Modeling Of Distributed Energy Resources In An Onshore Hybrid Power System

Stephen Bliss Utibe-Abasi[1]
Department of Electrical/Electronic and Computer Engineering, University of Uyo, AkwaIbom, Nigeria

Kalu Constance[2]
Department of Electrical/Electronic and Computer Engineering, University of Uyo, AkwaIbom, Nigeria
constance.kalu@yahoo.com

EyiboIniobong Eddie[3]
Department of Electrical/Electronic and Computer Engineering, University of Uyo, AkwaIbom, Nigeria

***Abstract*— In this paper, the detailed analytical models for the various distributed energy resources (DER) in an onshore hybrid power system are presented. The DER includes an electric load unit, an energy storage unit and three electric energy generators, namely, solar photovoltaic system, wind turbine and diesel generators. The study was for a hybrid power system microgrid located within University of Uyo Main Campus. The analysis included dynamic models that accounted for the stochastic nature of the load profile, the solar photovoltaic system and the wind turbine power generator system. Sample numerical examples are also presented to demonstrate the application of the analytical models proffered in this study. Sample numerical computation with the models showed that for the given daily energy demand and load fraction of each DER units, about 534 PV modules are needed, along with 89 wind turbines and 10 powerpacks of 210 kWh capacity per pack.A diesel electric generator of about 185 KVA is also required to power one-third of the total peak load. Although the cost analysis is not conducted in this paper, the idea presented in this paper provided the relevant analytical models that can be used to size the various DER components which are required for detailed life cycle cost analysis of the microgrid system.**

***Keywords*— Distributed Energy Resources, Solar Photovoltaic, Wind Turbine, Diesel Generators, Hybrid Power System, Microgrid System**

I. INTRODUCTION

Over the year, the Nigerian national grid has generally been ineffective in meeting the daily electric demand of the teeming population of users across the country [1,2,3,4,5,6]. As such, institutions like the Universities across Nigeria are littered with several units of high capacity diesel generators as ready alternative electric power source. Consequently, every year, Universities in Nigeria spend several millions of Naira on diesel generators that are used to supply the missing power from the National grid.

However, in recent times, some Universities across Nigeria are beginning to adopt solar photovoltaic (PV) power and other renewable power technologies [7,8,9,10,11]. Furthermore, some Universities are already considering distributed energy generation hybrid power system whereby the University can leverage the available renewable energy resources at its disposal to meet its energy demand [12,13,14,15].

In this paper, detailed analytical models of distributed energy resources (DERs) [16,17] in a hybrid power system (microgrid) at University of Uyo Main Campus is presented. The DER includes an electric load unit, an energy storage unit and three electric energy generators, namely, solar photovoltaic system, wind turbine and diesel generators. Relevant mathematical expressions and sample numerical computations are presented to demonstrate the application of the ideas presented in this paper.

II. RESEARCH METHODOLOGY

A. *DESCRIPTION OF THE CASE STUDY OF THE ONSHORE HYBRID POWER SYSTEM*

The onshore hybrid power system, which is a microgrid, is made up of the power supply units and load components interconnected to make up the system. Figure 1 displays the configuration of the onshore microgrid to be considered in this work. The microgrid is connected to the main distribution grid, which feeds the network with electricity. Three local generation sources are additionally considered: solar photovoltaic system, wind turbine and diesel generators. Both the PV systems and the wind turbine are uncontrollable generation devices with a stochastic behavior while the diesel generators are controllable devices that consume diesel to produce electrical energy. These diesel generators also serve as support for power balancing during energy peak periods. Furthermore, electrical energy storage for the PV system serves during periods of low or zero irradiance. The electrical loads also connected to the network are stochastic in nature and cannot be rescheduled or curtailed.

