Simulation of load-sharing in standalone distributed generation system

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Abstract. This paper presents a study on load-sharing among the component generating units of a multi-source electric microgrid that is operated as an autonomous ac supply-mode system. Emerging trend in power system development permits deployment of microgrids for standalone or stand-by applications, thereby requiring active- and reactive power sharing among the discrete generating units contained in hybrid-source microgrids. In this study, therefore, a laboratory-scale model of a microgrid energized with three renewable energy-based sources is employed as a simulation platform to investigate power sharing among the power-generating units. Each source is represented by a source emulator that captures the real operational characteristics of the mimicked generating unit and, with implementation of real-life weather data and load profiles on the model; the sharing of the load among the generating units is investigated. There is a proportionate generation of power by the three source emulators, with their frequencies perfectly synchronized at the point of common coupling as a result of balance flow of power among them. This hybrid topology of renewable energy-based microgrid could therefore be seamlessly adapted into national energy mix by the indigenous electric utility providers in Nigeria.

1. Introduction

There is currently a prevalent of energy deficit across sub-Saharan Africa where close to 70 % of the population general do not have access to electricity, while Nigeria in particular has 40% of its population living without electric power [1]. At present, gas-fired plants accounts for not less than 64% of the electricity generation in Nigeria, with most of the power system infrastructures currently operated near their steady-state stability limits. According to the Energy Commission of Nigeria (ECN), the current generation capacity of the country is about 4,000 MW for a population of approximately 140 million [2]. As predicted by the ECN, demand for electric power in Nigeria may increases to hit 250,000 MW by year 2030 and so there is an urgent need for improvement on the existing generation mix in order to meet both the current and the projected demands. Any further expansion would definitely require huge investments in plant infrastructures, such that could be very difficult to achieve in the face of the prevailing national economic downturn. However, one realistic way to tackle this challenge is to increase the renewable energy quota in the national power generation

mix [3], [4], since Nigeria is abundantly endowed with renewable energy resources that are yet to be adequately harnessed [5], [6].

With regards to the emerging trend in power system development across the globe, renewable energy-based electric microgrids are being employed for stand-alone, stand-by, grid-connected, co-generation or peak-shaving applications and to ensure a seamless adoption of renewable energy technology (RET) into the Nigerian electric power sub-sector, the place of research and development is very critical in the exploration of the local energy resources. Energy development requires on-going research into understanding new systems, including renewable energy systems [7] and, according to [8], [9], reduced-scale models of renewable energy technology systems could be used to understudy the behaviours of the actual systems in the real-life scenario.

In the drive towards renewable energies, reliably balancing load and demand is important as the share of renewables in the energy mix increases in the growing importance of distributed generation (DG). In this study therefore, load-sharing among the component generating units of a microgrid system with multiple energy sources, which is operated in standalone ac supply-mode is investigated using a laboratory-scale model (lab-grid) of the system. Load-sharing is very crucial in distributed power systems because real- and reactive power controls must operate independently of each other and share a common real- and reactive load in proportion to a pre-determined ratio regardless of plant parameters [10].

Load-sharing in distributed generation systems has been investigated by various authors. Small-signal stability analysis of combined droop and average power method for load sharing control of multiple distributed generation systems in a standalone ac supply mode is discussed in [11] where the authors show that the small-signal model accurately predicts the stability of the parallel systems. The focus in [10] is on improvement to the conventional frequency droop technique of real power-sharing and also to develop a new reactive power-sharing scheme. The improvement allows the operator to tune the real power-sharing controller to achieve desired system response without compromising frequency regulation. The author in [12] studies the flow of active- and reactive powers in two distributed generators that has common load but with different control functions. The simulation is done with PSCAD software and voltage source converter is employed for compensation. In [13], droop controller is analyzed and optimized based on small-signal dynamic modelling.

