##### BACTERIAL FORAGING ALGORITHM BASED TUNING OF ON-LOAD TAP CHANGING TRANSFORMER FOR VOLTAGE REGULATION IN POWER TRANSMISSION NETWORK

**BY**

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**BACTERIAL FORAGING ALGORITHM BASED TUNING OF ON-LOAD TAP CHANGING TRANSFORMER FOR VOLTAGE REGULATION IN POWER TRANSMISSION NETWORK**

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**A DISSERTATION SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY ZARIA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE**

##### AWARD OF MASTER OF SCIENCE (M.Sc.) DEGREE IN POWER SYSTEMS ENGINEERING

**DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING, FACULTY OF ENGINEERING,**

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**DECLARATION**

I, Bukhari Tanko RABIU hereby declare that the work in this dissertation entitled **“**Bacterial Foraging Algorithm Based Tuning of On-load Tap Changing Transformer for Voltage Regulation in Power Transmission Networks**”** has been carried out by me under the supervision of Dr Yusuf Jibril and Prof. Boyi Jimoh as part of the requirement for the award of Degree of Master of Science (M.Sc) in Power Systems Engineering in the Department of Electrical and Computer Engineering, Ahmadu Bello University Zaria. The information derived from literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution to the best of my knowledge.

Bukhari Tanko RABIU

Signature Date

##### CERTIFICATION

This Dissertation entitled “Bacterial Foraging Algorithm Based Tuning of On-Load Tap Changing Transformer for Voltage Regulation in Power Transmission Network” by Bukhari Tanko RABIU meets the regulations governing the award of Degree of Master of Science (MSc) in Power Systems Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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##### DEDICATION

This dissertation is dedicated to Almighty Allah; the Most Beneficient, the Most Gracious and Most Merciful. Also, to the memory of my late father Alhaji Rabiu Tanko and to my mother Hajiya Saadatu Isiyaku.

##### ACKNOWLEDGEMENTS

I am indeed grateful to Almighty Allah for His Infinite Blessings and Guidance towards the successful completion of this work.

I wish to express my utmost gratitude to my supervisor and also the chairman of my supervisory committee, Dr Y. Jibril for his time, immense contributions and valuable guidance towards the success of this work. Indeed, the completion of this work could not have been possible without your consistent participation and assistance. I am proud to have you as my supervisor. You helped me a lot in providing valuable suggestions to the solution of the problems. Thank you very much sir. My thanks also go to my co- supervisor Prof. Boyi Jimoh for his valuable input and constant encouragement throughout the stages of the work. I really appreciate the training I received from you.

I acknowledge and appreciate the contributions of all the lecturers of Electrical and Computer Engineering Department, Ahmadu Bello University Zaria, namely: Prof. B.

G. Bajoga, Prof. U.O Aliyu, Prof. M.B Muazu, Dr A. M. S. Tekanyi, Dr S. M. Sani, Dr

T.H. Sikiru, Dr S. Man-Yahaya, Dr. I. J. Umoh, Dr. K.A. Abu-Bilal, Dr A.D. Usman, Dr G. A. Olarinoye, Engr. M. J. Mu’azu, Engr. A. I. Abdullahi, Engr Olaniyan Abdurrahman, Engr Tijjani Ahmed Salahuddeen and those whose names could not be mentioned. My sincere appreciation also goes to mallam Abdullahi Tukur for his administrative support towards the completion of this work.

My deepest appreciation goes to all my colleagues in Power System Engineering M.Sc. class of 2013, Engr. S.M. Aminu, Engr. Imamuddeen Kabir, Engr. Bashir Umar Charanchi, Engr. Umar Musa, Engr. Lawal Idogwu, Engr. Magaji Muhammad Batagarawa, Engr. Murtala Mahmud, Engr. Sale Yakubu Gelta, Engr. Musa Muhammad, Engr. Soliu Abdollahi (Alfa), Engr. Ekpa Dickson, Engr. Yusuf Habeebullah and Engr. Muhammad Dudu Usman. Furthermore, my appreciation and

thanks goes to all members of M.Sc. class of 2013 in Control, Telecommunication, Computer and Electronic Engineering options. I am indeed grateful to you all; your handsome reward is with God.

Above all, I am really indebted to my wife, Hajiya Badiya Adamu for her endless love, support and understanding towards the successful compilation of this work. Thank you very much. My gratitude also goes to my children, Rabiu Bukhari Rabiu and Hauwau Bukhari Rabiu, may Allah in his infinite mercy continue to shower his blessings in your endeavor.

Finally, to my sisters, Hajiya Hadiza Ismaila Ahmed, Hajiya Hauwa Ismaila Rufai, Malama Ramatu Rabiu Tanko and to my brothers Yusuf Ismaila Ahmed, Isiyaku Rabiu Tanko and Sulaiman Rabiu Tanko whose love, prayers and elderly advices have kept me strong and sound all through my life.

##### Bukhari Tanko RABIU August, 2017

**ABSTRACT**

The control of voltage level has been identified as one of the most important operational needs for efficient and reliable operation of power system equipment. Due to the fact that both the utility and customer equipment are designed to operate at certain voltage ratings. Prolonged operation of the equipment at voltages outside the allowable range could adversely affect their performance and may cause forced outages. Therefore, voltage at terminals of all equipment in the system has to be kept within acceptable limits. This dissertation presents the use of Bacterial Foraging Algorithm (BFA) based tuning of on-load tap changer (OLTC) also known as under load tap changer (ULTC) transformer for voltage regulation in power transmission network with the intent of minimizing bus voltage deviation and reduction of transformer tap changing operation. A standard IEEE C57.131 2012 requirements for tap-changer control (0.85-1.15p.u) was adopted for this work and the simulation was carried out in MATLAB 2016 platform using power system analysis toolbox (PSAT), the results obtained when applied on the standard IEEE 14-bus test network, the BFA has demonstrated its superiority over the conventional method and the ABC algorithm in terms of reduction in Bus voltage deviation by 0.25% and 0.12% and reduction in transformer taps changing operation by 0.6% and 0.3% respectively. When applied on the Practical 32- bus Nigerian power system network, the BFA has also shown a superiority over the conventional method and the ABC algorithm in all parameters used, with 4.31%, 0.22% and 0.48% reduction in computational time, bus voltage deviation and transformer tap changing operations respectively.

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##### LIST OF ABBREVIATIONS

|  |  |
| --- | --- |
| AVC | Automatic Voltage Control |
| ABC | Artificial Bee Colony Algorithm |
| AC | Alternating Current |
| AIS | Artificial Immune System |
| BFO | Bacterial Foraging Optimization |
| COA | Chaotic Optimization Algorithm |
| CRO | Coral Reef Optimization Algorithm |
| CS | Cuckoo Search Algorithm |
| DC | Direct Current |
| DE | Differential Evolution |
| DETC | De-Energized Tap Changer |
| EP | Evolutionary Programming |
| ES | Evolutionary Strategy |
| FA | Firefly Algorithm |
| FACTS | Flexible Alternating Current Transmission System |
| GA | Genetic Algorithms |
| GSA | Gravitational Search Algorithm |
| HS | Harmony Search Algorithm |
| HV | High Voltage |
| HVAC | High Voltage Alternating Current |
| HVDC | High Voltage Direct Current |
| ICA | Imperialistic Competition Algorithm |
| IGBT | Insulated-Gate Bipolar Transistor |
| IWD | Intelligent Water Drops Algorithm |

|  |  |
| --- | --- |
| kV | Kilo Volt |
| kVA | Kilo Volt Ampere |
| kW | Kilowatt |
| LDC | Line Drop Compensation |
| LV | Low Voltage |
| MOA | Magnetic Optimization Algorithm |
| MVMO | Mean-variance Mapping Optimization |
| MV | Medium Voltage |
| OLTC | On-Load Tap Changer |
| OPF | Optimal Power Flow |
| PIO | Pigeon Inspired Optimization |
| PID | Proportional-Integral-Derivative |
| p.u | Per Unit |
| PSO | Particle Swarm Optimization |
| PWM | Pulse Width Modulation |
| rms | root mean square |
| S | Seconds |
| SA | Simulated Annealing |
| SCADA | Supervisory Control and Data Acquisition |
| SFLA | Shuffled Frog Leaping Algorithm |
| STATCOM | Static Synchronous Compensator |
| SVC | Static VAR Compensator |
| T | Time |
| TLBO | Teaching-Learning Based Optimization Algorithm |
| Trfr | Transformer |

ULTC Under Load Tap Changer

VAr Volt-Ampere reactive

1 *and* 2

##### LIST OF SYMBOLS

Weighting metrics

*OLTCt*

Total operations of OLTC for hour t

1. Active power
2. Reactive power

*tapTr,min* Minimum Tap position of transformer *Tr*

*tapTr,max* Maximum Tap position of transformer *Tr*

*v*min

Minimum voltage magnitude of the buses

*v*max

Maximum voltage magnitude of the buses

v Voltage magnitude of the buses

*s*max

Maximum flow limit through the transmission line

s Flow through the transmission line

i Current flow through the cables, lines and transformers

*i*max

Maximum current flow through the cables, lines and transformers

|  |  |  |
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##### CHAPTER ONE INTRODUCTION

##### Background Information

Power system engineering forms a vast and major portion of electrical engineering studies. It is mainly concerned with the generation of electrical power and its transmission from sending end to the receiving end as per consumer requirements, incurring minimum amount of losses. Power at the transmission level is often subjected to changes due to disturbances incurred within the length of the grid, for this reason the term power system stability is of utmost importance in this field (Acha *et al*., 2011).

The control of voltage level has been identified as one of the most important operational needs for efficient and reliable operation of power systems equipment, due to the fact that both the utility and customer equipment are designed to operate at a certain voltage rating (Salem, 2007). In general, there are two ways of regulating the voltage; by injection or absorption of reactive power from the system using Flexible Alternating Current Transmission System (FACTS) devices and by direct control of voltage amplitude using On Load Tap Changer (OLTC) (Mohammed, 2011).

A tap changer is a connection point selection mechanism along a power transformer winding that allows a variable number of turns to be selected in discrete steps. A transformer with a variable turn’s ratio is required to enable stepped voltage regulation of the output. The tap selection may be made via an automatic or manual tap changer mechanism. Generally, tap changers are classified into two types: off-circuit also known as De-Energised Tap Changer (DETC) and on-Load Tap Changer (OLTC), (Vigneshwaran and Yuvaraja, 2015).

OLTC is considered in this work and is generally classified as mechanically and electronically assisted as well as solid state tap changers. Earlier, mechanical type and solid state on-load tap changers were in practice, but they had considerable limitations such as arcing, high maintenance cost and slow reaction times.

To overcome the above mentioned limitations, a meta-heuristic optimization technique known as Bacterial Foraging Algorithm (BFA) was employed; which was developed by Kevin Passino, (2002). It was inspired by the foraging behaviour of Escherichia Coli (E.Coli) bacteria found in the human intestines (Xing and Gao, 2014). The algorithm was formulated on the basis of four principal processes: Chemotaxis, Swarming, Reproduction and Elimination-dispersal (Boussaid *et al*., 2013). The rationale behind selecting BFA is that it is not largely affected by the size and non-linearity of the problem; also it converges to the optimal solution in many problems where most analytical methods have failed to converge. The algorithm also has advantages such as global convergence, high exploration capacity and can handle more number of objective functions when compared to other evolutionary algorithms. However, this work seeks to use the algorithm for optimal tuning of OLTC in reduction of transformer tap changing operations as well as bus voltage deviation in power transmission networks.

##### Problem Statement

The control of voltage has been identified as one of the most important operational requirements for efficient and reliable operation of power systems equipment, due to the fact that both the utility and customer equipment are designed to operate at some certain acceptable voltage ratings (Salem, 2007). Prolonged operation of the equipment at voltages outside the allowable range could adversely affect their performance, resulting in forced outages. Therefore, voltage at each terminals of all equipment in the system

has to be kept within acceptable limits of (0.85 - 1.15p.u) as defined by IEEE standard C57.131 2012 OLTC control requirement (Hashemi, 2011).

##### Aim and Objectives

The aim of this research is to apply Bacterial Foraging Algorithm for tuning of on-load tap changing transformer for voltage regulation in power transmission network.

The objectives are:

* + 1. Application of BFA for tuning of OLTC transformer in standard IEEE 14-Bus network.
    2. Validation of the results obtained in item (i) using BFA by comparison with those of the work of Mostafa Abdollah *et al*., (2013)
    3. Implementation of the proposed approach on the Nigerian 32-Bus Power system network.

##### Research Methodology

The objectives as outlined in this research were actualized in line with the following procedures:

* + 1. Acquire relevant networks data (line data, bus data, network base voltage, etc.) from TCN Mando Kaduna;
    2. Perform network base-case power flow analysis using Newton Raphson technique;
    3. Adoption of Bacterial Foraging Algorithm on the standard IEEE-14 Bus Network.
    4. Formulation of multi-objective functions for standard IEEE 14-bus network comprising of bus voltage deviation and transformer tap changing operation to be used in both ABC and BFA;
    5. Application of BFA with the formulated multi-objective functions for reduction of bus voltage deviation and transformer tap changing operation.
    6. Comparison between the results obtained for ABC and BFA in both graphical and tabular forms.
    7. Implementation of the proposed approach by repeating the fourth and fifth procedures on the Nigerian 32-bus power system network using graphical and tabular form representation.

##### Research limitation

Although one of the objectives of the research was to solve the problem of voltage instability associated with the Nigerian 32 bus power system network, but after the application of BFA on OLTC the results obtained are still not within those defined by the standard, as some of the voltages of the buses are still not within the limits.

