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Load Flow Analysis for Transient Stability Studies of Nigerian 132kV Power Transmission Network using Artificial Bee Colony

Anthony A. Oko[1], Christopher O. Ahiakwo[2], Dikio C. Idoniboyeobu[3] and Sunny Orike[4]
Department of Electrical Engineering, Rivers State University
Nkpolu-Oroworukwo, Port-Harcourt
[1]tonyoko1@yahoo.com, [2]ahiakwo.christopher@ust.edu.ng,
[3]idoniboyeobu.d@ust.edu.ng, [4]orike.sunny@ust.edu.ng

ABSTRACT:

Load Flow Analysis (LFA) represents an important and first step to determining the optimal network states of a power system prior to transient stability analysis (TSA). Existing LFA solutions or soft programs for TSA problems such as Newton-Raphson and Gauss-Seidel techniques have been successful in the solution of a number of power networks; however, when the initial power network states are ill defined or there is high transmission loading, these solutions fail to converge and hence cannot be used as a TSA state variable pre-solver. In this paper, we propose a swarm optimized LFA solution for optimally finding the network states of a power system network which in turn is used for performing transient stability studies on some buses in a section of the Nigerian 132kV power transmission network Port-Harcourt Region considering single phase line to ground faults. The results of simulation show that critical stability limits (critical clearance time) of the system is about 0.4s; thus, circuit breakers should break earlier than this time to secure the interconnected power system.

Keywords: Load flow analysis, Optimization, Power system, Swarm intelligence, Transient stability.

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1. INTRODUCTION:

The Nigerian power system network is currently faced with an epidemic of network failures typically arising from poor power management for which the very large simulation trials are needed to determine the safe limits of operation of the existing power network prior to live activation is a major limitation. In this regard, this has led to the disruption of services of existing and potential customers who in the long run may later resort to alternative sources of power supply. Current research has revealed one of the root causes of these failures is due to three-phase (transient) faults that occur on the power transmission lines. Thus, one of the ways to resolve the imminent crisis of power failure is to perform an LFA/TSA study of the power network under consideration. For certain power networks, the use of traditional LFA may not be a feasible option for solving network system states due to reasons such as high transmission loading and failure to converge.

In this paper, we study the performance of a variant of swarm intelligence load flow technique called Artificial Bee Colony (ABC) applied to the LFA prior to TSA study of the Nigerian 132-kV power transmission network (Port Harcourt Zone). ABC uses a swarm heuristic algorithm for constrained optimization of the load flow in a power system network. Initially developed by Karaboga (2005), ABC is an emerging swarm intelligence technique inspired by the beautiful organizational and foraging ability of honey bee swarms while combining the global optimum capabilities of evolutionary computers with a fitness based model (Anireh & Osegi, 2019). This paper combines the benefits of swarm intelligence in a LFA solution prior to a TSA study.

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1.1 Review of Related Work

Several works abound in the literature investigating the behaviour of a power system network in terms of LFA and TSA. In Grob *et al.* (2018), the conditions necessary for admitting a steady state behavior were established based on dynamical model of a multi-machine three phase detailed power system. Ekinci *et al.* (2017) proposed an open source MATLAB based software educational tool called the PowSysGUI which include both application programs and algorithms for LFA and TSA studies.

Stability as applied to electric power system is defined as the attribute which enables it to develop restoring forces between the system constituents, equal to or greater than the disturbing forces so as to re-establish the equilibrium condition between the constituents (Basu & Harinchandan, 2009). Power system stability describes a condition in which the various synchronous machines of the system remain in synchronism, or "in step" with each other. It should also be noted that the opposite term "instability" signifies a condition pertaining to "loss of synchronism: or falling "out of step" (Gangadhar, 2006).

Stability limit denotes the maximum feasible power flow through some point in the power system when the entire system or part thereof under investigation is operating with stability. The limiting value of power is the threshold power below which the system is stable and above which the system is unstable. State of stability is the classification of normal condition under which the system is operating when analyzed for stability.

Generally, power system stability is classified based on the following categories (Tirtashi, 2015):

(i) State of stability
(ii) Operating modes
(iii) Hunting.

