and social barriers because of their intermittency nature and uncertainty issues [6]. Moreover, the interconnection of these renewables into the grids/MGs creates some technical problems such as frequency and voltage regulations. Operational issues in distributed system also raised due to high/low penetrations of distributed renewable sources [7]. Therefore,

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these problems need the attention of researchers and regulatory authorities to provide the best feasible solution. In this article, the frequency regulation issue raised during the operation of MG connected HPS has been discussed. The frequency stability of the system is mainly affected by mismatching of load generation balance and irregular loadings. Therefore, energy storage technology has been introduced to mitigate the frequency stability issue in micro-grid. Currently, storage technologies are capable of handling multifunctional tasks as backup powers, active/reactive power injection or absorption from/to the grid [8–10]. The conventional energy storage such as Battery energy storage system, Hydro pump storage, etc. is proposed by various researchers in the literature [11–13]. However, these storages have several problems such as high response time, limited Lifecycle, storage capacity, large unit volume and hazardous environmental impact, etc. Therefore, in this paper, SMES based technology has been proposed for the stable operation of hybrid power system. The potential capabilities such as fast response, inherently huge storage efficiency and injecting/absorbing real or reactive power ability endorse the SMES as a viable solution [14, 15]. The effect of SMES during the transient disturbance condition for a grid-connected power system has been analyzed in [15]. Various authors [15–17] have presented the application of SMES with the on grid and off grid mode. Neural network based frequency control of single and two area system is well documented in [18]. Authors in [19] have been presented the power flow control and management scheme with energy storage devices. A knowledge domain based concept for power flow controller has been discussed in [20]. Various efforts had been carried out by the authors to minimize the frequency fluctuation in hybrid power system with SMES in [4, 5, 21].

This paper presents the extension work performed previous research work in [16]. However, for the aspect of novelty of the following additional work has been incorporated in this paper. (I) Small stability analysis of the solar based hybrid system with step load response (II) System frequency response has been controlled with PI controller. (III) Controller parameters are tuned with Genetic Algorithm based optimization approach. (IV) An additional hybrid power system based on purely renewable power generation is analyzed with SMES. The effect of SMES during the steady and dynamic state operation has also been discussed in this study.

Description and Modeling of HPS

In this section, description and modeling of hybrid power system have been carried out. Figure 1 shows the schematic diagrams of HPS connected to the microgrid. HPS is categorized in three parts as follows:

Fig. 1 Schematic diagram of hybrid Power system with SMES

- i Power Generation Sources (Solar PV, Wind, and DEG)
- ii Storage System
- iii Power Conditioning System (PCS) and load Demand.

Power generation sources and storage facility have connected to the local grid. SMES has been consumed and supplying power from the local grid. Modeling of different power generating plants such as PV, wind, DEG, and storage system has been carried out below in this section. Modeling of PCS system has not been considered in this study. It is assumed that all required PCS system is working properly in the system. The system model is also useful for distributed and isolated mode of operation.

Solar Photovoltaic Model

The Solar PV system is composed with PV arrays, connections and protective parts [13]. Arrays are the combination of solar cells. The equivalent circuit of a PV cell is the combination of a current source in parallel with a diode. The current source output is directly proportional to the light falling on the cell. The equation of ideal solar cell [1, 7] that symbolizes the solar cell model is [13]:

$$I = I_L - I_R \left[\exp \left(\frac{V}{AV_i} \right) - 1 \right] \quad (1)$$

Fig. 2 Wind speed to power generation model [23]

Fig. 3 Schematic diagram of the SMES unit

where: “ I_L ” is photocurrent (A); “ I_R ” is reverse saturation current (A); “ V ” is diode voltage (V); “ V_i ” is thermal voltage, “ A ” is diode ideality factor. The composition of solar cells in series and parallel combination with their protection device is known as the solar module [13]. Current-voltage characteristic equation of equivalent circuit for a PV module arranged in series N_s and parallel N_p can be defined as [7, 22]:

$$I^M = N_p I_L - N_p I_R \left[\exp \left(\frac{V^M / N_s + I^M / N_s}{A V_i} \right) \right] - \frac{(N_p / N_s) V^M + I^M R_{Se}}{R_{Sh}} \quad (2)$$

“ N_p ” is cells parallel number; “ N_s ” is cells series number. Detailed modeling of PV system has discussed in [1, 13].

