Impact of Coordination of Intertie Transformer Tap Changers on Active Power Losses Assessed by Big Bang Big Crunch Algorithm

Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Philosophy Electrical Engineering in Power and Energy Systems

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Abstract:

Power utilities worldwide face significant technical power losses. There are two categories of power losses: technical and non-technical losses. Technical losses occur on the transmission and distribution lines, transformer windings, and capacitors. These include active power losses which are caused by resistive components and reactive power losses which are caused by reactive components. Transformer tap changers play a key role in the minimization of power losses.

Many researchers have already investigated the effect of transformer tap changers on power systems. However, none of their publications have assessed the impact of transformer tap changers on power flows in the context of interties to minimize active power losses using BBBC algorithm. The aim of this study is to assess the impact of intertie transformer tap changers on active power losses using BBBC algorithm.

In order to bridge the gap in current knowledge, the following objectives have been identified: to assess the impact of the coordination of transformer tap changers in order to meet the objective functions of facilitating the apparent power flow between two areas of a system and to minimize the overall amount and life-cycle cost of active power losses. These have been achieved by coding the BBBC algorithm in Python language and by directing the code to Power System Simulation for Engineers.

The results of the study show that the careful choice of tap changer settings has a significant impact on the power flow between the intertie and the rest of the system. Secondly, it improves the efficiency of the system as measured by the total amount of active power losses in the system. Finally, it has a significant impact on the life-cycle cost of active power losses. As a result, the coordination of the tap changers of the intertie transformers should be done carefully in order to support an unstable area, to increase the efficiency of the system and the techno-economic impact.

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Chapter 1: Introduction

1.1 Background

The reduction of distribution losses is a crucial issue for Distribution System Operators (DSO), due to the heterogeneous levels of both technical and non-technical losses, but also due to differences in the definition, measurement or control of losses. For this reason, a global framework that would be general enough to include all DSO situations about losses and specific enough to bring adapted answers to losses management [1] is necessary.

Technical losses are losses due to energy dissipation in the conductors, equipment used for transmission lines, transformers, distribution lines and magnetic losses in transformers [2]. The cost of generating electricity is high; therefore, the amount of losses must be reduced as much as possible, since zero losses or 100 % regulation of power systems in the AC system is almost impossible due to the various causes of losses [3].

Technical losses depend on the design of the power grid, the voltage, transformation levels and the length of the power lines. They can be further divided, into: variable losses (load related); fixed losses (not related to load), and network services (consumptions of network equipment) [1, 4]. Technical losses are related to investments in equipment (lines, transformers) and long term signals (compromise between investment costs and operational expenditure).

These losses are around 22.5 % of the generating power in general [2]. In South Africa, between 2011 and 2014, the technical power losses of Eskom Company increased from just below 8.25 % to 9.07 % [5]. The losses vary from one country to another; for instance Iraq, Moldova, U.S.A, and Japan lose 42, 40, 6 and 5 % respectively each yearly [4, 6]. Hence, no matter how well the system is designed, losses are inevitable [4, 7].

Technical losses represent an economic loss for the power utility and should be minimized for the reliability, stability and efficiency of the power systems [8]. Although, the AC system is widely used, this system still suffers from urge power losses, particularly active power losses [9]. Technical losses in power systems occur naturally as they consist of energy dissipation in electrical system components such as lines, transformers, connections, measurement systems and other equipment that carry energy to and from customers [10].

The optimization of technical losses in power transmission and distribution grids is an engineering issue involving conventional power systems planning and modeling tools. Such tools are very costly and therefore force power utilities to improve the efficiency of their power systems. One of the best ways to do so is to reduce the active power losses.

1.2 Problem Statement

The large amount of power losses is one of the main challenges for power systems. There are two categories of power losses namely: technical and non-technical losses. Technical losses are the losses that occur on the transmission and distribution lines, transformer windings, and capacitors of a power system. Resistive components cause active power losses and reactive power losses are caused by reactive components. NTLs are also referred in the literature as commercial losses are non-natural losses associated with the 10 amount of non-billed electricity and billed electricity that is not paid for [11]. However, this dissertation will only focus on technical active power losses.