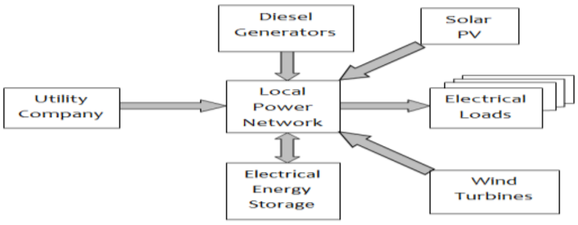


Figure 1: The Distributed Energy Resources (DER) components in the case study onshore microgrid system

B. DESCRIPTION OF THE ONSHORE CASE STUDY SITE: UNIUYO MAIN CAMPUS

The case study site is University of Uyo (UNIUYO) main campus which is situated in Uyo in AkwaIbom State. The campus is located at latitude of 5.022 and longitude of 7.854 and spans about 600km stretch of land. Currently it is serviced by Port-Harcourt Electricity Distribution Company (PHEDC) network, through an 11/33 kV three phase, four wire, 50-60Hz grounded neutral, wye connected radial system. The power network is supplied by one primary feeder which connects via 33kV power service lines to the substations at Use-Offot along Nwaniba road. The overhead electrical system includes about 250 concrete ladder poles and one 300kVA 33/0.415 kV ONAN transformer substation, with 100 mm^2 All Aluminum Conductor (AAC) cable and 100mm^2 Aluminum Conductor Steel Reinforced (ACSR) cable for high tension and low tension lines respectively across the campus. Figure 2 shows the entire UNIUYO Main Campus power distribution network created in ArcGIS software. The load demand profile of the UNIUYO Main Campus is given in Table 1. The site peak load demand is439569 W or 439.6 kW.

