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Sizing and operation of pumped hydro storage for isolated microgrids

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Abstract

Energy storage has an effective role on establishing isolated microgrids (MGs) that contain intermittent renewable energy sources. Energy storages depending upon their technologies can ensure stable and reliable operation, control, and resiliency of the MGs. Therefore, it is indispensable to study MGs operation using appropriate, cost effective and sustainable energy storages along with necessary control. In this paper, sizing, operation and control of a suitable energy storage method for a case study MG system is presented. Due to the excellent geographical location of the case study MG system, a pumped hydro storage is selected; and the sizing of this storage unit is provided using mathematical models that is based on the system physical dimension. In addition, governor-excitation control based on power-frequency droop is designed for the pumped hydro storage unit. The controller performance is tested under various load changes in the MG and the results are presented to show the effectiveness of the designed controller. The performance of the MG frequency and the voltage at the MG bus under load disturbances indicate that the proposed pumped hydro storage is capable to maintain stable operation of the study MG system. Sizing outcomes and performance analysis of the designed controller have been carried out using MATLAB/Simulink software package.

Keywords: Microgrids, renewable energy, pumped hydro storage, energy storage, sizing, operation and control

1. Introduction

Microgrid (MG) is an integral sub-system of a smart grid network that interconnects multiple different power generations, storages, and loads, and has the ability to operate as one controllable unit [1]. MG system can operate with or without the presence of the utility grid. MG operation in conjunction with the utility grid is called as grid connected MG, and MG operation without the presence or connection of the utility grid is called isolated or standalone MG. MGs offer a wide range of benefits such as resiliency, reliability, ability to integrate renewable or alternative energy sources, increase efficiency, and provide grid support [2]. However, operation and control of a MG system without the presence of the utility grid is challenging because it requires sufficient energy storage to ensure power demand by the load, and to maintain MG system voltage and frequency at its appropriate operating level [3, 4].

Energy storage plays an important role in operation and control of MG voltage and frequency when MG operates without the presence of the utility grid [5, 6]. An appropriate energy storage with proper control techniques can provide reliable and efficient power balance between the generation and the load in an isolated MG. Energy storage can improve isolated MG system reliability, reduce load shedding, and maximize the use of intermittent energy sources available in the MG. In addition, the type and proper size of the energy storage are also important for an isolated MG with intermittent energy sources since the frequency and amplitude of the available renewable energy sources are varying stochastically [7].

Various storage technologies, which are based on electrical, mechanical, chemical, and thermal system, can be utilized to store energy for many applications. Such applications include energy arbitrage, load

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following, spinning reserve, voltage support, frequency regulation, power quality, power reliability, peak shaving, time shifting, smoothing, and firming of renewable energy use, and isolated services [8, 9]. However, the integration of energy storages with isolated MGs has underlying issues related to technology selection, sizing, and of course their operation and control [10]. Over the last decade, the utilization of suitable energy storage for isolated MGs although has become interesting, yet challenging research topic.

Techno-economic analysis of a community scale renewable source based MG using battery storage is investigated in [11, 12]. In [13], energy management of a photovoltaic (PV)-battery based MG is presented, where it was shown how PV system with battery storage can operate as a MG. The design and control of a PV-wind-battery based MG is examined in [14], and energy management and control of a laboratory scale PV-wind-battery based MG was conducted in [15]. In [16], a central controller for efficient energy management of a PV-wind-biomass-battery based MG has presented. Aziz et al [17] have investigated the feasibility of combined dispatch control strategy for a battery storage PV-diesel MG system. An optimal design of a PV-wind-diesel MG system using battery storage for a mountain house application is conducted in [18].

An alternative to battery storage, flywheel energy storages gain popularity for MG applications because of its higher lifetime and does not depends on charging or discharging cycle [19]. In [20], flywheel energy storage is integrated for ensuring critical load supply during isolated operation of a MG. A conceptual design of a liquid-based flywheel energy storage with variable inertia for MG application is proposed in [21]. The development of a simplified flywheel energy storage model and its controls for MG application is conducted in [22], where the flywheel energy storage is highlighted as more efficient energy storage technique as compared to the battery storage medium. Arani et al have developed a droop-based controller for flywheel energy storage to tackle transient power balance in a MG system [23].