##### Organisation of the Dissertation

Chapter one presents the general introduction of the dissertation while chapter two presents the fundamental concepts that include all relevant assumptions, theories and modelling equations needed for the actualization of the research and a comprehensive review of similar works carried out. Chapter three presents an elaborate procedure for the actualization of the research, which include all the materials and the methodology adopted. The results obtained from the application of the theoretical and modelling concepts presented in the two previous chapters and their discussions are presented in chapter four. Chapter five covers the conclusion, recommendation and possible areas of further work. Finally, references of the works used and appendices are presented.

##### Introduction

##### CHAPTER TWO LITERATURE REVIEW

The literature review comprises of the overview of fundamental concepts as well as the review of similar works. In the review of fundamental concepts, most of the pertinent works and the fundamental theories that are used for the success of this research are reviewed, after which review of similar works followed.

##### Review of Fundamental Concepts

In this subsection, concepts that are fundamental and pertinent to the understanding of OLTC and its control are reviewed.

* + 1. Voltage Regulation in Transmission systems

The voltage control problem can be defined as the assurance of maintaining electric power quality at all levels (Fusco and Russo, 2007). Disturbances like over-voltage, under-voltage, voltage unbalance, and voltage harmonic distortion affect the power quality which causes serious problems. The two approaches for voltage control are the off-line control that depends on dispatch schedule ahead of time as a forecast of the voltage changes; and the on-line (automatic) that depends on real-time measurements of voltage. Moreover, the active network management of a power system may be categorized into coordinated control, semi-coordinated or decentralized control strategies. Centralized or coordinated control strategy provides voltage control from the substation towards the rest of the network. On the other hand, semi-coordinated and decentralized control strategies must be able to control each unit locally in an active manner while coordinating it with a limited number of other network devices (Hashim *et al*., 2012).

In a centralized or co-ordinated voltage control scheme, several techniques are implemented including distribution management system control, distribution system

components (like VAr compensator and step voltage regulator), intelligent centralized method like meta-heuristic algorithm as well as multi-agent system (Viawan, 2008).

The techniques implemented in the decentralized voltage control scheme are summarized into reactive power compensation, power factor voltage control, on-load tap changer, generation curtailment and intelligent decentralized systems. By reviewing the research conducted on voltage regulation at both transmission and distribution systems, it is concluded that tap-changing transformers, VAR compensators and line drop compensation are the techniques that are mostly used for voltage control.

### Line Drop Compensation

Line Drop Compensation (LDC) is a traditional method of calculating the voltage drop along each line, hence calculating the voltages at each terminal accordingly. This method can be applied once by setting the voltage according to the calculated voltages at the consumer, or using a tap changer. This method doesn’t provide accurate results due to several reasons. For instance, the addition of distributed generation makes the line drop calculations not accurate.

The voltage drops on a line between the source bus-bar and the load is calculated by Automatic Voltage Control (AVC) relay using the input current and the impedance value of the line (Dai, 2012). The relay adjusts the control parameter to increase or compensate the source bus-bar voltage by an amount equal to the calculated voltage drop. The impedance of a line might not be accurate since there might be several branches extending from one feeder like in tree network arrangement. In addition, the AVC relay can have one feeder resistance (R) and reactance (X) setting although most substations have multiple feeders. In order to resolve these shortcomings, the R and X settings on the LDC is based on a hypothetical composite feeder model that has to cater for the worst combination of demands on each of the feeders (Dai, 2012).

### Tap-changing transformers

Tap-changing transformer technique uses an off-line or on-line tap changer to regulate the voltage to a reference level. The tap changer can be placed at the primary or secondary side of the transformer. It varies the number of turns in a transformer by adjusting the turns’ ratio in order to achieve the required voltage at the secondary side of the transformer (Viawan, 2008).

### VAR Compensation

VAR compensation or reactive power control is a technique to regulate the voltage using reactive elements or FACTS devices such as static synchronous compensator (STATCOM), static VAR compensator (SVC), static synchronous series compensator (SSSC) and unified power flow controller (UPFC) or switched fixed capacitors/inductors e.g. shunt capacitors (Romero, 2010). The method is based on measuring the line voltage, comparing it with a reference level and connecting compensators (reactive or capacitive) to regulate the voltage. VAr compensation has considerable limitations; the latest technique considers the use of VAr compensation with DG.

## Comparison of the three Techniques

The three techniques as mentioned earlier play an important role in the regulation of voltage. However, several problems arise at transmission networks such as voltage instability, line drops, etc. All the three techniques depend on forecasted voltages which are not real and accurate. In addition, they mostly depend on power flow analysis which can resolve static equations and cannot provide dynamic analysis.

The line drop compensation is simple; however, it doesn’t provide accurate results due to the change in loads and the addition of feeders in the network. The VAR compensation technique requires several capacitors at the feeders. The control in the

tap-changing transformer is more complex, even though OLTC can provide better values than line drop and VAr compensation. However, the control still is based on forecasted and not real loads since the voltages at the end customers cannot be measured in the traditional distribution networks. The evolution towards advanced metering infrastructure and the use of smart meters to measure the voltages in real time plays an important role in the enhancement of voltage control techniques. Hence, the OLTC became more attractive and promising solution for much more accurate, faster and simple dynamic voltage control at sub-transmission and distribution systems (Dai, 2012).

##### Tap Changer

A tap changer is a selection tool in power transformer windings that permits a variable number of turns to be selected in discrete steps. A transformer with a variable primary to secondary turns’ ratio is formed, allowing stepped voltage regulation of the output. The tap selection may be made via an automatic or manual tap changer mechanism. The mechanism of tap-changing can be made on-load or off-load. If there is no load connected to the transformer, the tool is called off-load, DETC or no-load tap changer. However, the tap-changer that works during load is called under-load tap changer or on- load tap changer (Faiz and Siahkolah, 2006).

* + 1. On-Load Tap Changer

The OLTC of power transformers has been proven to have a fundamental importance as a voltage regulating mechanism. The switching principle is that the turn ratio of a transformer can be changed by adding to or subtracting turns on either the primary, or the secondary windings. As indicated by its name, changing the tap position is possible only when the power transformer is carrying load. With transformers equipped with OLTC the voltage can be controlled within acceptable range. The OLTC can be located

at the primary or the secondary side of the transformer, although in the most case the variable tap is on the HV side. One reason for this choice is that the current on the HV side is lower, and consequently the commutation is easier. In addition, the more turns that are available in this side enable a more accurate voltage regulation. Figure 2.1 shows the diagram of OLTC transformer (Viawan, 2008).

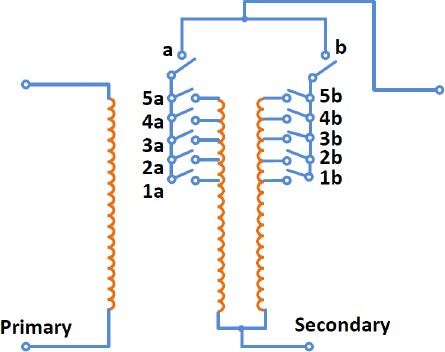


Figure 2.1: On-load Tap Changer (Romero, 2010)

One important constraint is the finite number of tap positions existing in the device. A typical OLTC has 16 lower taps, 16 upper taps and one neutral tap for a total of 33 taps. Some OLTCs have multiple neutral taps or may have only 8 lower and 8 upper taps. Thus, the voltage regulation is restricted to a range defined by the lower and the upper voltage limit ranging from 0.85 p.u to 1.15p.u (Gohil and Verma, 2016).

The OLTC have to be more frequently regulated in order to maintain the voltage profiles between the acceptable ranges. This leads to an increased operation and maintenance cost of the transformers. Consequently, the limitation of OLTC operations is included in the proposed approach (Viawan, 2008).

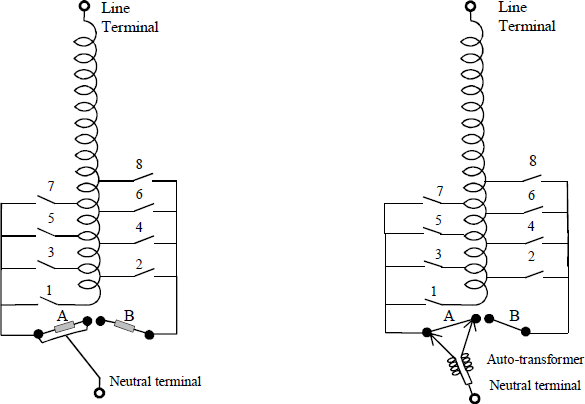
### OLTC Categories

OLTCs may be classified into three different categories

* + - * 1. Mechanical tap changer
        2. Electronically-assisted tap changer
        3. Solid-state tap changer

A mechanical tap changer makes physically the new tap connection before releasing the old one, using multiple tap selector switches. It avoids creating high circulating currents by using a diverter switch to temporarily place large diverter impedance in series with the short-circuited turns as shown in Figure 2.2a. This technique overcomes the problems with open or short circuit taps. In a resistance type tap changer, the changeover must be made rapidly to avoid overheating of the diverter.

A reactance type tap changer uses a dedicated preventive auto-transformer winding to function as the diverter impedance. A reactance type tap changer is usually designed to sustain off-tap loading indefinitely as shown in Figure 2.2b (Romero, 2010).



Resistance Type (b) Reactance Type Figure 2.2: Mechanical Tap Changer with Diverter (Romero. 2010)

The mechanical tap-changers have many disadvantages like arcing in the diverter switches during tap changing process, high maintenance cost, slow taps changing speed and high losses in the tap change (Nadeem *et al*., 2013). The arc in the contacts of diverter switches during the tap-changing process is an essential problem in the mechanical under-load tap changer (Faiz and Siahkolah, 2011).

Electronically-assisted tap changers are developed to resolve this issue by reducing the arc with more controllability of the switches. One type of such tap changers uses thyristor to take the on-load current while the main contacts change over from one tap to the other (Martinez *et al*., 2013).

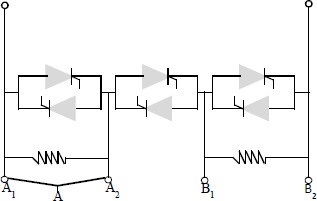
A sample connection between contacts A and B of a certain tap is shown in Figure 2.3 below:

Figure 2.3: Electronically Assisted Tap Changer (Ram *et al*., 2015)

An OLTC with electronically-assisted tap changer is designed in (Ram *et al*., 2015) and a lab setup illustrating its application is presented in (Romero, 2010). The use of hybrid configuration of mechanical and bidirectional electronic switches that switch between no-load and on-load situations was proposed by (Martinez et al., 2013).

Solid-state tap changer uses bidirectional solid state relays (SSR) to switch the transformer winding taps and to pass the load current in the steady state. The design and implementation of SSR can be made from several configurations of power electronic devices including Insulated-Gate Bipolar transistor or gate turn-off thyristor (Romero, 2010). The performance comparison of mechanical and electronic tap-changers indicated that the following differences are required in goals and responsibilities of controllers of these two categories of tap-changers (Faiz and Siahkolah, 2011). A reduction of the tap-changing frequency in the controller of mechanical tap-changer is one of the design objectives, while this is not the case in an electronic tap-changer. In a

mechanical tap-changers controller, taps must be changed step-by-step, while there is no such limitation in an electronic tap-changer (Faiz and Siahkolah, 2011).

A complicated arrangement of taps and switches in the control system of an electronic tap-changer makes it necessary to have a look-up table for storing the position of each switch which corresponds to each of the output states. Such a look-up table is not required in mechanical tap-changer. The tap-changing process is very quick with an SSCT, so there is a need to use an algorithm for quick and accurate detection of the amplitude and phase of the sinusoidal variables such as primary and secondary voltages and load current. In contrast, the tap-changing process is much slower in a mechanical tap-changer, so averaging methods over several cycles to determine the rms voltage and current are sufficient. In electronic tap-changer controller, it is necessary to detect the zero-crossing of the load current in order to have soft switching of the tap-changer switches. In a mechanical tap-changer, the tap-changing process is slower, so soft switching cannot be realized (Faiz and Siahkolah, 2011).

* + - 1. *OLTC Control System*

Whenever the electrical supply network voltage is less than the optimal value, there is a chance of nuisance tripping of voltage sensitive equipment and devices. The OLTC is therefore very necessary in order to maintain a constant bus voltage on the Medium Voltage terminals of a transformer for varying load conditions. It is essential that no tap change operation is made unless the voltage change on the system is sufficient to justify the tap change operation, and for this reason it is desirable that operation is not initiated for a momentary change in voltage. The introduction of an appropriate amount of time delay reduces the wear and tear on the mechanism and prolongs the life of the OLTC contacts and the oil in which the arcing takes place (Faiz and Siahkolah, 2011).

* + - 1. *Representation of Transformer with Tap-Changer*

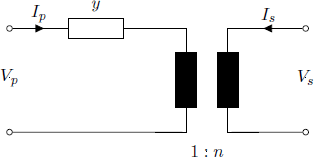
A transformer with nominal turn’s ratio is represented with series admittance (Prada, 2003). A tap changing transformer has the ability of changing the turn’s ratio and with a changed ratio, the ratio becomes off-nominal, and the series admittance is different from both sides of the transformer. With an off-nominal ratio, it is necessary to modify the admittance to include the effect of changing turns ratio. Figure 2.4 illustrates a transformer with series admittance and a turn’s ratio with off-nominal tap ratio 1: *n*. *n* is the off-nominal tap position, and if the transformer is a phase shifting transformer, *n* is a complex number (Prada, 2003).