Other classification is provided by Tirtashi (2015), which includes a consideration of functional and time frame perspectives. The functional perspectives account for the rotor-angle stability, frequency stability, voltage stability and rotor speed stability. Time frame perspective includes short and long-term stabilities.

Based on state of stability, power system stability is further classified as:

(i) Steady-state
(ii) Transient-State

The steady-state condition corresponds to the operating state of the power system which is characterized by gradual or relatively slow (incremental) changes. For example, the load is gradually applied, at a rate sufficiently slow in comparison with the natural frequency of oscillation of the major part of the system or with the rate of change of field flux in the rotating machine in response to the variation in load. On the other hand, the transient state is an operating state of a power system which is characterized by sudden changes in load or circuit conditions. Transient state may be considered as the ability of the system to remain in synchronism when subjected to an "aperiodic disturbance". The transient stability limit is given by the maximum transmissible power without loss of stability when the system is subjected to such a disturbance. The disturbance is said to be aperiodic if it is not a periodic one, such as a sudden change of condition tending to desynchronize the machines connected to the system. Also, based on transient conditions, transient stability may be referred to as "first-swing-transient-stability" and "multi-swing-transient stability" in order to signify the extent to which the stability analysis is made. Essentially, the transient disturbances are of three types:

(i) Sudden increase or decrease of load,
(ii) Switching operations and
(iii) Severe faults either sustained or subsequently cleared.

Based on operating modes, the steady state is further classified as:

(i) Static steady state: Here, the operating equilibrium is without voltage regulators, speed governors, etc. The excitation voltages here are usually assumed to be constant.

(ii) Dynamic steady-state: Here, automatic voltage regulators and well-designed excitation systems are used to maintain the terminal voltages constant at specified points.

The transient state is similarly be classified as:

(i) Static transient state – in which the operating equilibrium is without circuit breakers, surge protectors, and relays, etc.

(ii) Dynamic transient state – in which circuit breakers, surge protectors, and relays are used to protect the power system at specified points.

Huntingrefers to a situation when synchronous machines are swinging under sustained or cumulative oscillations. A study of this phenomenon involves the determination of damping characteristics or the dynamic stability of the system following a sudden load change of small magnitude.

It must be emphasized that the combined steady and transient stability operating conditions is generally referred to as the "overall stability". Also, the "power limit" of a transmission network is, in general, not fixed by network alone, but is dependent on the nature and characteristic of the various power system components. Thus, the power limit is reached when the synchronous apparatus at the two ends of the transmission line break from synchronism.

1.2 Power System Stability Studies

In power system stability studies, LFA is often required to solve the power network and generate the needed data. LFA requires two primary compositions:

(i) Formulation of a Load Flow (LF) problem

(ii) The solution of the LF using an appropriate solver

While the formulation can be easily described using conventional algebraic mathematics, the solution most often times require an iterative solver that is expected to converge to a specified minimum for the solution to be found and acceptable. Some recent researches have applied swarm intelligence to LFA problems, such as the work of Al-Anbarri and Naief (2017), Acharjee and Goswami (2007), Acharjee and Goswami (2009a), Acharjee and Goswami (2009b), Acharjee and Goswami (2009c), Gnanambal *et al.* (2010), Gnanambal et *al*. (2011), Jain *et al*. (2016), etc. They provided good results in comparison with other classical techniques. But it is a well-known fact that there is no universal algorithm or technique that is inherently much better than another for a variety of presented tasks. In the context of optimization problems these tasks require at the basic level a minimization or maximization of an objective or cost function. Presently, there is no known research that has studied the effectiveness of the state-of-the-art ABC algorithm in this power system network.

2. MATERIALS AND METHODS:

This section presents the details of the problem and the solution technique, based on transient stability.

