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Security Study on Freestanding Minigrid with Multiple Rotary Energy Sources

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Abstract

Traditional grid has been extensively studied for system security. For freestanding renewable energy-based minigrid, a three-source stand-alone minigrid is in this study examined for system security under large disturbances. By real-time simulation, rotor responses of the generators and voltage characteristics of the buses, at sudden load change and under fault condition, are assessed. Post-perturbation behaviour of the system shows synchronism is not compromised by any of the generators and the bus voltage profiles remains within their pre-perturbation statutory limits. This implies that a number of rotating machine-based energy mini-sources could be interconnected into a freestanding minigrid without compromising the stability of the system. The assessment could find use in predictive and corrective compensation for stability issues in mini integrated power systems and serve as simple generic investigative approach that could be integrated into Minigrids Remedial Action Scheme or Minigrids Energy Management System for dynamic security assessment of multi-machine island minigrids.

Keywords: Disturbances, freestanding, multi-machine, minigrids, security, synchronism

1.0 INTRODUCTION

Evolving tendency in power system advancement allows deployment of alternative energy-based electric minigrids for either island or standby applications**.** In addition to under-development of the traditional grid, improper management of grid infrastructures has also been identified as a major among the reasons for the problems confronting electric power supply [1], [2] and so electric utility is being re-conceptualized to accommodate many more island minigrid systems as a strategy to reach both the under-served and the un-served consumers in the most secured and affordable way [3]. As electric minigrid technology gains foothold in the world of electric power systems, a number of autonomous minigrids are getting interlinked to strengthen security of power supply. In the operation of the resulting network of interconnections, dynamic security assessment (DSA) has been found to be very germane. In manners similar to the management of the traditional grid structures, thus minigrids also require security assessment, especially when such system is operated in the island mode or with the minigrid energized by a number of energy sources blended into a hybrid.

After over three decades of intensive and extensive technical research into the subject, literature on DSA of the traditional grid architecture continues to be on high demand [4] – [7]. In some relatively recent examples, varying methodologies are employed by different authors in [8] – [14] to study power system security. By an extended calculation of the risk of steady state security, the authors in [8] obtained DSA index using variance and mean of load uncertainty. Numerous essential constraints are considered in the wide-area security assessment that [9] presents. To achieve this, tools that were deployed include: numerical analysis, linear inequalities in a multi-dimensional space, piecewise approximation, phasor measurement unit (PMU) data, together with known system limits and constraints. Using a systematic approach, online power system DSA is obtained by [10] with the used method based on decision trees. Reference [11] presents a contingency selection by preventive control approach, in which fast decoupled load flow (FDLF) analysis carried out in the MATLAB environment is used to calculate for single transmission line outage, the active- and the reactive power performance indices, and, based on the values of the indices, ranking of the most severe contingency is done. Continuation power flow (CPF) approach, using power system analysis toolbox (PSAT) with MATLAB, is deployed in [12], wherein power system contingency study is considered by focusing on analyzing the static voltage stability based on the maximum loading parameter point. Voltage stability of power system is investigated in [13] using eigenvalues method, with the stable and the unstable systems respectively identified and showed by the positive and the negative eigenvalues that quantify the system's voltage stability. Authors in [14] considers the highest voltage magnitude-reactive power (V-Q) sensitivity in power system as indication that the concerned bus is prone to voltage instability and thus the least eigenvalue, obtained from the Jacobian matrix of power system, is used in calculating the sensitivity. While artificial neural network (ANN) is employed in [15] and [16] for contingency screening, [17] uses Newton-Raphson load flow (NRLF) for same.

Assessment of the operational security of off-grid hybrid-source electric minigrid systems must also be accorded proper attention, for efficient performance of the technology. However, it has been shown that the protection schemes employed on the traditional grid will not produce same result on minigrid systems [18] and; therefore, designing appropriate protection scheme is a major concern of minigrids implementation in the autonomous mode [19], [20]. The conventional method of symmetric analysis has been employed for studying fault behaviours in grid-tied minigrid systems [21]; while simulation approach was deployed in [22] to investigate the transient behaviour of a grid-connected photovoltaic-based power generator. Likewise in the attempt to establish safe and reliable balance between supplied and demanded power, [23] from the viewpoint of power (reactive and active) sharing among the constituent mini-generating units of a minigrid reports an assessment carried out on autonomously minigrid comprising of a number of energy sources that are blended into an hybrid. Stability of hybrid-source island minigrid system has been studied under power generation deviation due to variations in solar insolation [24], with all the components that usually make a minigrid, such as: photovoltaic (PV) and diesel engine generators, transmission line parameters, three-phase transformers, passive and reactive loads; inculcated in the developed simulation model and the testing of the system carried out under varying PV penetration scenarios.