In [24], compressed air energy storage is applied for frequency regulation of a MG system. It is reported in [25] that the compressed air energy storage combining with other energy storage would provide better energy management in MGs in terms of energy capacity, energy density, storage duration, and efficiency. Zhang et al have investigated compressed air energy storage for a PV-wind-diesel MG [26], where the storage is shown as a reserve source for reliable operation of the isolated MG. The compressed air energy storage has unique characteristic such as high capacity and long-duration compared to the other storages that makes it suitable for isolated MG applications, as proclaimed in [27]. A support system using super capacitor based storage is studied in [28]. The large-scale energy storage using super capacitor is restricted due to its fast charging and discharging characteristics e.g. in between millisecond to second [29]. Thus, the application of super capacitor in conjunction with other type of storages that is called hybrid energy storage are presented in [29, 30-32]. A few study based on superconducting magnetic energy storage for enhancing MG operation and controls are reported in [33-35]. Thermal energy storage for MG applications are presented in [36-38]. Using hydrogen to support energy back up for microgrid operation are investigated in [39-42].

The pumped hydro storage for a wind-solar hybrid system is investigated in [43], where it is shown that this storage based hybrid system has potential of establishing fully energy automated power network. In [44], with the optimal scheduling of pumped hydro storage and implementing demand response, economical and technical performance indexes of an isolated MG are significantly enhanced. Pumped hydro storage is used as an aid to develop an energy management system for high penetration solar PV generation in smart grid application is investigated in [45]. Jing et al showed that the utilization of pumped hydro storage in MG could replace the battery storage and reduce the investment cost of a MG [46].

Literature survey reveals that battery storage to deal with intermittency of renewable power sources has vastly investigated. While deployment of battery storage for renewable power applications is growing gradually, it is reported that pumped hydro storage is a proven and cost effective technology to store energy for a longer period and at a higher capacity [27, 47]. However, the major limitation of the pumped hydro storage is the availability of the reservoir, or the area and cost required to build the reservoir near the generating station. Thus, the utilization of pumped hydro storage can be considered if the reservoir is available in the location of the possible MG establishment. The case study MG presented in this paper avail this favor of using the existing reservoir in order to store energy when it is available from the wind generation system. However, the sizing of the pump hydro storage is crucial because of limited size of the available reservoir. This paper presents sizing of the pumped hydro storage for a MG application and examine the operational viability of the MG using pumped hydro storage.

2. Microgrid System Description

Fig. 1 shows the study MG system, which is located in St. John's, Newfoundland, Canada. The total average load demand (P_{L1} and P_{L2}) in the MG system is 6.76 MW. The hydro generation unit (HGU) and the wind power generation unit (WPGS) are two main sources of power generation in the MG that can meet the load demand P_{L1} and P_{L2}. HGU is able to produce 5.3MW, which operate at a flow rate of 14 m^3/s and at a head of 54.8 m. The power generation from the hydro system hardly varies over a year because of steady water reserve in the upper reservoir. This indicates that the HGU is a firm power generation plant in the study MG system. The WPGS represents a 27 MW wind firm that has nine wind turbines and each of them rated at 3 MW [48]. However, in this isolated MG system, only 2 wind turbines (6 MW) will operate due to the stability issue and lack of sufficient reactive power required by the wind turbines. Since there is an uncertainty of power generation by the WPGS due to lack of wind speeds, the MG will face energy deficiency when sufficient wind speed is not available. On the contrary, the MG will attain excess energy during the operation of WPGS because of the light load in the system. Moreover, the WPGS operates at maximum power extraction so that all power generated by the WPGS will be delivered to the load, which would produce an excess energy. Therefore, there is an opportunity to utilize excess energy to pump water into the existing upper reservoir when WPGS produces power and latter to utilize this water potential to generate electricity in order to meet the load demand when WPGS is not available. A 21.2 km transmission line TL1 connects the HGU and the WPGS. The motor M represents the load of a motor-pump set that requires pumping water into the upper reservoir. The hydro storage unit (HSU) is the electricity generating plant, which will use the pumped water potential to produce electricity when WPGS is not available.

