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Reduced Order Model of A Microgrid System for A University Community in Nigeria

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Abstract *–* This paper presents a reduced order model of a microgrid system for a university community in Nigeria. The designed microgrid system is simulated in MATLAB/Simulink environment to determine the system dynamics. The obtained dynamic system is then reduced to a single block subsystem with multiple inputs and a single output using system linearization. The microgrid model is then linearized with the aid of linearization tool in MATLAB/Simulink using linearized perturbation method. The transfer function of the multiple inputs with respect to the single output of the microgrid system is determined in MATLAB environment. The transfer functions obtained for both inputs are then incorporated to the subsystem to linearize the entire system. The obtained linearized system is reduced with the aid of model reducer using the balanced truncation method in Simulink. The achieved results indicate that the system response of the obtained linearized model is linear compared to the step response of the nonlinear microgrid model of the campus. The results also reveal that the obtained reduced order model - compared to the nonlinear microgrid model - has lesser states with more than 4 times faster simulation response time.

Keywords**—** Microgrid; MATLAB/Simulink; Model reducer; Perturbation method; System linearization; Transfer function.

1. INTRODUCTION

System linearization is the process whereby a nonlinear real system is linearized about an operating point to improve responses. This includes creating linear approximation of the nonlinear system in Simulink to produce a linear state space or transfer function model of the nonlinear system. This linearized model analyses stability, disturbance rejection and reference tracking of the system.

In [1], a reduced order model for modeling the inverter based microgrid system, which is computationally efficient and accurate was proposed. With the aid of developed reduced-order model, the main factors affecting microgrid stability were analyzed. It was revealed that the stability limits for conventional droop-based system ($\omega - P/V - Q$) were determined by the ratio of inverter rating to network capacity, resulting into a smaller stability region for microgrids with shorter lines. This was also verified theoretically on the simplified and generalized network configurations. Their research revealed that the proposed reduced-order model didn't only maintain the modeling accuracy, but also enhanced the computational efficiency. Both frequency and time domains were used to verify detailed model. The linearization of each model was not considered in their analysis.

In [2], an inverter-based microgrid reduced-order model was reviewed and the accuracy of their predictions for stability was investigated by comparing it with a corresponding detailed average model. Their study showed that the simplified reduced order models affect the accuracy in various regimes of the line R/X ratios, and that

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inappropriate model choices would result in substantially inaccurate stability results. Finally, a reduced order model for the stability analysis of microgrids was recommended. This work did not reveal the simulation time for the reduced order model obtained with respect to the microgrid system.

In [3], an AC microgrid consisting of inverter-interfaced distributed generators (IIDGs) was studied. This is a nonlinear complex system with multiple time scales which includes time delay measurements, frequency control and electromagnetic transients. Droop control-based IIDG in an AC microgrid was selected as the objective for this study which includes voltage and current-loop controllers, power droop controller and filter and line. Based on singular perturbation theory, the multi-time scale characteristics of the detailed IIDG model were divided. In addition, the IIDG small signal model, the use of quadratic approximation method of the stability region boundary, and the static and transient stability consistency of the IIDG model order reduction were all demonstrated. By Prony transformation, the dynamic response consistencies of the IIDG model order reduction were evaluated using the frequency damping and amplitude. The obtained results were applicable to a simplified model for the dynamic characteristic analysis of IIDG systems in AC microgrid. With the aid of the eigenvalue comparison, the transient stability index comparison and the dynamic time-domain simulation, the accuracy of this proposed method was verified. The difference in the speed of simulation between the original microgrid system and the reduced order model was not considered.

In [4], a reduced order modeling method of inverter-based microgrid for stability analysis was presented. In this work, a singular perturbation method was applied to reduce the full order model of the microgrid system. Based on the participation analysis of the original model, the dynamic system was divided into two subsystems with preserving the state that has considerable effect on the x dominant dynamics, and eliminating the state with negligible impact. The reduced order obtained in this work was verified using numerical simulation and eigenvalue analysis to compare both original and reduced models but the simulation time for each model was not taken into consideration.

A generic reduced-order modeling method suitable for exploring the dynamic stability of DC voltage control with two modes was proposed in [5]. It was discovered that each droop-based DC voltage control unit could be modeled as an RLC parallel circuit in these two modes. The essential causes of system dynamic stability difference and the physical control parameters for the two modes were revealed. Analysis also revealed that a modified RLC model could be used to obtain its influence if the inner current control with slow dynamic could not be ignored. Analytical solutions of dynamic performance indexes were obtained based on reduced-order model through the impact of the control parameters on the dynamic performance of the DC bus voltage. Detailed and experimental results were used to verify the effectiveness of the proposed reduced-order model. In this analysis, the linearization of the obtained reduced order model was not discussed.

In [6], the dynamic behavior of a microgrid system using system identification techniques and eigen analysis were presented. In this study, a nonlinear microgrid was developed in MATLAB/Simulink environment that was used to achieve linear approximation to perform eigen analysis. System identification technique was used to analyze system dynamic responses. The obtained results were then compared and evaluated in their work, but the speed of simulation was not considered for each case.

In [7], a new distributed secondary control method for voltage and frequency regulation in islanded microgrids was presented. A large-single dynamic model of inverter-interfaced distributed generation (DG) was formulated with multi-input multi-output nonlinear system that was converted to a partly linear one using input–output feedback linearization. The linear-distributed model predictive controller was then designated in each DG to realize the secondary voltage control by incorporating the forecasted behaviors of the local and neighboring DG units. With the nonlinear DG dynamics transformed into a first-order linear system, a distributed proportional integral algorithm was introduced in the frequency restoration while maintaining the accurate active power sharing. The effectiveness of the proposed control methodology was verified in the obtained simulation results but time for simulation of each model was not presented.