On islanded microgrid, [25] discusses a mechanism that employs various stages of data conversion by digital over/under frequency relay (OUFR) for coordinating digital frequency protection (DFP) and load frequency control (LFC), and demonstrates the mechanism through simulation that experimented with load change and different penetration levels of renewable energy systems (RESs). Protection of minigrid systems by a technique that uses digital relay deployed alongside with communication network is a proposal presented in [19], in which for demonstration the study employs SimPowerSystem toolbox of MATLAB/Simulink to model the scheme for the protection of a system that has high penetration of inverter-connected sources against high impedance faults. For protection of low-voltage minigrids, a strategy that uses a set of microprocessor-based relays is proposed in [26]. On demonstration using PSCAD/EMTDC, it is found that the strategy depends not on magnitude of fault current and neither is communications or adaptive protection required. In alternating current (AC) minigrid structure that is under the influence of load changes, variation of wind speed and variation of solar irradiance, deployment of proportional integral derivative (PID) controller for frequency regulation was optimized using genetic algorithm (GA) and by comparison it offers an improvement over Ziegler-Nicholas tuned PID controller. Introduced in [27] is a minigrid protection mechanism that is digital relay-based and operationally comprehensive in the sense that the DG, the point of common coupling (PCC) and the lines are protected by the mechanism.

In [28], a three-stage approach is employed in studying minigrid security: offline analyses using dynamic security models; online calculation using the offline models; and real-time protection using real-time data for detecting dynamic security status. Reference [29] proposes the use of convolutional neural networks (CNN) for online analysis of voltage security in minigrids and the approach is reported to perform better than back-propagation neural network (BPNN) or decision tree and support vector machine, thus making the proposed algorithm to be adjudged as having great potential for future applications. In a comparative study between optimal proportional-integral (PI)-based virtual inertia controller and H-controller, the obtained result shows a better control effect and robustness of the latter over the former in the aspects of precise disturbance attenuation and reference frequency tracking [30]. Dynamics of the rotor angles of all the generators contained in a multi-machine grid-independent district minigrid is examined by [31], which presents the variations that occur in the rotational angles and frequencies of the rotors in response to a balance three phase fault on the minigrid.

This current study focuses on screening freestanding minigrid for the contingencies that are liable to result in stability challenge on the system, as well as presenting a simple approach to the investigation of the transient stability of autonomous minigrid system that contains a number of rotary power sources. In electrical power systems, voltage magnitude and frequency are fundamental parameters and so are essentially employed as criteria for determining whether a power system will experience failure or difficulty. Thus, the standard thresholds of these parameters are in this study used to evaluate the protection capabilities (over-voltage, under-voltage, over-frequency and under-frequency) of minigrid systems. A salient feature of this technique is that it is generic, and so could easily be integrated into Minigrids Remedial Action Scheme (MRAS) or Minigrids Energy Management System (MEMS) for determination of the transient state of hybrid-source standalone minigrids in the case of large disturbances occurring on such systems. This paper is organized thus: in Section 2, an overview of the test system (TS) that is employed for the analysis is provided; while the responses of the perturbed system are presented and discussed in Section 3; and Section 4 provides conclusion to the study.

2. METHODOLOGY

A minigrid TS with three rotary power-generating units, two of which are synchronous machine-based mini-hydropower source emulators and the third being an induction machine-based wind turbine (WT) emulator [31], is employed for this study. Presented in figure 1 (a) is the block diagram of the TS, while figure 1 (b) shows its design structure. As shown in the figures, each source has a grid-side interface converter that is controlled using voltage orientation control method with the algorithm of the control implemented in the synchronous reference frame of the grid-voltage. One synchronous source (Source 1) establishes the magnitude and the frequency of the operating voltage of the TS, and the local grid so created is fed with electric power by the second synchronous (Source 2) and the induction source (Source 3). The synchronous sources are each designed for 250W maximum output, while the maximum output of the Source 3 is 300W at wind speed rating of 12 m/s.

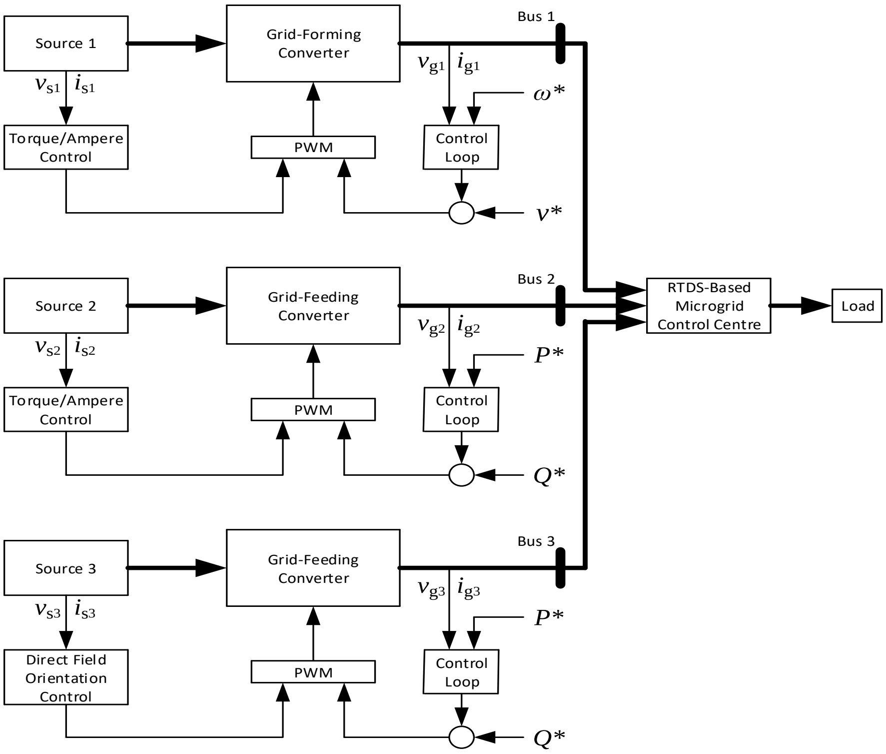

Fig 1a Block Diagram of the Test System. Adapted from [32]