Figure 2.4: Transformer Tap-Changer with Turns Ratio 1:n (Prada, 2003) From figure 2.4, the following relations can be set up (Prada, 2003):

*I*  *y*.*V*  *y* .*V*

( 2.1)

*p p n s*

Rearranging equations (2.1):

*I*  1 . *I*

*s n p*

( 2.2)

Inserting equation (2.1) into (2.2) leads to equation (2.3):

# 

*y*

*I P*  

*y* 

*n*  *VP* 



*I*    *y*

*y*  . *V* 

(2.3)

 *S*  

*n*



  *S* 

*n* 2 

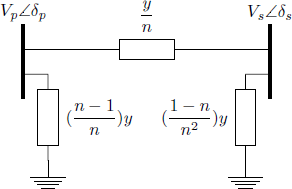
If the off norminal turns ratio n is a real value, it is possible to use equation (2.3), and represent the equation with an equivalent circuit. Figure 2.5 is a π equivalent model representing a transformer with a tap-changer (Saadat, 2010).

Figure 2.5: Equivalent Circuit for Tap-Changing Transformer (Saadat, 2010) Modelling the tap-changing transformer in the linearized power flow equations takes the general form of equation (2.4) in which specified voltage is a control variable and n becomes a dependent variable (Prada, 2003).

 *P* *P*

*P*

*P* 

 

     *V*

*n* .*V* 

*Q*

*Q* *Q*

*Q*   

(2.4)

  

  *V*



*n* 

 *n* 

##### Power Flow Analysis for Power System Network

Classical power flow techniques such as Gauss-siedel, Fast-decoupled and Newton- Raphson are more suitable for transmission system networks (Tinney, 2012). The Newton-Raphson (N-R) approach is the most preferred load flow method because of its various advantages (Tinney, 2012). The N-R approach is particularly useful for large networks as computer storage requirements are moderate and increase with problem size almost linearly. The N-R method is very sensitive to a good initial condition. The use of a suitable starting condition reduces the computation time remarkably, as well as ensures the convergence. No acceleration factors have to be determined, the choice of slack bus is rarely critical, and network modifications require quite less computing

effort. The N-R method has great generality and flexibility, hence enabling a wide range of representational requirements to be included easily and efficiently, such as on-load tap changing and phase-shifting devices, area interchanges, functional loads and remote voltage control (Tinney, 2012). The N-R load flow is central to many recently developed methods for the optimisation of power system operation, sensitivity analysis, system-state estimation, linear-network modelling, security evaluation and transient- stability analysis, and it is well suited to online computation (Stott, 2009).

* + 1. Typical Bus of the Power System

The relationship between real and reactive power in power system network can be established from Figure 2.6:

*Vi*

*Y*

*V*1

*i*1

*Yi* 2

*V*2

*Ii*

*Yin*

*Vn*

*Yio*

Figure 2.6: Typical Bus of the Power System (Stott, 2009)

Power flow equations are formulated in polar form for the n-bus system in terms of bus admittance matrix Y as follows: (Stott, 2009).

*n*

*Ii* *YijV*

*j* 1

(2.5)

Where i, j are to denote *ith*

and

*jth* bus.

Expressing equation (2.5) in polar form yields the following (Stott, 2009):

*n*

*Ii*  *Vij*

*j* 1

*Vj* *ij*  *j*

(2.6)

The current can be expressed in terms of the active and the reactive power at bus *i* as:

*Pi*  *jQi*

*V*



*I*

*i* 

*i*

(2.7)

Substituting for *Ii*

from eqn. (2.7) in eqn. (2.8):

*n*

*PI*  *jQi*  *Vi* *i*  *Vij*

*j* 1

*Vj* *ij*  *j*

(2.8)

Separating the real and imaginary parts of equation (2.8) yields the following (Stott, 2009):

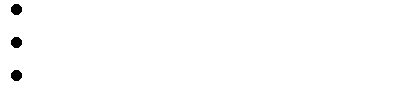
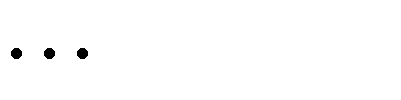
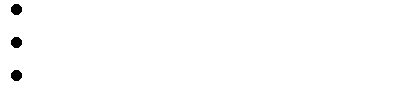
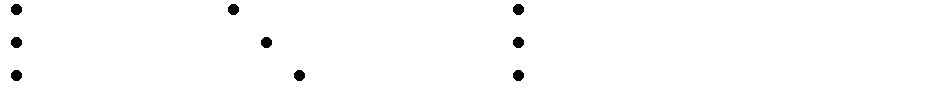
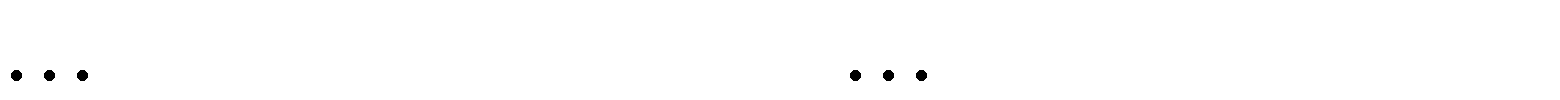
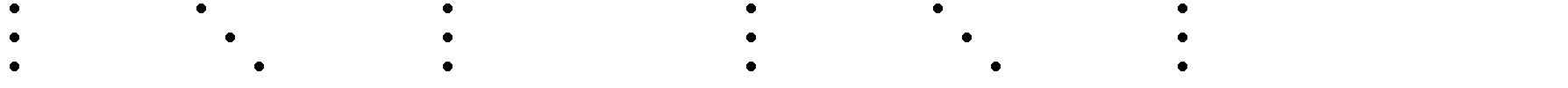
*Pi*  *Vi Vj j* 1

*n*

*Vij* cos(*ij* *i*  *j* ) (2.9)

Expanding equations (2.8) and (2.9) in Taylor's series about the initial estimate neglecting higher order terms, leads to equation (2.10)

  *P*( *k* )

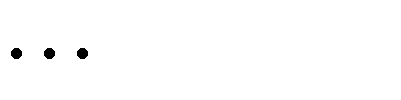


  *P*(*k*)  

  2    

2

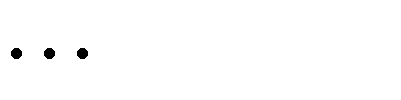
 *V*2



2

 *Vn*

*P*( *k* )



2

*P*( *k* )

 ( *k* )

*n*

   ( *k* )  

2



 

  

*P*2

  

2

*k*  

   

   

 (*k* ) 

    *P*( *k* )

*P*( *k* )   *P*( *k* )

*P*( *k* )    

 ⁝ 

  *n n*

 *n n*    

*P* ( *k* )

 ( *k* )

 (*k*)   *V*

 *V* 

(*k* )

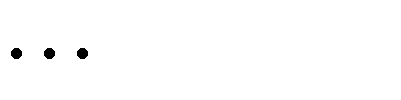
 *n* 

   2 *n*   2 *n*    *n* 

(2.10)

*Q* ( *k* ) 

 

(*k* )



*Q*(*k* )   *Q*(*k* )

*Q*(*k*)     *V*

(*k* ) 

 2 

 *Q*2

*n*   2

2    2 

 ⁝ 

  (*k* )

 (*k* )

 *V*2

 *Vn*

  

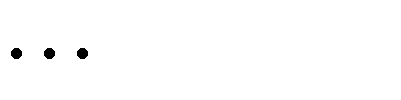
*Q* ( *k* ) 

2 2      

 *n* 

       *V* (*k* )

 



*Q*(*k* )

*n*

 (*k* )

*n*

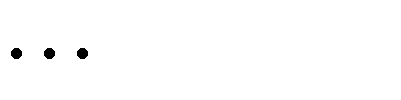
*Q*(*k* )



(*k* )

  *n* 

(*k* ) 

 *Qn*   *Qn*  

*n*

 *Vn*



  (*k* )

  

  2

 *V*2

   

The Jacobian matrix gives the linearized relationship between small changes in

 (*k* ) and voltage magnitude

*i*

*i*

*P*(*k* ) and *Q* ( *k* ) .

*i*

*i*

*V* (*k* )

with the small changes in real and reactive power

*P*    *J*1

*J*2   

(2.11)

*Q*

 *J J*

 *V* 

   3 4   

The diagonal and the off-diagonal elements of

*J*1 are as follows:

*Pi*  *n*

*Vi V*

*Y* cos(

 

) (2.12)

*i*

*j* 1

*k ij*

*ij i j*

*Pi*

 *V V Y* sin (

 

) (2.13)

 *j*

*i j ij*

*ij i j*

*J* , *J and J*

*P*(*k* )

Similarly, the diagonal and off-diagonal elements of 2 3 4 . The terms *i*

and

*Q* ( *k* )

are the difference between the scheduled and calculated values, known as the

power residuals.

*i*

*P*(*k* )  *Psch*  *Pk*

*i i i*

(2.14)

*Q*(*k*) *Qsch* *Q*(*k*) (2.15)

*i i i*

Values of the power residuals and the Jacobian matrices,

 (*k* )

and

*V* (*k* )

are

calculated from the equation (2.10), to complete the particular iteration and the values calculated as shown below are used for the next iteration (Stott, 2009).

*i*

*i*

 (*k* 1)  (*k* )  (*k* ) (2.16)

*i i i*

*V* (*k* 1)  *V* (*k* )  *V* (*k* )

(2.17)

*i i i*

##### The Standard IEEE Test Benchmarks

The standard IEEE Test Platforms are made available for researchers in order to have a common IEEE Standard test beds for uniform comparisons. These test beds are used both in transmission and distribution systems. Some of the IEEE transmission test

networks are 11 bus, 14 bus, 30 bus, 33 bus, 40 bus, 57 bus, 69 bus, 118 bus, 200 bus and 300 bus etc.

Furthermore, there are 10 Indian bus networks and 33 Turkey networks, 200 England bus networks, as part of standard test networks (Cai, 2010).

* + 1. Standard IEEE 14-Bus Test Network

The standard IEEE 14 bus test system will be used to test the proposed BFA method. Figure 2.7 shows the test system. The system bus and line data are given in Appendix A1 & A2 respectively. The transformer between bus 4 and 9 is OLTC transformer and it aims at controlling the voltage at bus 9 (Abdollah *et al.*, 2013).



13

12

14

11

10

1

9

6

7

8

4

5

2

3

Figure 2.7: Standard IEEE 14 Bus Test Network (Abdollah *et al*., 2013)

* + 1. Nigerian 32 -Bus Power System Network

The Nigerian grid is a power system network of 32-buses, 33 transmission lines and 8 generating stations. The Transmission Company of Nigeria (TCN), projected it to have

the capacity to deliver about 12,500MW in 2014, has the capacity of delivering 4475.87MW of electricity. Nigeria has a transmission capability of 5,228MW with peak production of 4,500MW against a peak demand forecast of 10,200MW (Eseosa and Odiase, 2015).

This shows that if the generation sector is to run at full production, the transmission grid will not have the capacity to handle the produced power reliably (Eseosa and Odiase, 2015). Figure 2.8 shows the single line diagram of the Nigerian 32-bus power system network. The Bus data of the Nigerian 32-bus power system network was provided in Appendix A4 and the Line data was also provided in Appendix A5.

28 B / Kebbi T.S

2 Kano T.S

5 Kainji G.S

4 Gombe T.S

8 Jebba T.S

1Kaduna T.S

6 Jebba G.S

29 Ganmo T.S

7 Shiroro G.S

3 Jos T.S

10 Ayede T.S

9 Osogbo T.S

30 Katampe T.S

25 Geregu G.S

11Olorun T.S

24 Ajaokuta T.S

23 N / Heaven T.S

12Sakete T.S

14 Ikeja West T.S

17 Omotosho G.S

13 Akangba T.S

18 Benin T.S

21Onisha T.S

22 Okpai T.S

20Sapele G.S

32 Alaoji G.S

16 Aja T.S

15 Egbin G.S

19 Delta G.S

26 Alaoji T.S

27 Afam T.S

31Aladja T.S

Figure 2.8: Nigerian 32-Bus Power System Network (Eseosa and Odiase, 2015)

##### Meta-heuristic Optimization Techniques

Meta-heuristic optimization techniques represent a group of intelligent algorithms that make analogy of the natural evolution process based on Darwinian principles or mimic

a certain natural phenomenon in search for an optimal solution. These techniques are capable of describing and solving complicated relationships from basic inherent conditions and rules with little or zero knowledge of the search domain. They have been successfully applied to a wide range of power system optimization problems where non- differentiable regions exist and the global solutions are extremely difficult to be estimated (Ming *et al.*, 2014).

Figure 2.9: Classification of Optimization Algorithms (Aimilia, 2016)

* + 1. Artificial Bee Colony (ABC) Algorithm

The ABC algorithm was first proposed by (Karaboga, 2005). Similar to other intelligent swarm algorithms, it simulates the foraging behaviour of honeybees. There are three groups of honeybees in the ABC algorithm, employed bees, onlooker bees, and scout bee. Employed bees take the responsibility of searching new food sources. After the process completed, they fly back to the hive and share the position and nectar amount information with onlooker bees in the dancing area. By observing the dance of employed bees, onlooker bees decide the food sources which they want. Scout bees carry out the random search while the food source is exhausted. In the original ABC

algorithm (Karaboga, 2005), the number of food sources is equal to the number of employed bees. The number of employed bees is equal to number of onlooker bees simultaneously. In other words, a half of the colony size is employed bees. The process of the artificial bee colony algorithm is shown below (Liao *et al*., 2013):

Step 1: Initialize the population.

Step 2: Send the employed bees to the food sources.

Step 3: Memory the best food source in employed bees by fitness evaluation.

Step 4: Employed bees come back to hive and share information of food sources with onlooker bees, then onlooker bees fly to the food sources which they have chosen.