There are two types of transformer losses namely: load and no-load losses. Load losses occur in the windings and they increase depending on the loading of the distribution transformer. No-load losses are mainly due to poor cores quality, including improper core thickness and coating, successive degradation due to the loss of core materials during repairs and the reduction in the number of turns during repairs. High no-load losses manifest in the form of higher than standard magnetic flux inside the distribution transformers [10].

A literature review was conducted to identify and examine various studies on the impact of transformer tap changers. The authors [12] assessed the tap changers of transformers directly connected to generators in order to minimize the bus voltage deviations of the system. An evaluation of the variation of the medium voltage / low voltage transformer tap changer setting was done to monitor the reactive power flow, limit the reversing of the power flow, bring over-voltages within limits, and reduce feeders [12].

The authors [10] presented a technique for the reduction of technical losses using winding compensation only, with no change to the core. Study [13] investigated the impact of the parameter of high voltage transmission lines interconnecting transformers and concluded that transformer reactance values need to be carefully selected.

Although there are several studies on the impact of transformer tap changers such as those discussed above; none of these publications assessed the impact of interties of transformer tap changers on power flows to reduce active power losses and corresponding lifecycle costs. In this dissertation, the Big Bang Big Crunch (BBBC) algorithm is used to assess the impact of combination of transformer tap changers on active power losses and related life-cycle costs.

1.3 Aim and Objectives

In view of the above, the main aim of this study is to assess the impact of the coordination of intertie transformer tap changers in order to reduce the overall amount of technical active power losses and the related life-cycle costs. The specific objectives of this research are as follows:

- To demonstrate the impact of the combination of transformer tap changers on the apparent power loading of the intertie line, a program is developed in Python programming language. This program used the BBBC algorithm and the code is directed to the Power System Simulator for Engineering (PSS/E).
- To assess the impact of coordinating a combination of transformer tap changers on the amount of active power losses of the power system. A module is developed from the program to determine the amount of active power losses with the corresponding candidate for each combination.
- To assess the impact of coordinating a combination of transformer tap changers on the lifecycle costs of the system' active power losses. Similarly, a module recording the corresponding life-cycle costs of the active power losses will be added to the program.

1.4 Contribution to Knowledge

This study assesses whether it is necessary to coordinate the transformer tap changers in order to meet the objective functions of reducing the technical active power losses and the corresponding relative life-cycle costs using the BBBC algorithm. This will be useful for power utilities to know whether it is important to perform this task in the event of power losses.

1.5 Publications

Two papers are ready for publication in the IEEE and/ or internationally peer reviewed conferences. The following are the titles of papers that are ready for publication.

- N. Mbuli, W. S Ngaha, and J. H. C Pretorius, “A Survey of Big Bang Big Crunch Algorithm in Electric Power Systems”.

- N. Mbuli, W. S Ngaha, and J. H. C Pretorius, "Optimal Setting of Tap Changer Transformer using Big Bang Big Crunch Algorithm".

1.6 Layout of Dissertation

Chapter 2 is the literature review of the study. It presents a review of publications on the use of the BBBC algorithm to deal with power systems issues according to the time series from 2008 to 2018, the type of algorithms, the decision variables, the objective functions and the area of applications.

Chapter 3 is the overview of the BBBC algorithm, which sets out the physical theory on which the BBBC algorithm is based. The pseudo-code of the algorithm is also presented in this chapter, and the application of the BBBC algorithm to coordinate transformer tap changers is discussed.

Chapter 4 presents the theory of coordinating the transformer tap changers to deal with power systems' issues. It also includes the general formulation of optimization problems, decision variables, objective functions and constraints related to the coordination of transformer tap changers.