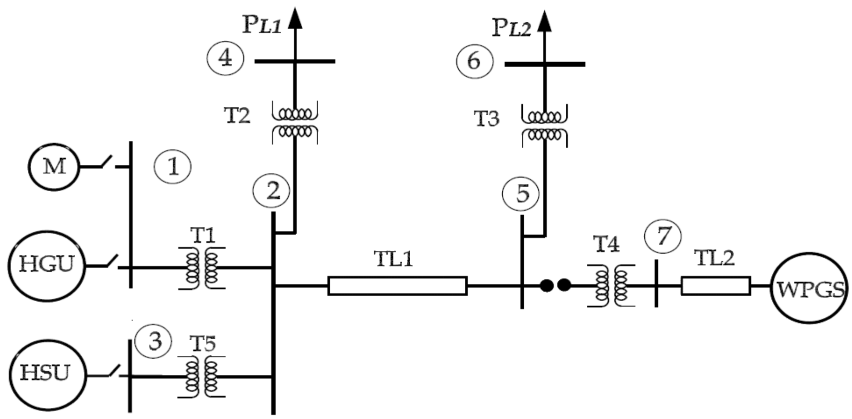

Fig. 1. Generation units and components of the study microgrid system

3. Hydro Storage Unit (HSU) Sizing

Sizing of an energy storage unit for MG applications has influence on cost of the MG establishment, reliability of supplying power demand, and tackle intermittency effect of the renewable sources [8, 9]. The pumped hydro storage system is sized based on the power requirement of the isolated MG system.

The total average load demand in the MG system is 6.78 MW. As mentioned, the HGU is a firm generation unit and has the ability to produce 5.3MW over the year. This generation unit is called firm and produce it rated real power because of the steady water flow rate through the penstock over the year. The shortage of power demand in the isolated micro-grid system while WPGS is not available is about 1.48 MW. Therefore, it is required to supply the shortage amount of power in the MG from the HSU. The power requirement for motor-pump sets to store water in the upper reservoir, and power generation capacity supplied by the HSU using reserved water are calculated as follows.

3.1. Power required for motor-pump sets

It is assumed that a 1 m diameter steel pipe is used to pump water at a 54.8 m height with a 4 m^3/s flow rate. The water velocity is determined as given in [49]

$$v = \frac{4Q}{\pi d^2} = 5.1\, m/s \tag{1}$$

where Q is the flow rate of the water , and d is the diameter of the pipe or penstock.
The Reynolds number, R_e for a steel pipe is found by

$$R_e = \frac{\rho_w v d}{\mu} = 5.1\times 10^6 \tag{2}$$

Relative roughness of the steel pipe is calculated as

$$\frac{\in (\mathrm{mm})}{d(\mathrm{m})} = 0.5\times 10^{-4} \tag{3}$$

The Reynolds number and the relative roughness of the steel pipe are fitted into the Moody's diagram, and thus the friction factor for the selected pipe is found to be 0.017 [54].
The head loss, H_L is thus determined as

$$H_L = \frac{flv^2}{2gd} = 1.23\, m \tag{4}$$

Hence, the total head required for lifting water by the motor is

$$H_t = (54.8 + 1.23) = 56.03\, m$$

The power required at the pump impeller, P_{imp} is calculated as

$$P_{imp} = \frac{9.8\mathrm{QH}_t}{0.75} = 2.92\, MW \tag{5}$$

Considering the motor efficiency is 90 percent, the power required at motor input, P_m is 3.25 MW.

The power required to run the motor-pump set comes from the isolated MG system while the micro-grid has surplus power. A motor-pump set is required to turn on, depending on how much surplus power is available in the isolated MG system when WPGS is generating power in the MG. The amount of surplus power in the isolated MG system depends on wind speed availability and will vary over the time. An arrangement that consists of at least seven parallel motor-pump sets, each rated at 460 kW, is preferred, rather than choosing a bigger motor-pump set which requires a higher amount of power to turn on. If the isolated MG system has surplus power of about 500 kW, one motor-pump set is required to turn on by the MG supervisory controller. Similarly, other motor-pump sets have to be turned on individually depending upon the available power. Such an arrangement keeps open an opportunity to add more motor-pump sets into MG whenever excess energy is available.