2.1 Load Flow Analysis

A load flow analysis (LFA) is a first-step requirement for stability studies with the primary function of finding the solution points (power system variables) that are responsible for network balance. The network balance seeks to match the input real and reactive power injections with the computed state variables of the considered power network; the network balance requirement is usually referred to as the power-mismatch error condition value of the power system. Some of these variables (state variables) such as the bus voltages and angles are unknown and must be found by solving the network using a deterministic or stochastic approach. The primary equations for modelling of the power-mismatch condition or balance are shown in (1) to (3):

$$\Delta P_i = P^{inj} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}) \quad (1)$$

$$\Delta Q_i = Q^{inj} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \quad (2)$$

$$\max\{|\Delta P_i| \cup |\Delta Q_i|\} \le \varepsilon \ \ \forall\ i \quad (3)$$

Where:

ΔP_i = Active power mismatches at bus i

ΔQ_i = Reactive power mismatches at bus i

P^{inj} = Injected active power at bus i

Q^{inj} = Injected reactive power at bus i

$|V_i|$ = Absolute value of complex voltage at bus i

$|V_j|$ = Absolute value of complex voltage at bus j

$|Y_{ij}|$ = Absolute value of the admittance matrix of the ij^{th}element

θ_{ij} = Admittance angle at bus i, j

δ_i = Voltage angle of the bus$i$

δ_j = Voltage angle of the bus j

ε = Stopping criterion

2.2 Artificial Bee Colony Solution Representation

The Artificial Bee Colony (ABC) is a meta-heuristic evolutionary and swarm intelligence technique that uses the foraging behavior of honey bees to source for foods. These foods represent possible solutions to a problem and are evolved for a period of time to find better food sources using an explorative and exploitative approach. In power systems load flow solution, these foods represent the unknown variables (bus voltage and angles) and must be solved using stochastic swarming conditioned by an objective or cost function. In swarm load flow, the cost function is usually the power mismatch error as defined in (3). The operations governing this principle of exploitative-exploration are presented in (4) to (7) as:

Random Food Source Generation:

$$x_{ij} = x_{\min j} + rand[0,\ 1](x_{\max j} - x_{\min j}) \quad (4)$$

Fitness Value (FV):

$$x_{ij}^{j} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \quad (5)$$

Probabilistic FV solution selection:

$$prob_i = \frac{fitness_i}{\sum_{i=1}^{SN} fitness_i} \quad (6)$$

Abandoned food source replacement:

$$x_{ij} = x_{\min j} + rand[0,\ 1](x_{\max j} - x_{\min j}),\quad for\ j \in \{1,2,\dots,D\} \quad (7)$$

Where:

x_{ij} = Position of food source i in direction j

$x_{\min j}$ = Lower bound of x_i in direction j

$x_{\max j}$ = Upper bound of x_i in direction j

SN = Food source number

D = Dimension of the problem

ϕ_{ij} = Random number between -1 and +1

$fitness_i$ = Fitness value of solution i

2.3 Load Flow Analysis Procedure

The LFA optimization (ABC-LFA) has been applied to load flow studies of Nigerian 132-kV power transmission network and was integrated in the Transient Stability Analysis (TSA) program. The procedure for conducting an LFA optimization (ABC-LFA) is as itemized in steps:

Step 1: Define power network initial parameter conditions including the bus data and line data values. These values are needed later on for defining the LFA optimization boundary constraints.

Step 2: Compute the line admittance of the power network buses and the corresponding angles.

Step 3: Define the ABC constraints (upper and lower bounds) basing on the power system optimization parameters: bus voltage, bus angle,

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bus and generator real and reactive powers and power injections.

Step 4: Define the fitness (objective) function of the ABC. This function computes the load flow, power mismatch errors and the net power mismatch errors using the aforementioned constraints defined in step 3.

Step 5: Solve the power network by finding the best foods in accordance to the ABC algorithm routine and the fitness function defined in step 4.
The flowchart describing the procedures above is as given in Fig.1.

