NANOGRID SIZING USING NESTED INTEGER LINEAR PROGRAMMING AND TIME-OF-USE BASED LOAD MANAGEMENT

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ABSTRACT

Electrical utility services are evolving from centralized conventional systems to distributed grids (DGs) attributing to clean energy production, customer participation and low energy cost. Integration of renewable energy (RE) systems into existing grids results in complex grid structure which requires optimization methods in planning and operational schemes. In RE system planning, capacity sizing and component placements are typically implemented using classical methods, application software and intelligent-based methods. The software-based methods are static, hence, cannot be tuned to a customized application. Whereas, intelligent-based methods produce results that are acceptable, however, not optimal. Linear programming (LP) based algorithms as classical methods are preferred due to its simplicity, speed and accuracy which yields global optimal results without branching at local solutions. The mixed integer linear programming (MILP) is used in microgrid's components sizing. However, MILP has limitations of large formulations, high computational burdens and hardly consider multi-objective analysis. To overcome the MILP problems, nested integer linear programming (NILP) is proposed in this study to implement a multi-configurational sizing in residential nanogrid to achieve low energy cost. A residential located in sub-Saharan semiarid climates of northern Nigeria is chosen as a case study. The proposed NILP is implemented in a multi-stage hybridization of relaxation LP and MILP in a nested loop for nanogrid configurations using photovoltaic (PV), wind turbine (WT) and battery energy storage system (BESS). Effectiveness of the NILP is verified by comparison with the classical MILP and particle swarm optimization (PSO). Operation schemes in RE systems include power dispatch and demand side management (DSM). The DSM is preferred as it allows more options for customer participation and can simply follow supplies. DSM is implemented using the conventional time-of-use (C_{TOU}) methods. However, the C_{TOU} is time-bound, utility-centred, incur additional energy costs and affects customer comforts. To balance the conflicting objectives of energy cost and customer comfort, the time-of-use fitness (TOUF) which is an improved version of C_{TOU} has been proposed. The method is introduced to achieve load management for the nanogrid's optimal energy utilization and to reduce consumption cost. The proposed TOUF considered local RE supplies, BESS, grid interaction and customer demands based on a fitness function ($F_{function}$). The $F_{function}$ is a demand response initiative used alternately for energy based on real-time energy cost to define a fitness costs (F_{cost}) as the energy consumption cost. Both the sizing and load management schemes are implemented using MATLAB programming. The NILP achieved reductions in nanogrid's capacity, the levelized cost of energy (LCOE), and net present costs (NPC) as compared to the MILP. The PV/WT hybrid nanogrid configuration achieves NPC and LCOE reductions by 11% and 33% compared to MILP and PSO, respectively. The TOUF achieved up to 43.40% and 53.09% F_{cost} reductions under the BESS support. The autonomous nanogrid operations were analysed using the Markov Chains as a stochastic tool. The probabilistic information indicates that the proposed nanogrid is able to achieve up to 61.54% autonomy in a 25-year lifetime analysis.