Wind Speed to Power Conversion Model

Wind velocity to power conversion model has been used to represents the wind power model. The detailed modeling of wind power has been already discussed in previously reported research work [16]. Wind velocity is the combination of following four components: average speed (v_{wa}),

wind speed ramp (v_{wr}), wind gust (v_{wg}) and wind turbulence (v_{wt}) in general. Therefore, the resultant wind velocity can be given in [12, 23]:

$$v_w(t) = v_{wa}(t) + v_{wr}(t) + v_{wg}(t) + v_{wt}(t) \quad (3)$$

To approximate the fluctuation effects low pass filter is deployed in the wind power conversion model as shown in Fig. 2. The following equation governs the power generated by wind turbine:

$$P_w = c_p(\lambda, \beta) \frac{\sigma}{2} \pi r^2 v_w^3 \quad (4)$$

where c_p is the power coefficient of wind turbine and λ is the tip speed ratio, which is defined by:

$$\lambda = \frac{\omega_T r}{v_w} \quad (5)$$

Diesel Engine Generator Model

Diesel engine power generation is governed by following equation generally.

$$\Delta P_d = - \left(\frac{1}{R} + \frac{K_I}{s} \right) \left(\frac{1}{T_{sg}s + 1} \right) \left(\frac{K_{DEG}}{T_{DEG}s + 1} \right) \Delta f_e \quad (6)$$

Fig. 4 SMES control unit block diagram [16]

Fig. 5 Mathematical model of Micro-grid connected HPS

where, R is the speed regulation. DEG automatically starts up with proper control.

SMES Model

Schematic diagram of SMES model has been shown in Fig. 3. The SMES model has been divided into three parts mainly. First is as superconducting coil i.e. also known as the heart of the system and second deals with power conditioning system. The third is control unit which has been shown in Fig. 4 separately. A detailed description of SMES modeling is well explained in [16, 24]. From Fig. 3, DC voltage is given by:

$$E_d = 2V_d \cos \alpha - 2I_d RC \quad (7)$$

Where E_d is the DC voltage applied to the inductor in KV, α is the firing angle in degrees, I_d is the current flowing through the inductor in kA, RC is equivalent commutating resistance in $k\Omega$ and V_{do} is the maximum circuit bridge voltage in kV [16]. Controlling of charging and discharging of the superconducting coil is done with the altering of commutation angle α . The converter operates in the charging mode (converter mode), when α is less than 90° and in discharging mode (inverter mode) when α greater

Table 1 Parameters of GA

Parameter	Value
Population size	30
Max no. of generation	50
Mutation probability	0.15
Crossover probability	0.8
Length of chromosomes	8 bits
No. of variables	4
Maximum iteration	30

Fig. 6 Flowchart of Genetic Algorithm

than 90° [14, 21]. When there is a drop in frequency, power is supplied back into the system. The direction of current flowing through inductor and thyristor does not change suddenly, so the control voltage is negative in nature. The

Fig. 7 Flow chart of the operation strategy

Table 2 Rating and parameters of hybrid model

Parameter	Value (Rating)
System power rating	2 MW (Base)
Capacity of SMES	2 KA
Initial Inductor current(I _{do})	100KW
Upper limit of Inductor current(I _{dU})	150% of Initial inductor current
Lower limit of Inductor current (I _{dL})	30% of Initial inductor current
M	0.12
D	0.1
K _{DEG}	1
T _{DEG}	0.5s
R	0.5
DEG Power	250KW
Peak PV Power	200 KW
Wind power	160 KW

incremental change in the voltage applied to the inductor is expressed as:

$$\Delta E_d = \left[\frac{K_{SMES}}{1 + sT_{dc}} \right] \Delta F \quad (8)$$

Where, ΔE_d is the incremental change in converter voltage, T_{dc} is the converter time delay, K_{SMES} is the control loop gain and ΔF is the actuating signal to the control unit of SMES. The inductor current deviation (ΔI_d) is calculated by following Eq. 9:

$$\Delta I_d = \frac{\Delta E_d}{sL} \quad (9)$$

The overall change in SMES power flow ΔP_{SMES} due to system frequency (ΔF) change is shown below Eq. 10:

$$\Delta P_{SMES} = \Delta E_d I_d \quad (10)$$

$$I_d = I_{do} + \Delta I_d \quad (11)$$

Where I_d is net inductor current

Fig. 8 Load demand Variations profile

Fig. 9 Temperature Profile throughout a typical day

Mathematical Modelling of HPS

This subsection described the mathematical model of HPS. The transfer function based model of HPS has been shown in Fig. 5. Assumed that, PCS is properly working at their defined positions. Table 1 shows the parameters of HPS used in modeling. The load generation balance must be maintained for the smooth operation of the grid-connected system. The control strategy is determined by the controlling error which is the difference between the change in load demand (ΔP_D) and change in net power production (ΔP_T).