In this study, a laboratory-scale model of a multiple-energy-source microgrid system is employed to investigate load-sharing among the component energy sources of the system. Since cutting-edge facilities required for research in renewable energies are still lacking in most of the Nigerian tertiary institutions [6], the model is a simulation platform developed for use as an improvised teaching and research facility. The lab-grid is made of three energy source emulators that are interconnected at a point of common coupling to supply an aggregate of electrical loads. The emulators capture and mimic the operational characteristics of two pico-hydropower (PHP) sources and a wind turbine (WT) source with the three sources synchronized and monitored by the aid of a hierarchical control function.

System modelling has been a useful approach in investigating microgrid technology, yet [14] submits that models demonstrated with implementation of simulated weather data and load demand profiles may not accurately represent the real-world-scenario operational behaviours of the actual system. More so, the indigenous utility providers in Nigeria do not want to adopt any of the emerging renewable energy technologies without exhaustive validations using real-life data and profiles obtained from the local terrain.

Therefore, a real-life wind speed profile of a Nigerian locale is implemented on the WT emulator to investigate the behaviours of the lab-grid under a near-real-world operating condition. Implementation of real-life weather data and load demand profiles on system models has yielded more precise emulations of actual systems [15]-[17], therefore the load sharing among the three source emulators of the system under study is demonstrate through the real-time simulation of the system. The emulators complement one another through their proportionate generation of power, while the output frequencies of the three are perfectly synchronized as a result of the balance flow of power among the three units and, between the units and the load.

This paper is organized as follows: Section 2 of this paper describes the mathematical representation and the design structure of the lab-grid with the load-sharing control mechanism, while Section 3 presents and discusses the result obtained from the simulation and, Section 4 concludes the paper.

2. System structure

The simulation model has, by design, two PHP source emulators and a WT emulator. As shown in figure 1, one of the PHP source emulators is made to form a local grid that sets the magnitude and the frequency of the system's operating voltage. The ac voltage generated by the grid-forming source makes the reference to which the other two sources are synchronized as the two feed power to the local grid.

An important requirement of the application is that the two grid-feeding sources had to be perfectly synchronized to the local grid to keep the system voltage and frequency close to the rated values. Mechanism of the control is oriented in such a way as to minimize the operational cost of the lab-grid, while maximizing its efficiency, reliability, and controllability. Each of the source emulators is interfaced with the grid bus through a separate converter system using voltage orientation control. The control function is based on the transformation between the *abc* stationary reference frame and the *dq*-axis synchronous reference frame and the algorithm is implemented in the grid-voltage synchronous reference frame that makes all the variables to be of dc components in the steady state and, thus facilitates the control of the converters for synchronized power delivery.

Rotor speed feedback control is employed on the rotor circuit of the synchronous generator of the grid-forming source using the maximum torque per ampere technique. For a salient pole machine, the dynamic model is given by [18] as:

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases} \tag{1}$$

$$T_e = \frac{3P}{2}\left[\lambda_r i_{qs} - \left(L_d - L_q\right)\left(i_s^2 - i_{qs}^2\right)^{-1} i_{qs}\right] \tag{2}$$

$$P_m = \frac{3}{2}\left(v_{ds}i_{ds} + v_{qs}i_{qs}\right) \tag{3}$$

$$\begin{cases} i_{qs}^* = \dfrac{2T_e^*}{3P\left[\lambda_r - \left(L_d - L_q\right)\right]i_{ds}} \\ i_{ds}^* = \dfrac{\lambda_r}{2\left(L_d - L_q\right)} \pm \left[\dfrac{\lambda_r^2}{4\left(L_d - L_q\right)^2} i_{qs}^2\right]^{-1} \end{cases} \tag{4}$$

Where v_{ds}, v_{qs}, i_{ds}, i_{qs}, are *dq*-axes stator voltages and currents respectively, i_{ds}^* and i_{qs}^* are *dq*-axes reference currents, L_d, L_q, are *dq*-axes stator self-inductances, R_s, is the stator resistance, ω_r, λ_r, are rotor electrical angular speed and rotor flux linkage respectively, *P* is number of pole, while T_e, P_m are the electromechanical torque and the mechanical power respectively of the synchronous machine. At the grid side, the grid-forming converter is controlled to generate a sinusoidal voltage whose magnitude and frequency is determined by the reference amplitude *v** and frequency *w**. The voltage is delivered to the lab-grid bus via the converter and the external loop of the scheme controls the grid voltage to match its reference values, while the internal control loop regulates the current supplied by the converter [19].