ABSTRAK

Perkhidmatan utiliti elektrik berkembang dari sistem konvensional terpusat ke grid teragih (DG) disebabkan penghasilan tenaga bersih, penyertaan pelanggan dan kos tenaga yang rendah. Integrasi sistem tenaga boleh diperbaharui (RE) ke dalam grid sedia ada menyebabkan struktur grid menjadi kompleks dan memerlukan kaedah pengoptimuman dalam perancangan dan skim operasi. Dalam perancangan sistem RE, pensaizan kapasiti dan penempatan komponen biasanya dilaksanakan menggunakan kaedah klasik, perisian aplikasi dan kaedah berasaskan kecerdasan. Kaedah berasaskan perisian adalah bersifat statik, justeru itu, tidak dapat ditalakan kepada aplikasi tersuai. Manakala, kaedah berasaskan kecerdasan menghasilkan keputusan yang boleh diterima, namun, tidak optimum. Algoritma berasaskan pengaturcaraan linear (LP) sebagai kaedah klasik lebih disukai disebabkan keringkasan, kelajuan dan ketepatannya yang menghasilkan keputusan optimum global tanpa bercabang pada penyelesaian tempatan. Pengaturcaraan linear integer campuran (MILP) digunakan dalam pensaizan komponen microgrid. Walau bagaimanapun, MILP mempunyai had pada jumlah rumus yang besar, beban komputasi yang tinggi dan sukar mempertimbangkan analisis pelbagai objektif. Untuk mengatasi masalah MILP, pengaturcaraan linear integer bersarang (NILP) dicadangkan dalam kajian ini untuk melaksanakan pensaizan pelbagai konfigurasi dalam nanogrid kediaman untuk mencapai kos tenaga yang rendah. Satu kediaman di iklim sub-Sahara di utara Nigeria dipilih sebagai kes kajian. NILP yang dicadangkan dilaksanakan dalam hibridisasi pelbagai tahap kelonggaran LP dan MILP dalam gelung bersarang untuk konfigurasi nanogrid menggunakan fotovoltaik (PV), turbin angin (WT) dan sistem simpanan tenaga bateri (BESS). Keberkesanan NILP disahkan dengan perbandingan dengan MILP klasik dan Pengoptimuman Kawanan Zarah (PSO). Skim operasi dalam sistem RE termasuk penghantaran kuasa dan pengurusan sisi permintaan (DSM). DSM lebih disukai kerana ia memberi lebih banyak pilihan untuk penyertaan pelanggan dan mudah mengikut bekalan. DSM dilaksanakan menggunakan kaedah *time-of-use* konvensional (C_{TOU}). Walau bagaimanapun, C_{TOU} bargantung pada masa, berpusat pada utiliti, menanggung kos tenaga tambahan dan mempengaruhi keselesaan pelanggan. Untuk mengimbangi objektif bertentangan di antara kos tenaga dan keselesaan pelanggan, *time-of-use fitness* (TOUF) yang merupakan versi C_{TOU} yang diperbaik telah dicadangkan. Kaedah ini diperkenalkan untuk mencapai pengurusan beban bagi penggunaan tenaga optimum nanogrid dan mengurangkan kos penggunaan. TOUF yang dicadangkan mempertimbangkan bekalan RE tempatan, BESS, interaksi grid dan permintaan pelanggan berdasarkan fungsi kecocokan ($F_{function}$). $F_{function}$ adalah inisiatif respons permintaan yang digunakan secara bergantian untuk tenaga berdasarkan kos tenaga masa nyata untuk menentukan kos kecocokan (F_{cost}) sebagai kos penggunaan tenaga. Kedua-dua skim pensaizan dan pengurusan beban dilaksanakan dengan menggunakan program MATLAB. NILP mencapai pengurangan kapasiti nanogrid, kos tenaga yang diratakan (LCOE), dan kos kini bersih (NPC) berbanding dengan MILP. Konfigurasi nanogrid hibrid PV/WT mencapai pengurangan NPC dan LCOE masing-masing, sebanyak 11% dan 33% berbanding MILP dan PSO. TOUF mencapai pengurangan sehingga 43.40% dan 53.09% F_{cost} dengan sokongan BESS. Operasi nanogrid autonomi dianalisa menggunakan Markov Chains sebagai alat stokastik. Maklumat kebarangkalian menunjukkan bahawa nanogrid yang dicadangkan dapat mencapai sehingga 61.54% jangkauan autonomi dalam analisis sepanjang 25 tahun.

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LIST OF ABBREVIATIONS

AC - Alternating current
Ah - Ampere-hour
ANN - Artificial Neural Network
BESS - Battery energy storage system
CG - Conventional grid
CRF - Capital recovery factor
DC - Direct current
DG - Distributed grid/generation
DoD - Depth of discharge of battery system
DR - Demand response
DSM - Demand side management
DT - Decision tree
EE - Energy efficiency
EM - Energy management
ESS - Energy storage systems
EV - Electric vehicle
FLC - Fuzzy logic control
GA - Genetic Algorithm
HOMER - Hybrid optimization of multiple energy renewables
KEDCO - Kano Electricity Distribution Company
LCOE - Levelized cost of energy
LP - Linear programming
LPSP - Low power supply probability
MILP - Mixed integer linear programming
NILP - Nested integer linear programming
NOCT - Nominal operating cell temperature
NPC - Net present cost
OMP - Okinawa Microgrid Project
PDN - Power distribution network
PCEC - Per capita electricity consumption