$$\Delta P_T = \Delta P_{PV} + \Delta P_w \pm \Delta P_{DEG} \pm \Delta P_{SMES} \quad (12)$$

$$\Delta P_S = \Delta P_T - \Delta P_D \quad (13)$$

where ΔP_S is net power controlling error.

Following equation finds the change in frequency variation (ΔF):

$$\Delta F = \frac{K_{PS}}{1 + T_{PS}} \cdot \Delta P_S \quad (14)$$

Since an inherent time delay exists between system frequencies. Transfer function for system frequency variation to per unit power deviation is expressed in below equation:

$$\Delta F = \frac{1}{D + sM} \cdot \Delta P_S \quad (15)$$

$$D = \frac{1}{K_{PS}}, M = \frac{T_{PS}}{K_{PS}}$$

Fig. 10 Solar Irradiation profile throughout a day

Fig. 11 PV Power profile for a typical day

Where M = The equivalent inertia constant (p.u) & D = Damping constant (p.u).

Optimal Design of PI Controllers with Genetic Algorithm (GA)

The actuating signal for PI controller is the summation of proportional and integral of the error signal. Gain of PI controller is shown as:

$$G(s) = K_P + \frac{K_I}{s} \quad (16)$$

Where K_P and K_I are the Proportional(P) and Integral(I) gain constant respectively.

Objective Function

The tuning of PI controller depends upon two parameters (K_P & K_I) to regulate the change in frequency error (Δf). The values of PI parameters are calculated through genetic algorithm optimization technique. In order to achieve, optimum system response and to minimize the frequency error integral time square error method is used here as shown below:

$$F(X) = ITES = \int_0^\infty t * (\Delta f)^2 dt \quad (17)$$

X is the variable in terms of the values of K_P and K_I . The optimal values of PI parameter are determined with the genetic algorithm optimization technique.

Genetic Algorithms

Genetic algorithms (GA) are a biologically inspired algorithm. GA search algorithm is based on the mechanics of natural selection that copycats biological evolution. GA

Fig. 12 Wind Power profile through a day

combines the survival of the fittest among string structures with a structured randomized information exchange to develop a search algorithm with the innovative flairs of human search. Generally, GA used to find out high-quality optimization and solution in search problems. In each iteration, a new set of artificial string is formed using bits and pieces of the fittest of the previous [25, 26]. A simple GA that produces good results in many real-world problems is composed of three operations as 1) Selection or Reproduction. 2) Crossover. 3) Mutation. Reproduction or selection is a process in which individual strings are copied according to their objective function values. After reproduction, simple crossover carried out in two steps. First, a member of newly reproduced strings in the mating pool is mated at random. Second, each pair of strings undergoes crossing over as an integer position. Mutation operator shields beside irrecoverable loss [25]. Figure 6 shows the flowchart of Genetic Algorithm.

Step Procedures

Step procedure used for tuning of PI controllers with GA is shown below

- i. Initialize the population for variables(x) with 8 bits length of chromosomes for each one. Size of the population is in between 15-30 and set iteration (r) =1
- ii. Calculate the fitness function based on Eq. 9 for all candidate solutions.
- iii. Sort all the fitness functions in ascending order. $[F_1^r(x), F_2^r(x), \dots, F_p^r(x)]$, Best cost = $F_1^r(x)$, best candidate solution = x , where r is no of iterations.
- iv. Set the probability of chromosomes and mutation
- v. Select all the parent chromosomes and apply crossover on each candidate solution
- vi. Apply mutation to the all chromosome
- vii. Again calculate fitness function for all candidate solution and sort them in ascending order $[F_1^{r+1}(x), F_2^{r+1}(x), \dots, F_p^{r+1}(x)]$,

Fig. 13 Frequency Response with increased step load (peak load.)

Fig. 14 SMES power injection response during the peak load (0.25p.u.)

Fig. 15 Frequency Response with decreased step load (Off peak load.)