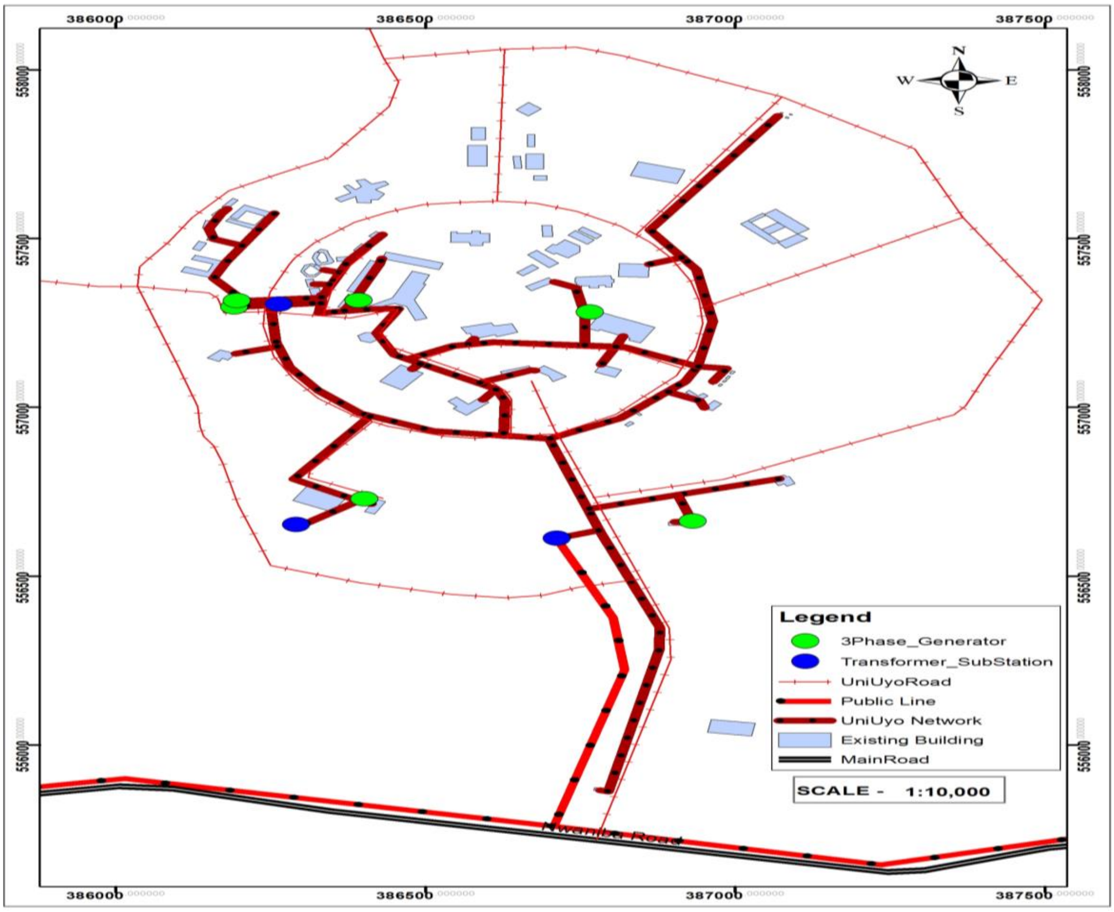


Figure 2: University of Uyo Existing Electric Power Network

Table 1: Load demand profile of UNIUYO Main Campus

End-Use Appliance	Quantity			Total	Unit Power (W)	Total Power (W)
	Residential	Academic	Admin			
Freezer	3	-	2	5	80	400
Fridge	5	12	20	37	140	5180
Water Filter	2	10	15	27	100	2700
Fan	120	270	294	684	85	58,140
Air Conditioner	_	30	50	80	1120	89,600
TV	5	10	15	30	100	30,000
Lighting	240	554	770	1565	30	46,950
Washing machine	4	_	_	4	1800	7,200
Pressing Iron	4	_	_	4	1000	4,000
Uninterrupted Power Supply (UPS) device	5	15	25	45	900	40,500
Computer	100	73	45	218	450	98,100
Internet Router	_	4	9	13	15	195
Photocopier	19	37	61	117	80	9,360
Scanner	12	_	6	18	18	324
Printer	54	17	31	102	30	3060
Water Pump	1	2	2	5	400	2000
Lab Technology	_	80	_	80	300	24,000
Miscellaneous	50	85	100	235	76	17,860
					Total	**439569**

(Source: 2017 field data by the author)

Specifically, the demand profile data consists of average hourly data, for the weekdays and for the weekend days taken from every week in a year. Annual averages of daily load curves for each weekday and weekend day is shown in Figure 3.

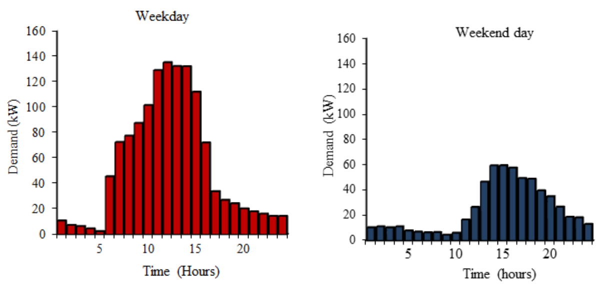


Figure 3: Annual averages of daily load curves obtained from UNIUYO main campus

(Source: 2017 field data by the author)