Chapter 5 presents the methodology of the study; the IEEE 39 bus system and the Eskom system are used to test the program code on Python language and simulate on PSS/E. The predicted nominal values of the annual average long-run marginal costs of power generation are provided for the years 2019 to 2042.

Chapter 6 presents the results and discussions on the basis of simulation tests on the IEEE 39 bus system and Eskom system. The apparent power flow in the corridor, the relative active power losses and the corresponding life-cycle costs are revealed. In order to draw conclusions, these results are contrasted with previous research.

Chapter 7 presents the conclusion and proposal for future studies. The overall conclusion focuses on the impact of coordinating interties transformer tap changers on active power losses. Recommendations are made for power utilities, power consumers and the research community.

Chapter 2: A Survey on Big Bang Big Crunch Algorithm in Power Systems

2.1 Introduction

Chapter 1 discussed the background on active power losses, the issue of active power losses in the power system, the aim and objectives of coordinating intertie transformers tap changers, the contribution of this research and the structure of the dissertation. In order to support this research, two papers mentioned in the preceding chapter are ready for publication.

This chapter discusses the publications on the overview of the BBBC algorithm for solving the issues of technical active power losses. This section also covers the algorithm classifications as follows: Time series, application in power systems, type of algorithms, decision variables and objective functions. All these are done to demonstrate the success of BBBC algorithm in power systems. The papers are summarized by pointing out what was done, how it was done, key findings, results, and conclusions.

Following the introduction of this chapter, the next section classifies the publications from 2008 to 2018. The BBBC algorithm is classified according to the application areas: the review paper of optimal placement of Distributed Generation (DG), the reconfiguration of power systems, the control of power systems and other electrical power systems.

2.2 BBBC Related Published Papers Each Year in Power Systems

The aim of this section is to present the BBBC survey. Research on power systems has the benefits of applying BBBC algorithm to various optimization problems. Figure 1 shows the number of published papers in which BBBC has been applied to different areas of electrical power systems (based on IEEE/ ScienceDirect/ Elsevier databases). Since the development of

BBBC in 2006, it has been used effectively to solve power systems issues from 2008. Figure 1 presents the annual time series from 2008 to 2018.

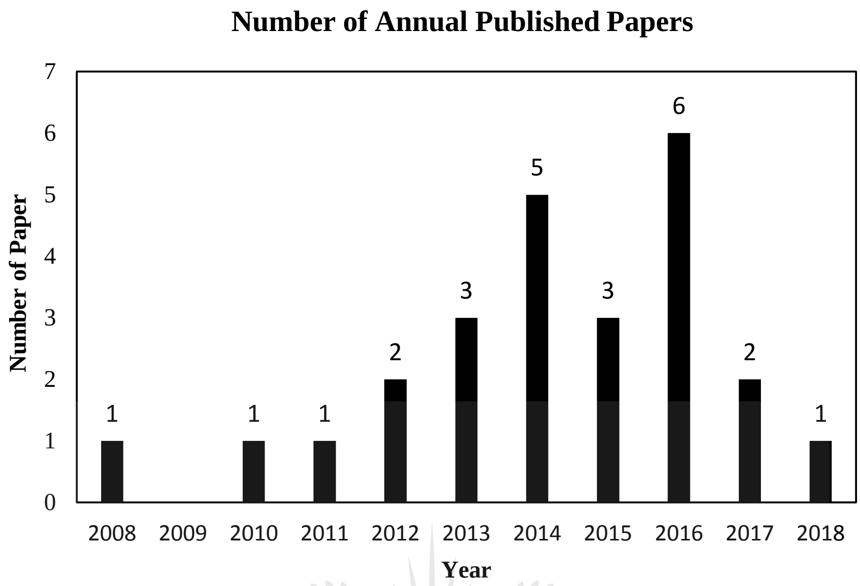

Figure 1: Number of BBBC related published papers each year in power system areas

The above Figure 1 shows that there is increased interest in the BBBC algorithm by the researchers to solve power system issues. The method became popular in 2016; this may be due to its simplicity as compared to other methods in different application areas [13, 14, 15].