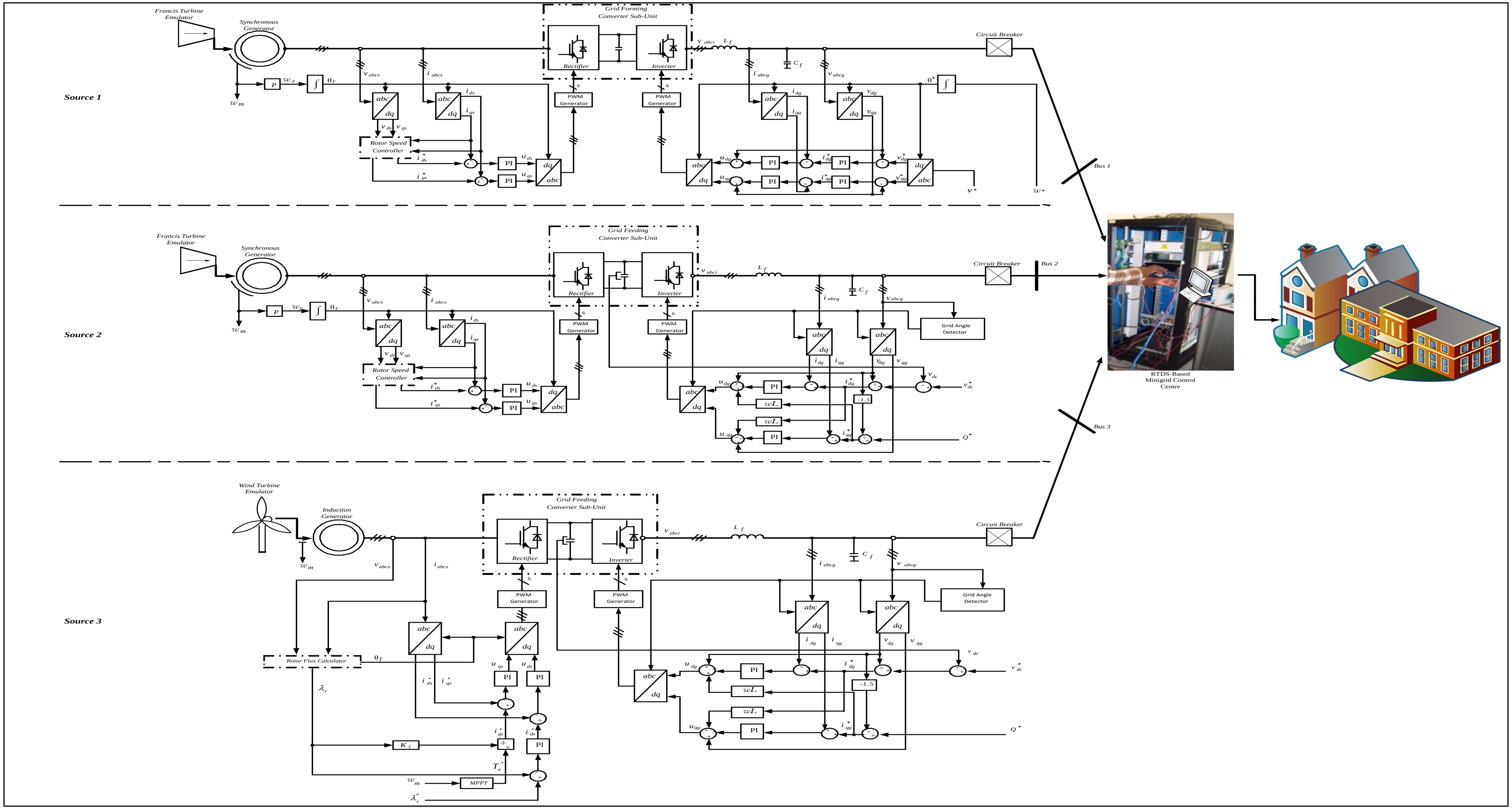
Source 1
Francis Turbine Emulator
Synchronous Generator
Grid Forming Converter Sub-Unit
Rectifier
Inverter
PWM Generator
Rotor Speed Controller
PI
Circuit Breaker
Bus 1
Source 2
Grid Feeding Converter Sub-Unit
Grid Angle Detector
Bus 2
RTDS-Based Minigrid Control Centre
Source 3
Wind Turbine Emulator
Induction Generator
Rotor Flux Calculator
MPPT
Bus 3

Fig 1b Design Structure of the Test System. Adapted from [31]