PSO - Particle Swarm Optimization
PV - Photovoltaic system
RE - Renewable energy
SLI - Vehicles starting, lighting and ignition
SOC - State of charge
TOUF - Time-of-use fitness
V - Wind speeds (wind velocities)
Wh - Watt-hour
WT - Wind turbine system

LIST OF SYMBOLS

A_d - Days of autonomy

C_{cap}^{bess} - Capital cost of battery energy storage system

C_{cap}^{inv} - Capital cost of the inverter

C_{cap}^{pv} - Capital cost of the photovoltaic system

C_{cap}^{wt} - Capital cost of wind turbine

C_{cap}^{sys} - Capital cost of the nanogrid system

C_{fuel}^{bess} - Fuel cost of battery energy storage system

C_{fuel}^{inv} - Fuel cost of the inverter

C_{fuel}^{pv} - Fuel cost of the photovoltaic system

C_{fuel}^{wt} - Fuel cost of wind turbine

C_{fuel}^{sys} - Fuel cost of the nanogrid system

C_{om}^{bess} - Operation and maintenance cost of battery system

C_{om}^{inv} - Operation and maintenance cost of the inverter

C_{om}^{pv} - Operation and maintenance cost of the photovoltaic system

C_{om}^{wt} - Operation and maintenance cost of the wind turbine

C_{om}^{sys} - Operation and maintenance cost of the nanogrid system

C_{sal}^{sys} - Salvage cost of the nanogrid system

C_{rem}^{sys} - Remaining cost of nanogrid system

C_{boiler} - Capital cost of boiler system

C_{tan} - Annualize total cost of nanogrid system

C_{rep}^{bess} - Replacement cost of battery energy storage system

C_{rep}^{inv} - Replacement cost of inverter

C_{rep}^{pv} - Replacement cost of photovoltaic system

C_{rep}^{wt} - Replacement cost of wind turbine

C_{rep}^{sys} - Replacement cost of the nanogrid system

C_{mg} - Main grid’s cost of energy

C_{ng} - Nanogrid’s cost of energy

E_{served} - Electric energy served by the nanogrid

F_{cost} - Fitness cost

F_{crit} - Critical fitness

F_{flex} - Flexible fitness

$F_{function}$ - Fitness function

F_{l} - Flexible load

H_{served} - Heat energy served by the nanogrid

I_{g} - Incident global solar radiation

I_{s} - Global standard radiation

k_{p} - Photovoltaic power coefficient

L_{comp}^{sys} - Frequency of nanogrid component replacements

L_{r} - Residential load

L_{r_D} - Residential day load

L_{r_N} Residential night load

L_{proj} - Nanogrid system project life span

L_{rem}^{sys} - Remaining life of the nanogrid system

L_{rep}^{sys} - Frequency of nanogrid system replacements

L_{res_D} - Residential day load

L_{res_N} - Residential night load

N_{1} - Nanogrid configurations 1

N_{3} - Nanogrid configurations 2

N_{3} - Nanogrid configurations 3

N_{bess} - Battery energy storage system capacity

N_{inv} - Inverter system capacity

NPC_{tot} - Total net present cost

N_{pv} - Photovoltaic system capacity

N_{sys} - Nanogrid system capacity

N_{wt} - Wind turbine system capacity

n_{a} - Number of hours in nanogrid autonomous operations

n_{r} - Number of hours in for energy storage recharge

P_{bess} - Power of the battery energy storage system

P_{Dch} - Battery energy storage system discharging power

P_{Ch} - Battery energy storage system charging power
P_{l} - Load demands
P_{Mg} - Power of the main grid
P_{Ng} - Power of the nanogrid