3.2. Generation capacity of HSU

The power generation capacity of the hydro turbine generator in the hydro storage system is determined using a flow rate of 4 m^3/s and a head of 54.8 m. Considering the efficiency of the generator-turbine as 72 percent, the power generation capacity of the hydro turbine generator is calculated as [49]

$$P_{gc} = 9.8\eta_{gt}QH = 1.55 \text{ MW} \tag{6}$$

3.3. Reservoir availability and back up duration

The case study MG system in this paper has an opportunity to utilize the existing reservoir. The area of the water reservoir that is currently available to store water is approximately 3.1 km^2. Considering the reservoir condition, the water level of the reservoir can be raised by 0.5 m with the extra amount of water that will be pumped by the motor-pump set. The total volume of water that can be stored in the reservoir is 1,550,000 m^3. Since the discharge rate of water for generating power is 4 m^3/s, the designed storage system can generate power for 107 hours (approximately 4.5 days) at its rated value of 1.55 MW.

4. Control System for HSU

Fig. 2 represents the study MG system along with the proposed concept of MG control coordinator and the HSU control. Microgrid control coordinator detects the WPGS availability, connects and disconnects the motor-pump set based on the available excess energy, and activates the HSU control when the WPGS is not available. This paper concentrates on verifying the effectiveness of the HSU controller for MG operation.

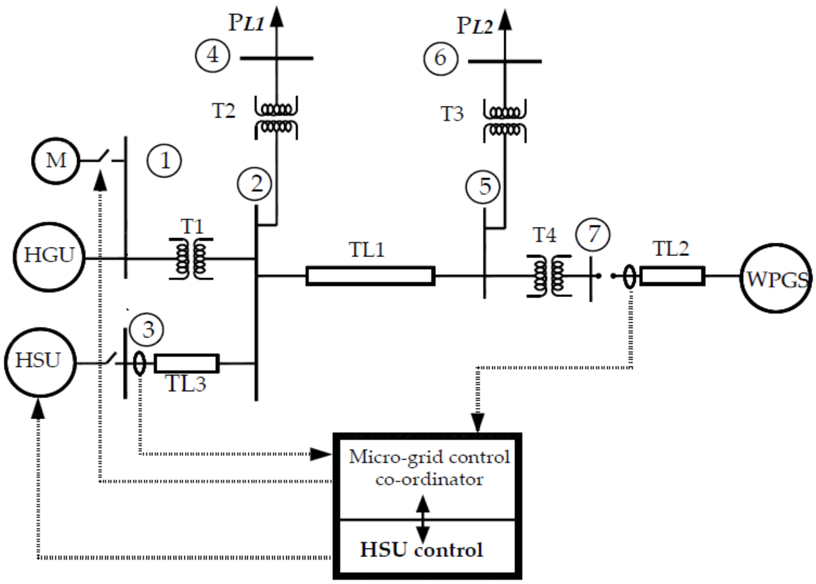

Fig. 2. Control block diagram for the study microgrid system

The concept of energy conversion of a HSU is similar to a conventional hydro generation unit (HGU). The combination of a synchronous generator coupled to a hydro turbine is utilized as the HSU in this paper. The topological similarities between the HSU and HGU are the main motivation to choose the conventional governor and excitation control for the HSU. However, the differences between the HGU and the HSU are in their generation capacities, as well as the operation of the HSU being only on a demand basis and in discrete time. The difference in generation capacities is a result of the differences between the water flow rates and the penstock dimension in HSU and HGU. The on-demand and discrete time factors demonstrate that the HSU needs to operate when WPGS is not available, which can happen at any point of time. Such differences in the operation of the hydro storage system create a challenge to design a control system for storage. However, the similarities between the HGU and HSU allow the conventional governor and excitation control to be applied to the HSU. The function of the governor system in the HSU is to control the frequency of the isolated micro-grid system using the speed and power variation information acquired from the system, while the excitation system is used to control the generator terminal voltage by controlling the excitation voltage in the field of the synchronous generator. Fig. 3 shows detail for controlling frequency and terminal voltage of the hydro storage generator.