Fig. 16 SMES power consumption response during the off peak load

- viii. If, $F_1^{r+1}(x) < \text{Best Cost}$, Update Best cost = $F_1^{r+1}(x)$ & best candidate solution = x , Else, best cost = best cost
- ix. Put $r = r + 1$, if no of iteration(r) < max_iter, go to step 2

Else, stop and store best cost and best candidate solution.

Parameters of GA used to tune the PI controllers are given in Table 1.

Operating Strategy

In this section, operation strategy for considered HPS is discussed and flow chart has been shown in Fig. 7. The system/grid frequency is very sensitive to load demand change. Therefore, whenever variations in load demand occur, system frequency changes according to it. Grid frequency must lie within the acceptable range for stable and smooth operation of HPS. In order to neutralize, the frequency fluctuations, the power supply should be controlled according to load variations. When the frequency of the grid is reported below 50 Hz or change in frequency is negative, SMES starts injecting the power into the grid. However, SMES

Fig. 17 Variation of SMES Power in both charging & discharging mode

Fig. 18 Change in DEG. Power output

unit must check the status of superconducting coil current (I_d) and verify its capacity to lower limit of the inductor current (I_{dL}). If $I_d > I_{dL}$, SMES will turn on and start discharging; otherwise, it will remain in off mode. In another case, when the frequency of the grid is reported above 50 Hz or change in frequency is positive, SMES starts absorbing (charging the SMES coil) some excess power from the grid. Before consuming the power, I_d has to check and compared to its upper limit of the inductor current (I_{dU}). If $I_d < I_{dU}$ then SMES control unit allows to charge the coil otherwise SMES remains in off mode. During constant frequency operation (change in frequency zero), SMES neither in charge mode nor in discharging mode. It stays remains in standby mode conditions.

Simulation Results and Analysis

In this section, simulation results of considered HPS have been analyzed. Parameters and system ratings has been shown in Table 2. Simulations of HPS are carried out in two different scenarios as follows:

- A. Scenario 1- HPS with Solar PV+DEG+SMES
- B. Scenario 2- HPS with Solar PV+Wind+SMES

Each scenario is simulated in two phases of studies. The first phase is the steady-state stability analysis using step load

Fig. 19 The frequency response of the system throughout the day

Fig. 20 Frequency Response with increased step load (peak load.)

response of system model. The second is the dynamic stability analysis with 24 hours simulations with random variation in load demand. Phase I is further divided into two cases as step load analysis during the peak load and off-peak load time. Variations of a typical day load demand have been shown in Fig. 8. The temperature and solar irradiations variations for a typical day have been shown in Figs. 9 and 10 respectively. The power produced with PV and wind plant has been shown in Figs. 11 and 12 respectively.

Scenario 1- HPS with Solar PV+DEG+SMES

Scenario 1, consists the study of HPS containing the solar PV, DEG, and SMES storage facilities. The penetration of

solar power is hundred percentage of generated PV power. The study of this scenario is carried out in two phases with two cases as discussed below:

Phase I: Steady state Stability Analysis

Considered HPS is analyzed through step load change response during peak and off-peak load demand with the presence or absence of SMES. The system is simulated for the duration of has carried 30 seconds.

(i) Case I: During peak load

Step load change of 0.25 p.u is considered for the analysis of this cases. Due to a sudden rise in load demand, the frequency will go down to below a defined limit. Therefore, to maintain the system

Fig. 21 SMES power injection response during the peak load (0.25p.u.)

Fig. 22 Frequency Response with decreased step load (Off peak load.)

frequency, SMES will start supplying the power into the microgrid. Because of this act, SMES is operating in the discharging mode. Frequency response with the sudden increase in step load demand has been shown in Fig. 13. The effect in frequency response with, without SMES and with GA-PI controller is shown the Fig. 13. From Fig. 13 it is observed that frequency deviation is minimized maximum during the operation of HPS with the combination of optimized controller and SMES. Power injected by the SMES has also shown in Fig. 14.

(ii) Case II: During off peak load

Step load change of 0.045 p.u. has been considered for the analysis of this cases. Due to a sudden decrease in load demand, there is a rise in system frequency is reported. However, to compensate this frequency fluctuations, power generation should be minimized or/and store the energy in SMES. In order

to maintain the system frequency, SMES will start consuming the power from the microgrid. This state of SMES is known as the charging mode. The effect in frequency response with, without SMES and with GA-PI controller is shown the Fig. 15. From Fig. 15 it is observed that frequency deviation is minimized maximum in the operation of HPS the combination of optimized controller and SMES. Power absorbed by the SMES with negative sign has also shown in Fig. 16.