Using the technique of maximum torque per ampere, speed feedback control was implemented on the rotor circuits of the salient pole wound rotor synchronous machines. Dynamics of the implementation is given as:

$$\left[\begin{array}{l} \begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d\, p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q\, p i_{qs} \end{cases} \\ \begin{cases} i_{qs}^* = \dfrac{2T_e^*}{3P\left(\lambda_r - \left(L_d - L_q\right)\right) i_{ds}} \\ i_{ds}^* = \dfrac{\lambda_r}{2\left(L_d - L_q\right)} \pm \sqrt{\dfrac{\lambda_r^2}{4\left(L_d - L_q\right)^2} i_{qs}^2} \end{cases} \end{array}\right. \quad (1)$$

where i_{ds}, i_{qs}, v_{ds}, v_{qs}, describe the dq-axes stator currents and voltages respectively, i_{ds}^*, i_{qs}^* are reference currents on the dq-axes, and stator self-inductances on dq-axes are L_d, L_q. Stator resistance is given as R_s,, while rotor flux linkage and rotor electrical angular speed are described by λ_r, ω_r respectively. T_e, and P are respectively the reference electromechanical torque and the number of poles.

For the WT emulator, a reduced-capacity converter combined with a wound rotor induction generator of the variable-speed type, is employed. High dynamic performance is achieved by decoupled control of the electromagnetic torque and the rotor flux, which is realized through direct field oriented control of the rotor side as:

$$\left[\begin{array}{l} P_m = K\omega_t^3 \\ \begin{cases} \lambda_r = \sqrt{\lambda_{dr}^2 + \lambda_{qr}^2} \\ \theta_f = tan^{-1} \dfrac{\lambda_{qr}}{\lambda_{dr}} \end{cases} \\ T_e = \begin{cases} \dfrac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs} \right) \\ \dfrac{3PL_m}{2}\left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \\ \dfrac{3PL_m}{2L_r}\left(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr} \right) \end{cases} \\ P_m = T_e\omega_m = \left(\dfrac{2}{P}\right)\omega_r\left(1 - S\right) \end{array}\right. \quad (2)$$

where P_m describes the maximum mechanical power of the WT emulator, ω_t depicts the rotational speed of the turbine and i_{ds}, i_{qs}, λ_{ds}, λ_{qs} describe the dq-axes stator current and flux respectively. The dq-axes rotor current and flux are described by i_{dr}, i_{qr}, λ_{dr}, λ_{qr} respectively. L_r is the rotor inductance, while L_m is the mutual inductance between rotor and stator. The number of poles is P and T_e is the electromechanical torque, while ϖ_m, ϖ_r are the rotor mechanical speed and electrical speed respectively, and S is the percentage slip.

Transient stability study examines power system for synchronism as the system is subjected to severe disturbance. In this study, rotor angles and frequencies, and terminal voltage behaviours of the three rotating machines, as well as the bus voltage profile are examined under a sudden load change and a balance three phase fault. How well the transient stability of the multiple-source minigrid system can be examined during dynamic security assessment is determined by the accuracy of the rotor angle dynamic responses. When the system is at the steady state condition prior to perturbation, the local grid is supplied power by Source 3 and to the maximum rating of the source. During imbalance flow of power on the system, which is occasioned by either deficiency of the source due to low wind speeds or system power demand that exceeds the capacity of the source or both, the excess demand in power is supplied by Source 1 and Source 2 collectively.

Rotor responses of the mini-generators and voltage behaviours of the system buses were studied as the TS was on different occasions subjected to a sudden load change and a balance three-phase short circuit. Deviation of the dynamics of the system from its initial operating points is a measure of how critical the disturbances are on the system. The load change response was obtained as the initial aggregate load supplied by the system was suddenly increased at a time *t* into the simulation. For the other experimentation, the test-fault was introduced across the terminals of the Source 3 during a steady operating condition of the TS at a time *t* into the simulation, and the fault was cleared *0.2s* later. Three-phase fault was applied because though it is not common in occurrence, but is the most fatal of electrical faults whenever it occurs.

3. RESULTS AND DISCUSSION

In describing the operating conditions of the TS, the variable considered is the system voltage. Synchronism among the three energy sources is also considered. At the terminals of the mini-generators and on the system buses, voltage magnitudes and frequencies were observed and compared with thresholds provided in the IEEE 1547 Standard presented in [33] and [34]. By the Standard, overvoltage threshold-1 and threshold-2 are +10% and +20% respectively, with undervoltage threshold-1 and threshold-2 being –30% and –55% for voltage magnitude; while in the case of voltage frequency, overfrequency threshold-1 and threshold-2 are 1.2Hz and 2Hz respectively, with underfrequency threshold-1 and threshold-2 being –1.5Hz and –3.5Hz. Normal operating voltage ranges between the base voltage magnitude and the threshold-1; while between thresholds-1 and thresholds-2, a delay or trip time occurs before the protection triggers and prior to the minigrid system's ceasing to energize [35].