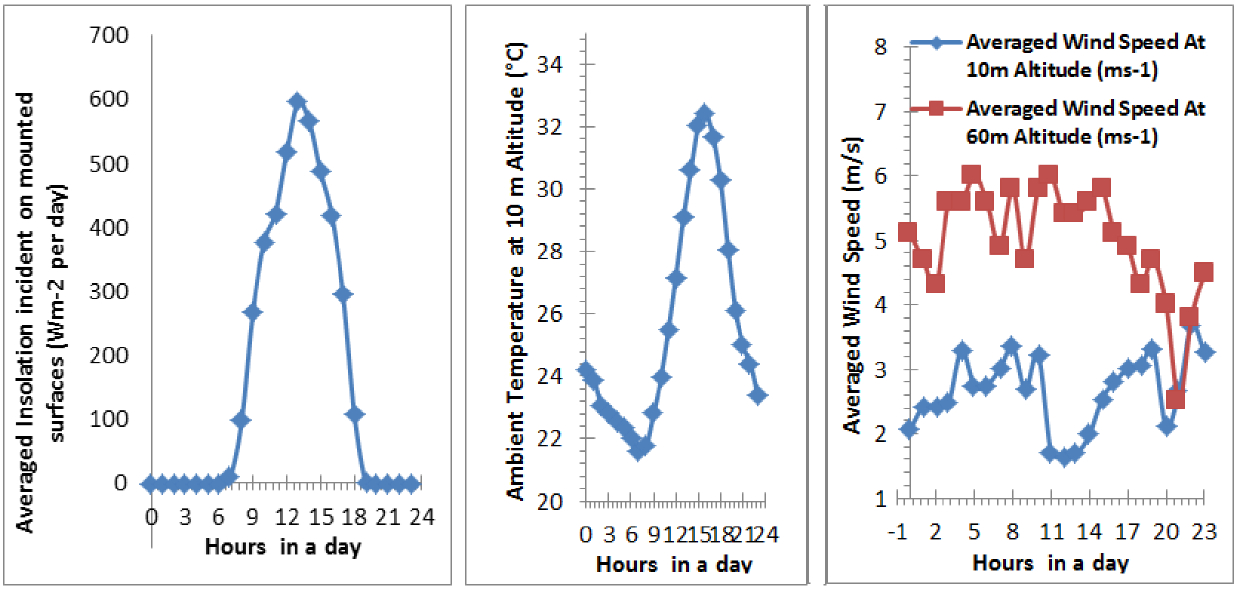
The daily loads generally peak between 12:00PM and 2:00PM. From the measured load curves, the total annual demand, D is estimated by weighting totals for weekdays and weekend days as follows:

$$D = 261 \times \sum_{h=1}^{24} P_{wd}(h) + 104 \times \sum_{h=1}^{24} P_{wed}(h) \quad (1)$$

where $P_{wd}(h)$ and $P_{wed}(h)$, with $h = 1, \ldots, 24$, are load curves for 261 weekdays and 104 weekend days respectively. Therefore, the total annual load demand for UNIUYO main campus is determined as follows;

$$D = 261 \times (1300) + 104 \times (600)$$
$$= 401{,}700\ kWh\ per\ year$$

The meteorological data for the case study site are obtained from NASA website and it consists of the average hourly insolation incident on tilted plane of the PV module, the ambient temperature and the wind speed at 10 m and at 60 m altitudes. The meteorological data are plotted as shown in Figure 4. The average daily ambient temperature, T_a is 29.08 °C , the average daily wind speed, u is 1.69 ms^{-1} and the average hourly insolation incident on the horizontal plane ,G_T is 196Wm^{-2}..



(a) (b) (c)

Figure 4: The meteorological data for the case study site (a) Averaged Insolation incident on mounted surfaces (Wm^{-2} per hour) (b) Ambient Temperature at 10 m Altitude (^oC) (c) Averaged Wind Speed At 10m Altitude (ms^{-1}) and At 60m Altitude (ms^{-1})

C. MODELING OF THE POWER BALANCE IN THE MICROGRID:

The power balance equation determines the relationship between the power generation and the power on the demand side. The power unbalance, denoted as ΔP can be determined as follows:

$$\Delta P = P_G + P_S + P_W + P_F + P_E - P_D \qquad (2)$$

Where ΔP can be expressed in the differential form as follows:

$$\Delta \dot{P} = \dot{P}_G + \dot{P}_S + \dot{P}_W + \dot{P}_F + \dot{P}_E - \dot{P}_D \qquad (3)$$

where P_G represents the grid power, P_S is the solar PV power, P_W characterizes the wind turbine power, P_F is the diesel generator power, P_E is the power transferred to and from the electrical storage, and P_D is the power demanded by the loads.