P_{pv} - PV generated power
P_{rated} - Wind turbine ratings
P_{RE} - Renewable energy system aggregated power
P_{wt} - Wind turbine generated power
Q_{bess} - Charge in a battery
Q_{f} - Capacity fading factor in battery
R_{s} - PV series resistance
SOC_{max} - Battery energy storage system’s maximum state of charge
SOC_{min} - BESS minimum state of charge
T_{a} - Ambient temperature
T_{c} - PV cell temperature
T_{stc} - Nominal PV cell operating temperature
V_{d} - PV equivalent diode voltage
V_{module} - PV module output voltage
v_{ci} - Cut-in speed of a WT
v_{co} - Cut-out speed of a WT
v_{r} - Rated speed of a WT
Y_{d} - Solar PV derating factor
Z_{bess} - Objective function for the BESS
Z_{inv} - Objective function for the inverter system
Z_{NILP} - Objective functions for NILP optimizations
Z_{pv} - Objective function for the PV system
Z_{sys} - Objective function for nanogrid system
Z_{wt} - Objective function for the wind turbine system
$\eta_{AC/DC}$ - Efficiency of a DC-AC converter
η_{bess} - Efficiency of the BESS
$\eta_{DC/AC}$ - Efficiency of a DC-AC converter
η_{inv} - Inverter efficiency

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Electrical utilities are considered as universal service obligations [1]. The assertion may be attributed to impacts of electricity supply to residential, commercial and industrial developments. There are many sources in electrical power generation, which include thermal systems operating on fossil fuels (such as coal, natural gas and diesel), hydro systems, renewable energy (RE), biotechnologies and chemical processes. In large power systems, generation voltages ranging between 5 kV to 34.5 kV are kept at distance from load centers due to factors such as technology, economy and environment. Generation and transmission systems are coupled using large power transformers with capacity ranging between 75 MVA to 500 MVA [2]. Referring to Consider Figure 1.1, where the step-up transformers are normally used for generation-transmission systems coupling and for controlling lower generation voltages to higher transmission voltages.

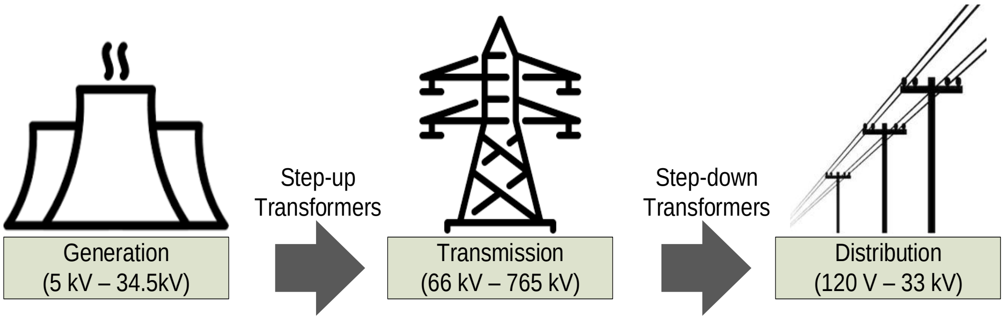

Figure 1.1 Basic structure of a conventional grid system

Transmission infrastructure are generally rated in kV due to the voltage size they handle. The range of voltages mostly handled in transmission systems are 66 kV to 765 kV [2]. The voltages are transported in bulk to load centers and stepped down for distribution purposes. Power ratings in distribution system transformers mostly depends on customer demands in the supply location, while voltage sizes range within 120 V to 240 V (single-phase), 220/420 V (three-phase) to 33 kV (three-phase). Electricity at transmission and distribution levels reaches customers through retails. In reference [3], two systems of retails were discussed as illustrated in Figure 1.2. The forward contracts, which is an electricity purchase by retailers from generation for regular intervals of time that are usually long periods, and spot markets that enable retailers to periodically purchase electricity according to customer demands.