While figures 2 and 3 describe the load change responses of the TS, its fault behaviours are presented in figure 4 and figure 5. Dynamics of the rotors and the buses of the system were expected to settle at the original pre-perturbation operating conditions or attain new stable conditions at post-disturbance.

Deviations from the steady state behaviour of the rotors, due to the sudden load change from 400W to 800W at time *t = 2.5s* into the simulation, are as figure 2 describes. Minor excursions, of approximately 10° and ±1Hz deviations, were noticed in the angles and the frequencies respectively, of the rotors; whereas, there was no noticeable deviations in the magnitudes of the output voltages of the generators. While the angular deviations lasted till *t = 4.5s* (that is, for a duration of *2.0s*), deviations in the frequencies was for *0.5s* period. It could be noticed from the figure that synchronism was maintained among the generators.

In the case of the bus voltages under the load change, figure 3 shows that there was a lot of excursions with approximately 50°, ±1Hz and –0.6 p.u. deviations in the angles, frequencies and magnitudes respectively, of the bus voltages. Under this condition, deviations in the voltage angles lasted till *t = 4.5s*, while frequencies deviations were for *0.5s* period, and the voltage magnitudes deviated for about *1.0s* duration. At the moment of the load change, magnitudes of the voltages at V_{bus1} and V_{bus2} reduced to 0.5 p.u each, while V_{bus3} reduced to 0.4 p.u magnitude.

Compare to the IEEE 1547 Standard; while the dynamics of the three mini-generators (energy sources) are found to be within operational safety, the maximum permissible operating limits of the bus voltages are exceeded. The trajectory of the voltage magnitudes, which shows up to 60% (0.6 p.u.) reduction from the base value, as recorded on bus 3 where the highest deviation is experienced, is a reflection of a heavy transient under the influence of the disturbance. Such low voltage level could impact consumer terminals negatively, resulting from its attendant load shedding and increase in amperage consumption by electrical appliances.