2.3 Characterization by Type of BBBC Algorithm

To improve the performance of the BBBC algorithm, the algorithm is modified to form a variant or it is combined with more than one algorithm to form a hybrid. The following characterization divides the BBBC algorithm into standard, hybrid and modified BBBC algorithm (variant). Figure 2 illustrates the three variants of the BBBC algorithm as presented in the different publications.

- Standard BBBC algorithm has been used to solve power system issues [16, 17, 18, 19, 20].

- Hybrid BBBC (HBBBC) algorithm [13, 21, 22, 23, 24, 25, 26, 27] uses the Particle Swarm Optimization (PSO) and/ or Genetic Algorithm (GA) capacities to improve the capability of the BBBC algorithm for a better exploration.
- Modified BBBC algorithm (Variant) modified the standard BBBC algorithm to demonstrate the efficiency of the optimization algorithm [15, 28, 29, 30].

The following graph groups the different BBBC algorithms used to solve power system issues from 2008 to 2018.

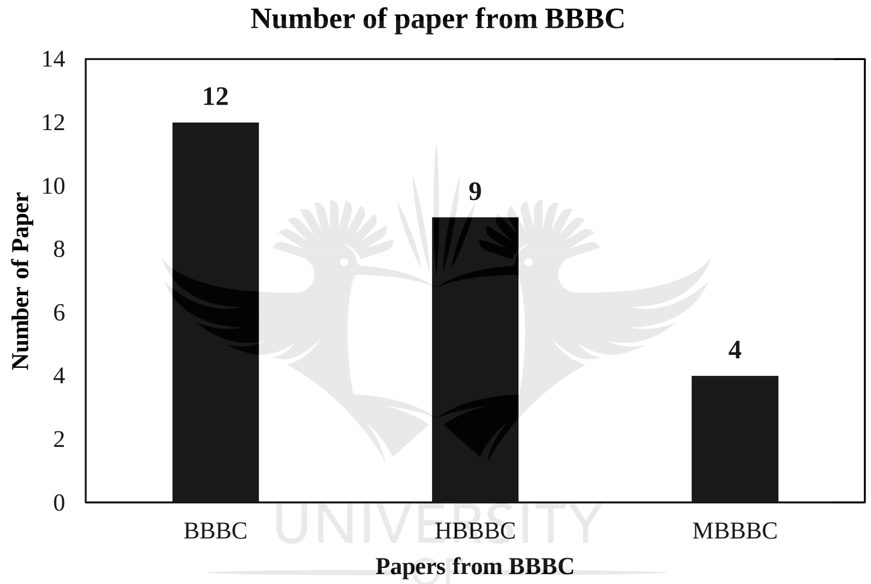

Figure 2: Evolution of BBBC algorithm

2.4 Classification According to Decision Variable

The decision variable is the quantity that the decision-maker controls. So, there is a decision variable for each optimization problem. Figure 3 illustrates the decision variable used in different publications using the BBBC algorithm. In power systems, the decision variables can be classified as follows:

- The location of the DG [23, 27, 30, 31].
- The size of the system [19, 22, 30, 30, 31, 32].

- The time and frequency [13, 15, 17, 18, 19, 24, 28, 33].
- The torque [34].
- The cost [20].
- The trajectory [34].