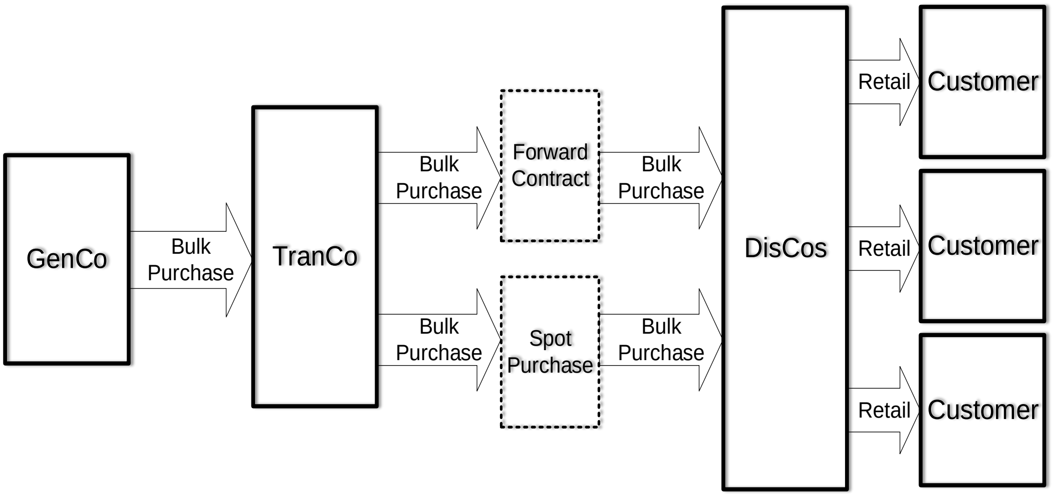

Figure 1.2 Features of electricity retail system in a conventional grid [3]

Under a span of nearly two decades, Nigerian Electricity Supply Industry (NESI) has been implementing reforms that is transforming the monopolized structure of the defunct National Electric Power Authority (NEPA) as the sole operator in the NESI. The reforms have been carried out through transitory frameworks of the Power Holding Company of Nigeria (PHCN) into the currently autonomous Generation Companies (GenCos), Transmission Company of Nigeria (TCN) and Distribution Companies (DisCos). The effort was to break the monopoly of a single structure of

NEPA affected by number of issues that include poor maintenance, low revenues, high losses, power theft and poor tariffs described in Figure 1.3. It is reported in [4] that part of Nigeria's electricity industry's poor performance arose from unmetered and estimated billings. While poor tariffs and estimated billings are attributed to poor performance of Nigerian DisCos as electricity retailers in the new power structure, the country's transmission infrastructure continues to remain radial which highlights concerns for reliability. The 7.4% losses incurred in transmission system is thus higher than global benchmarked losses of 2 – 6%. Moreover, GenCos' production from records shown in Table 1.1 are much lower than the generator's installed capacities.

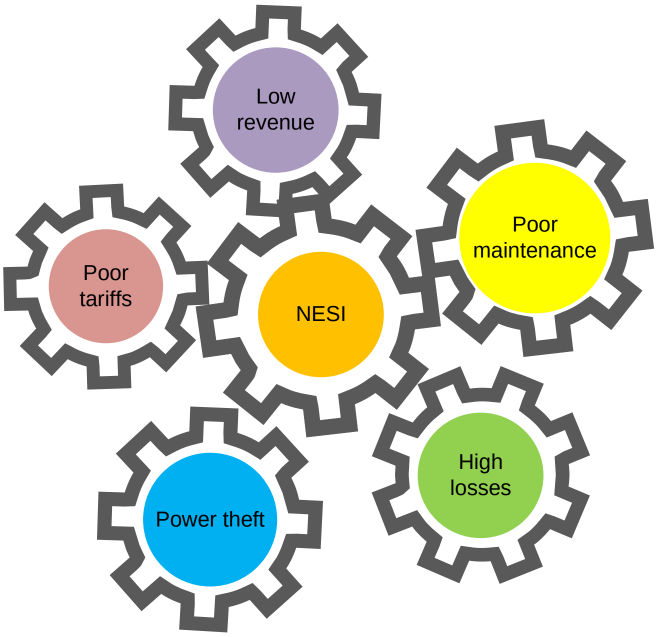

Figure 1.3 Issues related to Nigerian Electricity Supply Industry's poor performance [4]

Table 1.1 Nigerian GenCos installed and available generation [5]

System	Installed Capacity (MW)	Available capacity (MW)
Thermal Generation	8,457.00	4,996
Hydro Generation	1,938.40	1,060
Total	10,395	6,056