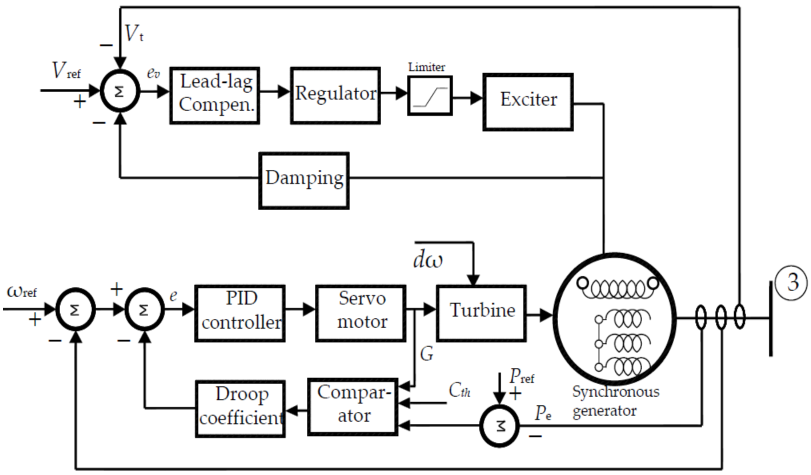

Fig. 3. Detail block diagram representation of the hydro storage unit (HSU) controller

The governor and the excitation system for the HSU are adopted according to [50, 51]. The parameter for the generator unit in HSU is obtained from [52]. In addition, the initial parameter settings for the governor and excitation system are obtained from [53] and are modified according to the requirements of the study MG system in this paper. The desired speed of the synchronous generator is set the reference speed, which is compared with the actual speed of the synchronous generator. The speed error is combined with the output of the droop compensated power deviation or droop compensated gate opening of the valve. The comparator allows information regarding the gate opening of the valve or power deviation based on the comparator threshold, C_{th}. The MG control coordinator sets the threshold such that if the power deviation is more than 0.5 pu, then the gate opening, G will be modulated with droop coefficient. Otherwise, the power deviation will be modulated by the droop coefficient. The droop coefficient is defined based on the power-frequency droop method [54]. The error, e due to the real power deviation or speed deviation is then corrected using PID controller, which is fed to the servomotor model that produces the valve rotation from minimum to maximum gate opening defined in the controller. This gate opening information along with the actual speed deviation with respect to the nominal value are applied to the hydro turbine model. The generator required terminal voltage is set as the reference voltage, which compares with the actual terminal voltage, and the error e_v is then regulated using lead-lag compensator. The regulator, exciter and damping are modeled as a first order differential function as provided in [50].

5. Simulation and Results

The model of the isolated MG system shown in Fig. 2, hydro storage turbine described in Section 3, and detailed control of HSU shown in Fig. 3 are implemented using Simscape power system block sets available in MATLAB/Simulink tool. In addition, the block sets are created when necessary using other available features in the MATLAB/Simulink tool. The simulation is performed for a 100 seconds interval.

The utility grid is isolated from the system at t = 5 seconds because of a fault or regular maintenance in the upstream power line. Therefore, the system constitute as an isolated MG system at t = 5 seconds and onward. Since the WPGS is not available during this operational case, at t = 5 seconds, the HSU is connected to the system to meet the power demand of the micro-grid load. Due to the control action of the HSU as shown in Fig. 3, the frequency of the MG system is managed to be within the acceptable limit. As both the HGU and HSU use the same reservoir to generate power, either generation unit can meet the power shortage in the micro-grid during this operation case. The effectiveness of the HSU control is also examined for a case where a step load is applied or released from the isolated MG system. The amount of the load used for a step change is about 2-7.5 percent. The simulation for a step load change is performed for 150 seconds interval. The grid disconnection occurs at t = 5 seconds, and load rejection and addition occurs at t = 50 seconds and t =100 seconds, respectively.