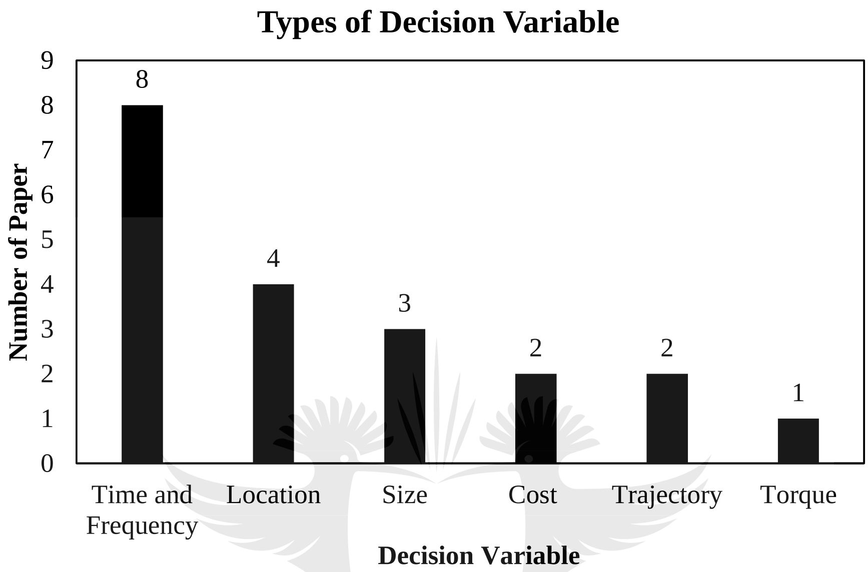

Figure 3: Decision variable in publication from 2008 to 2018

2.5 Classification According to Objective Functions

An optimization problem is one in which function is either maximized or minimized relative to a given set of alternative functions called the objective functions. Figure 4 displays the objective functions used in publications using the BBBC algorithm. In power systems, the objective functions can be classified as follow:

- Total Harmonic Distortion (THD) value [19].
- Minimum power losses of power systems [13, 15, 22, 30].
- Voltage enhancement [22, 27].
- Minimum cost [13, 24, 30].
- Dynamic security [16, 20].

- Test function [26].
- Proportional Derivative Integral (PID) controller for solving power system problems [18], Undershoot and Overshoot [27].

Some studies can combine more than one objective function. These are called multi-objective functions. In the scope of this study the main objective function in multi-objective problems is considered.

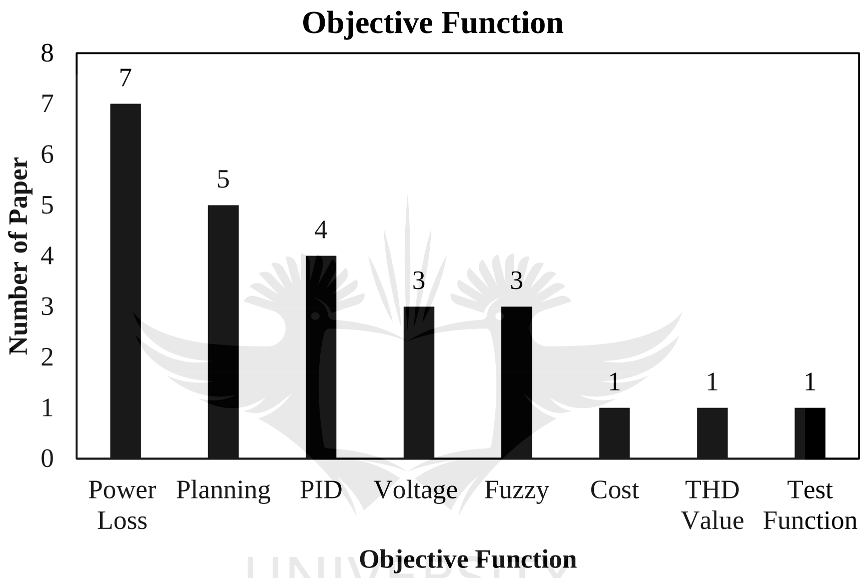

Figure 4: Objective functions of publication from 2008 to 2018

2.6 Areas of BBBC Algorithm Applications in Electric Power Systems

Classification is a technique used to categorize data into a given number of classes. The main goal of the classification is to identify the category or class under which a new data will fall. The BBBC algorithm technique has demonstrated its effectiveness in solving complex optimization problem by improving the solutions accuracy and computation time. The following are the main areas in which BBBC algorithm was applied. Figure 5 illustrates the number of publications in each area.