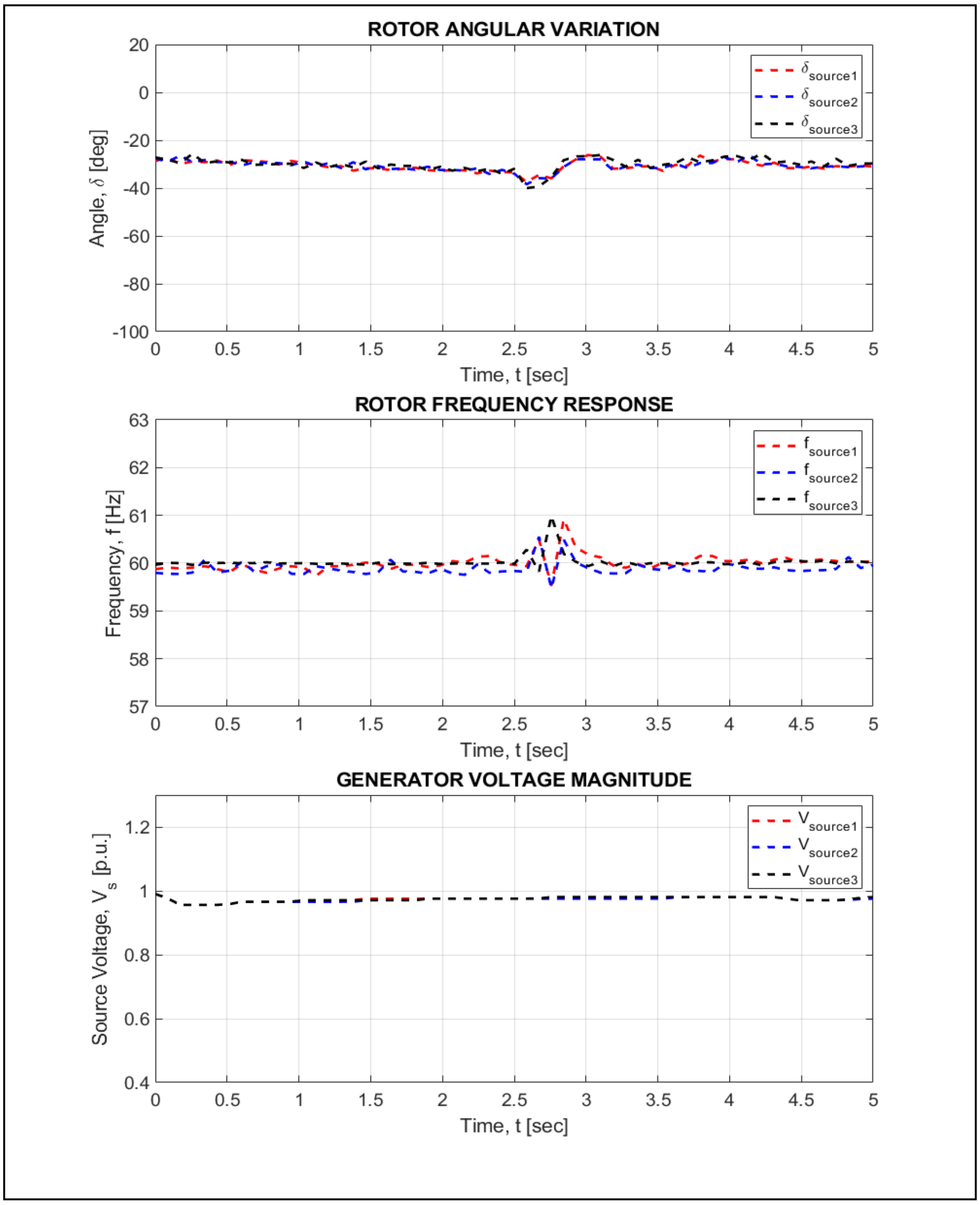

Fig 2 Rotor Dynamics of the Generators under Load Change

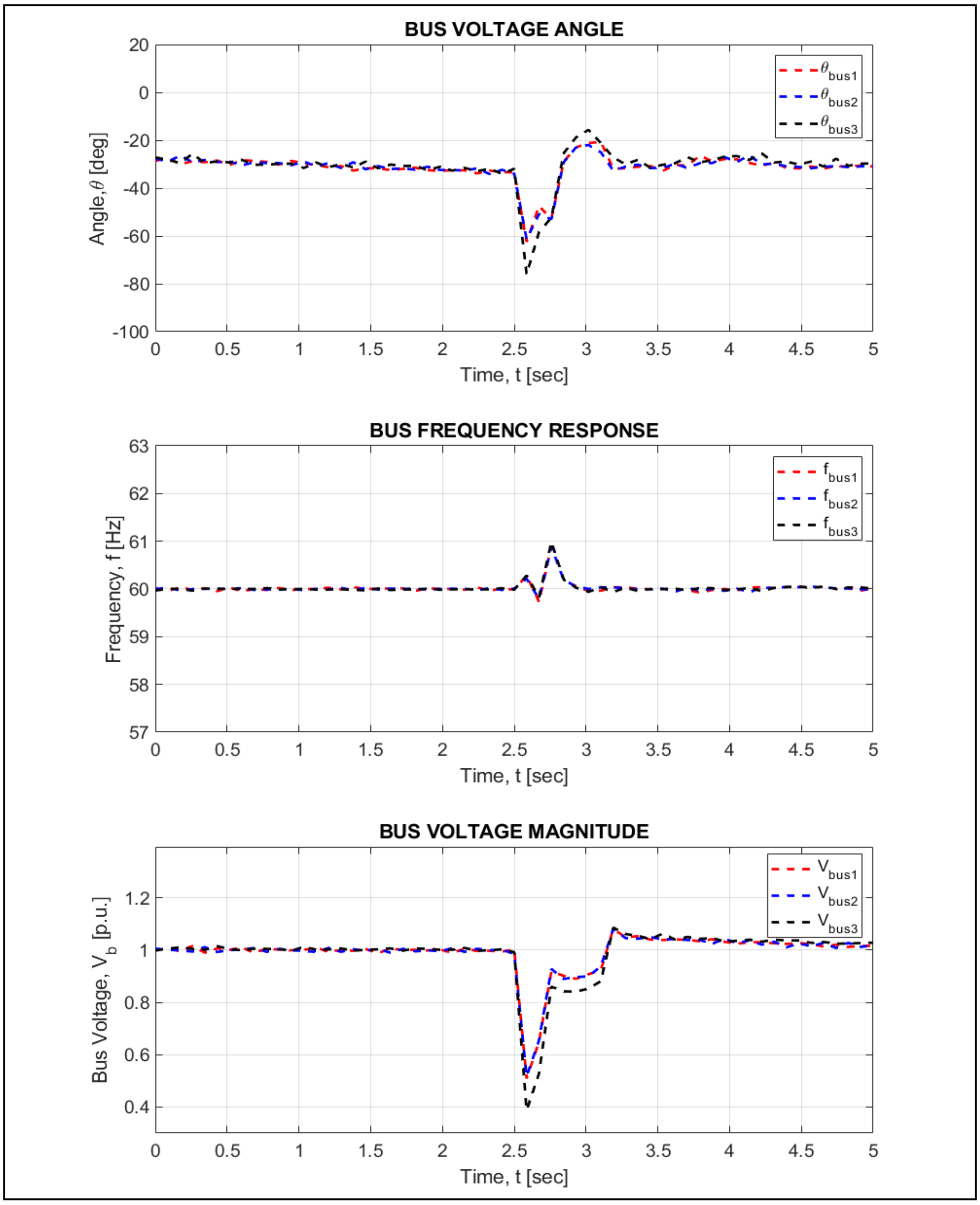

Fig 3 Dynamic Responses of the Buses under Load Change

With the system subjected to a balance three-phase test-fault applied at the terminal of the Source 3 at time $t = 0.5s$ into the simulation, figure 4 shows there are notable excursions in the rotor angles, frequencies and the magnitudes of the output voltages of the generators during the on-fault operation. For each generator, there was about 45° rotor angle deviations and around +0.45Hz rotor frequency deviations, as well as voltage magnitudes deviations of approximately –0.09 p.u. However, the post-fault trajectory shows that the generating units did not forfeit synchronism to the disturbance.