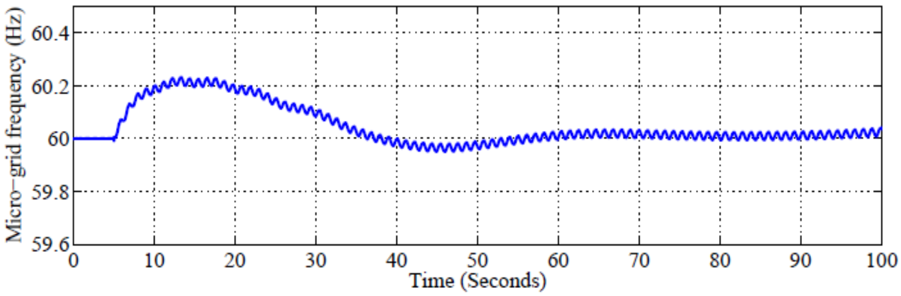

Fig. 4. Micro-grid frequency using governor control in hydro storage system

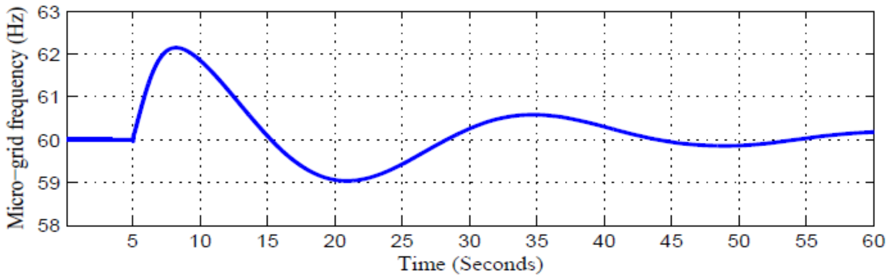

Fig. 5. Micro-grid frequency without using hydro storage system

The simulation results for operation of an isolated MG with HSU are presented in Figs. 4 and 6-8. The performance of the system frequency of the isolated MG with HSU control and without HSU control are shown in Figs. 4 and 5, respectively. The MG system frequency remains at its rated value until t = 5 seconds because the MG was connected with the utility grid for this time period. At t = 5 seconds, the utility grid is disconnected from the system and the WPGS is not available because of insufficient wind speeds. Therefore, the MG becomes isolated with HGU only which requires to operate with storage unit. Fig. 4 shows that the isolated MG system with HSU operates at a desired frequency level because of the power contribution from the storage unit. The frequency deviation is reached to the 60.2 Hz, which sets back to the nominal value within an acceptable time. However, the system frequency of the isolated MG system without HSU shown in Fig. 5 deviates in an undesirable magnitude. The power generated by the HGU and HSU, generator load angles, and voltage at the load bus are shown in Figs. 6, 7, and 9, respectively. Fig. 9 reveals that the voltage at the load bus during isolated MG operation becomes same as that of during the utility grid connected system followed by a small dip at the time of grid disconnection. In contrast, Figure 8 shows the voltage at the MG load bus when there was no HSU in the isolated MG. The voltage level shown in Figure 8 is not at the level of standard that the MG system can operate, however, after utilizing HSU and its control, the voltage level reaches and remains at the operating level.