The need to prepare existing power grids such the NESI against challenges of 21st century is highlighted in reference [6]. In that regard, reliability, efficiency, cost effectiveness and environment are mentioned in reference [7], [8] and [9] as major factors to be considered. Challenges affecting performance of Conventional Grids (CG) include high costs of fuels [10], transmission losses [11], [12], carbon emissions [13] and initial costs [14]. Part of the solutions discussed in literature include reliability improvement through increased generation [15], [16]. Distributed Grid (DG) structures can be used to reduce transmission losses [17], and the need for expansion of the existing structure could hence be minimized [18]. The DGs are good in renewable energy (RE) integration for reduced carbon emissions and minimization of fuel costs [19], [20], [21] and [22]. Photovoltaic (PV) cells, wind turbines (WT) and fuel cells (FC) are some examples of RE generating components. There are RE support in low capacity generations (microgeneration) for customers to optionally be part of electricity production through a term referred to as “prosumption” [23]. Penetration of DG resources into CGs as proposed in [24] and [25] could however result into emergence of complex structures. Hence, grouping of distributed energy resources (DER) into smaller and functional units of microgrids and nanogrids that can operate in autonomous modes are suggested in references [25] and [26].

Integration of RE technologies into existing CGs face numerous challenges, such that effective control is needed to maintain and stabilize system parameters. Moreover, the control is needed for power balance and economic dispatch of resources under seamless grid crossovers [27]. There are lots of discussions in literature relating to the issues of developments and integrations of RE systems into existing CGs. Hence, the foregoing literature investigations highlight the potentials of RE systems towards contributions to the transformations and performance of CGs such as NESI. Realizing the RE potentials is important to the trending issues regarding the preferred characteristics of modern power grids, typical of the 21st century NESI.

1.2 Problem Statement

Integration of RE systems into NESI structures suggests an effort towards a reliable and more cost effective energy supplies. Example of such CG integrations with RE systems used mixed integer linear programming (MILP) methods. The MILP algorithm achieves relatively lower costs of energy and lower net present costs (NPC) through optimal sizing and operations of RE based community microgrid connected to a main grid. The RE-based sizing scheme utilized advantages such as simplicity, speed, and accuracy of the MILP. MILP produces results that are optimally global without branching at local solutions. However, MILP does not consider nonlinear effects. It considers all time periods at once, may have high dimension problems and time consuming. Hence, the foregoing indicates that the MILP results obtained indicate it's limited multi-objective capabilities. Hence, a need arises for de-compositioning high dimensions of the MILP for multi-configurational designs and energy cost reduction in RE-based system interacting with main grids.

Real-time costs of energy in RE systems differ from fixed energy tariffs in the CG system. In grid-connected systems, customers are subjected to difficulties in implementing decisions between the fixed and varying energy prices and as such, residential customer comforts are mostly compromised. In this regard, demand side management (DSM) is mostly considered as it ensures customer participation. Conventional time-of-use (C_{TOU}) methods are used in achieving DSM strategies such as peak shaving, valley filling, load shifting and energy arbitrage. The foregoing strategies are traditional and mostly suitable to CG systems, where power generation are easily predictable under varying load conditions. Moreover, the C_{TOU} methods are time-bound and mainly utility-centered. Hence, a modified C_{TOU} may need to be developed and implemented in a grid connected RE system for consumption cost reductions and preservation of customer comforts.

1.3 Objectives of the Study

The aim of this study is to develop and implement algorithms for optimal sizing and DSM implementations in a grid-connected RE-based nanogrid to achieve low energy cost. The study aim is proposed to be achieved based on the following objectives:

1. to develop and a nested integer linear programming (NILP) algorithm as an improved MILP algorithm for optimal sizing of the RE components in a proposed grid-connected PV/WT/Battery nanogrid to reduce the energy cost and net present cost.

2. to design a time-of-use fitness (TOUF) as an improved C_{TOU} algorithm for implementation of optimal load management in the proposed nanogrid operations to reduce the energy consumption cost, sustainable for customer comforts and to improve the nanogrid's autonomy.

3. to benchmark the performance of the proposed system optimization with the referenced MILP and intelligent-based particle swarm optimization (PSO) method.

4. to analyze the worthiness of energy interactions between the nanogrid's RE supply and main grid's energy imports using Markov Chains as statistical tool of analysis.