Step 5: Memory the best food source in onlooker bees by fitness evaluation. Step 6: The scout bees fly to the search area and look for the new food sources.

Step 7: While the terminal condition is met or maximum cycle number is reached, Algorithm stop; otherwise, go back to step 2.

Simulated to other swarm evolution algorithms, the ABC algorithm has its own operators such as employed bee phase, onlooker bee phase and scout bee phase.

* + - 1. *The employed bee phase*

In the employed bee-phase, artificial bees update the new food sources by following expression (Liao *et al*., 2013):

*mij =xij +fi j (xij - x j )*

*k*

(2.18)

Where

*i i*



*m j and x j*

represents the new and old solution (food source) in

*jth* dimension of

the

*ith* individual respectively:

*i* is a random real number between {-1, 1}

corresponding to *x j* . It controls the effectiveness of the distance between *j* and *x j* , *k*

*i*

*x*

*k*

*j*

*i*

is an index number selected randomly in food sources. Obviously, a new food source is affected by the status of the bee colony distribution. After the new food source updated, original ABC chose the food source by the fitness value of each corresponding

employed bee. Greedy selection has been applied in the ABC algorithm in order to determine which food source is better and would be remembered after the employed bee phase.

* + - 1. *The onlooker Bee phase*

In the onlooker bee phase, employed bees go to a dance area share the nectar amount information of a food source, and onlooker bees waiting in the hive chose the employed bees randomly, but probability is related to the nectar amount. In the ABC algorithm, the nectar amount represents the fitness value of food source. Therefore, the food sources which have higher nectar amount information are more likely to be chosen after onlooker bee phase completed (Liao *et al*., 2013).

* + - 1. *Scout Bee phase*

After onlooker bee phase, a modified bee colony distribution is determined. If one of these food sources cannot be improved in pre-determined cycle ‘‘limit’’, it will be replaced by a new one according to following equation (Liao *et al*., 2013):

#### xij = x j

*min max min*

*+ rand [0,1] (x j*

#### - x j )

(2.19)

Where

*j*

min

*x*

and

*j*

max

*x*

represent the lower and upper boundary in dimension *j*,

respectively; *rand* {0, 1} is the random number between {0, 1}; Scout bee phase in ABC is applied to abandon the solution which cannot be improved (Liao *et al*., 2013).



Figure 2.10: Flow Chart of ABC Algorithm (Abdollah *et al.*, 2013)

* + 1. Overview of Bacterial Foraging Algorithm (BFA)

It was originally proposed by Kevin Passino in 2002, the algorithm mimics the foraging behavior of E. Coli bacteria found in the human intestines (Xing and Gao, 2014). The algorithm is formulated on the basis of four principal processes namely: chemotaxis, swarming, reproduction and elimination-dispersal (Boussaid *et al.,* 2013).

* + - 1. *Chemotaxis*

Chemotaxis explains the procedure in which the E. Coli bacteria conducts their movements towards certain chemicals within the surroundings. The bacteria moves in either of two ways: swimming or tumbling, with the sole purpose of finding nutrient- rich areas and avoiding toxic environments. Tumbling is the movement of the bacteria in a haphazard manner (random direction) whereas swimming is the movement in a specified direction mostly a unit walk in a previous tumble (Kiani *et al*., 2013). The

movement of the *ith*

bacterium after one step is given by (Xing and Gao, 2014).

 *i* (*i*  1, *l*)  *i* ( *j*, *k*, *l*)  *C*(*i*)(*i*)

(2.20)

Where:

 *i* ( *j*, *k*, *l*)

is the location of

*ith*

bacterium at

*jth*

chemotactic,

*kth*

reproductive,

*lth*

elimination and dispersal step, C(*i*) is the length of unit walk,

 (i)

is the direction angle of the

*jth*

step,

The fitness function of the

*ith*

bacterium is determined based on its position and is

represented by

*j*  *j* (i, j, k, l) (Kiani *et al.,* 2013). The direction angle  (*i*) describes the

tumble of the bacteria and is given by (Boussaid *et al*., 2013):

 (*i*) 

(*i*)

*T* (*i*)(*i*)

(2.21)

Where:

(i)   *p* is a randomly generated vector with elements within the interval [-1,1]

* + - 1. *Swarming*

The attractive and repulsive effects possessed by each bacterium are used as a medium of communication to others. The bacteria under the stresses circumstances, release attractants to signal bacteria to swarm together, while repellent are released to signal others to maintain a minimum distance from it (Xing and Gao, 2014). The cell-to-cell signalling of the bacteria can be represented by (Xing and Gao, 2014):

s

 ( , P(j, k, l))  J

i

J

cc cc

i1

s

( , i (j, k, l))

 p

i 2 

= [dattract exp attract m m  ]

i1

s 

 m1

 p



i 2 

(2.22)

+ hrepellant exp repellant m  m  

Where:

i1 

 m1 

Jcc ( , P(j, k, l))

functions,

is the objective function value to be added to the actual objective

S is the total number of bacteria,

P is the number of variables to be optimized which are present in each bacterium,

   

... 

T

denotes a point in the *p-*dimensional search domain,

dattract

attract

1 2 p

is the depth of the attractant released by the cell, is a measure of the width of the attractant signal,

hrepellant

is the height of the repellant effect,

repellant

is a measure of the width of the repellant.

The fitness of each position is determined by (Boussaid *et al*., 2013):

J(i, j, k, l) J(i, j, k, l)  Jcc ( , P(j, k, l))

* + - 1. *Reproduction*

(2.23)

The idea behind reproduction in E. Coli bacteria is that nature tends to eliminate animals with poor foraging strategies and retain those with better ones (Kiani *et al*.,

2013). After Nc

chemotaxis steps, the reproduction step should be performed by

sorting the health of all bacteria based on fitness described by fitness function (Kiani *et al., 2013*):

*i health*

*J*

*N* 1

  *J* (i, j, k, l) (2.24)

*c*

*j*

The Sr

bacteria (the population of the bacteria divided into two equal halves) with least

health due to insufficient nutrient eventually die leaving the healthiest to split into two identical bacteria and placed at the same location (Xing and Gao, 2014).

* + - 1. *Elimination and Dispersion*

The process of elimination and dispersion is executed after

*Nre*

reproduction steps in

order to avoid being involved in local optima. Each bacterium is subjected to

elimination and dispersal within the environment according to probability ( *Ped* ). *Nel* is

the number of elimination and dispersal steps. If a bacterium is eliminated then it is dispersed to a new (random) location of the nutrient environment in order to maintain the original bacteria population (Boussaid *et al.,* 2013).

The flow chart for the implementation of the BFA is presented in Figure 2.11.

*Bacterium counter* :

*i*  *i*  1

*Chemotaxis loop* :

*j*  *j*  1

*C*

*No*

Start

*A*

*J* (*i*, *j* 1, *k*,1)

 *J* (*i*, *j*, *k*,*l*)?

*E*

*Yes*

*No*

*m*  *N s* ?

*Yes*

*Yes*

*B*

*No*

*i* 

*C No*

*Yes*

*j*  *N c* ?

*Yes*

*No*

*k*  *N* ?

*re*

*Yes*

*No*

*l*  *N*

*ed*

*Yes*

En

*Move bacteria* :

 *i* ( *j* 1, *k*,*l*)  *i* ( *j*, *k*,*l*)  *C*(*i*)(*i*)

*Swim* , *m*  *m*  1

*hrepellant*, *hattractant*, *attract*, *dattract*

*p,S,Ns,Nc,Nre,Ned , c(i),*

*Initialization*

*Tumble*

*k*  *k* 1

*Rep*

*Elimination and disparsal loop :*

*l* *l* 1

*D*

*B*

*D*

*A*

*Calculate cost function :*

*J* (*i*, *j*, *k*)  *Jcc* ( , *P*,( *j*, *k*,*l*))

*E*

Figure 2.11: Flow Chart of Bacterial Foraging Algorithm (Passino, 2002)

##### Review of Similar Works

In order to have adequate knowledge of what is obtainable presently in the area of this research, it is very important to carry out a review of some related works done by different authors. Below are some of the works reviewed:

Millano (2011) presented a hybrid control model of on-load tap changers. The proposed model was based on the well-known discrete and continuous control models. The model was designed to preserves the discrete behaviour of the tap ratio while allowing small- signal stability and Eigen value analysis. The proposed model was tested on the standard IEEE 14-Bus system and a real world 1488-bus model of a sub-transmission and distribution system. However, the computational complexity of the model as compared with the continuous method is a serious setback which involves complex mathematical analysis.

Sagastabeitia *et al*., (2011) presented a remote control system for transformers with on- load tap changer. The tool was designed and implemented in Remote Telecontrol Units (RTU) located in transformation centres with on load tap changing capability. Its final application is to provide an integral solution of the Telecontrol on load tap changer from a remote operation control position (ROCP), located in the electric company’s operation office. The main advantages of this method are: it doesn’t need a great investment to accomplish because the automatism was implemented in existent hardware and also only small modifications have to be made. Secondly, it reduces the number of outages that the users could suffer unnecessarily and it also improves the quality of the electric supply. The shortcomings of this work are; the remote system design can only control a maximum of 8 transformers and the distance between the remote operation control position and the devices is short (1km) and which in practice is not feasible.

Abdollah *et al*., (2013) presented the use of Artificial Bee Colony Algorithm in tuning of ULTC for voltage regulation. Simulation results showed that the proposed method is better than the conventional methods. However, it was observed that, increasing tap step leads to system instability. Therefore, increasing of transformer tap step should be carried out with careful attention and could be achieved by the application of a more robust technique. It was also observed that the algorithm although has good exploration capability, but exploitation capacity to find the food sources is very bad, which in turn resulted to serious setback.

Hartung *et al*., (2014) presented the comparative study of tap changer control algorithms for distribution networks with high penetration of renewables. The research shows that on a clear day it is usually not possible to reduce the number of tap changes and it is evident that small time delays produce best results. For cloudy days there is a trade-off between minimum number of tap changes and compliance with the permissible voltage band. Regulation requirements and the resistance to wear and tear of the OLTC devices influence the optimal setting of the time delay. It was shown that the magnitude of the voltage fluctuations can be significantly reduced by using definite two type timers instead of simple definite timers. However, the work only provides comparison of results obtained in different scenario but fails to address a specific problem of concern.

Nikunj *et al*., (2014) presented the implementation of a fast On-Load Tap Changer regulator. The control strategy is microcontroller based, ensuring flexibility in programming the control algorithms. The experimental results demonstrate that the fast OLTC is able to correct several disturbances of the ac mains besides the long duration in variation and is much lower than the corresponding traditional regulations. However,

the research illustrates how micro-controller can be configured but failed to address the decision making algorithms for the controller which select the best tap.

Shirvani *et al*., (2014) presented the application of on-load tap changer for voltage control. The research aimed at showing the effects of on-load tap changers for voltage control as well as showing OLTC on power system performance. A typical test system installed with OLTC is investigated following change in input voltage. Simulation results showed the effectiveness of OLTC in regaining the system voltage after drip. However, delay in fast response of the voltage back to normalcy is a shortcoming. Therefore, a smart method of tuning the OLTC is required to limit the time of operation of the OLTC.

Rolga *et al*., (2015) presented the different methods of on load tap changer selection such as Remote control system, Solid state on load tap changer using microcontroller and supervisory control and data acquisition (SCADA). Finally, the research showed that SCADA has more advantages than the remote control system and solid state on load tap changer using microcontroller. The SCADA can control a number of substations by a single SCADA centre. It can store a very large amount of data and the data can be displayed in anyway the user wants. Data can be viewed from anywhere not just on site. The shortcomings of this method are it uses communication network which is usually associated with noise, interference and network failure. So, an in built and highly intelligent system is required.

Rolga *et al*., (2015) presented tap changing in parallel operated transformers using SCADA where transformers are connected in parallel to meet the increasing loads demand in power system. The parallel operation of tap changing transformers is done by using the remote tap changer control cubicle (RTCC), which control the tap

changing of parallel connected transformers from the control room near the yard. The main advantages of SCADA compared to RTCC are to minimize fault response time, reduce planned down times, reduce operations overhead, reduce manpower requirement and maximize equipment lifetime. But there are many drawbacks since SCADA system uses communication networks, such as noise, interference and network failure. As such, meta-heuristic algorithms are more efficient and robust than the SCADA as they don’t need an external communication network.

Vigneshwaran and Yuvaraja, (2015) presented voltage regulation by solid state tap changer mechanism for distribution transformer. The research deals with the replacement of conventional electro-mechanical way of on load tap changers with the solid state tap changers for voltage regulation. The research shows that with fully electronic control of tap changing the problems associated with the mechanical on load tap changing which include excessive conduction losses, slow operation and arcing in the diverter switch have been properly rectified. The sequential switching of the thyristor using Pulse Width Modulation (PWM) to regulate the voltage based on the voltage feedback taken from the output side was adopted. However, its major disadvantage is that when two thyristors are turn ON over short period during the tap changing process, the circuit of the diverter switch gets burnt; which in turn reduces the reliability of the system.

Gohil and Verma, (2016) presented the review on influence of the transformer tap changer on voltage stability. The review provides different methods of achieving voltage stability such as small and large disturbance stability. Steady state voltage stability is concerned with the limits on the existence of steady state operating points on the network. FACTS devices can be utilized to increase the transmission capability, the

stability margin and dynamic behaviour or serve to improve power quality. The research proposed the use of on-load tap changer for voltage control in power system network. The algorithm was developed for voltage level control with on-load tap changer operation. However, the research fails to consider any of the standard test bed as a framework for comparison.