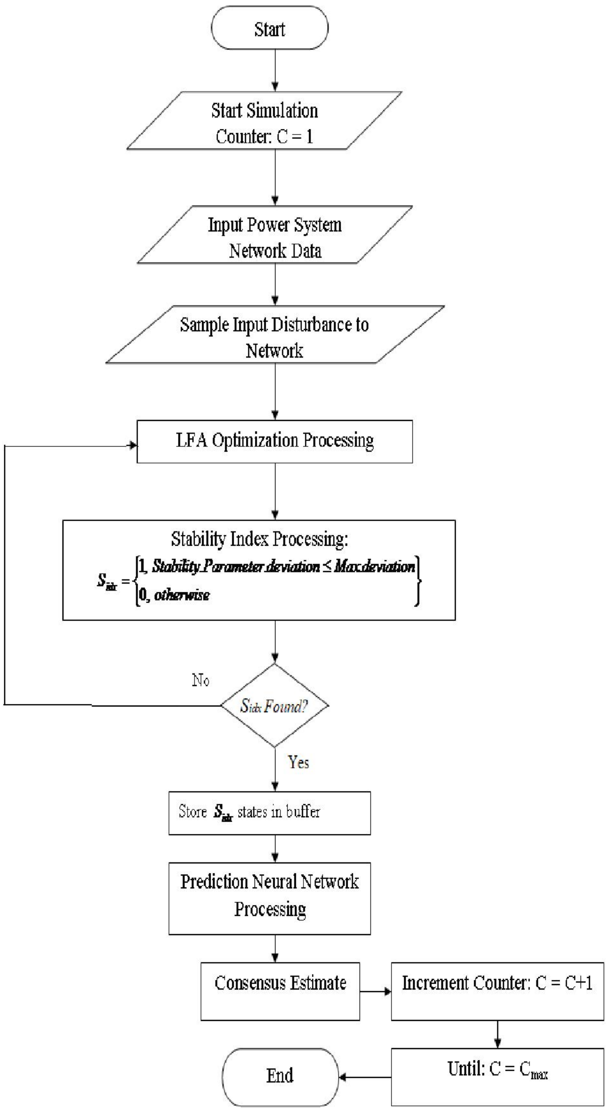

Fig. 1: Flowchart of the proposed TSA system

2.4 Transient Stability

Transient stability (TS) defines the maximum power transmissible without loss of generators synchronism when the network is subjected to an aperiodic disturbance. The solution typically involves the computation of a first-swing stability which succeeds the load flow solution after a short-circuit is inserted into the network. The primary equations governing a TS solution are described by (8) to (14):

$$\delta_p = \omega_p - \omega_0 \tag{8}$$

$$P_a = M_p \frac{d^2\delta_p}{dt^2} = P_{m_p} - P_{e_p} \tag{9}$$

$$\left|\delta_p - \delta_{COI}\right| \leq \delta_{\max} \qquad p \subseteq S_G \tag{10}$$

$$\delta_{COI} = \frac{\sum_{p=1}^{N_{PV}} M_p \delta_p}{\sum_{p=1}^{N_{PV}} M_p} \tag{11}$$

$$M = \frac{S.H}{\pi f} \tag{12}$$

$$\omega = \frac{d\delta_1}{dt} = \sqrt{\frac{2}{M}\int_{\delta_0}^{\delta_t} P_a \, d\delta} \tag{13}$$

$$Swing = \begin{cases} 0, & iff\ \omega = 0 \\ 1, & otherwise \end{cases} \tag{14}$$

Where:
$\delta_{\max}$ = Maximum permissible deviation of generator rotor angle with respect to the COI
δ_p = Rotor displacement angle of generator p
ω_p = Angular speed of generator p
M_p = Moment of inertia of generator p
S_G = Synchronous generators set,
S = MVA rating of the generator

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Experiments were conducted in two parts using the MATLAB:

Part 1 is the ABC-LFA algorithm for optimizing the power mismatch errors, adapted from a related research in Ekinci&Demiroren (2016). The default parameters for ABC are:

Colony size = 50
Limit = 500
Max cycle = 15000
Food number parameter = 25.
Part 2 uses a standard transient stability program developed earlier in Saadat (1999) for TSA studies; this program requires the user to specify of the faulted bus, it's interconnecting bus and the accompanying fault clearance and simulation times.