In [8], single perturbation method and particle swarm optimizations were used to simplify the model of an islanded microgrid system. The paper also presented two model order reduction methods through direct truncation - where sixth order was reduced to fourth order approximation - and particle swarm optimization further reduces the model order to the power of two. Comparing various responses, simulated results showed that the second order reduction with particle swarm optimization showed more improved response than the other used methods.

The study in [9] presents an optimal reduction technique where 36th order model microgrid system was reduced to the 9th order approximant with the significant dynamics of the original system retained. The obtained results indicated that the proposed method was superior to the balanced truncation method in time and frequency domain. For the system stability, state perturbation in state space model was considered in full as well as reduced order dynamics and eigenvalue analysis.

Rasoolzadeh and Salmasi presented a reduced-order dynamica modelling of droop-controlled inverter-based on low-voltage AC sub-microgrid in a hybrid AC/DC microgrid system [10]. In their work, non-linear dynamic and algebraic equations were derived for the low-voltage AC side which was then linearized around an operating point. Simulated results for the developed model in MATLAB/Simulink were validated with that obtained from PSCAD. Validated results of the developed comprehensive reduced-order model can be used for fault detection. The speed of the reduced order model obtained relative to that of the nonlinear microgrid was not taken into account.

In this paper, the reduced order model of a university campus microgrid is analysed and presented. In this case, linearization tool in MATLAB/Simulink environment - that uses perturbation method - is utilized to reduce the nonlinear model of the campus microgrid.

2. METHODOLOGY

The reduced order model for a university community microgrid is considered in this paper. A microgrid for a university community with electrical load consumption of 969,000 kWh is designed in Homer Pro software. The dynamics of the microgrid system obtained from Homer Pro software is then simulated with the aid of MATLAB/Simulink software. The realized dynamic system is then linearized by linearized perturbation method and finally, the reduced order model of the linearized system is obtained by model reducer using the balanced truncation method in MATLAB/Simulink environment. The speed of simulation of the reduced order model as compared to the full microgrid system is determined.

2.1. System Design

The selected campus for the system design is Edo State University Uzairue, Auchi, Edo State, Nigeria (7° 8′8.25″N, 6°18′28.13″E) located at Kilo-meter 7, Auchi-Abuja Road, Iyamho-Uzairue, Edo State, Nigeria. The pictorial and google Earth view of cross section of the university campus are shown in Figs. 1 and 2, respectively.

Fig. 1. Pictorial view of cross section of the university campus.

Fig. 2. Google Earth view of cross section of the university campus.

Based on the energy consumption of the university community as exhibited in Table 1, a microgrid was designed with the aid of Homer Pro software. This system consist of PV cells, utility grid, inverter, generator and electric load. Schematic diagram of the microgrid system which was presented in [11] is depicted in Fig. 3.

Table 1. Annual energy consumption of Edo State University Uzairue from October 2020 to September 2021.

Months	Previous meter reading [kWh]	Present meter reading [kWh]	Energy consumption [kWh]
October	3635000	3655000	20000
November	3655000	3689000	34000
December	3689000	3781000	92000
January	3781000	3836000	55000
February	3836000	3893000	57000
March	3893000	3986000	93000
April	3986000	4097000	111000
May	4097000	4254000	157000
June	4254000	4324000	70000
July	4324000	4411000	87000
August	4411000	4516000	105000
September	4516000	4604000	88000
Annual energy consumption			969000

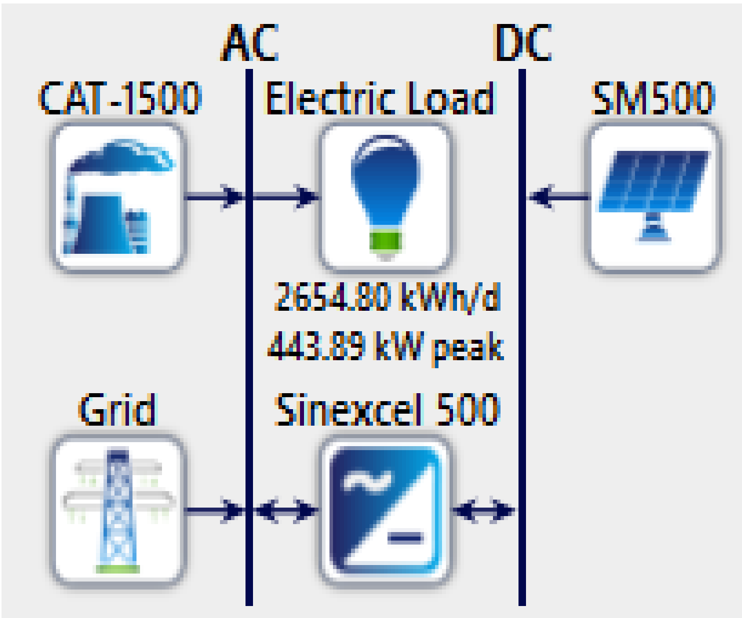

Fig. 3. Schematic diagram of the microgrid system.

2.2. Dynamic Simulation

The system obtained from Homer Pro design was simulated in MATLAB/Simulink environment to determine the dynamics of the system. The system consists of a 675.2 kW PV array, comprised of 96 cell modules each of 500 W, with 25 connected in series and 54 in parallel. Based on the PV size, an inverter of 700 kW was used; also utility grid and a generator were incorporated in the system. Fig. 4 shows the system diagram used for the dynamic simulation in MATLAB/Simulink environment.