The power delivered to the local grid by the two grid-feeding sources is in synchronism with that of the grid-forming source. The first grid-feeder is also a PHP source emulator that is also based on wound rotor synchronous generator with rotor speed feedback control employed on the rotor circuit. The second grid-feeding source is a WT emulator of the variable-speed configuration that employs a wound rotor induction generator with reduced-capacity converter. To permit the adjustment of the amplitude and the frequency of the output voltage through reference powers *P** and *Q**, the grid-feeding interface converters are controlled using grid voltage orientation control technique.
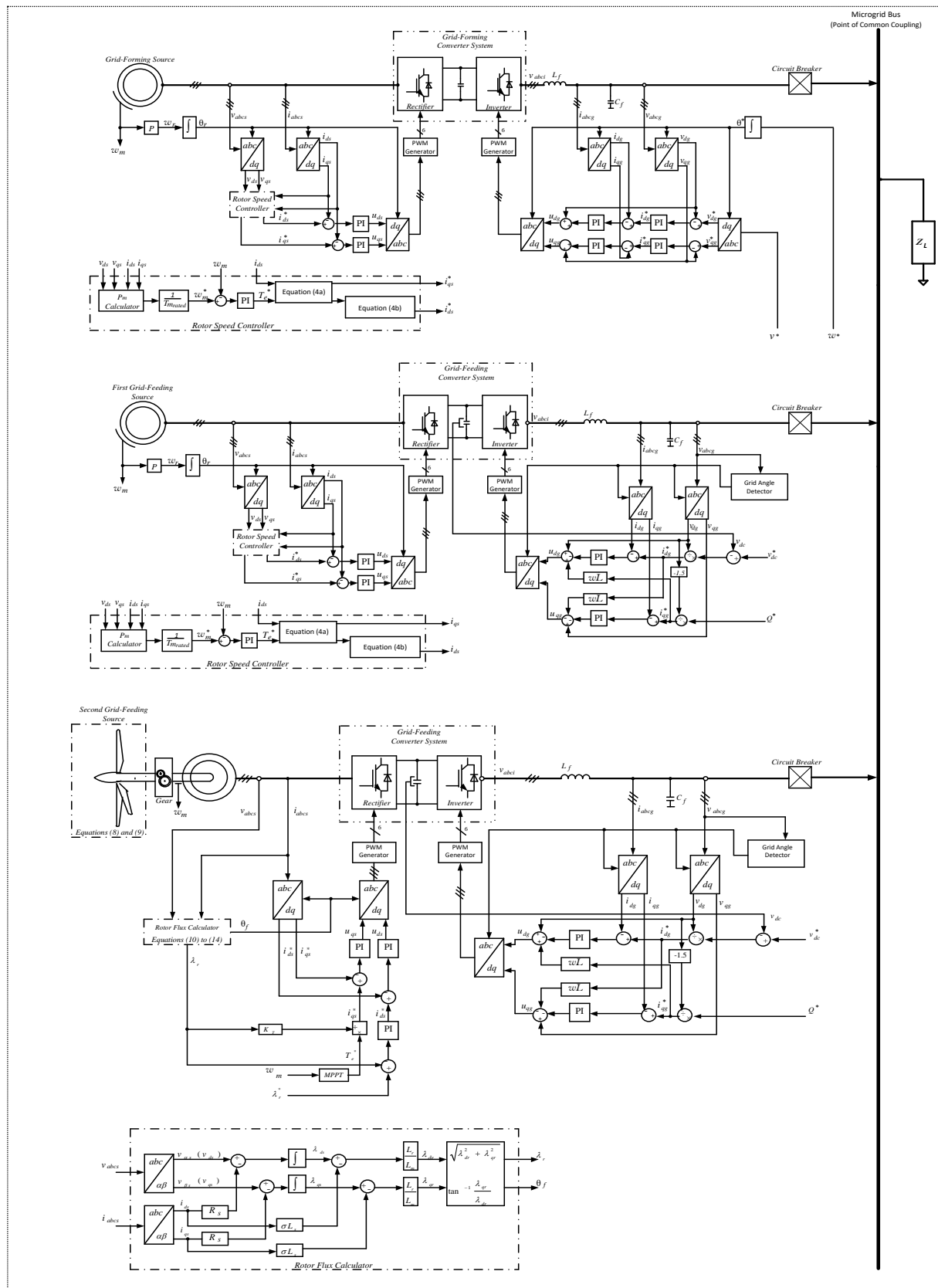
Figure 1. The stand-alone lab-grid.

