Automatic Load Frequency Control in an Isolated Micro-grid with Superconducting Magnetic Energy Storage Unit using Integral Controller

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Abstract. Due to depletion of fossil fuels and increasing power demand, employing Renewable Energy Sources (RES) in the form of micro-grid has become very essential. However, the reliable operation and control relies on the intermittent nature of RES and maintaining the frequency within the acceptable limit is the challenging task in isolated micro-grid. This paper presents the Automatic Load Frequency Control (ALFC) in an isolated Micro-Grid (MG) with Superconducting Magnetic Energy Storage (SMES) unit using Integral controller, to enhance the stability of the system frequency. The simulation result shows that the dynamic performance of the proposed system is significantly improved while incorporating the SMES Unit. The simulations are carried out in MATLAB –Simulink.

1. Introduction
Micro-Grid is an autonomous power system which includes renewable sources and backup by controllable sources. The major benefits of an isolated micro-grid are high reliability, reduced emissions and high energy consumption efficiency. However, with random variations in load, photovoltaic and wind power are sporadic, random and unpredictable, which results in a significant deviation in frequency from the rated value. The above-mentioned issues are solved by Load Frequency Control (LFC). LFC aims at minimizing the mismatch between the power generation and demand thereby maintaining the system frequency deviations within the specified limits. Energy Storage System is used to enhance the dynamic performance of the system and its stability. In the recent years, lot of research are carried out in this field as follows.

A Fractional Order Proportional Integral Derivative (FOPID) controller for frequency control in micro-grid is presented and also proved that Grasshopper Optimization Algorithm (GOA) based FOPID controller is superior [1]. For LFC in an islanded micro-grid, Artificial Bee Colony (ABC) optimization algorithm is used to develop an intelligent Terminal Sliding Mode Control (TSMC). And also proved that the proposed control approach is superior in damping out frequency oscillations when the system is subjected to severe disturbances [2]. A robust LFC for islanded microgrid through high wind power penetration is addressed with a novel optimal PID controller using genetic moth swarm algorithm [3]. A novel LFC model of hybrid micro-grid has been developed [4]. The frequency regulation of a micro-grid is investigated using a new dual stage adaptive controller [5]. The
combination of ultra-capacitor and SMES devices with distributed generation and electric vehicles results in enhanced dynamic performance [6]. A fuzzy based model predictive control is employed in order to get efficient frequency regulation of typical microgrid [7]. A fuzzy logic controller with Teaching Learning Optimization (TLO) is employed to solve the frequency control issues in self-contained micro-grid [8]. A robust LFC approach for micro-grid in autonomous mode of operation is introduced. A novel fuzzy logic with improved harmony search algorithm is used to tune the PI – controller. And also, the simulation outcomes proved the efficacy of the proposed controllers [9]. The isolated micro-grid system’s LFC model is created, and the AGC controller is developed using the reinforcement learning process [10]. An Adaptive Neuro – Fuzzy based LFC in autonomous micro-grid is introduced. In addition, the proposed intelligent controller's output is compared to that of conventional & fuzzy PID controllers [11].

2. Modelling of Isolated Micro-grid

![Mathematical Model of an Isolated Micro-grid](image)

**Figure 1.** Mathematical Model of an Isolated Micro-grid.
Figure 1 shows the mathematical model of an isolated micro-grid which includes Diesel Engine Generator (DEG), Wind Turbine Generator (WTG), Photo-Voltaic (PV) system, Fuel Cell (FC), SMES unit, Battery Energy Storage System (BESS) and Load.

2.1. DEG Model
The power generation due to solar and wind, depends on wind speed and solar radiation which are random in nature. The power deficiency is met by diesel engine generator in order to keep the generation-load balance of an isolated micro-grid. The mathematical model of diesel engine generator is shown in figure 2.

![Figure 2. Mathematical Model of DEG.](image)

2.2. WTG Model
The output power of wind turbine generator is depending on wind speed which introduces non-linearity in the system. In order to minimize the frequency oscillations, pitch controller is used in wind turbine. Figure 3 shows the transfer function model of wind turbine generator by neglecting all non-linearities in the system.

![Figure 3. Transfer Function Model of WTG.](image)

2.3. PV Model
Photo-Voltaic array includes the combination of multiple modules which are connected in series & parallel. This series and parallel mixture depend on the coveted voltage and current rating of the micro-grid. In PV system, the ratio of voltage to current is non-linear in nature. In general, the PV array's output capacity can be varied either by change in load current or by solar radiation. Whereas here, the PV array's output capacity varies only because of solar radiation is considered. Figure 4 depicts the PV system’s transfer function model.