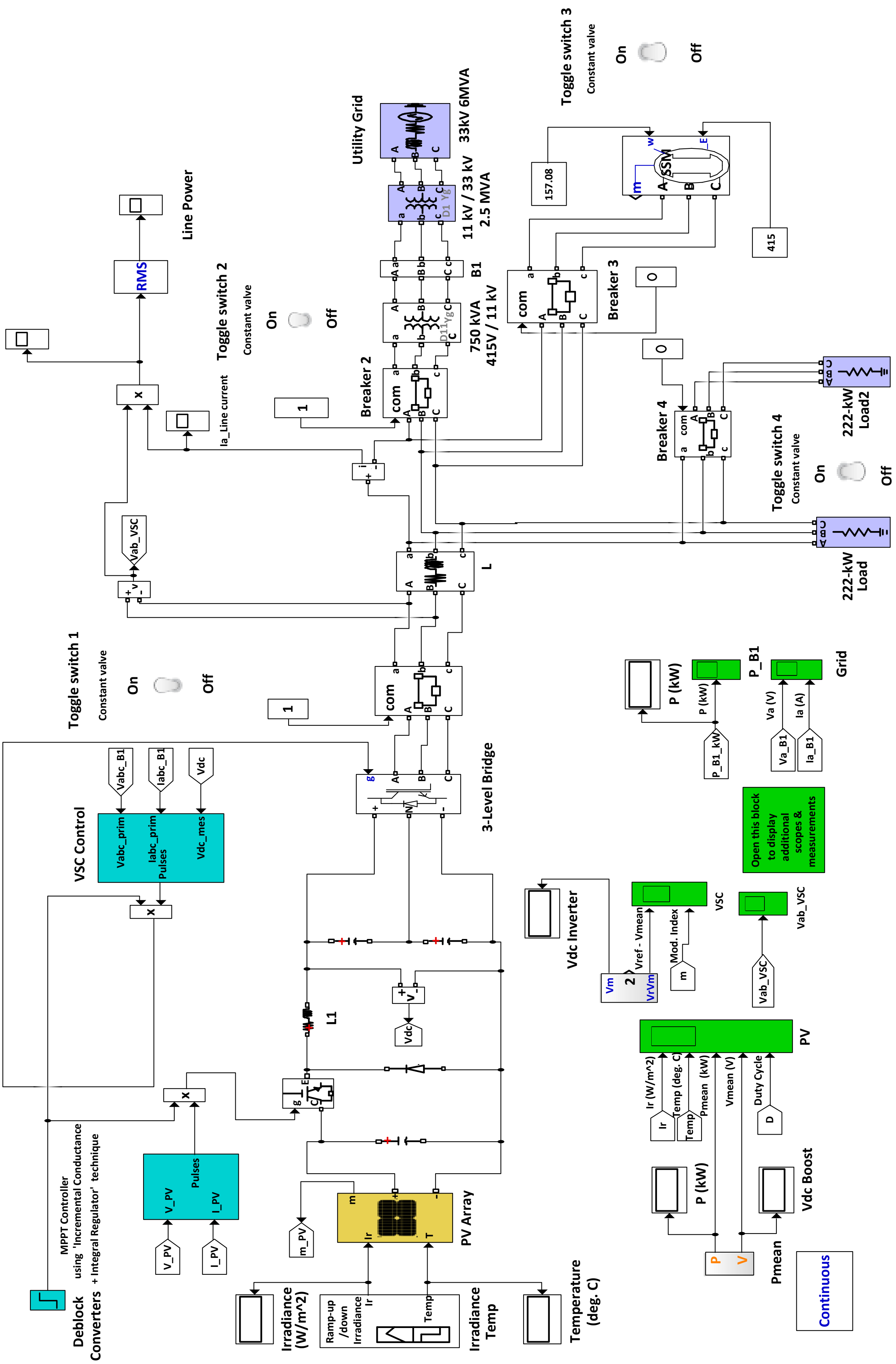

Fig. 4. MATLAB/Simulink diagram of the microgrid system used in the dynamic simulation.

2.3. System Linearization

Linearization of the dynamic system was carried out in MATLAB/Simulink environment, with the aid of model linearizer, using linearized perturbation method. Linearization was done based on the system multiple inputs (irradiance and temperature) and a single output which is the power (i.e. current × voltage). The transfer functions of the inputs with respect to the output was determined by linearized perturbation method. The resulting transfer function obtained was incorporated into the subsystem block of the nonlinear system to linearize the system as shown in Fig. 5.