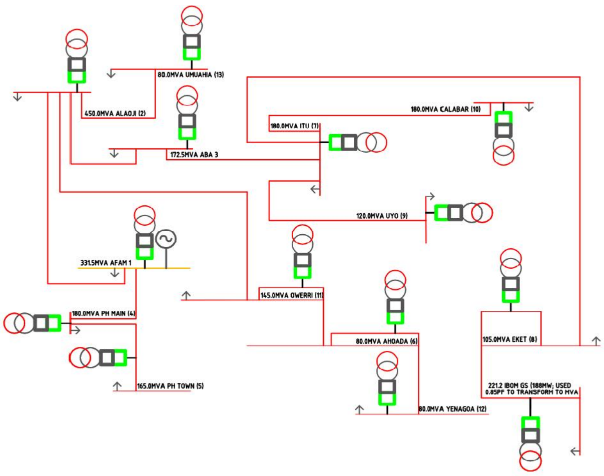

Fig. 2: NPHC-132 14-bus Power System Structure

The considered Nigerian 132kV sub-transmission network Port-Harcourt (PH) Zone (NPHC-132) is a 1-machine, 14-bus system with most interconnecting lines of the double circuit type. The data including the maximum MVA rating of the buses for the NPHC-132 1-machine, 14-bus power system is obtained from the Transmission Company of Nigeria Port-Harcourt Electricity Distribution (PHED) and is as shown in Fig.2. The parameters of the ABC used in the ABC-LFA solution has also been provided in Table 1, the bus data code label is given in Table 2, the system maximum and minimum loading is as provided in Table 3 while the line parameters are given in Table 4; the generator systems data has been provided in Appendix A.

Table 1: ABC Parameters

System Parameter	Working Value
Colony Size	100
Limit Trials	500
Max Cycle	2000

Table 2: Bus Nomenclature

Bus Code	Bus Name	Bus Type
1	Afam GS	Slack
2	Alaoji	PV
3	Aba	PQ
4	PH Main	PQ
5	PH Town	PQ
6	Ahoada	PQ
7	Itu	PQ
8	Eket	PQ
9	Uyo	PQ
10	Calabar	PQ
11	Owerri	PQ
12	Yenagoa	PQ
13	Umuahia	PQ
14	Ibom	PV

Table 3: System Maximum And Minimum Loading

Bus Code	S max (MVA)	S min (MVA)
1	331.50	23.90
2	450.00	150.00
3	172.50	30.00
4	180.00	60.00
5	165.00	30.00

6	80.00	40.00
7	180.00	60.00
8	105.00	45.00
9	120.00	40.00
10	180.00	60.00
11	145.00	30.00
12	80.00	40.00
13	80.00	40.00
14	221.20	41.20

Table 4: Line Parameters

Bus Sequence	**R (Ohm/km)**	**R_x (Ohm/km)**	**B (μS) 10E-05**
2 – 3	0.2223	0.4058	**2.8285**
1 – 2	0.2681	0.2002	**5.4886**
1 – 4	0.2681	0.2002	**5.4886**
4 – 5	0.2223	0.4058	**2.8285**
3 – 7	0.2220	0.4181	**2.7368**
7 – 8	0.2898	0.3168	**3.4688**
9 – 7	0.2898	0.3168	**3.4688**
7 – 10	0.2220	0.4181	**2.7368**
2 – 11	0.2223	0.4058	**2.8285**
11 – 6	0.1328	0.4000	**2.8750**
3 – 2	0.1328	0.4000	**2.8750**
2 – 13	0.1328	0.4000	**2.8750**
2 – 11	0.1363	0.3920	**4.0312**
6 – 12	0.1363	0.3920	**4.0312**
14 – 8	0.1800	0.2060	**5.3348**

3.0 RESULTS AND DISCUSSION

3.1 Load Flow Analysis using ABC-LFA

Load flow optimizations prior to TSA studies is conducted; this is done using the ABC-LFA on the NPHC-132 1-machine, 14-bus power system. The load flow results comprising the bus angles and bus voltages of the network is as shown in Figs. 3 and 4 respectively. The fitness (power mismatch error) plot during the optimization phase of ABC-LFA is also given in Fig. 5.