Babu and Varghese, (2016) presented voltage compensation of OLTC transformer using Proportional Integrator (PI) controller. PSCAD platform was used for the simulation. The result shows that the proposed approach is capable of raising the voltage to some limits. However, the results obtained failed to reach the load voltage requirement. Therefore, a more robust technique is needed to compensate the voltage to the load voltage level.

##### CHAPTER THREE MATERIALS AND METHODS

##### Introduction

In this chapter, an elaborate procedure for the actualization of the work is discussed. The materials employed and the parameters setting used for the BFA algorithm, the minimum and maximum voltage limits as well as the OLTC limits are presented. Also, a comprehensive methodology adopted for this work is given.

##### Materials

The materials employed for the actualization of this research are as follows:

* + 1. Computer Specifications

All simulation analyses were carried out using SAMSUNG DESKTOP QEQ2NTB computer with the following specifications:

* + - 1. Intel(R) Pentium (R) CPU B8950;
      2. 2.10GHz 64-based processor;
      3. 4.00GB installed memory (RAM) and;
      4. 64-bit windows 10 Operating System (OS).
    1. MATLAB 2016a Software

Simulations were performed under virtual platform using MATLAB 2016a, PSAT Toolbox for analysis. The details of the codes for both ABC and BFA are provided in appendix B1.

* + 1. Network Parameters

The standard IEEE 14-bus and a dedicated Nigerian 32-bus power system network with the following network parameters: slack bus, active and reactive powers, bus voltages and bus voltage angles have been adopted for this research.

##### Methodology

The objectives as outlined are achieved in line with the following procedures:

* + 1. Acquisition of Relevant Networks Data

Data of the standard IEEE 14-bus test network and the Nigerian 32-bus power system network used are:

* + - 1. Line data (resistance and reactance of each line in ohms)
      2. Bus data (active and reactive power demand in kW and kVAr respectively)
      3. Network base voltage
      4. Sending and receiving end buses
    1. Base-case Power Flow Analysis

The pseudo-code used in developing the algorithm for running the base-case power flow analysis of the transmission networks are presented below; and the complete flow chart is shown in Figure 3.1.

* + - 1. Load the network line and bus data
      2. Assume a flat start voltage profile of 1.0 p.u at all buses
      3. Calculate the voltage and phase angle at each bus of the network
      4. Compute the line losses ( *Pik and Qik* ) using equations (2.8) and (2.9)



Figure 3.1: Base Case Power Flow Analysis of Transmission System Network

* + 1. Multi-Objective Algorithm Formulation

The optimization task aims at the minimization of voltage deviation at the buses and also to limit transformer OLTC operations to the minimal level. The objective function is presented with two different formulations. Thus, the formulation of objective function is presented below:

*P = min* (1.V*D* 2.OLTC*t* ) (3.1)

Where 1 *and* 2

are the weighting metrics used for adjusting the network total voltage

deviation

*VD* , and transformer tap changing operation functions

*OLTCt*

respectively.

Due to the equal importance attached to both objectives in equation (3.1), a unit weighting metric was assigned to both objective functions. Thus, 1 = 2

* + - 1. *Constraints*

The optimal tuning of OLTC transformer is considered as a constrained optimization problem that deals with the equality and inequality constraints.

*Equality Constraints*

The equality constraints represent equations expressed as:

*tapTr*.min  *tapTr*  *tapTr*.max (3.2)

*Q*min *Q*

*Q*max (3.3)

*bus bus bus*

*In equality Constraints*

The system operating constraints constitute the in-equality constraints on the dependent variables such as the voltage magnitude of the buses, current through the cables, line and transformer flow limits. They have the form described in the following equations:

*V*min *V* *V*max (3.4)

*i*  *i*lim (3.5)

*s*  *s*lim (3.6)

The network voltage constraint limits has been set as 0.85p.u and 1.15p.u for

*V* min *and V* max respectively.

* + - 1. *Parameters Selection*

For the purpose of this research, the initialization and user-defined parameters for the BFA are presented in table 3.1.

Table 3.1: Parameters Settings for BFA

|  |  |
| --- | --- |
| **Parameters** | **Values** |
| Dimension of search space*, P* | 2 |
| Number of bacteria, *S* | 4 |
| Number of chemotactic steps, *Nc* | 10 |
| Number of swim steps, *Ns* | 4 |
| Number of reproduction steps, *Nre* | 4 |
| Number of elimination-dispersal steps, *Ned* | 2 |
| Run-length unit *C(i)* | 0.1 |
| Number of bacteria reproductions (splits) per generation, *Sr* | S/2 |
| The probability that each bacteria will be eliminated/dispersed, *Ped* | 0.25 |
| Depth of attractant, *dattract* | 0.1 |
| Width of attractant, *attract* | 0.2 |
| Height of repellant, *hrepellant* | 0.1 |
| Width of repellant, *repellant* | 10 |

* + 1. Validation

The steps involved in validating the BFA are presented below. Figure 3.2 shows the flow chart of the algorithm.

* + - 1. Load the line and bus data of the standard IEEE 14-bus test network
      2. Perform base-case power flow analysis for the 14-bus power system network
      3. Initialization of BFA parameters
      4. Formulate a multi-objective function using equation (3.1)
      5. Application of BFA with the formulated multi-objective functions
      6. Perform final power flow analysis with the OLTC transformer incorporated at the optimum bus

Start

Load the Network Lineand Bus Data for the14 bus Power Transmission Network

Performa basecasepower flow analysis

Initialization of the BFA parameters

Formulation of a multi - objectivefunctions using equation (3.1)

Application of BFA with theformulated multi - objectivefunction

Perform thefinal power flow analysis with BFA applied to the OLTC transformer

End

Display the resultsshowing the voltagedeviation reduction and transformer OLTCoperation minimized

Figure 3.2: Flow Chart for the Implementation of the Proposed Research

* + 1. Comparison of the Results obtained

The results obtained from validation are compared with those of the base case, ABC algorithm and BFA by:

* + - 1. Graphical representation (voltage deviation reduction and transformer tap changing operation reduction)
      2. Tabular representation (comparison between the conventional method, ABC method and the proposed BFA method)
    1. Implementation of the results on the Nigerian 32-bus Power System Network

The results will finally be implemented on the Nigerian power system network in order to test the performance and effectiveness of the proposed approach using graphical and tabular form representation.

##### Introduction

##### CHAPTER FOUR RESULTS AND DISCUSSIONS

In this chapter, results and discussion of the theoretical concepts from the previous two chapters are presented. The effectiveness of the BFA is validated on the standard IEEE 14-bus power system network and comparison was made between the ABC and BFA. A real 32-bus Nigerian power system network was considered for implementation of the proposed technique. In both networks, two different cases were considered for analysis. Case I: Network without BFA (Base-case) and

Case II: Network with BFA

##### The Standard IEEE 14-Bus Power System Network

The standard IEEE 14-bus power system network discussed in section 2.5.1 with line and bus data given in Appendix A1 and A2 respectively is modelled based on the theoretical concepts presented in chapter two. The results obtained are used for case I and case II are used for comparison with the existing results reported in literatures.

* + 1. Case I: Network without BFA (Base Case)

The network base case power flow analysis was performed using the theoretical concept given in sub-section 2.5.1. The results of the analysis for each bus are presented in Table 4.1.

Table 4.1: Standard IEEE 14-Bus Power System Network Base Case Power Flow Results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage Magnitude  (p.u) | P (MW) | Q (MVar) |
| 1 | 2 | 0.760 | 30.80 | 17.78 |
| 1 | 5 | 0.845 | 26.80 | 3.987 |
| 2 | 3 | 1.010 | 131.88 | 26.60 |
| 2 | 4 | 1.000 | 66.92 | 10.00 |
| 3 | 4 | 0.801 | 10.64 | 2.240 |
| 4 | 7 | 0.833 | 15.68 | 10.50 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage  Magnitude (p.u) | P(MW) | Q(MVar) |
| 7 | 8 | 1.000 | 6.876 | 6.345 |
| 7 | 9 | 1.090 | 3.987 | 5.345 |
| 5 | 6 | 1.160 | 41.30 | 23.24 |
| 6 | 12 | 1.000 | 12.60 | 8.12 |
| 6 | 13 | 1.000 | 4.900 | 2.52 |
| 12 | 13 | 1.000 | 8.540 | 2.24 |
| 13 | 14 | 1.171 | 18.90 | 8.12 |
| 9 | 10 | 1.103 | 20.86 | 7.000 |

* + 1. Case II: Network with BFA

After the network base case power flow analysis results were obtained, the BFA in sub- section 2.6.2 was then applied to the standard 14 bus network. The results obtained after final power flow analysis with the application of BFA showed a reduction of voltage deviation from the defined limits. A clear picture of the effect of BFA on the minimization of voltage deviation is given in Table 4.2.

Table 4.2: Standard IEEE 14-Bus Power System Network Power Flow Results using BFA

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage Magnitude  (p.u) | P (MW) | Q (MVar) |
| 1 | 2 | 1.129 | 30.30 | 16.72 |
| 1 | 5 | 1.010 | 25.80 | 2.987 |
| 2 | 3 | 1.011 | 132.88 | 24.50 |
| 2 | 4 | 0.999 | 65.92 | 9.501 |
| 3 | 4 | 1.010 | 10.04 | 2.240 |
| 4 | 9 | 0.965 | 14.68 | 10.50 |
| 7 | 8 | 0.990 | 7.876 | 6.345 |
| 7 | 9 | 1.000 | 2.987 | 5.345 |
| 5 | 6 | 1.120 | 40.30 | 23.24 |
| 6 | 11 | 1.173 | 11.70 | 7.120 |
| 11 | 10 | 1.020 | 4.954 | 2.521 |
| 12 | 13 | 1.102 | 9.540 | 1.241 |
| 13 | 14 | 1.000 | 17.90 | 7.020 |
| 9 | 14 | 0.852 | 21.86 | 7.112 |

* + 1. Network Bus Voltage Deviation Reduction using Base case and ABC Algorithm The application of ABC algorithm to the standard IEEE 14 Bus network has reduced the bus voltage deviation of the entire network as shown in Table 4.1. The bus voltage magnitudes shown in Figure 4.1 are plotted against their corresponding time. A clear reduction in bus voltage deviation was recorded from the graph using the Base case and ABC algorithm shown in Figure 4.1.

The bus voltage deviation of the network was reduced using the base case and the ABC algorithm by 1.0125% and 1.0112% respectively. It was also seen from the graph that the computational time was reduced from 6.67sec to 4.37sec respectively.



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Figure 4.1: Bus Voltage Deviation Reduction using the Base case and ABC algorithm

* + 1. Performance Comparison for Transformer Tap Changing Operation Reduction using the Base case and ABC Algorithm



The application of ABC algorithm to the standard IEEE 14 Bus network has reduced the transformer tap changing operation of the entire network as shown in Figure 4.2. The

transformer tap ratios shown in Figure 4.2 are plotted against their corresponding time. A clear reduction in transformer tap changing operation was recorded from the graph using the Base case and ABC algorithm shown in Figure 4.1.

The entire transformer tap changing operation of the network was reduced using the base case and the ABC algorithm by 0.6 %. It was also seen from the graph that the settling time was reduced from 50sec to 20sec respectively as in figure 4.2.





Figure 4.2: Transformer Tap changing operation Reduction using the Base case and ABC

The performance results for both cases of the network using the Base case and ABC are summarized in Table 4.3.

Table 4.3: Summary of Simulation Results for the 14-bus Standard IEEE Power System Network using the base case and ABC algorithm

|  |  |  |
| --- | --- | --- |
| Parameter  Description | Base case | ABC |
| Total Bus Voltage Deviation Reduction | 1.0125 | 1.0112 |
| Percentage Reduction in Bus Voltage Deviation (%) | - | 0.25 |
| Total Tap Changing Operations Reduction | 0.9102 | 0.8975 |
| Percentage Reduction in Tap changing operations (%) | - | 0.6 |
| Reduction in Computational  Time (sec) | 6.67 | 4.32 |

* + 1. Network Bus Voltage Deviation Reduction using the Base case, ABC and BFA The application of BFA to the standard IEEE 14 Bus network has reduced the bus voltage deviation of the entire network as shown in table 4.3. The bus voltage magnitudes shown in figure 4.3 are plotted against their corresponding time. A clear reduction in bus voltage deviation was recorded from the graph using the Base case ABC and BFA algorithm as in Figure 4.3. It can be deduced from the graph that the BFA algorithm outperform the conventional method and the ABC algorithm in reduction of bus voltage deviation from 0.25% to 0.12% respectively.

It was also seen from the graph that the settling time from the horizontal axis of the graph was reduced from 18sec to 13sec respectively.





Figure 4.3: Bus Voltage Deviation Reduction using the Base case, ABC and BFA

* + 1. Performance Comparison for Transformer Tap Changing Operation Reduction using the Base case, ABC Algorithm and BFA

The application of BFA to the standard IEEE 14 Bus network has reduced the transformer tap changing operation of the entire network as shown in table 4.3. The transformer tap ratios shown in figure 4.4 are plotted against their corresponding time. A clear reduction in transformer tap changing operation was recorded from the graph using the Base case, ABC and BFA algorithm shown in Figure 4.4. It can be deduced from the graph that the BFA algorithm outperform the conventional method and the ABC algorithm in reduction of transformer tap changing operation from 0.6% to 0.3% respectively.

It can also be seen from the graph that the settling time from the horizontal axis of the graph was reduced from 20sec to 17sec respectively.



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Figure 4.4: Transformer Tap Changing Operation Reduction using the Base case, ABC and BFA

The performance results for both cases of the network using the Base case, ABC and BFA are summarized in Table 4.3.