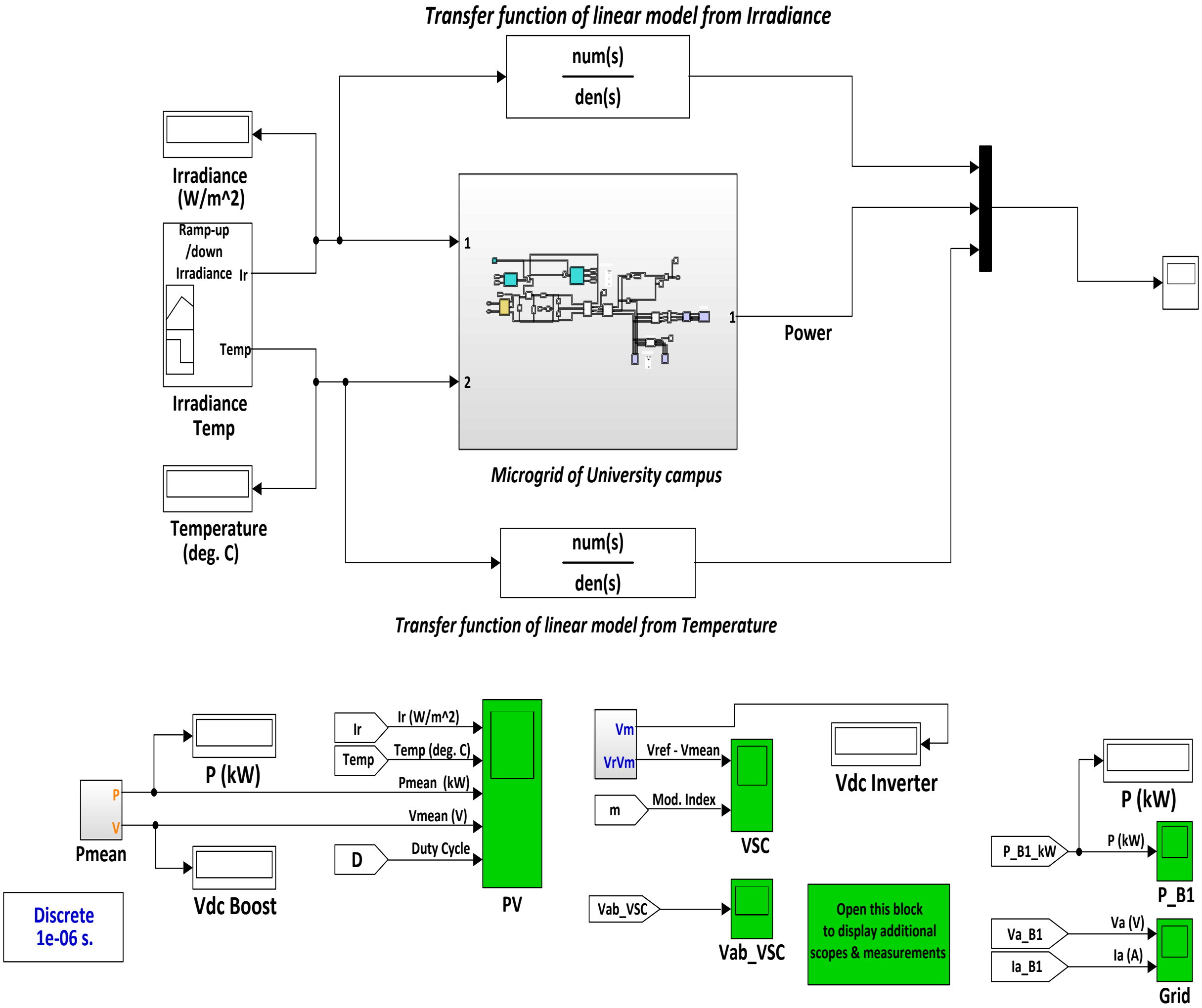

Fig. 5. Linearized microgrid model.

With the aid of perturbation method, the linearized microgrid system was then simulated to determine the system response as compared to the step response of the nonlinear microgrid system.

2.4. System Reduction

The transfer function of the linearized model for both inputs as obtained in MATLAB environment with a simulation time of 81 s at sample time set at 2 s was first obtained as follows:

```
tf =

  From input "Irradiance Temp/1" to output "Subsystem/Power":

  -2.201e-11 z^17 + 2.106e-10 z^16 - 8.715e-10 z^15 + 1.984e-09 z^14 - 2.501e-09 z^13 + 1.142e-09 z^12

          + 1.45e-09 z^11 - 2.771e-09 z^10 + 1.668e-09 z^9 + 1.957e-10 z^8 - 9.087e-10 z^7 + 5.181e-10 z^6

                      - 4.447e-11 z^5 - 8.629e-11 z^4 + 4.652e-11 z^3 - 1.025e-11 z^2 + 8.781e-13 z - 1e-16

  -----------------------------------------------------------------------------------------------------

  z^18 - 10.76 z^17 + 50.96 z^16 - 137.1 z^15 + 219.9 z^14 - 183.8 z^13 - 11.32 z^12 + 214.2 z^11

          - 233.3 z^10 + 82.52 z^9 + 55.89 z^8 - 77.02 z^7 + 31.78 z^6 + 1.713 z^5 - 7.309 z^4 + 3.224 z^3

                                                                    - 0.6452 z^2 + 0.0517 z + 1.193e-05


 From input "Irradiance Temp/2" to output "Subsystem/Power":

 -1.295e-11 z^17 + 1.239e-10 z^16 - 5.128e-10 z^15 + 1.167e-09 z^14 - 1.471e-09 z^13 + 6.714e-10 z^12

         + 8.533e-10 z^11 - 1.63e-09 z^10 + 9.811e-10 z^9 + 1.153e-10 z^8 - 5.347e-10 z^7 + 3.048e-10 z^6

                 - 2.611e-11 z^5 - 5.078e-11 z^4 + 2.737e-11 z^3 - 6.027e-12 z^2 + 5.156e-13 z + 3.583e-17

 -----------------------------------------------------------------------------------------------------

 z^18 - 10.76 z^17 + 50.96 z^16 - 137.1 z^15 + 219.9 z^14 - 183.8 z^13 - 11.32 z^12 + 214.2 z^11

         - 233.3 z^10 + 82.52 z^9 + 55.89 z^8 - 77.02 z^7 + 31.78 z^6 + 1.713 z^5 - 7.309 z^4 + 3.224 z^3

                                                                   - 0.6452 z^2 + 0.0517 z + 1.193e-05
```

Then, the reduced order model of the linearized model was achieved by model reducer with the help of balanced truncation method in MATLAB/Simulink with its 20 states reduced to 5 states as shown in bode diagram in Fig. 6. As shown in the figure, the two results match well up to frequency of 100 rad/s.