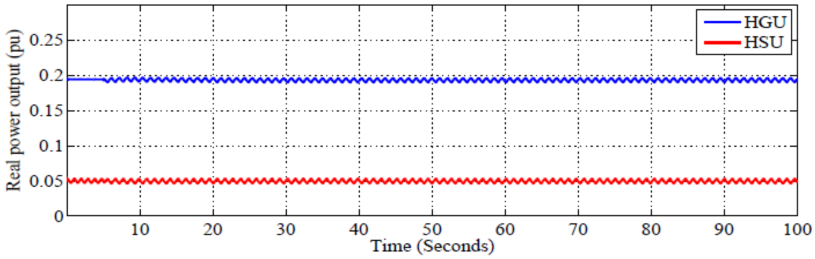

Fig. 6. Real power generated by the hydro generation unit and hydro storage unit

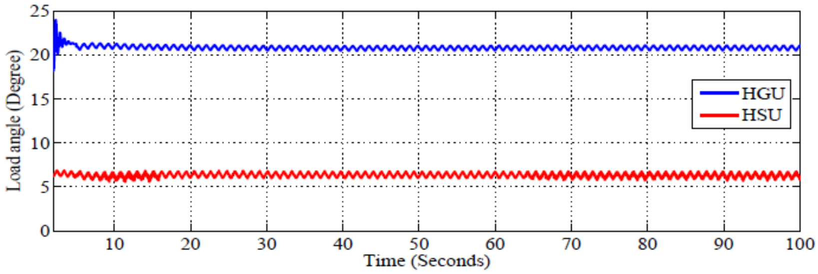

Fig. 7. Load angle of hydro generation and hydro storage unit

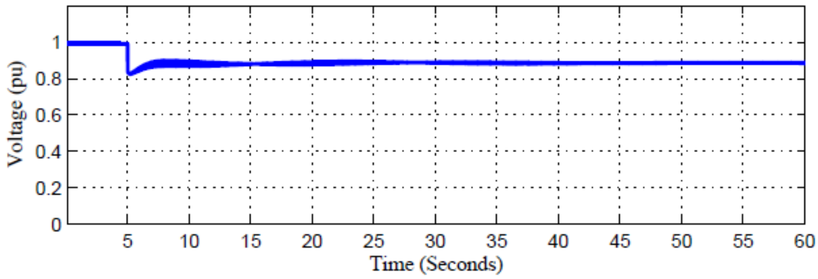

Fig. 8. Voltage at MG load bus without HSU control

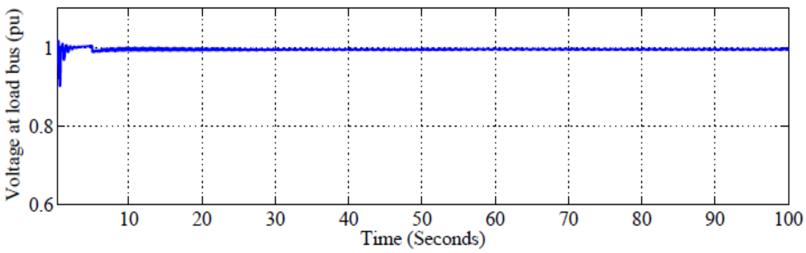

Fig. 9. Voltage at MG load bus with HSU control

The operation of the isolated MG system using HSU control is also verified while a step change in load occurs in the MG, and the simulation results are shown in Figs. 10-12. A decreased step change in load occurs at t = 50 seconds in an amount of 2 percent of the total load demand in the MG while an increased step change in load occurs at t = 100 seconds in the same amount. The step change in load is shown in Fig. 11. After the step change in load, the frequency of the isolated MG system with HSU control remains in an acceptable range and is shown in Fig. 10. In each time of step change in load, the frequency sets to back to the nominal value followed by an acceptable deviation. Moreover, the voltage at the load bus remains within the acceptable limit as can be seen from Fig. 9 in case of step changes in the loads.

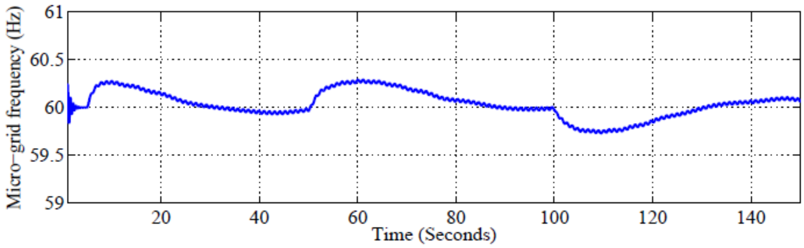

Fig. 10. Micro-grid frequency using HSU control with a step (2 percent) change in load

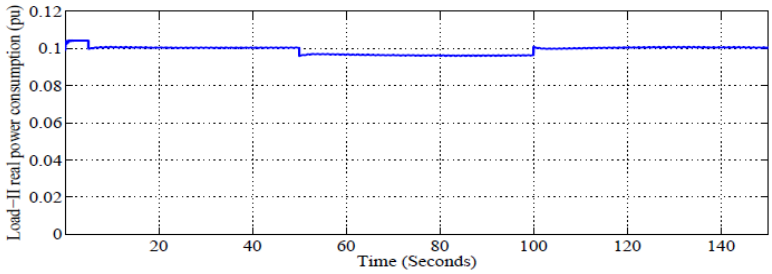

Fig. 11. A step (2 percent) decrease in load at t = 50, and a step (2 percent) increase in load at t=100 seconds