In figure 5, the fault behaviour of the buses in terms of angles, frequencies and magnitudes of the bus voltages are presented. There is a little excursion on the buses, with approximately 18° deviation in the voltage angles, about +0.45Hz frequency deviation, but no noticeable deviations in the voltage magnitudes.

Going by the IEEE 1547, the fault operation of the TS does not violate the maximum permissible operating limits of minigrid and distributed energy resources (MDER) systems standards. The system rides through the disturbance without endangering its stability. An implication of this that if the minigrid is meant to provide dynamic support, it will not fail in performing the duty.

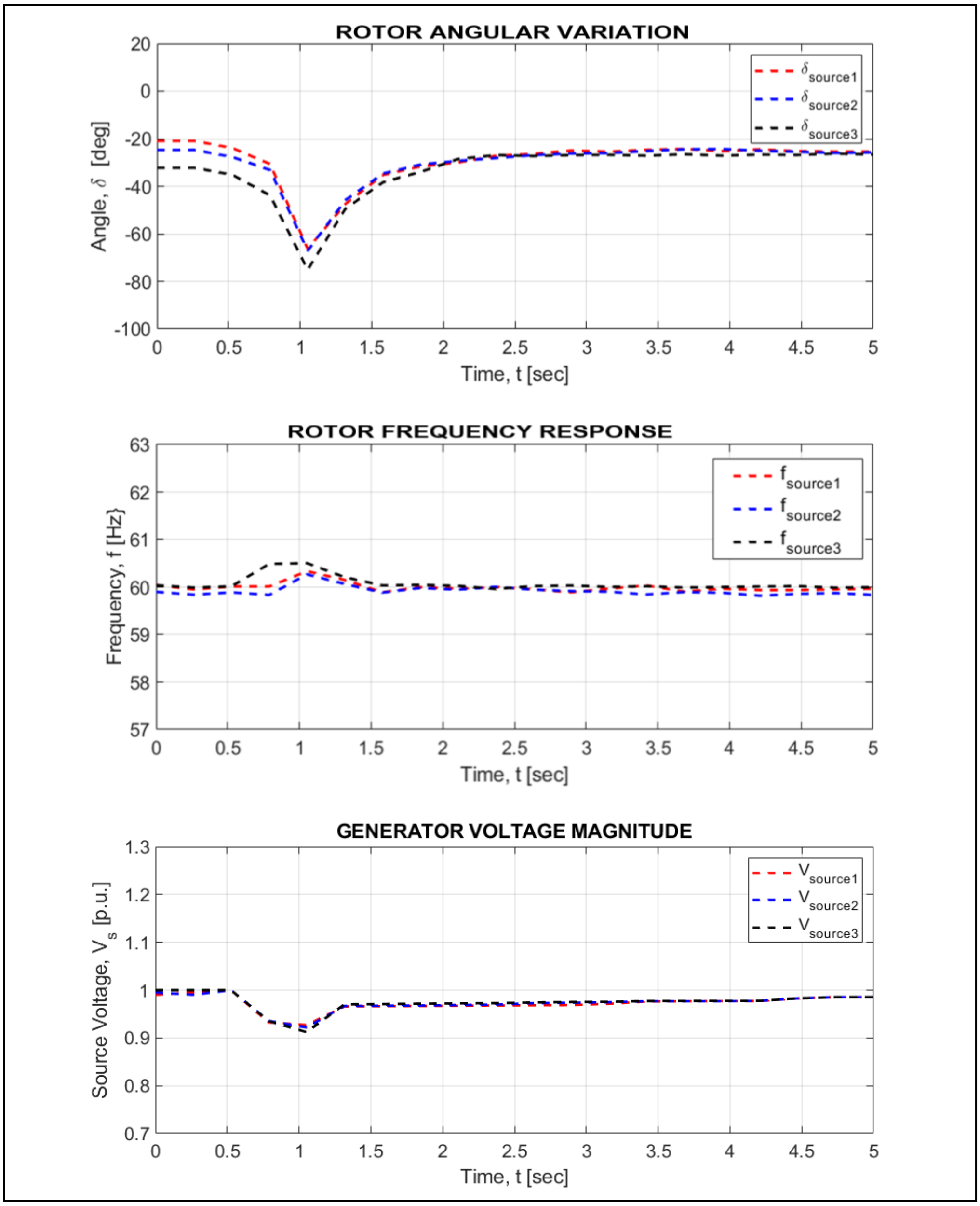

Fig 4 Rotor Dynamics of the Generators under Fault

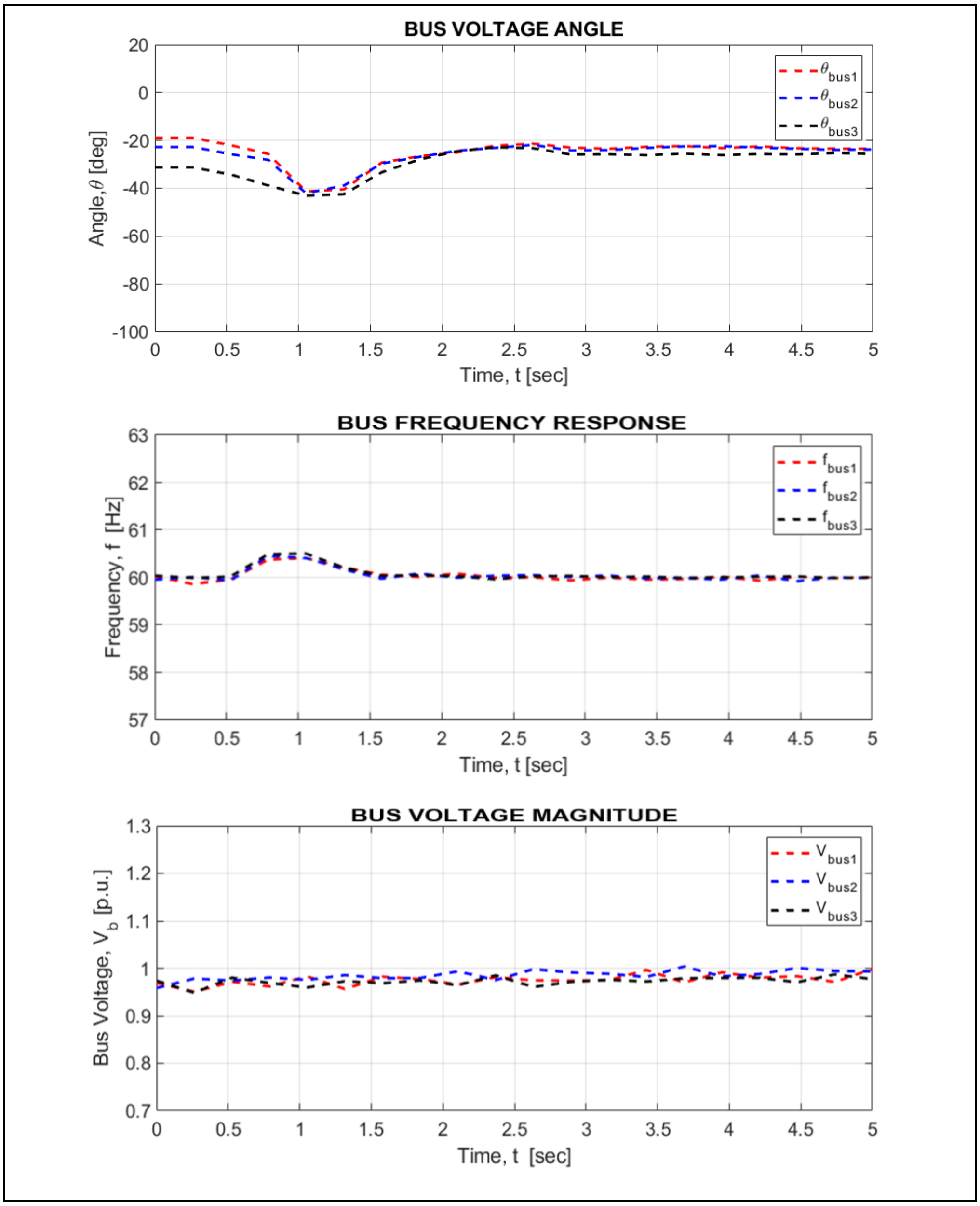

Fig 5 Dynamic Responses of the Buses under Fault

In general, notable effects are produced on all the generators and the entire buses of the TS by the two test disturbances. The resulting dynamics show that there is no difference in the pre-perturbation and the post-perturbation steady state operations. It could be observed that after the clearance of either of the disturbances, none of the generators compromised its synchronism in any way. This is an indication that with proper design, minigrid protection schemes would work efficiently to bring any stability issues under proper control.

4. CONCLUSION

Application of freestanding minigrids in electric utility systems is on the rise and to this end, the dynamic security of standalone minigrids is gradually becoming a significant part of power systems reliability assessment concerns.