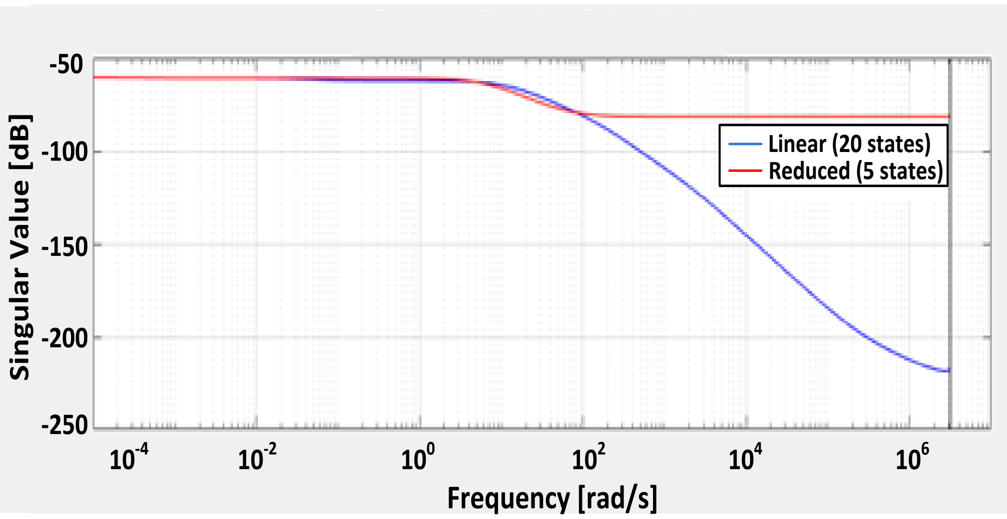

Fig. 6. Linear and reduced order model states.

The large difference between the two states after the frequency of 100 rad/s, as shown in Fig. 6, is a result of the change in states from 20 to 5. The transfer functions for both inputs of the reduced order model as obtained in MATLAB environment with a simulation time of 48 s at sample time set at 2 s are as follows:

```
tf =

  From input "Irradiance Temp/1" to output "Subsystem/Power":
  7.043e-05 z^5 - 0.0003522 z^4 + 0.0007043 z^3 - 0.0007043 z^2 + 0.0003522 z - 7.043e-05
  ---------------------------------------------------------------------------------------
                         z^5 - 5 z^4 + 10 z^3 - 10 z^2 + 5 z - 1

  From input "Irradiance Temp/2" to output "Subsystem/Power":
  4.146e-05 z^5 - 0.0002073 z^4 + 0.0004146 z^3 - 0.0004146 z^2 + 0.0002073 z - 4.146e-05
  ---------------------------------------------------------------------------------------
                         z^5 - 5 z^4 + 10 z^3 - 10 z^2 + 5 z - 1
```

3. RESULTS AND DISCUSSION

Simulated results obtained from the full microgrid system were compared to those obtained from the reduced order model. The comparison shows that the results of line voltages – depicted in Figs. 7 and 10 - as well as the results of line current – exhibited in Figs. 8 and 11 - are in close agreement. The output power waveforms are shown in Figs. 9 and 12.

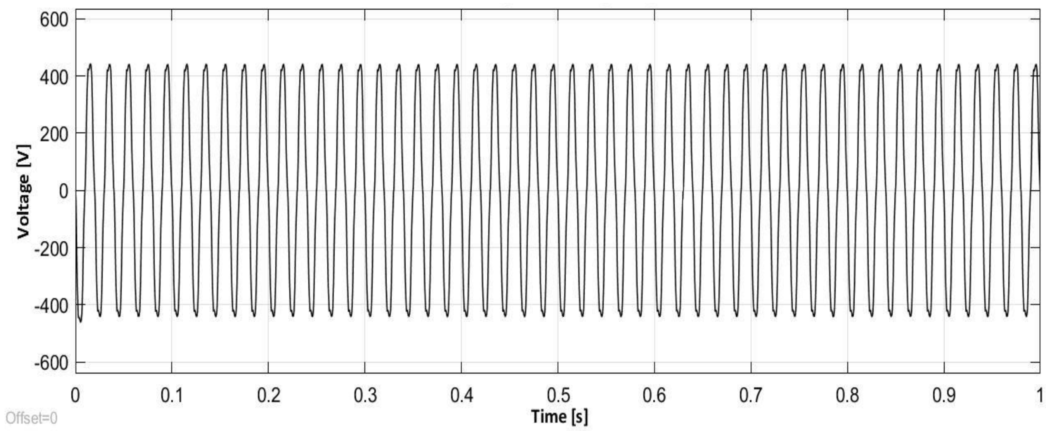

Fig. 7. Line voltage of the microgrid system.