Phase II: Dynamic Simulations for 24 Hours

The considered HPS model has simulated for 24 hours in this phase of the study. The dynamic stability study is carried out with varying load demand and power generations throughout a day. The study is further divided into two cases, i.e. during the increase in load and decrease in load demand.

Fig. 23 SMES power consumption response during the off peak load

Fig. 24 Frequency response of the system throughout the day

(i) **Case I: Increase in load demand**

Due to increase in load demand, system frequency decreases. Therefore, power generation should be increased to maintain the frequency. PV power is regularly supplying the power to the system. Due to dip in system frequency, DEG power can be enlarged to supply the power to the system, up to its rated capacity. To compensate the load demand, SMES supplying power to the system as shown in Fig. 17.

(ii) **Case II: Decrease in load Demand**

Change in frequency increases, as a change in load demand, decreases. So, in order to maintain frequency, the total power generation should be decrease and/or increase the load consumptions. Due to variation in frequency, the net change in DEG power shown in Fig. 18. Power supplied by SMES should be decreasing response reached zero as shown in Fig. 17. However, the surplus power is still more than load demand so for balancing power SMES starts consuming power from the system. Now SMES is in charging mode.

Figure 19 shows the frequency response of the considered HPS including both increase and decrease of the load demand with and without SMES throughout a day. From Fig. 19, it can be observed that frequency fluctuations can be mitigated with the addition of SMES into the system.

Scenario 2- HPS with Solar PV+Wind+SMES

Scenario 2 consists the study of HPS containing the solar PV, Wind and SMES storage facilities. HPS system is also known as 100% power generations from renewable. The penetration of solar power is fifty percentage of generated PV power. The study of this scenario is carried out in two phases with two cases as discussed below:

Phase I: Steady state Stability Analysis

Considered HPS is analyzed through step load change response during peak and off-peak load demand with the

Fig. 25 SMES Power variation in both charging & discharging mode

presence or absence of SMES. The system is simulated for the duration of has carried 30 seconds.

(i) **CASE I: During peak load**

Step load change of 0.25 p.u. is considered for the analysis of this cases. The operation of the system is same as discussed in Case I of Phase I of Scenario 1(HPS with Solar PV+DEG+SMES). The effect in frequency response with, without SMES and with GA-PI controller is shown the Fig. 20. From Fig. 20 it is observed that frequency deviation is minimized maximum during the operation of HPS with the combination of optimized controller and SMES. Power injected by the SMES has also shown in Fig. 21.

(ii) **CASE II: During off peak load**

Step load change of 0.045 p.u. has been considered for the analysis of this subcase. The operation of the system is same as discussed in Case II, Phase I of Scenario 1(HPS with Solar PV+DEG+SMES). The effect in frequency response with, without SMES and with GA-PI controllers are shown in the Fig. 22. From Fig. 22, it is observed that frequency deviation is minimized maximum, in the operation of HPS with the combination of optimized controller and SMES. Power absorbed by the SMES has also shown in Fig. 23.

Phase II: Dynamic Simulations for 24 Hours

The considered HPS model has simulated for 24 hours in this phase of the study. The dynamic stability study is carried out with varying load demand and power generations throughout a day. The operating scheme in this phase is similar to previous section phase II of Scenario 1- (HPS with Solar PV+DEG+SMES). However, in this study, DEG is not incorporated. Frequency response throughout the day has shown in Fig. 24. SMES power profile during both the charging and discharging mode has shown in Fig. 25. From the above figures, it is

demonstrated that fluctuations in system frequency can be smoothened or mitigate perfectly with the integration of SMES units.

Conclusion

The mitigation of frequency fluctuations in micro grid connected PV, wind based hybrid power systems has been analyzed with SMES technology. The performance of the considered system has been assessed with the variable load demand and renewable power sources. The small signal stability analysis is carried out with and without PI controllers. The parameters of PI controllers is optimized with genetic algorithm. Simulation results demonstrates that SMES based system gives better frequency response in comparison to the only diesel generator and without SMES. However, it seems that SMES technologies are not so much economically. However, this issue may compensate with its fruitful applications such as fast response, high efficiency, capability of control of real power and reactive power flows. With the emergence of smart grids, this technology is receiving more attention in the field of power and energy systems. Therefore, it is hoped that its potential advantages and environmental benefits will make SMES units a viable alternative for energy storage source.

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