$$\begin{cases} L_f \, pi_{dg} = v_{dg} - v_{di} + \omega_g L_f i_{qg} \\ L_f \, pi_{qg} = v_{qg} - v_{qi} - \omega_g L_f i_{dg} \end{cases} \tag{5}$$

For a satisfactory dynamic performance [20], a decoupled proportional-integral (PI) controller is employed, which eliminates the cross-coupled effect of the *d-* and *q*-axes currents.

$$\begin{cases} L_f \, pi_{dg} = K\left(i_{dg}^* - i_{dg}\right) \\ L_f \, pi_{qg} = K\left(i_{qg}^* - i_{qg}\right) \end{cases} \tag{6}$$

$$\frac{i_{dg}}{i_{dg}^*} = \frac{k_p p + k_I}{L_f p^2 + k_p p + k_I} \tag{7}$$

Where L_f is the inductance of the grid-interface filter, v_{dg}, v_{qg}, i_{dg}, i_{qg} are the *dq*-axes grid voltages and currents respectively, ω_g is the angular frequency of the local grid. $K=(k_p+k_i/S)$ is the gain of the controller, with k_p being the proportional gain while k_i is the integral gain.

The WT emulator is designed to have both software and hardware components. The soft component is developed on the platform of the real-time simulation computer aided design, which is a software integral of the real time digital simulator [21]. While the emulator is designed for 8m/s and 14m/s cut-in and cut-out speeds respectively, signal output of the soft component excites a direct current motor that is conditioned to operate in the torque control mode with an external analogue voltage signal. The actual electric power is generated by a wound rotor induction machine being driven at super-synchronous speed by the motor. In the approximate, the mechanical power extractable from the wind by the rotation of turbine blades is generally expressed as [22], [23].

$$P_{mech} = \frac{1}{2} \rho A C_p v^3 \tag{8}$$

Where P_{mech}, ρ, A, C_p and v are the mechanical power developed by the turbine, air density, swept area of the rotor blade, the power coefficient and wind speed respectively.

Equation (8) is modelled on the real-time simulation computer aided design platform using the component model library of the simulator, with the maximum mechanical power being

$$P_{mech_{max}} = K\omega_{t\,max}^3 \tag{9}$$

Where ω_t is the rotational speed of the turbine. The torque output of the soft model is multiplied by a gear ratio and converted to voltage signal for the excitation of the interfaced motor. Voltage signals, corresponding to the torques developed at instantaneous speeds of the wind, thus feed into the motor through the drive and the electric power is thereby generated as the motor drives a directly connected three-phase induction machine at super-synchronous speed. Grid side control of the wind turbine emulator is also based on the grid voltage orientation control technique. However, the rotor side control is achieved through direct field oriented control method for a decoupled control of the rotor flux and the electromagnetic torque in order to achieve a high dynamic performance. Using rotor flux orientation, the stator current is decomposed into a flux-producing component and a torque-producing component with the two components controlled independently [18, 20].

$$P_m = T_e \omega_m = 2P^{-1}\omega_r (1-S) \tag{10}$$

P is the number of poles, T_e, and P_m are the electro-mechanical torque and the mechanical power respectively and, ω_m and ω_r are the rotor mechanical speed and the electrical speed respectively.