This is very important in order to ensure that electricity end-users that are remote from the conventional grids are securely supplied. A real time simulation test rig is employed as tool for transient stability based dynamic security assessment of autonomously operated district minigrid system that has a number of complementary rotating energy sources. Dynamic responses of the generators and the buses of the minigrid to large system disturbances is investigated. As obtained from the study, both the angular variations and the frequency responses of the rotary parts of the all the generators contained in the system, as well as the voltage profiles of all the buses of the system are affected by the disturbances. However, the post-disturbance steady state conditions of the system show that the generators, including the faulted one, as well as the system buses did not in any way compromised their synchronisms after the removal of either type of disturbance.

While this investigation reveals that a number of rotating machine-based energy mini-sources could be integrated without compromising the stability of standalone minigrids, it is also shown by the study that protection scheme that is properly designed could enhance the integrity of operations in minigrid applications. It is likewise deduced that the approach of this study provides a simple and generic means of evaluating the security of multi-machine freestanding mini power systems. The approach could therefore be integrated into minigrids remedial action scheme (MRAS) or minigrids energy management system (MEMS) for the determination of the transient states of island minigrids in the case of large disturbances. Using the approach of the study, all instability-prone contingencies on district minigrid system could be examined and screened.

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Consent for publication – There was a mutual agreement among the authors on the publication of the findings of this study.

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