![Figure 4. Transfer Function Model of PV System.](image)
2.4. BESS Model
Whenever sudden change in load occurs in micro-grid leads to frequency deviations which are exceeded the acceptable limit due to sluggish response of diesel engine generator. To overcome the above issue, BESS is introduced which helps to damp out the frequency oscillations. Figure 5 shows the mathematical model of BESS.

![Mathematical Model of BESS](image)

**Figure 5.** Mathematical Model of BESS.

3. Modelling of SMES Unit
The energy is stored in the SMES unit as a magnetic field. Superconducting coil is charged to a fixed value during regular grid operation, which is lower than the maximum utility grid charge. The Power Conversion System (PCS) consists of Inverter/Rectifier which is used to connect the superconducting coil with the AC grid. The coil conducts current without substantial loss once it has been charged. The energy that has been accumulated is returned to the AC grid with the help of PCS. Once meeting the required demand, the coil reverts to its initial current value. Frequency deviation (ΔF) is an input signal to the SMES unit. The mathematical model of SMES unit is shown in figure 6.

![Transfer Function Model of SMES unit](image)

**Figure 6.** Transfer Function Model of SMES unit.

4. Integral Controller Model
The integral control is made up of frequency sensor & integrator. To detect the frequency error (ΔF), a frequency sensor is used. In an integral control loop, the frequency error provided to the integrator is known as Area Control Error (ACE), which forces the steady state frequency error to zero. The transfer function model of an integral controller is shown in figure 7. The optimum integral gain (K_I) has to be calculated with the assistance of integral square error technique and its objective function is given by $J = \int_0^\infty (\Delta F)^2 dt$.

![Mathematical Model of Integral Controller](image)

**Figure 7.** Mathematical Model of Integral Controller.
5. Results and Discussion

Figure 8. Automatic Load Frequency Control in an Isolated Micro-grid without SMES unit using Integral Controller.
Figure 9. Automatic Load Frequency Control in an Isolated Micro-grid with SMES unit using Integral Controller.
Figure 10. Performance Index Curve for Optimal $K_1$ (Without SMES unit).

Figure 11. Performance Index Curve for Optimal $K_1$ (With SMES unit).

Figure 12. Frequency Deviation in an Isolated Micro-grid.
The simulation diagram of Automatic Load Frequency Control in an Isolated Micro-Grid without & with SMES unit using Integral Controller are shown in figure 8 & 9 respectively. The optimal values of integral controller gain ($K_I$) for both the systems (without & with SMES unit) are found by Integral Square Error (ISE) technique and it is illustrated in figure 10 & 11 respectively. Figure 12 shows the frequency deviation of the proposed micro-grid with & without SMES unit. All the simulations are performed in MATLAB/Simulink software and the system parameter values & optimized controller gains are given in appendix. The results of the simulation show that the system with SMES unit yields the improved dynamic performance (frequency oscillations, peak overshoot & settling time) than that of the other system.

6. Conclusion
Automatic Load Frequency Control is a simple and effective method to control the system frequency. In this paper, Automatic Load Frequency Control in an isolated micro-grid with SMES unit using integral controller is analysed. The integral controller gains are determined with the help of integral square error technique and the system performance is observed for the step load perturbation of 0.2 p.u. The simulation result shows that the dynamic performance of the system (such as frequency oscillations, peak overshoot & settling time) is significantly improved in the system with SMES unit.

7. Appendix

| Table A1. Optimized controller gains & System parameters. |
|-------------|-------------|-------------|
| Parameter   | Value       | Parameter   | Value       |
| $K_I$ (Without SMES) | 0.5         | $K_{SMES}$ | 1           |
| $K_I$ (With SMES)   | 0.95        | $T_{SMES}$ | 0.0181 s    |
| $T_1$           | 0.025 s     | $K_{FC}$   | 0.01        |
| $T_2$           | 2 s         | $K_{BESS}$ | 1.5         |
| $T_3$           | 3 s         | $K_{WTG}$  | 1           |
| $T_{FC}$        | 4 s         | $K_{PV}$   | 1           |
| $T_{BESS}$      | 0.1 s       | R           | 2.4 pu Hz/MW|
| $T_{WTG}$       | 2 s         | M           | 0.1667      |
| $T_{PV}$        | 1.5 s       | D           | 0.015       |
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