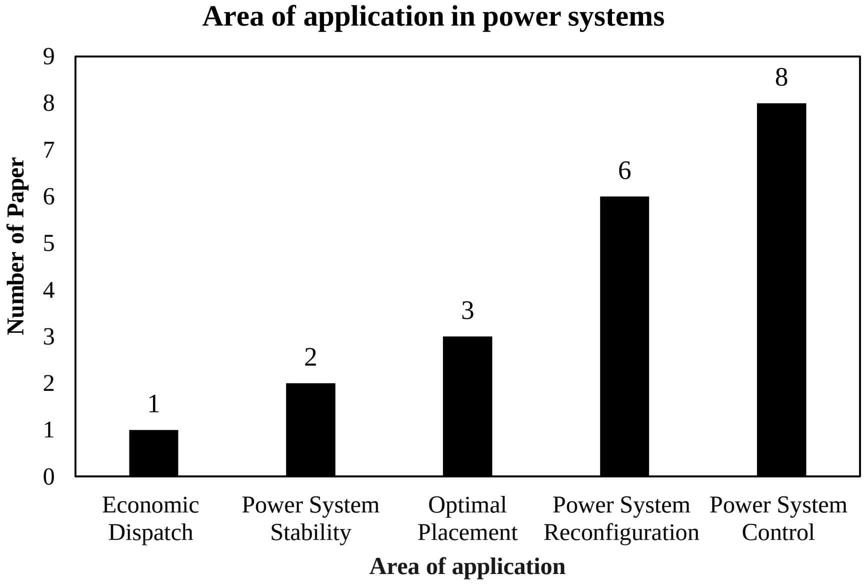

Figure 5: Area of application of BBBC algorithm in publication from 2008 to 2018

2.6.1 Economic Dispatch

Economic dispatch (ED) is at the heart of the economic operation of a power system [29]. The purpose of economic dispatch is to schedule the outputs of all available power generation units, such as fuel costs, which are minimized while system constraints are satisfied.

Paper [24] discussed the Economic Load Dispatch (ELD) using HBBBC algorithm as an optimization tool. The authors affirmed that it has been difficult to find a globally optimized solution, even with the aid of classical mathematical methods. The proposed algorithm has been applied to an IEEE 30-bus test system. Simulation results show the algorithm's ability to successfully find the minimum active power losses. It is concluded that the algorithm has the appropriate speed and accuracy compared to the most regular optimization methods.

2.6.2 Power System Stability

According to [35] the tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the equilibrium state is known as stability.

Power system stability problems are usually divided into two types: Steady-state and transient.

Power System Stabilizers (PSSs) [**Error! Bookmark not defined.**] are used to enhance the damping of electromechanical oscillations that occur in power systems after small or large disturbances using BBBC. The objective functions are used to stabilize the system and increase the damping of this type of oscillations. This method is used to optimize the parameters of PSSs. The success of the proposed method is demonstrated on a two-area test system through simulations in which both local and inter-area oscillations are effectively damped. It is found that through the proposed algorithm, the parameters of the conventional PSSs are successfully determined for the test system.

The BBBC algorithm [34] is proposed to find optimum values for path parameters and a cost function in order to minimize applied torque and tracking error. For this purpose, the mathematical model of the manipulator is derived with mainly used methods, such as Denavit Hartenberg, Jacobian and Euler-Lagrange methods.

2.6.3 Optimal Placement of Transmission and Distribution Devices

There are many reasons to place devices on the power system; some are used to enhance the maximum load ability of the transmission system [36] or to reduce losses [31]. Electrical devices are also used to enhance the performance of the power system [37]. The key issue is to optimize the placement of these devices.

This paper [30] focuses on the optimal placement of DG generators in distribution networks in order to minimize the overall system losses. The BBBC algorithm was used to identify the optimum allocation of DGs. Based on these identified locations, the DGs were allocated and the load flow was performed on a 33 bus distribution network to evaluate the total losses of the network. The lowest active power losses were obtained.