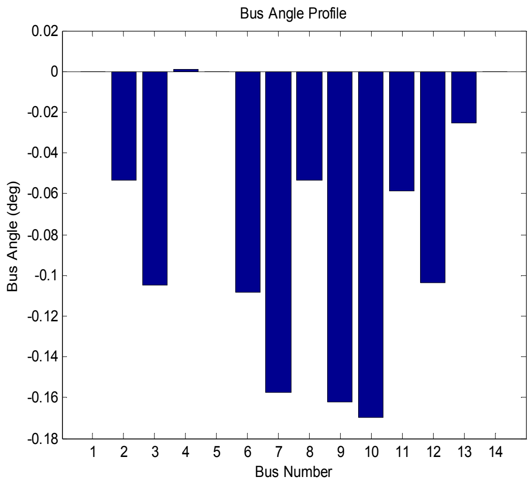

Fig. 3: Bus Angle response of the NPHC-132 1-Machine, 14-Bus System at a Single Trial Run

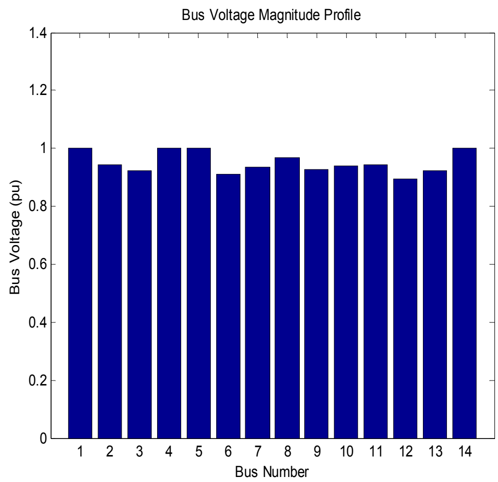

Fig. 4: Bus Voltage response of the NPHC-132 1-machine, 14-bus system at a single trial run.

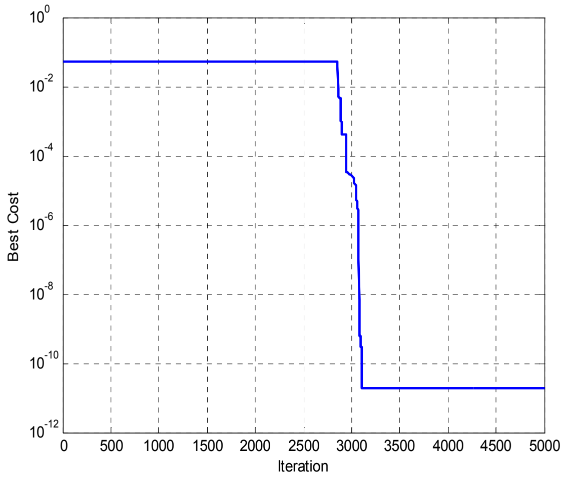

Fig. 5: Fitness response of the ABC-LFA solution

3.2:Transient Stability Analysis

Transient stability is performed on bus sites 1-2; first we simulate sustained fault at bus 1 where the clearance time (t_c) is longer than the fault simulation time (t_f). This is shown in Fig.6. Then we simulate the case of cleared faults i.e. when t_c is shorter than t_f. This is also shown in Fig.7.