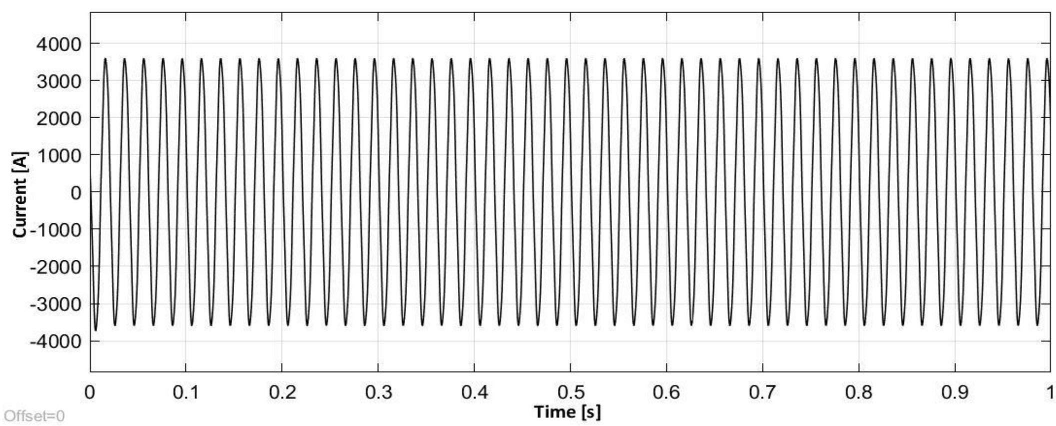

Fig. 8. Line current of the microgrid system.

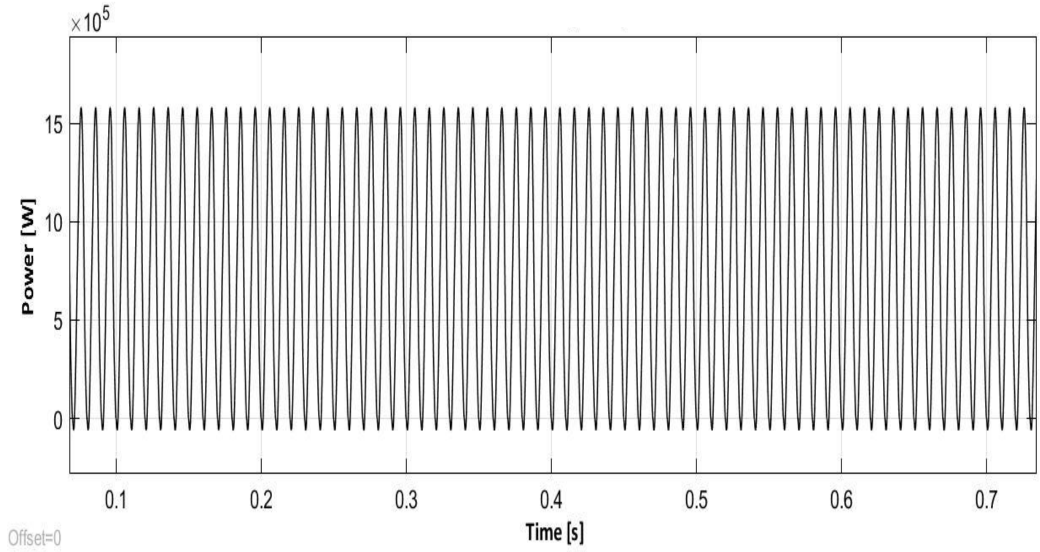

Fig. 9. Output power of the microgrid system.

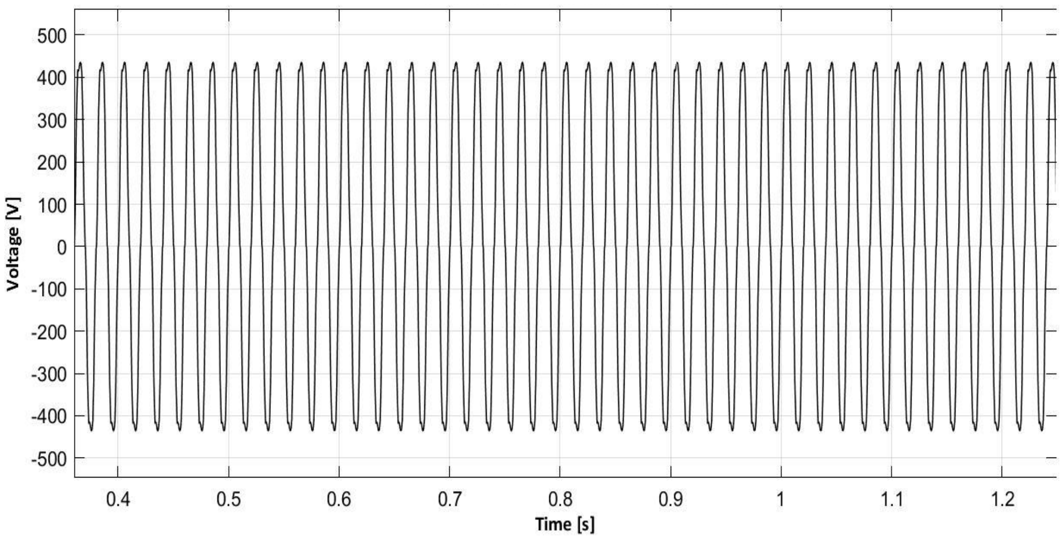

Fig. 10. Line voltage of the reduced order model.