Table 4.4: Summary of Simulation Results for the 14-bus Standard IEEE Power System Network using the base case, ABC and BFA

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter  Description | Base case | ABC | BFA |
| Total Bus Voltage Deviation Reduction | 1.0125 | 1.0112 | 1.0101 |
| Percentage Reduction in Bus Voltage Deviation (%) | - | 0.25 | 0.12 |
| Total Tap Changing operations  Reduction | 0.9011 | 0.8975 | 0.8950 |

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter  Description | Base Case | ABC | BFA |
| Percentage Reduction in Tap changing operations (%) | - | 0.6 | 0.3 |
| Reduction in Computational  Time (sec) | 6.67 | 4.32 | 4.11 |

##### The 32-Bus Nigerian Power System Network

The 32-bus Nigerian power system network was discussed in sub-section 2.5.2 and its line as well as bus data are given in Appendix A3 and A4 respectively. Just like the standard IEEE 14-bus power system network, the network is modelled based on the theoretical concepts presented in chapter two. Two cases were also considered for analysis (case I and case II).

Case 1: Network without BFA (Base case) and Case II: Network with BFA

* + 1. Case I: Network without BFA (Base Case)

The power flow analysis was performed using the theoretical concept in sub-section

2.5.2. Table 4.5 presents the results of the analysis.

Table 4.5: Nigerian 32-Bus Power System Network Base Case Power Flow Results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage  Magnitude(p.u) | P(MW) | Q(MVar) |
| 1 | 2 | 0.7021 | 1.3626 | 0.4100 |
| 1 | 3 | 0.7870 | 1.1830 | 0.5587 |
| 1 | 7 | 1.0738 | 4.6476 | 0.7791 |
| 3 | 4 | 1.0531 | 0.7404 | 0.1879 |
| 5 | 8 | 0.8675 | 0.3316 | 0.0879 |
| 5 | 28 | 1.0540 | 1.4720 | 0.4321 |
| 6 | 8 | 0.8530 | 3.1801 | 0.8164 |
| 7 | 8 | 0.9453 | 1.1882 | 0.5376 |
| 7 | 30 | 0.9056 | 0.3356 | 0.0482 |
| 8 | 9 | 1.1412 | 0.2914 | 0.5802 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage  Magnitude (p.u) | P(MW) | Q(MVar) |
| 9 | 10 | 0.9328 | 0.1984 | 0.2939 |
| 9 | 14 | 0.7376 | 0.2060 | 0.1407 |
| 9 | 18 | 0.8213 | 2.2105 | 0.3969 |
| 9 | 29 | 0.9234 | 0.8063 | 0.6789 |
| 10 | 11 | 1.1754 | 0.9910 | 0.2361 |
| 11 | 14 | 0.9685 | 2.1578 | 1.1656 |
| 12 | 14 | 1.1543 | 2.0324 | 0.4301 |
| 13 | 14 | 0.9756 | 1.7433 | 0.9320 |
| 14 | 15 | 0.9342 | 1.1053 | 0.2345 |
| 14 | 17 | 0.7231 | 2.9214 | 1.1857 |
| 15 | 16 | 0.9765 | 1.2487 | 0.7677 |
| 17 | 18 | 0.8643 | 1.5191 | 0.1929 |
| 18 | 19 | 0.9765 | 0.4270 | 0.5647 |
| 18 | 20 | 0.8412 | 2.3411 | 0.3241 |
| 18 | 21 | 1.0312 | 0.4025 | 1.2767 |
| 18 | 24 | 0.9315 | 1.8928 | 1.2471 |
| 18 | 22 | 0.9213 | 2.4915 | 0.2345 |
| 18 | 23 | 0.8234 | 1.2035 | 0.1828 |
| 21 | 26 | 0.9922 | 0.5064 | 0.1818 |
| 21 | 26 | 1.1168 | 0.6015 | 1.1032 |
| 24 | 25 | 0.9943 | 0.7500 | 0.3456 |
| 26 | 32 | 1.1132 | 4.4450 | 0.4354 |

* + 1. Case II: Network with BFA

The power flow analysis was performed using the theoretical concepts in sub-section

2.5.2. There was a significant improvement in bus voltage deviation reduction. Table

4.6 presents the results of the analysis.

Table 4.6: Nigerian 32-Bus Power System Network Base case Power Flow Results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage  Magnitude(p.u) | P(MW) | Q(MVar) |
| 1 | 2 | 0.8021 | 1.3626 | 0.5101 |
| 1 | 3 | 0.8703 | 1.1830 | 0.4585 |
| 1 | 7 | 1.0738 | 4.6476 | 0.5791 |
| 3 | 4 | 1.0531 | 0.7404 | 0.2879 |
| 5 | 8 | 0.9675 | 0.3316 | 0.0878 |
| 5 | 28 | 0.9540 | 1.4720 | 0.4321 |
| 6 | 8 | 0.9530 | 3.1801 | 0.8164 |
| 7 | 8 | 0.9453 | 1.1882 | 0.5376 |
| 7 | 30 | 0.8456 | 0.3356 | 0.0482 |
| 8 | 9 | 0.9412 | 0.2914 | 0.5802 |
| 8 | 29 | 0.9312 | 0.1758 | 0.3254 |
| 9 | 10 | 0.9328 | 0.1984 | 0.2939 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| From Bus | To Bus | Voltage  Magnitude (p.u) | P(MW) | Q(MVar) |
| 9 | 14 | 0.9376 | 0.2060 | 0.1407 |
| 9 | 18 | 1.0131 | 2.2105 | 0.3969 |
| 9 | 29 | 1.1523 | 0.7063 | 0.5432 |
| 10 | 11 | 0.9754 | 0.9910 | 0.2361 |
| 11 | 14 | 0.9685 | 2.1578 | 1.1656 |
| 12 | 14 | 0.9543 | 2.0324 | 0.4301 |
| 13 | 14 | 0.8756 | 0.7433 | 0.9320 |
| 14 | 15 | 0.9342 | 1.1053 | 0.4324 |
| 14 | 17 | 0.8231 | 2.0214 | 0.1857 |
| 15 | 16 | 0.9765 | 1.2487 | 0.7677 |
| 15 | 18 | 0.9643 | 1.5191 | 0.1929 |
| 18 | 19 | 0.9765 | 0.4270 | 0.3456 |
| 18 | 20 | 0.9999 | 2.3411 | 0.3241 |
| 18 | 21 | 1.0312 | 0.4025 | 1.2767 |
| 18 | 24 | 0.8315 | 1.8928 | 0.2471 |
| 18 | 22 | 0.9213 | 2.4015 | 0.2345 |
| 18 | 23 | 0.8234 | 0.2035 | 1.1808 |
| 21 | 26 | 0.8922 | 0.5064 | 0.1818 |
| 21 | 26 | 0.9168 | 0.6015 | 1.1032 |
| 24 | 25 | 0.8943 | 0.6500 | 0.4362 |
| 26 | 27 | 0.7732 | 4.4450 | 0.1345 |

* + 1. Network Bus Voltage Deviation Reduction using Base case, ABC and BFA

The application of BFA algorithm to the Nigerian 32-bus power system network has reduced the bus voltage deviation of the entire network as shown in Table 4.6. The bus voltage magnitudes shown in figure 4.5 are plotted against their corresponding time. A clear reduction in bus voltage deviation was recorded from the graph using the Base case, ABC and BFA algorithm as shown in Figure 4.5. It can be deduced from the graph that the BFA showed a total superiority over the conventional method and ABC algorithm in reduction of bus voltage deviation by 0.25% and 0.22% respectively.

It was also seen from the graph that the settling time was reduced from 18sec to 12sec respectively.





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Figure 4.5: Bus Voltage Deviation Reduction using the Base case, ABC and BFA



* + 1. Performance Comparison for Transformer Tap Changing Operation Reduction using the Base case, ABC Algorithm and BFA

The application of BFA to the Nigerian 32 bus power system network has reduced the transformer tap changing operation of the entire network as shown in Table 4.3. The transformer taps ratios shown in Figure 4.6 are plotted against their corresponding time. A clear reduction in transformer tap changing operation was recorded from the graph using the Base case, ABC and BFA algorithm as shown in Figure 4.6. It can be deduced from the graph that the BFA algorithm outperform the conventional method and the ABC algorithm in the reduction of transformer tap changing operation by 0.6% and 0.48% respectively.

It can also be seen from the graph that the settling time from the horizontal axis of the graph was reduced from 20sec to 18sec respectively.



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Figure 4.6: Transformer Tap Changing Operation Reduction using the Base Case, ABC and BFA



The performance results for both cases of the network using the Base case, ABC and BFA are summarized in Table 4.7.

Table 4.7: Summary of Simulation Results for the 32-bus Nigerian Network using the base case, ABC and BFA

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter  Description | Base case | ABC | BFA |
| Total Bus Voltage Deviation Reduction | 1.0125 | 1.0112 | 1.0011 |
| Percentage Reduction in Bus Voltage Deviation (%) | - | 0.25 | 0.24 |
| Total Tap Changing operations  Reduction | 0.9011 | 0.8975 | 0.8965 |

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter  Description | Base Case | ABC | BFA |
| Percentage Reduction in Tap changing operations (%) | - | 0.6 | 0.48 |
| Reduction in Computational  Time (sec) | 6.67 | 4.32 | 4.31 |

##### CHAPTER FIVE CONCLUSION AND RECOMMENDATION

##### Summary

This chapter presents a detailed summary of the research findings. The research has applied a Bacterial Foraging Algorithm based for tuning of on-load tap changing transformer for voltage regulation in power transmission network. The research has finally resulted in reducing the voltage at the bus to the required limits; and transformer tap changing operation was also reduced which in turn increase the system stability.

##### Conclusion

When applied the algorithm on the 14-bus IEEE standard test network, the BFA has demonstrated its superiority over the conventional method and ABC algorithms in terms of reduction in bus voltage deviation by (0.25%) and (0.12%) and reduction in transformer taps changing operation by (0.6%) and (0.3%) respectively.

On the 32-bus Nigerian power system network, the BFA has shown a total superiority over the conventional method and ABC algorithms in all parameters with 4.31%, 0.22% and 0.48% reduction in computational time, bus voltage deviation and transformer tap changing operation respectively;

##### Significant Contributions

Numerous researches on tuning of on-load tap changer in transmission system networks have been carried out and reported in literatures. Also, a significant number of researches have employed different approaches in actualizing their results. The substantial contributions of this research work are enumerated as follows:

* + 1. The use of BFA in tuning of OLTC transformer for voltage regulation in power transmission networks.
    2. Implementation of the proposed approach on the Nigerian 32-Bus power system networks which led to reduction in bus voltage deviation and transformer taps changing operation from 0.25% to 0.22% and 0.6% to 0.48% respectively.

##### Recommendations for Further works

The following possible areas of further work are recommended for consideration for future research:

* + 1. The research can be extended to other members of swarm intelligence meta- heuristic algorithms such as AFSA, CSO etc.
    2. The use of BFA in tuning of OLTC transformer for voltage regulation in radial distribution network can also be considered.

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##### APPENDICES

**Appendix A1: Bus Data for Standard IEEE 14-Bus Network**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Bus No | Voltage  Magnitude | Angle Degrees | P (MW) | Q (MVar) |
| 1 | 1.06 | 0 | 30.8 | 17.78 |
| 2 | 1.045 | 0 | 0 | 0 |
| 3 | 1.01 | 0 | 131.88 | 26.6 |
| 4 | 1 | 0 | 66.92 | 10 |
| 5 | 1 | 0 | 10.64 | 2.24 |
| 6 | 1.07 | 0 | 15.68 | 10.5 |
| 7 | 1 | 0 | 0 | 0 |
| 8 | 1.09 | 0 | 0 | 0 |
| 9 | 1 | 0 | 41.3 | 23.24 |
| 10 | 1 | 0 | 12.6 | 8.12 |
| 11 | 1 | 0 | 4.9 | 2.52 |
| 12 | 1 | 0 | 8.54 | 2.24 |
| 13 | 1 | 0 | 18.9 | 8.12 |
| 14 | 1 | 0 | 20.86 | 7 |

##### Appendix A2: Line Data for Standard IEEE 14- Bus Network

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sending end Bus | Receiving end Bus | Resistance p.u | Reactance p.u | Half  Susceptance p.u | Transformer tap |
| 1 | 2 | 0.01938 | 0.05917 | 0.0264 | 1 |
| 2 | 3 | 0.04699 | 0.19797 | 0.0219 | 1 |
| 2 | 4 | 0.05811 | 0.17632 | 0.0187 | 1 |
| 1 | 5 | 0.05403 | 0.22304 | 0.0246 | 1 |
| 2 | 5 | 0.05695 | 0.17388 | 0.017 | 1 |
| 3 | 4 | 0.06701 | 0.17103 | 0.0173 | 1 |
| 4 | 5 | 0.01335 | 0.04211 | 0.0064 | 1 |
| 5 | 6 | 0 | 0.25202 | 0 | 0.932 |
| 4 | 7 | 0 | 0.20912 | 0 | 0.978 |
| 7 | 8 | 0 | 0.17615 | 0 | 1 |
| 4 | 9 | 0 | 0.55618 | 0 | 0.969 |
| 7 | 9 | 0 | 0.11001 | 0 | 1 |
| 9 | 10 | 0.03181 | 0.0845 | 0 | 1 |
| 6 | 11 | 0.09498 | 0.1989 | 0 | 1 |
| 6 | 12 | 0.12291 | 0.25581 | 0 | 1 |
| 6 | 13 | 0.06615 | 0.13027 | 0 | 1 |
| 9 | 14 | 0.12711 | 0.27038 | 0 | 1 |
| 10 | 11 | 0.08205 | 0.19207 | 0 | 1 |
| 12 | 13 | 0.22092 | 0.19988 | 0 | 1 |
| 13 | 14 | 0.17093 | 0.34802 | 0 | 1 |