D. MODELING OF THE GRID POWER:

Whenever the microgrid is connected to the main distribution grid, then, the grid power P_G compensates the power unbalance ΔP by a feedback mechanism, which can be defined as follows [18]:

$$\dot{P}_G = k_G \cdot \Delta P \qquad (4)$$

where k_G is a proportional coefficient. The feedback in Equation (4) is mainly implemented via primary frequency control, [18].

E. MODELING OF THE ONSHORE SOLAR PV SYSTEM OUTPUT AND SIZING OF THE ONSHORE PV ARRAY

The output of the PV array can be determined as follows [19];

$$P_S = P_{STC} f\left[1 + \alpha_p (T_c - T_{c,STC})\right] \qquad (5)$$

Where the PV array cell temperature, T_c can be determined as follows [20];

$$T_c = 0.943 T_a + 0.095 G_T - 1.528 u + 0.3529 \qquad (6)$$

Where u is the wind speed, T_a is the ambient temperature and G_T is the effective solar irradiance incident on the PV array plane with unit in $kWh \cdot m^{-2}$ $per\ day$. Hence, the corresponding continuous dynamics when the PV system is connected to the Microgrid ($S = 1$) are given as;

$$\dot{P}_S = \frac{P_{STC} f[\alpha_p (T_c - T_{c,STC}) + 1]}{G_{STC}} \cdot dG_T + \frac{P_{STC} G_T \alpha_p f}{G_{STC}} \cdot dT_c \qquad (7)$$

$$dT_c = 0.943 \cdot dT_a + 0.095 \cdot dG_t - 1.528 \cdot du \quad (8)$$

$$dG_T = \alpha_G(\overline{G_T} - G_T)dt + \sigma_G dW_t \quad (9)$$

$$dT_a = \alpha_T(\overline{T_a} - T_a)dt + \sigma_T dW_t \quad (10)$$

$$du(t) = -\frac{u(t)-\bar{u}(t)}{T}dt + \kappa\bar{u}\sqrt{2/_T}\,dW(t) \quad (11)$$

For the estimation of the variable, dG_T, α_G is the tracking coefficient, σ_G, the variation coefficient, and dW_t is a variable representing Wiener process. The PV module specifically selected for this research is the Global Solar Power FLEX BIPV. It was chosen because its design is especially for rooftops and also adaptable for floating due to its flexible nature. Now, given that $T_a = 29.08\ ^oC$, $u = 1.69\ ms^{-1}$ and $G_T = 196\ Wm^{-2}$ per day, hence, based on Equation 6, the cell temperature is computed as;

$$T_c = 0.943(29.08) + 0.095(196) - 1.528(1.69) + 0.3529 = 43.8\ ^oC$$

Therefore, putting $T_c = 43.8\ ^oC$ in Equation 5, gives;

$$P_{CPV} = 298.65[1 + (-0.43/100)(43.8 - 25)] = 298.65[0.91916] = 274.507134\ W$$

Now, the PV system is designed to supply one-third of the entire load demand with peak power of 439569 W. Therefore, the number of PV modules required for the system is given as;

$$N_{CPV} = \frac{\left(\frac{439569\ W}{3}\right)}{274.5} = \frac{146523}{274.5} \approx 534\ modules$$

F. MODELING OF THE WIND ENERGY AND SIZING OF THE ONSHORE WIND TURBINE:

The wind turbine is considered as a deterministic system which is affected by stochastic inputs. The power of the wind turbine is given by a non-linear static model expressed as follows [18];

$$P_w = \frac{1}{2}\rho A u^3 C_p \quad (12)$$

where u is the wind speed, ρ is the air density, A is the rotor swept area, and C_p is the power coefficient, an efficiency function depending on θ, the pitch angle and $\eta = \frac{\lambda}{u}$, the tip speed ratio, where blade tip speed, $\lambda = \omega r = \frac{2\pi r}{t}$. Both θ and ω are functions of time. However, for the sake of simplicity, a wind turbine model based on polynomial approximation of power curve is adopted for the wind turbine power production which is given as;