1.4 Scope of the Study

The aims of the proposed study are the optimal sizing and operations in a PV/WT/Battery grid-connected residential nanogrid. The following scopes are considered:

(a) energy demands in the proposed nanogrid comprise of all domestic appliances in the five selected residential buildings in Danladi Nasidi Housing Estate

Kano, Nigeria. The load profile in the case study is based on load estimation method derived from the customer demands survey.

(b) the local RE supply in the nanogrid comprises of the power generated from PV array, wind system, and battery stored energy configured based on the case study location's solar irradiance, ambient temperature and wind speed. The study considers the foregoing weather resources and corresponding RE generation based on hourly-average for a year-long analysis. The RE system in the nanogrid interacts with an 11 kV/415 V, 500 kVA main grid feeder. The proposed NILP consider all the RE, customer demands and main grid parameters in optimizing the nanogrid system capacities.

(c) the study considers the cost of energy in US$. The differences in the cost of energy among the RE sources and the main grid in designing a load management system using the proposed TOUF.

(d) the economic objectives in the proposed study include optimizations for lower levelized cost of energy (LCOE), lower NPC, and lower cost of energy consumption. While the technical objectives include optimizations for capacity reduction, reliability improvement and increased supply availability. The overall study investigates the foregoing nanogrid's techno-economic performance base on a 25-year life span.

(e) Reliability and stability analysis are based on Markov Chains as statistical tool to investigate worthiness of two-states transitions between local RE generation and energy imports from main grid.

(f) All algorithms are implemented in MATLAB environments using m-file scripts, without consideration for hardware investigations.

1.5 Significance of the Study

The significance of the study highlights the contributions of the proposed research in the area of the study as follows:

(a) introduction of NILP as improved MILP optimization tool in optimal sizing of PV/WT/Battery nanogrid system using the location's weather data for reduced energy cost and low system's net present cost.

(b) Introduction of a TOUF framework as improved C_{TOU} method for optimal load management in the proposed nanogrid operations for a reduction in energy consumption cost, with regard to the customer comforts and increased nanogrid autonomy.

(c) the use of Markov Chains in determining operational stability and economic prospects of the proposed grid-connected nanogrid.

1.6 Methodology Used in the Study

The proposed study methodology describes the sequential steps in implementation of the proposed algorithms. The methodology used in development of this work is categorized based on application of the proposed algorithms to implement the proposed schemes of sizing and load management, summarized as follows:

(a) preparation of literature review through consultations of literature materials as a strategy for underlying basic theories and concepts covering the intended area of the research. State of the art methodologies used in accordance with respective achievements and shortcomings in the related areas are also investigated.

(b) the case study data collection and analysis. This include the case study location's weather data such as solar radiation, ambient temperature and wind speeds. Other component of data collection is the location's residential customer surveyed load data.

(c) reference case analysis, case study location's weather and load data collection and analysis for study implementation and results analysis.

(d) implementations of the proposed NILP were carried out using MATLAB m-file script simulations to achieve optimal components sizing in a grid-connected residential nanogrid for energy cost reduction.

(e) the optimal load management schemes in the proposed nanogrid is implemented based on the proposed TOUF methods through simulations carried out in MATLAB m-file scripts for reduction in costs and consumptions of energy with regard to preservation of customer comforts.

(f) Markov Chains is used as statistical tool of analysis in forecasting energy prospects and system stability for the entire life span of the proposed nanogrid. Probabilistic information obtained from Markov model developed for two states of the nanogrid energy supply is important for decision making among utilities, customers and other project's stake holders.

1.7 Organization of the Report

The thesis is arranged in five chapters. Beginning with Chapter 1 containing general overviews such as the study background information, statement of the problem, study objectives, scopes of the study, significance of the study, methodologies used in research implementations.

Chapter 2 presents a literature review of most recent, most relevant and most related works in the area of the proposed research. The most prominently discussed area in the literature review include evolutions of power system structure from vertically structured conventional grids (CG) to emerging distributed grid (DG) systems, optimization algorithms as they are applied to DG planning and operation schemes as well as presentations of table of comparisons for analysis and identification of research study opportunities.

Chapter 3 discusses key points used as methodologies in the proposed research. The points include brief overview of Nigerian electricity industry as a basis for justifications in the choice of case study location. The chapter also presents reference study analysis, the case study overview and general details of the proposed NILP and TOUF algorithms used in implementation of sizing and load management schemes. The developed nanogrid is also modelled based on two-state transitions for analysis using Markov Chains.