**Appendix A3: Bus Data for the Nigerian 32-Bus Power System Network**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **BUS**  **NO.** | **PGi** | **QGi** | **PLi** | **QLi** | **VOLTAGE** | **BUSTYPE** |
| 1 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.05 | 1 |
| 2 | 0.0000 | 0.0000 | 1.3626 | 0.4100 | 1.00 | 2 |
| 3 | 0.0000 | 0.0000 | 1.1830 | 0.5587 | 1.00 | 2 |
| 4 | 0.0000 | 0.0000 | 0.7404 | 0.1879 | 1.00 | 2 |
| 5 | 1.8036 | 0.5200 | 0.0000 | 0.0000 | 1.00 | 3 |
| 6 | 2.4995 | 0.0000 | 0.0000 | 0.0000 | 1.00 | 3 |
| 7 | 3.2980 | 0.8164 | 0.0000 | 0.0000 | 1.00 | 3 |
| 8 | 0.0000 | 0.0000 | 1.9719 | 1.3419 | 1.00 | 2 |
| 9 | 0.0000 | 0.0000 | 1.8237 | 0.1407 | 1.00 | 2 |
| 10 | 0.0000 | 0.0000 | 0.7925 | 0.2361 | 1.00 | 2 |
| 11 | 3.9999 | 0.0000 | 3.1488 | 1.4017 | 1.00 | 3 |
| 12 | 0.0000 | 0.0000 | 2.0324 | 0.0430 | 1.00 | 2 |
| 13 | 0.0000 | 0.0000 | 1.7433 | 0.9320 | 1.00 | 2 |
| 14 | 0.0000 | 0.0000 | 4.3034 | 1.9876 | 1.00 | 2 |
| 15 | 5.3968 | 0.0000 | 0.0000 | 0.0000 | 1.00 | 3 |
| 16 | 0.0000 | 0.0000 | 1.2487 | 0.7677 | 1.00 | 2 |
| 17 | 3.9999 | 0.0000 | 0.0000 | 0.0000 | 1.00 | 3 |
| 18 | 0.0000 | 0.0000 | 3.2011 | 1.9963 | 1.00 | 2 |
| 19 | 0.4200 | 0.0000 | 0.0000 | 0.0000 | 1.00 | 3 |
| 20 | 3.5193 | 0.0000 | 2.3411 | 0.3241 | 1.00 | 3 |
| 21 | 0.0000 | 0.0000 | 1.7099 | 1.2860 | 1.00 | 2 |
| 22 | 2.4915 | 0.0000 | 1.4822 | 0.6242 | 1.00 | 3 |
| 23 | 0.0000 | 0.0000 | 1.2035 | 0.1828 | 1.00 | 2 |
| 24 | 0.0000 | 0.0000 | 1.8928 | 1.2471 | 1.00 | 2 |
| 25 | 0.0000 | 0.0000 | 0.7500 | 0.0000 | 1.00 | 2 |
| 26 | 0.0000 | 0.0000 | 0.7600 | 0.0000 | 1.00 | 2 |
| 27 | 4.4451 | 0.0000 | 0.0000 | 0.0000 | 1.00 | 3 |
| 28 | 0.0000 | 0.0000 | 1.4720 | 0.4321 | 1.00 | 2 |
| 29 | 0.0000 | 0.0000 | 0.9622 | 0.0000 | 1.00 | 2 |
| 30 | 0.0000 | 0.0000 | 0.3256 | 0.0482 | 1.00 | 2 |

##### Appendix A4: Line Data for the Nigerian 32-Bus Power System Network

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **From Bus** | **To Bus** | **Voltage Magnitude(p.u)** | **P(MW)** | **Q(MVar)** |
| 1 | 2 | 1.0000 | 1.3626 | 0.4100 |
| 1 | 3 | 0.9870 | 1.1830 | 0.5587 |
| 1 | 7 | 0.9738 | 4.6476 | 0.7791 |
| 3 | 4 | 0.9731 | 0.7404 | 0.1879 |
| 5 | 8 | 0.9675 | 0.3316 | 0.0879 |
| 5 | 28 | 0.9540 | 1.4720 | 0.4321 |
| 6 | 8 | 0.9530 | 3.1801 | 0.8164 |
| 7 | 8 | 0.9453 | 1.1882 | 0.5376 |
| 7 | 30 | 0.9456 | 0.3356 | 0.0482 |
| 8 | 9 | 0.9412 | 0.2914 | 0.5802 |
| 8 | 29 | 0.9312 | 0.1758 | 0.0000 |
| 9 | 10 | 0.9328 | 0.1984 | 0.2939 |
| 9 | 14 | 0.9376 | 0.2060 | 0.1407 |
| 9 | 18 | 0.9321 | 2.2105 | 0.3969 |
| 9 | 29 | 0.9234 | 0.8063 | 0.0000 |
| 10 | 11 | 0.9754 | 0.9910 | 0.2361 |
| 11 | 14 | 0.9685 | 2.1578 | 1.1656 |
| 12 | 14 | 0.9543 | 2.0324 | 0.4301 |
| 13 | 14 | 0.9756 | 1.7433 | 0.9320 |
| 14 | 15 | 0.9342 | 1.1053 | 0.0000 |
| 14 | 17 | 0.9231 | 2.9214 | 1.1857 |
| 15 | 16 | 0.9765 | 1.2487 | 0.7677 |
| 15 | 18 | 0.9643 | 1.5191 | 0.1929 |
| 18 | 19 | 0.9765 | 0.4270 | 0.0000 |
| 18 | 20 | 0.9412 | 2.3411 | 0.3241 |
| 18 | 21 | 0.9312 | 0.4025 | 1.2767 |
| 18 | 24 | 0.9315 | 1.8928 | 1.2471 |
| 18 | 22 | 0.9213 | 2.4915 | 0.0000 |
| 18 | 23 | 0.9234 | 1.2035 | 0.1828 |
| 21 | 26 | 0.9122 | 0.5064 | 0.1818 |
| 21 | 26 | 0.9168 | 0.6015 | 1.1032 |
| 24 | 25 | 0.9143 | 0.7500 | 0.0000 |
| 26 | 27 | 0.9132 | 4.4450 | 0.0000 |

**Appendix B1: m-File for Artificial Bee Colony**

%Power Flow Code for Standard IEEE 14-bus Power System Network

% and the 32-bus Nigerian Power System Network

% Bukhari Tanko Rabiu (rtanko19@gmail.com)

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% Ahmadu Bello University Samaru-Zaria, Nigeria

% May, 2017.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function fFitness=calculateFitness(fObjV) fFitness=zeros(size(fObjV)); ind=find(fObjV>=0); fFitness(ind)=1./(fObjV(ind)+1); ind=find(fObjV<0);

fFitness (ind)=1+abs(fObjV(ind)); function fm\_call(flag)

%FM\_CALL calls component equations

%

%FM\_CALL(CASE)

% CASE '1' algebraic equations

% CASE 'pq' load algebraic equations

% CASE '3' differential equations

% CASE '1r' algebraic equations for Rosenbrock method

% CASE '4' state Jacobians

% CASE '0' initialization

% CASE 'l' full set of equations and Jacobians

% CASE 'kg' as "L" option but for distributed slack bus

% CASE 'n' algebraic equations and Jacobians

% CASE 'i' set initial point

% CASE '5' non-windup limits

%

%see also FM\_WCALL fm\_var

switch flag

case 'gen'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

case 'load'

gcall(PQ) gcall(Shunt) gisland(Bus)

case 'gen0'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

case 'load0'

gcall(PQ) gcall(Shunt) gisland(Bus)

case '3' fcall(Syn)

case '1r'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

Syn = gcall(Syn); PV = gcall(PV); SW = gcall(SW); gisland(Bus)

case 'series'

Line = gcall(Line); gisland(Bus)

case '4'

DAE.Fx = sparse(DAE.n,DAE.n); DAE.Fy = sparse(DAE.n,DAE.m); DAE.Gx = sparse(DAE.m,DAE.n); Fxcall(Syn)

case '0'

Syn = setx0(Syn); case 'fdpf'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

PV = gcall(PV); SW = gcall(SW); gisland(Bus)

case 'l'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

PV = gcall(PV); SW = gcall(SW); gisland(Bus) Gycall(Line) Gycall(PQ) Gycall(Shunt) Gycall(PV) Gycall(SW) Gyisland(Bus

DAE.Fx = sparse(DAE.n,DAE.n); DAE.Fy = sparse(DAE.n,DAE.m);

DAE.Gx = sparse(DAE.m,DAE.n); Fxcall(PV)

Fxcall(SW) case 'kg'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

Syn = gcall(Syn); gisland(Bus) Gycall(Line) Gycall(PQ) Gycall(Shunt)

Syn = Gycall(Syn); Gyisland(Bus)

fcall(Syn)

DAE.Fx = sparse(DAE.n,DAE.n); DAE.Fy = sparse(DAE.n,DAE.m); DAE.Gx = sparse(DAE.m,DAE.n); Fxcall(Syn)

case 'kgpf' global PV SW

Line = gcall(Line);

gcall(PQ) gcall(Shunt)

PV = gcall(PV); greactive(SW) glambda(SW,1,DAE.kg) gisland(Bus) Gycall(Line) Gycall(PQ) Gycall(Shunt) Gycall(PV) Gyreactive(SW) Gyisland(Bus)

DAE.Fx = sparse(DAE.n,DAE.n); DAE.Fy = sparse(DAE.n,DAE.m); DAE.Gx = sparse(DAE.m,DAE.n);

case 'n'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

Syn = gcall(Syn); PV = gcall(PV); SW = gcall(SW); gisland(Bus) Gycall(Line) Gycall(PQ) Gycall(Shunt)

Syn = Gycall(Syn);

Gycall(PV) Gycall(SW) Gyisland(Bus)

case 'i'

Line = gcall(Line); gcall(PQ) gcall(Shunt)

Syn = gcall(Syn); PV = gcall(PV); SW = gcall(SW); gisland(Bus) Gycall(Line) Gycall(PQ) Gycall(Shunt)

Syn = Gycall(Syn); Gycall(PV) Gycall(SW) Gyisland(Bus)

fcall(Syn) if DAE.n > 0

DAE.Fx = sparse(DAE.n,DAE.n); DAE.Fy = sparse(DAE.n,DAE.m); DAE.Gx = sparse(DAE.m,DAE.n); end

Fxcall(Syn) Fxcall(PV) Fxcall(SW)

case '5'

end

function [Colony Obj Fit oBas]=GreedySelection(Colony1,Colony2,ObjEmp,ObjEmp2,FitEmp,FitEmp2,fb as,ABCOpts,i)

oBas=fbas;

Obj=ObjEmp;

Fit=FitEmp;

Colony=Colony1;

if (nargin==8) %Inside the body of a user-defined function, returns the number of input arguments that were used to call the function. for ind=1:size(Colony1,1)

if (FitEmp2(ind)>FitEmp(ind)) oBas(ind)=0; Fit(ind)=FitEmp2(ind); Obj(ind)=ObjEmp2(ind); Colony(ind,:)=Colony2(ind,:);

else

oBas(ind)=fbas(ind)+1;

end;

Fit(ind)=FitEmp(ind); Obj(ind)=ObjEmp(ind); Colony(ind,:)=Colony1(ind,:);

end; %for end; %if if(nargin==9)

ind=i;

if (FitEmp2(ind)>FitEmp(ind)) oBas(ind)=0; Fit(ind)=FitEmp2(ind); Obj(ind)=ObjEmp2(ind); Colony(ind,:)=Colony2(ind,:);

else

oBas(ind)=fbas(ind)+1; Fit(ind)=FitEmp(ind); Obj(ind)=ObjEmp(ind); Colony(ind,:)=Colony1(ind,:);

end;

end;

function ObjVal = griewank(Chrom,switch1); [Nind, Nvar] = size(Chrom);

nummer = repmat(1:Nvar, [Nind 1]); ObjVal = sum((Chrom.^2)')'

function ObjVal = rastrigin(Chrom,switch1);

% Dimension of objective function Dim=size(Chrom,2);

% Compute population parameters [Nind,Nvar] = size(Chrom);

% function 6, Dim\*A + sum of (xi^2 - A\*cos(Omega\*xi)) for i = 1:Dim (Dim=20)

% n = Dim, -5.12 <= xi <= 5.12

% global minimum at (xi)=(0) ; fmin=0 A = 10;

Omega = 2 \* pi;

ObjVal = Dim \* A + sum(((Chrom .\* Chrom) - A \* cos(Omega \* Chrom))')';

% ObjVal = diag(Chrom \* Chrom'); % both lines produce the same

% otherwise error, wrong format of Chrom function ObjVal = rosenbrock(Chrom,switc);

% Dimension of objective function Dim=size(Chrom,2);

% Compute population parameters [Nind,Nvar] = size(Chrom);

% function 11, sum of 100\* (x(i+1) -xi^2)^2+(1-xi)^2 for i = 1:Dim (Dim=10)