$$P_w = a_w u^3 + a_w^{'} u^2 + a_w^{''} u \quad (13)$$

where $a_w, a_w^{'}$ and $a_w^{''}$ are coefficients. For the sake of simplicity, only two discrete modes is considered: connected and disconnected. In the connected mode, the wind turbine is considered to be connected to the local power network and to be operating in the power optimization area, when the speed of its blade tip is less than the maximal tip speed. When on the other hand the wind turbine is disconnected from the local power network, then it does not feed the microgrid with power. Then, the corresponding continuous dynamics when the turbine is connected to the microgrid ($W = 1$) are;

$$\dot{P_w} = (3a_w u^2 + 2a_w^{'} u + a_w^{''})\, du \quad (14)$$

$$du = -\frac{u-\bar{u}}{T}dt + \kappa\bar{u}\sqrt{2/_T}\,dW \quad (15)$$

where $a_w, a_w^{'}, a_w^{''}$ are turbine output constants, $\bar{u}$ denotes monthly averages of daily wind speed altogether determined as the long run mean, κ is a factor that depends on the geographical location of the wind turbine, T is the turbulence factor and the parameter dW, is a Wiener process that models the uncertainty in the actual and forecasted wind speed. The specific wind turbine selected for this research is the BWC Excel 10kW model with the values of the polynomial approximation coefficients, a_w, $a_w^{'}$ and $a_w^{''}$ given as; $0.0112, -0.008$ and -0.0775 respectively. For the selected wind turbine, when $u_w = 6.0ms^{-1}$ the turbine output power, $P_{OWT} = 1.65\ kW$. Now, since the wind turbine system supplies one-third of the load demand, hence;

$$N_{LWT} = \frac{\left(\frac{1}{3}\right)439.569}{1.65} = \frac{146.523}{1.65} = 89\ turbines$$

G. MODELING OF THE DIESEL GENERATOR POWER SUPPLY

The diesel generator model is captured by the following first order differential equation [18];

$$J\frac{d\omega}{dt} = (T_M - T_E - D\omega) \quad (16)$$

where J is the moment of inertia of the generator rotor (kg m^2), T_E refers to the air-gap electrical torque or counteracting electromagnetic torque, T_M is the mechanical shaft torque produced by the engine (N.m), D is the damping-torque coefficient (N.m.s) and ω represents the rotor shaft velocity (rpm).

In the start-mode, a diesel engine is used to drive the alternator velocity to predefined revolutions per minute (RPM). In this configuration the mechanical torque is taken to be equal to zero – $T_M = 0$ because the minimal fuel flow maintains the combustion process but does not produce a mechanical torque. Hence, the electrical torque represents the driving force for the rotation of the generator, and is defined by [18] as:

$$T_E = a_0 + a_1 \cdot P_F + a_2 \cdot P_F^2 \quad (17)$$

where a_0, a_1, a_2 are real constants. Since the generator in this mode is connected to the electric motor, P_F represents the consumed electrical power, which is a negative value. When the rotor shaft is rotating at a predefined and nominal RPM, ω_{nom}, it starts to ignite fuel, warms up, and is synchronizing its voltage phase and frequency with the local power grid, however it still does not supply the Microgrid with power. Afterwards the generator is switched to the operational on- mode, where the generator produces power and then it is driven by a combustion process. The mechanical torque represents the driving force for the rotation of the generator, and can be characterized with the following polynomial as shown in [18];

$$T_M = a_3 + a_4 \cdot m_f + a_5 \cdot m_f^2 \cdot a_6 \cdot \omega \quad (18)$$

where a_3; a_4; a_5; a_6 are real constants, m_f is the fuel flow and ω is the angular velocity. The electrical torque acts along the mechanical one, and is decelerating the generator angular velocity. According to [18], the electrical torque can be defined by a second order polynomial:

$$T_E = a_7 + a_8 \cdot \omega + a_9 \cdot \omega^2 \quad (19)$$

where a_7; a_8; a_9 are real constants and ω is the current angular velocity. The generated power depends on the angular velocity and can be expressed as:

$$P_F = a_{10} + a_{11} \cdot \omega + a_{12} \cdot \omega^2 \quad (20)$$

where a_{10}; a_{11}; a_{12} are real constants, as shown by [18].