3. Simulation and demonstration

In demonstrating the load-sharing, a real-life wind speed profile is implemented on the second grid-feeder. Location of the wind capture is Obafemi Awolowo University, Ile-Ife, Nigeria (Latitude 7.5°North/Longitude 4.3°East) at a turbine height of 114 meter. Choice of the location for the wind speed profiling is premised on the desire of the university to leverage on the available renewable

energy resources for an autonomous electricity generation in order to enhance the security of power supply within the campus community.

While the grid-forming and the first grid-feeding source emulators are each designed with 250W rated synchronous generators, the induction machine of the second grid-feeding source has manufacturer rating of 300W. An aggregate load of 400W is supplied by the lab-grid and, considering the intermittent nature of the wind flow, the ability of the system to satisfy the reactive power need of the second grid-feeding source, the proportional supply of active power to the load by the three energy sources, and frequency synchronism among the three generating units are investigated.

4. Discussion of result

The waveform of the real-life wind speed profile that is implemented on the second grid-feeding source, as normalized by the giga-processor card of the real time digital simulator, is shown in figure 2. On the profile is a period of time with wind speed as low as 7.5 m/s, which is below the design cut-in speed of the WT emulator. Due to the pitching mechanism at such instant of low wind speed, there is neither active power generation nor reactive power consumption by the WT emulator, as could be found on figure 3 and figure 4. Consequently, both the grid-forming source and the first grid-feeding source jointly rise to meet the active power demand of the load at that instant, with no reactive power generation by the two sources.

Figure 3 and figure 4 respectively show the reactive- and the active power flow on the entire system. It is revealed through Figure 3 that all the reactive power requirement of the second grid-feeding source, which is about 290VAR at maximum and varies with the pattern of the wind speed profile, is jointly and adequately supplied almost equally by the grid-former and the first grid-feeder. The active power need of the load is shared by the three sources as shown in the figure 4.

While the second grid-feeding source, depending on the wind speed pattern, is able to supply power up to its maximum rating of 300W, the other two sources jointly make up for the excess power required by the load. Consequent upon this balance power flow among the three micro-generating units and between the units and the load, figure 5 shows the frequency of the grid-former perfectly tracked by the two grid-feeders, and so synchronism is established among the three micro-generating sources.
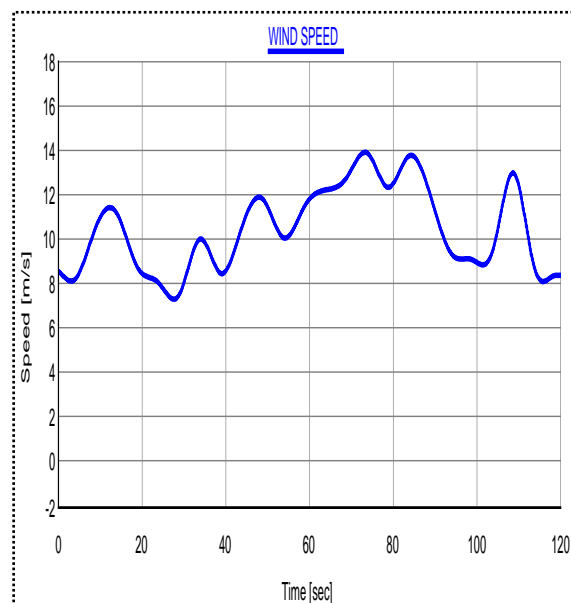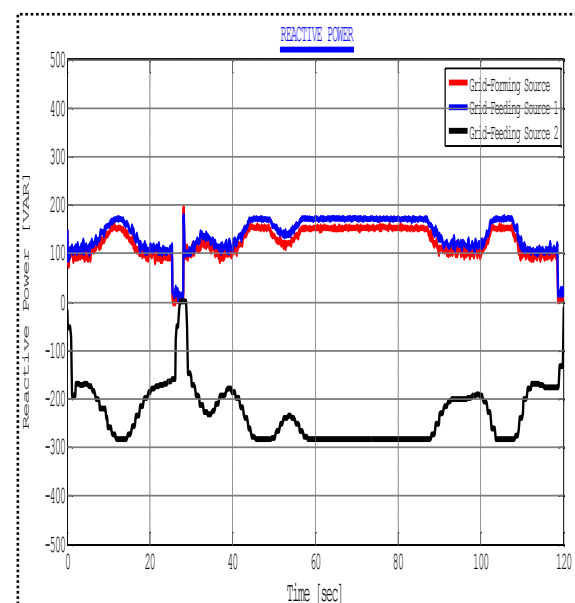