This paper modified the standard BBBC algorithm method for optimal placement and sizing of voltage controlled distributed generators. The proposed algorithm is the Supervisor BBBC algorithm. The objective function is to minimize the power as well as the energy loss in balanced/ unbalanced distribution systems (DS). The proposed algorithm was implemented in MATLAB and tested on the 33-bus feeder system and on the IEEE 37-node feeder. The lowest power losses are obtained using the supervised BBBC algorithm [31].

Paper [25] presented the network reconfiguration and optimal placement as useful measures taken to reduce losses and keep voltage profile within permissible limits in DS. The algorithm used was the HBBBC and was tested in three IEEE systems. The simulation results have shown that the lowest active power losses are obtained and the voltage is within limits.

2.6.4 Power System Reconfiguration

System reconfiguration means the restructuring of power lines connecting various buses in a power system. System reconfiguration can be accomplished by placing line interconnection switches into the network. Opening and closing a switch connects or disconnects a line from the existing network [38]. This is one of the most important ways to save electrical energy and reduce losses in the distribution system [39].

The authors [13] adapted the standard BBBC and mutation operator to form a new HBBBC optimization algorithm. This method was proposed to solve the optimal reconfiguration of the unbalanced DS for the reduction of active power losses. The simulations were approved on two test systems including 16 bus and 33 bus DS. It was concluded that the proposed method could help to find the best solution and the most feasible configurations in the shortest time possible.

The optimal reconfiguration of DS was examined in paper [37]. The proposed approach considered the minimization of power losses, interruption costs, and switching numbers. The method used was that of the HBBBC algorithm. The simulation was done on the 16 bus and 33 bus distribution test. The lowest power losses, the lowest interruption costs and the lowest switches numbers are obtained.

A control framework for a smart reconfiguration in Smart Distribution Grids (SDG) was discussed [15]. The objective function was to determine the nearest minimum power loss of SDG. This method was shown to be more effective than other optimization algorithms. MBBBC is compared to BBBC and other optimization methods including GA and ACO. The lowest active power losses are obtained.

The authors [23] proposed the reconfiguration of the network and the placement of the capacitor. The objectives functions were to minimize total real power losses, minimize bus voltage violation and load balancing in the feeders. The proposed algorithm has been implemented in three IEEE test systems. The lowest real power losses, the lowest voltage violation and the lowest load balancing are obtained.

In paper [15], the BBBC algorithm was modified to create a new algorithm called MBBBC to address reconfiguration problems. The objective function was to achieve a near minimum power loss in smart distribution grids. MBBBC was compared to BBBC and other optimization methods including GA and ACO. The lowest active power losses are obtained.

In order to solve an optimization problem, two objectives were considered in [22]: to minimize the active power losses and the voltage deviation index. The simulation was done on the IEEE 33 and Real 163 networks. The results obtained allow a comparison of the benefits obtained as a result of the reconfiguration taking into account DG placement. The lowest losses and the lowest voltage deviation are obtained.

2.6.5 Power System Control

Power system control is needed to maintain a continuous balance between power generation and load demand. According to [20], several control actions such as generation rescheduling, excitation control, generation tripping, load shedding, etc. can be used to enhance the dynamic security of the power systems.

The optimization of the dynamic security of the power system against transient instabilities using BBBC was examined in [20]. In the proposed approach, generation rescheduling was selected as a preventive control action, generation limits and loading capabilities of transmission lines. The proposed method was applied to 50 generators and 145 bus IEEE test systems. The BBBC method is suitable for the optimization problems in large-sized power systems where the computational cost is important.