Therefore, the diesel generator is in its on-mode ($M = 1$) and the corresponding continuous dynamics is captured as follows:

$$d\omega = \frac{1}{J}(T_M - T_E - D\omega) \cdot dt \quad (21)$$

$$\dot{P_F} = a_{11} \cdot d\omega + 2 \cdot a_{12} \cdot \omega \cdot d\omega \quad (22)$$

The *Shutdown* mode has a behavior that is analogous to the *Start* mode: the fuel combustion is stopped, the engine is driving the generator on a predefined RPM, and the generator is smoothly cooling down. After a given time, the generator is switched off and the alternator speed is naturally decelerated to zero. The diesel generator used in this study is the 500 kVA 400 ekW Caterpillar C15 Prime rated generator - Mantrac Unit.

H. MODELING OF THE ENERGY STORAGE:

A simplified energy storage model adopted expresses the stored energy P_{ES} as follows by [21];

$$\dot{P_{ES}} = -\eta \cdot P_E - P_L \quad (23)$$

where η denotes power exchange efficiency, P_E is the power exchanged between the storage device and the local power network, and P_L denotes power losses associated to the storage. The power exchange efficiency parameter, η is defined as

$$\eta = \begin{cases} \eta_s, & \text{for the } Supply \text{ mode } (P_E > 0) \\ 0, & \text{for the } Store \text{ mode } (P_E = 0) \\ \eta_l, & \text{for the } Load \text{ mode } (P_E < 0) \end{cases} \quad (24)$$

The Tesla Powerpack with energy capacity of 210 kWh per Powerpack was selected for energy storage . The energy storage capacity of 1900 kWh per day is accounted for, hence, the number of Tesla Powerpacks required for the storage is given as;

$$N_{ES} = \frac{1900}{210} \approx 10\, powerpacks$$

J. DEMAND MODELING

The electrical loads depend on activity patterns of users during the day. These dynamics are stochastic in nature and can be modeled by stochastic differential equations. The Ornstein-Uhlenbeck model is a suitable choice that can also be adopted for the modeling of the continuous dynamics of electrical loads in the connected-mode.

$$\dot{P_D} = \alpha \cdot (\overline{P_D} - P_D)dt + \sigma_D \cdot dW \quad (25)$$

where $\overline{P_D}$ is a given load profile, α represents a tracking coefficient, σ_D is a variation coefficient, and dW denotes the Wiener process. In the case of the disconnected mode, the dynamics of electrical loads is trivial as, $P_D = 0$, $\dot{P_D} = 0$.

III. CONCLUSION

In this paper, the detailed analytical models for the various distributed energy resources (DER) in an onshore hybrid power system are presented. The DER includes an electric load unit, an energy storage unit and three electric energy generators, namely, solar photovoltaic system, wind turbine and diesel generators. The study was for a hybrid power system microgrid located within University of Uyo Main Campus. The analysis included dynamic models that accounted for the stochastic nature of the load profile, the solar photovoltaic system and the wind turbine power generator system. Sample numerical examples are also presented to demonstrate the application of the analytical models proffered in this study.