Figure 2. Real-life wind speed profile.
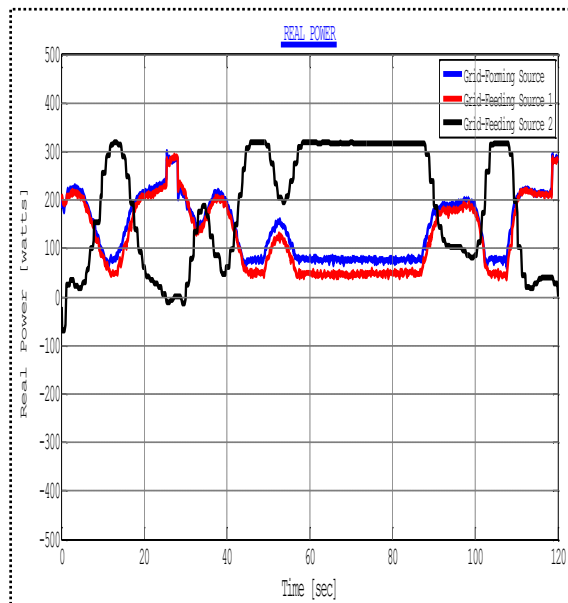

Figure 3. Reactive power flow of the system.

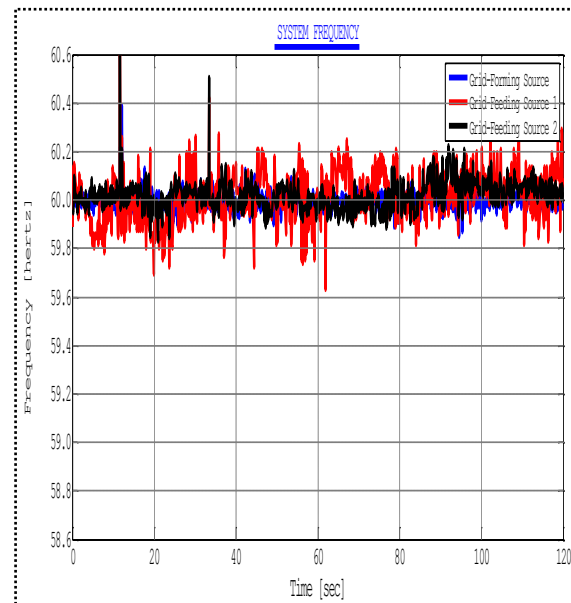**Figure 4.** Active power flow of the system.

Figure 5. Frequencies of the system.

5. Conclusion

In this study, load-sharing in a hybrid-source autonomous electric microgrid is demonstrated using a system model that is developed to serve as an affordable laboratory-scale teaching and research facility on renewable energy technology. One useful approach to studying microgrid technology is the use of system emulating models. Real-life weather data and load demand profiles are implemented on a model of the microgrid for an accurate emulation of the system. There is proportionate generation of power by the component micro-generating sources of the system. The sources are able to complement each other, which is the essence of the hybridization. Also, frequencies of the three micro-generating sources are perfectly synchronized as a result of the balance power flow among the and between the units and the load. This ability to share power proportionately, and consequently a stable frequency of operation throughout the simulation period, establishes a positive load-sharing capability by the system.

Therefore, this topology of renewable energy-based hybrid-source power generation could be seamlessly adapted into the Nigerian national energy mix in the effort to alleviate the prevailing shortage of electric power in the country.

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