The performance of the MG system is also tested using HSU while another step load change, 7.5 percent of the total MG load demand, is applied. The performance results obtained through simulation study are presented in Figures 12 and 13. The simulation results indicate that the HSU equipped with a conventional governor control is able to maintain the isolated micro-grid system frequency between 59.5-60.3 Hz while step changes in load are 2 percent and 7.5 percent of the total load demand. Although, the initial frequency deviations at two different step changes in load are different, the MG system frequency remains within the acceptable limit. Thus, the study MG system is technically viable to operate using HSU with the examined control in this paper. However, the better MG system frequency regulation can be achieved using some advanced control techniques that can be further investigated.

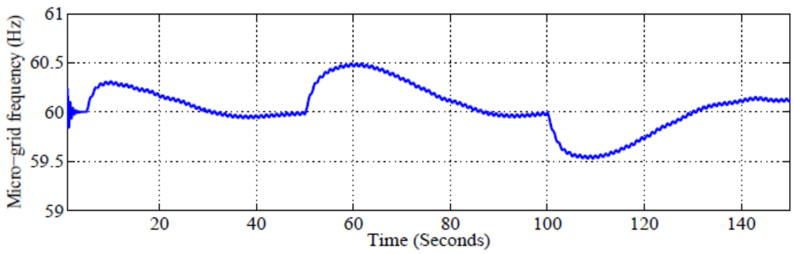

Fig. 12. Micro-grid frequency using HSU control with a step (7.5 percent) change in load

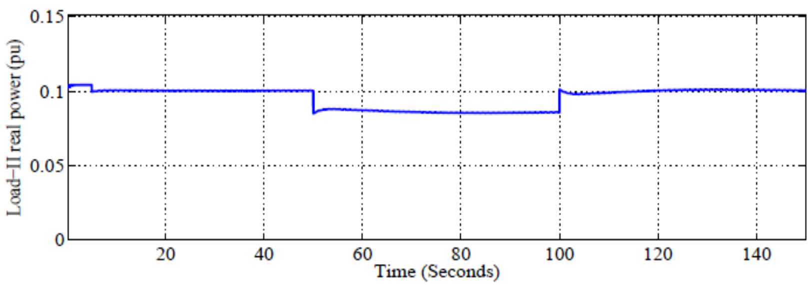

Fig. 13. A step (7.5 percent) decrease in load at t = 50, and a step (2 percent) increase in load at t=100 seconds

6. Conclusions

This paper presented sizing, modeling, controlling, and simulation of a pumped hydro storage system for operation of an isolated MG system. The sizing of the pumped hydro storage was performed using mathematical models that are based on the physical dimensions of the reservoir and associated components. The data for the physical dimensions are obtained from the location where MG system and the reservoirs are located. To demonstrate the use of the pumped hydro storage unit, a governor-excitation control is designed and applied to the case study MG system. The data for the case study MG model was obtained from Newfoundland Power, Canada. This study showed the operation of the pumped hydro storage coupled with a hydro generation unit (HGU) to serve the MG loads during an isolated operation with no power from the wind power generation system. Results indicated that the pumped hydro storage, coupled with the HGU, could supply secure and reliable power to support MG loads during the absence of both the utility grid and the wind power generation system. The MG frequency and the bus voltage set back to the nominal value followed by an acceptable overshoot due to the step change in load or the grid disconnection. The step change in load was applied in the isolated MG system as 2-7.5% of the total load in the isolated system. Since pumped hydro storage applications in providing power security, reliability, and resiliency for isolated MG applications are growing, there is not sufficient experimental data available for use in isolated MG studies. To fill this gap, this study can enable the engineers, designers and researchers to investigate operation and control of an isolated MG that includes renewable sources with the integration of pumped hydro storage operated by conventional power generators.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

R. A. developed the concept and model. R. A. carried out the simulation, analysed the results, and prepared the Manuscript. M. T. I. verified the concept and provided comments on modelling and simulation. M. T. I. further analysed the results and revised the manuscript. All authors had approved the final version.

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