Chapter 4 elaborates the detail of results obtained from implementations of the proposed NILP and TOUF algorithms with respect to the proposed sizing and load management schemes. Results of the Markov Chains implementations are also presented.

Chapter 5 presents the conclusions and contributions of the work. This include the research outcomes, the research’s contribution to knowledge and recommendations for future works.

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Appendix A Definition of New Terms Used in the Thesis

The methodologies used in the proposed study introduced terminologies that may not be traceable to conventional use. Some of the terminologies may lead a reader of this work to ambiguities as the terms appears and sounds similar. Brief meanings of the new terms used in the proposed methodologies are hence presented in this section to possibly reduce level of ambiguities. It is believed that the itemized definitions will simplify most of the concepts used in developing the methodologies applied in the proposed work.

1. *Nested integer linear programming*:

the nested integer linear programming (NILP) is the term given to the optimization algorithm introduced in this work to implement optimal sizing scheme for the proposed nanogrid components. The algorithm is developed as an offshoot of the known MILP through decomposition methods.

2. *Time-of-use fitness*:

the time-of-use fitness is another term introduced in this work and given to the methodology to be used in implementation of flexible load scheduling as DSM strategy for optimal operation of the proposed nanogrid. The methodology is a modified aspect of the time-of-use tariffs popularly used in achieving DSM strategies.

3. *Fitness function*:

fitness function $F_{function}$ is described here as customer ability to afford costs of either nanogrid sourced energy P_{Ng} or the main grid's imported energy P_{Mg}. Fitness function are usually determined by the level of customer demands falling within the magnitudes of nanogrid generated power or main grid's imported power for a given time t.

4. *Fitness cost*:

fitness cost F_{cost} is the cost of energy to be borne by a customer for a given time t, usually determined by the product of corresponding customer real-time demands and fitness functions for a given time t.

5. *Flexible fitness*:

flexible fitness F_{flex} is the fitness function applied to the energy served under RE based nanogrid's generated power P_{Ng}. The energy served under this condition is expected to have a lower cost, low carbon foot print and under complete nanogrid subsistence.

6. *Critical fitness*:

critical fitness F_{crit} refers to fitness function applied to energy served by the main grid imported power P_{Mg}. The energy served under this condition may incur higher costs, support traditionally vertical power system structures that operate with enormous environmental effects.

Appendix E List of Publications

1 **Dahiru, A. T.**, Tan, C. W. (2019). Optimal Sizing and Techno-economic Analysis of Grid-connected Nanogrid for Tropical Climates of the Savannah. *Sustainable Cities and Society*, 52(2020)101824, 2210-6707. https://doi.org/10.1016/j.scs.2019.101824. **(Q1, IF: 7.587)**.

2 **Dahiru, A. T.**, Tan, C. W., Bukar, A. L., Lau, K. Y. (2021). Energy Cost Reduction in Residential Nanogrid under Constraints of Renewable Energy, Customer Demand Fitness and Binary Battery Operations. *Journal of Energy Storage*, 39(2021)102520, 2352-152X. https://doi.org/10.1016/j.est.2021.102520. **(Q1, IF: 3.762)**.

3 **Dahiru, A. T.**, Tan, C. W. Multi-configurational Sizing and Analysis in a Nanogrid Using Nested Integer Linear Programming. *Journal of Cleaner Production*, S0959-6526(21)03345-X. https://doi.org/10.1016/j.jclepro.2021.129159. **(Q1, IF: 9.297)**.

4 **Dahiru, A. T.**, Tan, C. W. A Review of Intelligent-based Optimization Techniques for Planning and Operations in Microgrids. *Alexandria Journal of Engineering*. **Under Review**. (Q1, IF: 3.732).

5 **Bukar, A. L.**, Tan, C. W., Lau, K. Y., Dahiru, A. T. (2020) Optimal planning of hybrid photovoltaic/battery/diesel generator in ship power system. *International Journal of Power Electronics and Drive System,* 11(3), 1527-1535 https://doi.org/10.11591/ijpeds.v11.i3.pp1527-1535. **(Indexed by SCOPUS)**.