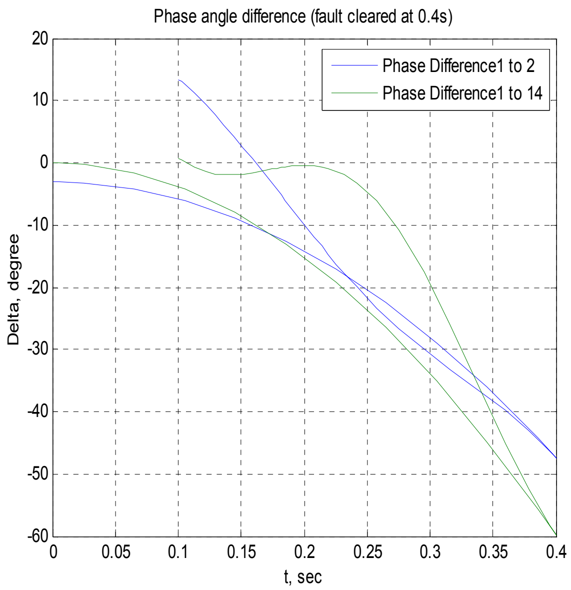

Fig. 6: Phase Angle of Participating Machines with Respect to Swing (Slack) Bus; ABC-LFA Sustained Fault Simulation Plot at Bus Sites 1 – 2; t_c =0.4s, t_f =0.1s

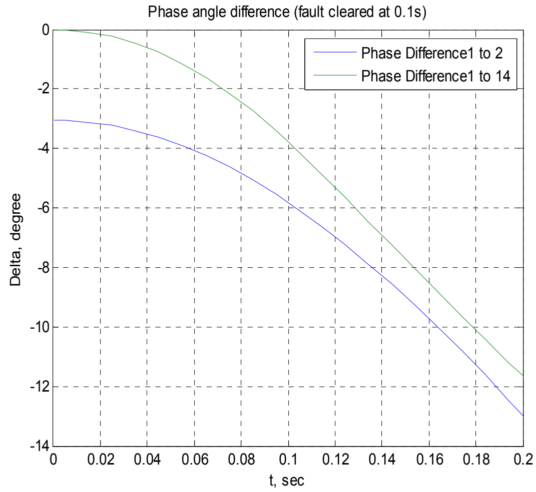

Fig. 7: Phase Angle of Participating Machines with Respect to Swing (Slack) Bus; BCO-LFA Online (Cleared) Fault Simulation Plot at Bus Sites 1 – 2; t_c =0.1s, t_f =0.4s

The results using ABC-LFA on the Nigerian 132kV power transmission line clearly shows that the ABC technique is an effective meta-heuristic for load flow optimization prior to stability studies as it can give very low power mismatch errors ($<10^{-12}$). The TSA program captured the case of out-of-step machines oscillating to infinity for sustained faults (Fig. 6) and the case of machines swinging together as in Fig. 7. Hence, the solved network states (bus voltages and angles) were successfully analyzed by the transient stability analysis (TSA) program; an earlier in-house experiment with the Newton-Raphson (NR) technique (details not reported here) failed to converge indicating that the NR-technique is unsuitable for the aforementioned network. Thus, using ABC-LFA as a front-end to TSA studies is very promising.

In particular, it is noticeable from Fig. 6that the machine angles (Generators 2 & 14) roughly swing together to a point of critical stability at about 0.4s; after which the machine angles begin to increase without limit swinging in different directions. The implication here is that the circuit breakers should break earlier than the critical clearance time.

4. CONCLUSION:

This paper presents an approach to stability studies that uses a swarm intelligence optimizer (ABC-LFA) prior to transient stability analysis (TSA). The study simulated the impact of sustained faults and cleared faults on the Nigerian 132-kV sub-transmission Port-Harcourt Region (NPHC-132). The results reflect the importance of such simulations on the power network.

The major contributions of the paper are:

(i) This paper has proposed a hybrid predictive technique including the swarm optimization and transient stability analysis based on Artificial Bee Colony (ABC) for a 132-kV power system network (Port-Harcourt Zone) Nigeria.

(ii) The determination of the critical stability limits of the power system. Till date, this is the first TSA study using swarm-predictive optimization on the aforementioned power systems network.

Future work will further explore the potential of the proposed ABC-LFA power system transient stability analyzer for various power system network settings. These studies should be conducted in comparison with other alternative and promising swarm intelligence techniques such as the Particle Swarm Optimisation (PSO) including variants of the original ABC technique.

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APPENDIX

Table A.1: Generator System Data

Bus Code	Ra	Xd'	H
1	0	0.146	23.64
2	0	0.250	04.00
14	0	0.195	01.37

Ra –armature resistance
Xd' – transient reactance
H – Machine inertia constant