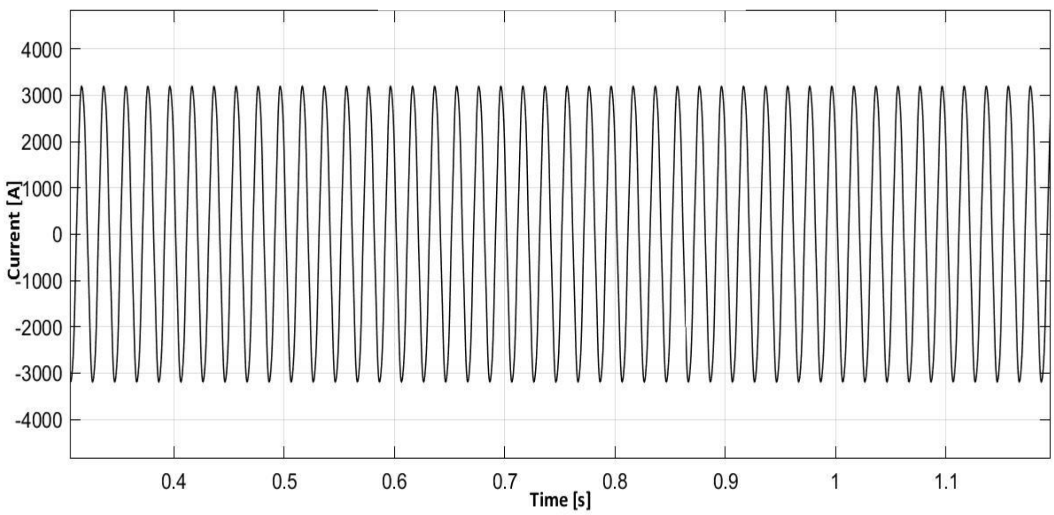

Fig. 11. Line current of the reduced order model.

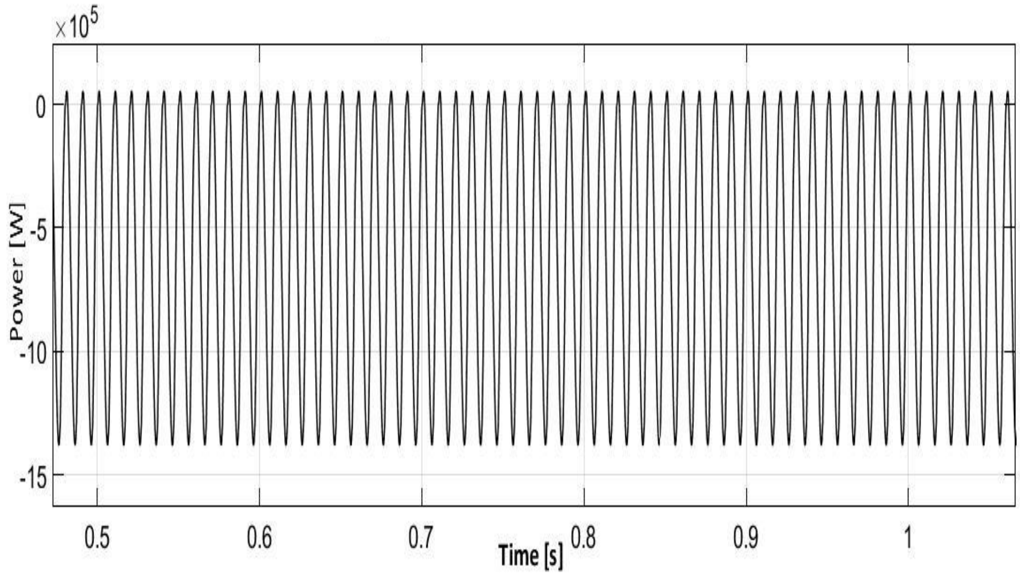

Fig. 12. Output power of the reduced order model.

The nonlinear response of the full microgrid system of the university community is shown in Fig. 13 and the linearized one - using linearized perturbation method in MATLAB/Simulink environment – is depicted in Fig. 14. The discrepancy of both figures is that Fig. 13 has a step response of nonlinear system while Fig. 14 has a response of linearized system.