% n = Dim, -10 <= xi <= 10

% global minimum at (xi)=(1) ; fmin=0 Mat1 = Chrom(:,1:Nvar-1); %1 to 9 Mat2 = Chrom(:,2:Nvar); % 2 to 10

if Dim == 2

ObjVal = 100\*(Mat2-Mat1.^2).^2+(1-Mat1).^2; else

ObjVal = sum((100\*(Mat2-Mat1.^2).^2+(1-Mat1).^2)')'; end

% End of function clear all

close all clc

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| % | | From | | | To | | | R | | | X | | | B/2 | | | X' | | | |
| % | | Bus | | | Bus | | | pu | | | pu | | | pu | | | TAP | (a) | | |
| linedata = [1 | | 2 | | 0.01938 | | 0.05917 | | 0.0264 | | 1 | | |  |
| 2 | | 3 | | 0.04699 | | 0.19797 | | 0.0219 | | 1 | | |  |
| 2 | | 4 | | 0.05811 | | 0.17632 | | 0.0187 | | 1 | | |  |
| 1 | | 5 | | 0.05403 | | 0.22304 | | 0.0246 | | 1 | | |  |
| 2 | | 5 | | 0.05695 | | 0.17388 | | 0.017 | | 1 | | |  |
| 3 | | 4 | | 0.06701 | | 0.17103 | | 0.0173 | | 1 | | |  |
| 4 | | 5 | | 0.01335 | | 0.04211 | | 0.0064 | | 1 | | |  |
| 5 | | 6 | | 0 | | 0.25202 | | 0 | | 0.932 | | |  |
| 4 | | 7 | | 0 | | 0.20912 | | 0 | | 0.978 | | |  |
| 7 | | 8 | | 0 | | 0.17615 | | 0 | | 1 | | |  |
| 4 | | 9 | | 0 | | 0.55618 | | 0 | | 0.969 | | |  |
| 7 | | 9 | | 0 | | 0.11001 | | 0 | | 1 | | |  |
| 9 | | 10 | | 0.03181 | | 0.0845 | | 0 | | 1 | | |  |
| 6 | | 11 | | 0.09498 | | 0.1989 | | 0 | | 1 | | |  |
| 6 | | 12 | | 0.12291 | | 0.25581 | | 0 | | 1 | | |  |
| 6 | | 13 | | 0.06615 | | 0.13025 | | 0 | | 1 | | |  |
| 9 | | 14 | | 0.12711 | | 0.27038 | | 0 | | 1 | | |  |
| 10 | | 11 | | 0.08205 | | 0.19207 | | 0 | | 1 | | |  |
| 12 | | 13 | | 0.22092 | | 0.19988 | | 0 | | 1 | | |  |
| 13 | | 14 | | 0.17093 | | 0.34802 | | 0 | | 1 | | | ]; |

frombus=linedata(:,3);

% Set ABC Control Parameters

ABCOpts = struct( 'ColonySize', 20, ... % 100 'MaxCycles', 1000,... % 1000

'ErrGoal', 1e-20, ... %

'Dim', 5, ... %

'Limit', 50, ... %

'lb', -600, ...

'ub', 600, ...

'ObjFun' , 'griewank', ... % 'RunTime',1);

GlobalMins=zeros(ABCOpts.RunTime,ABCOpts.MaxCycles) for r=1:ABCOpts.RunTime

%

Range = repmat((ABCOpts.ub-ABCOpts.lb),[ABCOpts.ColonySize ABCOpts.Dim]);

frombus = repmat(ABCOpts.lb, [ABCOpts.ColonySize ABCOpts.Dim]); Colony = rand(ABCOpts.ColonySize,ABCOpts.Dim) .\* Range + frombus;

Employed=Colony(1:(ABCOpts.ColonySize/2),:);

%

ObjEmp=feval(ABCOpts.ObjFun,Employed); FitEmp=calculateFitness(ObjEmp);

%

Bas=zeros(1,(ABCOpts.ColonySize/2));

GlobalMin=ObjEmp(find(ObjEmp==min(ObjEmp),end)); GlobalParams=Employed(find(ObjEmp==min(ObjEmp),end),:);

Cycle=1;

while ((Cycle <= ABCOpts.MaxCycles)),

Employed2=Employed;

for i=1:ABCOpts.ColonySize/2 Param2Change=fix(rand\*ABCOpts.Dim)+1; neighbour=fix(rand\*(ABCOpts.ColonySize/2))+1;

while(neighbour==i) neighbour=fix(rand\*(ABCOpts.ColonySize/2))+1;

end;

Employed2(i,Param2Change)=Employed(i,Param2Change)+(Employed(i,Param2C hange)-Employed(neighbour,Param2Change))\*(rand-0.5)\*2;

if (Employed2(i,Param2Change)<ABCOpts.lb) Employed2(i,Param2Change)=ABCOpts.lb;

end;

if (Employed2(i,Param2Change)>ABCOpts.ub) Employed2(i,Param2Change)=ABCOpts.ub;

end;

end;

ObjEmp2=feval(ABCOpts.ObjFun,Employed2); FitEmp2=calculateFitness(ObjEmp2); [Employed ObjEmp FitEmp

Bas]=GreedySelection(Employed,Employed2,ObjEmp,ObjEmp2,FitEmp,FitEmp2, Bas,ABCOpts);

NormFit=FitEmp/sum(FitEmp); Employed2=Employed;

i=1; t=0;

while(t<ABCOpts.ColonySize/2) if(rand<NormFit(i))

t=t+1; Param2Change=fix(rand\*ABCOpts.Dim)+1;

neighbour=fix(rand\*(ABCOpts.ColonySize/2))+1; while(neighbour==i)

neighbour=fix(rand\*(ABCOpts.ColonySize/2))+1;

end; Employed2(i,:)=Employed(i,:);

Employed2(i,Param2Change)=Employed(i,Param2Change)+(Employed(i,Param2C hange)-Employed(neighbour,Param2Change))\*(rand-0.5)\*2;%find a new value in the neighborhood

if (Employed2(i,Param2Change)<ABCOpts.lb) Employed2(i,Param2Change)=ABCOpts.lb;

end;

if (Employed2(i,Param2Change)>ABCOpts.ub) Employed2(i,Param2Change)=ABCOpts.ub;

end; ObjEmp2=feval(ABCOpts.ObjFun,Employed2); FitEmp2=calculateFitness(ObjEmp2); [Employed ObjEmp FitEmp

Bas]=GreedySelection(Employed,Employed2,ObjEmp,ObjEmp2,FitEmp,FitEmp2, Bas,ABCOpts,i);

end; i=i+1;

if (i==(ABCOpts.ColonySize/2)+1) i=1;

end; end;

%%%

CycleBestIndex=find(FitEmp==max(FitEmp)); CycleBestIndex=CycleBestIndex(end); CycleBestParams=Employed(CycleBestIndex,:); CycleMin=ObjEmp(CycleBestIndex);

if CycleMin<GlobalMin GlobalMin=CycleMin; GlobalParams=CycleBestParams;

end GlobalMins(r,Cycle)=GlobalMin;

%%

ind=find(Bas==max(Bas)); ind=ind(end);

if (Bas(ind)>ABCOpts.Limit) Bas(ind)=0;

Employed(ind,:)=(ABCOpts.ub-ABCOpts.lb)\*(0.5-rand(1,ABCOpts.Dim)); end;

ObjEmp=feval(ABCOpts.ObjFun,Employed); FitEmp=calculateFitness(ObjEmp);

Cycle=Cycle+1; end

end;

if ABCOpts.RunTime==1 semilogy(GlobalMins); end

title('');

xlabel('Time'); ylabel('Ratio of Tab'); fprintf('Mean =%g

Std=%g\n',mean(GlobalMins(:,end)),std(GlobalMins(:,end))); function ObjVal=Sphere(Colony,xd)

S=Colony.\*Colony;

ObjVal=sum(S');

function appfre s = tf('s');

R = 10; % resistor

resistance

Req = 40; % inductor

equivalent series resistance (ESR)

L = 1; % inductor

inductance

C = 510\*10^-6; % capacitor

capacitance

ei = 1.53; % battery

voltage

tstep = 1.22; % time step

occurred

G = 1/(C\*L\*s^2 + C\*(R+Req)\*s + 1); % model transfer function

[y,t] = step(G\*ei,0.5); % model step response with battery voltage scaling

plot(t,y) hold

plot(eo.Time(100\*tstep:100\*tstep+50)- tstep,eo.Data(100\*tstep:100\*tstep+50),'r:') % experimental data

xlabel('time (sec)') ylabel('output voltage (Volts)') title('LRC Circuit Step Response')

legend('model','experiment','Location','SouthEast') s = tf('s');

R = 10000; % resistance of

resistor in RC circuit

C = 100\*10^-6; % capacitance of

capacitor in RC circuit

G = 1/(C\*R\*s+1); % RC circuit

transfer function step (G)

title('RC Circuit Step Response (R = 10 kOhm, C = 100 uF)')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% **m-file for Bacterial Foraging Algorithm (BFA)**

%

% (1) Initialization

p = 2; % Dimension of search space

S = 10; % Number of bacteria in the colony Nc = 4; % Number of chemotactic steps

Ns = 4; % Number of swim steps

Nre= 4; % Number of reproductive steps

Ned= 3; % Number of elimination and dispersal steps

Sr =S/2;% The number of bacteria reproductions (splits) per generation Ped=0.25; % The probability that each bacteria will be eliminated/dispersed

n = 14;

ca(:,1)=0.01\*ones(S,1); % the run length unit (the size of the step taken in each run or tumble)

% Initial positions

for m=1:S % the initial positions B(1,:,1,1,1)= 2 + (n-2)\*rand(S,1)';

B(2,:,1,1,1)= 0.5 + (2-0.5)\*rand(S,1)';

%format short,B(2,:,1,1,1); end

%% Loops

% (2) Elimination-dispersal loop for l = 1:Ned

% (3) Reproduction loop for k = 1:Nre

% (4) Chemotaxis (swim/tumble) loop for j=1:Nc

% (4.1) Chemotactic step for i=1:S

% (4.2a) Fitness function

J(i,j,k,l) = fitnessIBFADSS33(B(:,i,j,k,l));

% (4.2b) Add on cell-to-cell attraction effect J(i,j,k,l)=J(i,j,k,l)+cell\_to\_cell\_func(B(:,i,j,k,l),B(:,:,j,k,l),S);

% (4.3) Jlast Jlast=J(i,j,k,l);

% (4.4) Tumble

Delta(:,i) = unifrnd(-1,1,p,1);

% (4.5) Move B(:,i,j+1,k,l)=B(:,i,j,k,l)+ca(i,k)\*Delta(:,i)/sqrt(Delta(:,i)'\*Delta(

:,i)); % with the original run length unit

%

B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01\*(abs(J(i,j,k,l)))))))

\*Delta(:,i)/sqrt(Delta(:,i)'\*Delta(:,i)); % with linear adaptive run length unit

%

B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01\*(((abs(J(i,j,k,l)))^2

) + (abs(J(i,j,k,l))))))))\*Delta(:,i)/sqrt(Delta(:,i)'\*Delta(:,i)); % with quadratic adaptive run length unit

%

B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01\*(exp(abs(J(i,j,k,l)))

)))))\*Delta(:,i)/sqrt(Delta(:,i)'\*Delta(:,i)); % with exponential adaptive run length unit

% (4.6a) New fitness function

J(i,j+1,k,l)= fitnessIBFADSS33(B(:,i,j+1,k,l));

% 4.6b) Add on cell-to-cell attraction effect

J(i,j+1,k,l)=J(i,j+1,k,l)+cell\_to\_cell\_func(B(:,i,j+1,k,l),B(:,:,j+1,k

,l),S);

if J(i,j+1,k,l)<Jlast Jlast=J(i,j+1,k,l);

B(:,i,j+1,k,l)=B(:,i,j+1,k,l)+ca(i,k)\*Delta(:,i)/sqrt(Delta(:,i)'\*Delt a(:,i)) ;

J(i,j+1,k,l)= fitnessBFADSS33(B(:,i,j+1,k,l)); else

m=Ns; end end

J(i,j,k,l)=Jlast; %???

end % (4.8) Next bacterium OPTIMUM\_BUS = B(1,:,j,k,l);

Q OLTC = B(2,:,j,k,l);

%format short,Q\_OLTC;

% if OPTIMUM\_BUS <=1;

% OPTIMUM\_BUS = round((abs(OPTIMUM\_BUS))+1);

% end

end % (5) if j < Nc, chemotaxis

% (6) Reproduction

% (6.1) Health

Jhealth=sum(J(:,:,k,l),2); % Set the health of each of the S bacteria [Jhealth,sortind]=sort(Jhealth);% Sorts bacteria in order of ascending values

B(:,:,1,k+1,l)=B(:,sortind,Nc+1,k,l);

ca(:,k+1)=ca(sortind,k); % Keeps the chemotaxis parameters with each bacterium at the next generation

% (6.2) Split the bacteria for i=1:Sr % Sr??

B(:,i+Sr,1,k+1,l)=B(:,i,1,k+1,l); % The least fit do not reproduce, the most fit ones split into two identical copies ca(i+Sr,k+1)=ca(i,k+1);

end

end % (7) Loop to go to the next reproductive step

% (8) Elimination-dispersal for m=1:S

if Ped>rand % % Generate random number B(1,:,1,1,1)= 2 + (n-2)\*rand(S,1)';

B(2,:,1,1,1)= 0.5 + (10-0.5)\*rand(S,1)';

%format short,B(2,:,1,1,1); else

B(:,m,1,1,l+1)=B(:,m,1,Nre+1,l); % Bacteria that are not dispersed end

end end

%% Results

reproduction = J(:,1:Nc,Nre,Ned);

[jlastreproduction,O] = min(reproduction,[],2); % min cost function for each bacterial

[Y,I] = min(jlastreproduction);

OPTIMUM\_BUS = round(pbest(1,:));% Return the optimal positions as Kp and Kd

Q\_OLTC = pbest(2,:);

%%%%%%%%%%%%%%%%%% End of BFA Code %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

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