REFERENCES

1. Olatomiwa, L., Mekhilef, S., Huda, A. S. N., &Ohunakin, O. S. (2015). Economic evaluation of hybrid energy systems for rural electrification in six geo-political zones of Nigeria. *Renewable Energy*, *83*, 435-446.
2. Onohaebi, S. O., & Igbinovia, S. O. (2010). DEVELOPMENT OF A MATLAB PROGRAM TO COMPUTE BUS VOLTAGES IN THE NIGERIA ELECTRICAL POWER SYSTEM. *International Journal of Academic Research*, *2*(4).
3. Ezirim, G., Onyemaechi, E., & Freedom, O. (2016). The Political Economy of Nigeria's Power Sector Reforms: Challenges and Prospects, 2005-2015. *Mediterranean Journal of Social Sciences*, *7*(4), 443.
4. Olaniyan, K., McLellan, B., Ogata, S., &Tezuka, T. (2018). Estimating residential electricity consumption in Nigeria to support energy transitions. *Sustainability*, *10*(5), 1440.
5. Etukudor, C., Abdulkareem, A., & Ayo, O. (2015). The daunting challenges of the Nigerian electricity supply industry. *Journal of Energy Technologies and Policy*, *5*(9), 25-32.
6. Tijjani, A. A. (2002). Statistical Analysis of Wind Power Density based on the Weibull and Rayleigh Models in North–Western Nigeria. *Unpublished*, *22*, 739-753.
7. Oghogho, I. (2014). Solar energy potential and its development for Sustainable energy generation in Nigeria: a road map to achieving this feat. *International Journal of Engineering and Management Sciences*, *5*(2), 61-67.
8. Akinboro, F., Adejumobi, L. A., & Makinde, V. (2012). Solar Energy Installation in Nigeria: Observations, Prospect, Problems, and Solution. *Transnational Journal of Science and Technology*, *2*(4), 73-84.
9. Ohunakin, O. S., Adaramola, M. S., Oyewola, O. M., & Fagbenle, R. O. (2014). Solar energy applications and development in Nigeria: drivers and barriers. *Renewable and Sustainable Energy Reviews*, *32*, 294-301.
10. Babatunde, E. (2007). Solar Energy, A Friendly Renewable Energy Option for Nigeria. *Solar Energy, A Friendly Renewable Energy option for Nigeria*, *1*(15).
11. Saka, A. B., Olawumi, T. O., & Omoboye, A. J. (2017). Solar Photovoltaic System: A Case Study of Akure, Nigeria. *World Scientific News*, *83*, 15-28.
12. Muljadi, E., & Bialasiewicz, J. T. (2003, November). Hybrid power system with a controlled energy storage. In *IECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society (IEEE Cat. No. 03CH37468)* (Vol. 2, pp. 1296-1301). IEEE.
13. Deb, G., Paul, R., & Das, S. (2012). Hybrid power generation system. *International Journal of computer and electrical engineering*, *4*(2), 141.
14. Jain, S., & Agarwal, V. (2008). An integrated hybrid power supply for distributed generation applications fed by nonconventional energy sources. *IEEE transactions on energy conversion*, *23*(2), 622-631.
15. Zhang, J., Huang, L., Shu, J., Wang, H., & Ding, J. (2017). Energy management of PV-diesel-battery hybrid power system for island stand-alone micro-grid. *Energy Procedia*, *105*, 2201-2206.
16. Kirsch, L. D., & Morey, M. J. (2015). Pricing retail electricity in a distributed energy resources world. *The Electricity Journal*, *28*(3), 112-121.
17. Carneiro, G. A. (2017). *Integrated assessment of buildings and distributed energy resources (DER) at the neighborhood scale* (Doctoral dissertation, Georgia Institute of Technology).
18. Machowski, J., Bialek J., Bumby, J. (2008) Power Systems Dynamics – Stability and Control. John Wiley and Sons, Ltd.
19. Duffie J.A. and Beckman W.A. (2006) Solar Engineering of Thermal Processes. Fourth Edition. John Wiley & Sons Inc. Hoboken.
20. Muzathik, A. M., (2014) Photovoltaic Modules Operating Temperature Estimation Using a Simple Correlation. *International Journal of Energy Engineering*, 4(4): 151-158.
21. Parisio, A. and Gilelmo, L. (2011). Energy Efficient Microgrid Management Using Model Predictive Control. IEEE Conference on Decision and Control and European Control, pp 5449-5454