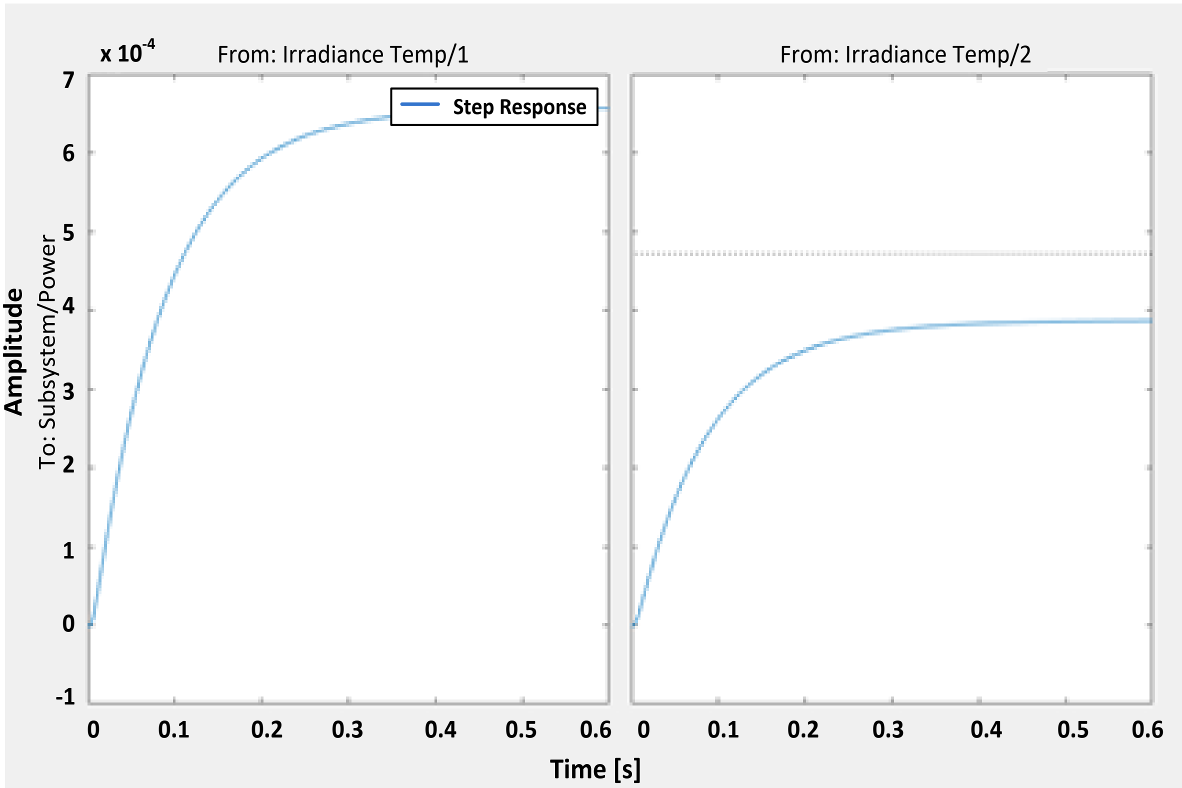

Fig. 13. Step response of the nonlinear model.

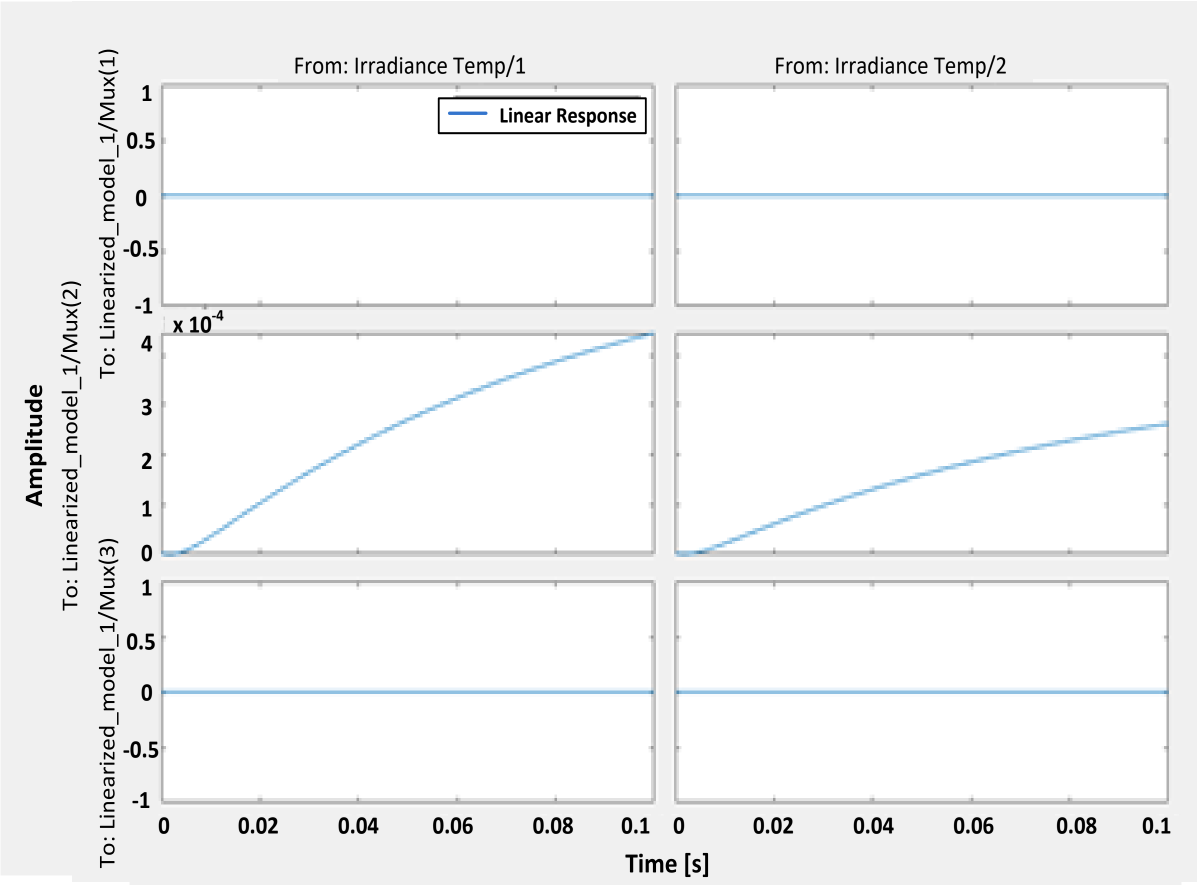

Fig. 14. Step response of the linear model.

The speed of simulation with three different sample times for the microgrid system and the reduced order model is shown in Table 2. It can be noticed that simulation speed for the reduced order model is 4 times faster than that of the nonlinear microgrid model.

Table 2. Simulation speed for the microgrid and the reduced order model for different sample times.

Sample time [s]	Microgrid model	Reduced order model
	Simulation time [s]	Simulation time [s]
1.0	86	20
2.0	222	48
5.0	589	120

4. CONCLUSIONS

The step-by-step linearization of a nonlinear microgrid model for a university campus in Nigeria was realized using linearized perturbation method in MATLAB/Simulink. The linearized model obtained with 20 states was then reduced to 5 states with the aid of model reducer using truncation method in Simulink. The results of the line voltage and line current for the two models are very close. Moreover, the simulation time response of the reduced order model runs 4 times faster than that of the nonlinear microgrid model on same computer.

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