This paper [1] presents a Fuzzy-PID controller for Maximum Power Point Tracking (MPPT) of photovoltaic (PV) systems. A DC/DC buck converter to regulate the output power of the photovoltaic system is considered. The original BB-BC is applied on the parameters of the proposed controller and upgrades the overall performance of the controller. The prime contribution of this study is a simple and effective solution for MPPT. The optimized fuzzy-PID controller is compared with a fuzzy-PID controller set up by the trial and error method in order to highlight the contribution of the offline algorithm in the overall performance of the system.

This study [2] was about the design of Load Frequency Control (LFC) in order to minimize the frequency deviation in all areas using variant 2. The testing system was a two-area power system. The studied simulations showed the advantage of the proposed BBBC2 based PID tuning method over conventional methods such as the Ziegler-Nichols tuning method, the standard BBBC based tuning, the GA based tuning and the Bacterial Foraging Optimization Algorithm (BFOA) based tuning method. The proposed BBBC2 provided the lowest performance index value and the lowest standard deviation in all areas.

This paper [40] discussed the optimal power flow (OPF). The objective was to minimize the total fuel cost using variant 1. The performance of this algorithm was tested on IEEE-30 bus test system. The results from BBBC algorithm is compared with Tabu Search and Differential Evolution. BBBC algorithm gave the lowest fuel cost.

Paper [27] proposed an optimal power control strategy for inverter-based DG units in autonomous microgrids. The objective functions were to minimize overshoots/undershoots, settling time, rise time and integral time in the output voltage. These objective functions were combined using fuzzy memberships. The HBBBC algorithm was used for optimal placement. HBBBC was found to provide a better solution than PSO and BBBC.

Paper [19] showed a method for optimization of Cascaded H-Bridge inverter harmonic performance under Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) control. The objective function was to reduce the total harmonic distortion value using variant 1. The testing model was the model of fuel-cell. The experimental results validate the theory. The simulation results showed third, fifth, seventh and ninth level harmonics had been eliminated.

In [18], the approach to control speed of linear brushless DC motor was discussed. This paper provided an overview of BBBC and presented it as an alternative to an evolutionary algorithm. The BBBC optimization algorithm was used to determine optimal PID gains. The

BBBC method was inspired by big bang theory. The proposed method showed its robustness over PSO and differential evaluation algorithm under critical conditions.

Paper [26] set out an accurate mathematical model of a proton exchange membrane fuel cell (PEMFC) for simulation and design analysis. In this work, the HBBBC was proposed to identify the PEMFC parameters. The HBBBC results were compared with the GA, PSO and BBBC results in order to study the usefulness of the proposed optimization method.

2.7 Recapitulation of the Literature Review

The total of 25 papers was found to be useful for the review of the BBBC algorithm in power system. The following Table 1 recapitulates the papers discussed above in terms of the annual time series of the BBBC algorithm, the type of BBBC algorithms, the decision variable, the objective function and the area of application. The decision variable and the area of application were not clear in 5 papers.

Table 1: Recapitulation of the literature review

Classifications of the algorithm	Number of papers
The annual time series of the BBBC	25
Type of BBBC algorithm	25
The decision variable	20
The objective function	25
The area of application	20

2.8 Conclusion

This chapter has covered the BBBC algorithm to solve problems in power systems, by giving more details on the application area of the algorithm. It was also noted that the algorithm became widely used in power systems around 2014. The algorithm is highly recommended for solving problems in power systems.

A lot of papers have been published to address power system optimization problems using BBBC algorithms, with different conventions and evolutional methods. The objective functions are commonly to reduce the total active power, enhance voltage limit and decrease the cost of kilowatt per hour using different optimization methods. There are not many papers on the coordination of transformers tap changers.

The next chapter covers an overview of BBBC and provides a demonstration of the physics behind the theory of evolution of the universe that inspired the authors of the algorithm. The pseudo-code and the implementation of the algorithm to solve problems in power systems will be presented.

Chapter 3: Overview of the Big Bang Big Crunch Algorithm

3.1 Introduction

The previous chapter has discussed the literature review on the different areas of application of the BBBC algorithm. It has shown that this algorithm is a popular and simple optimization algorithm. The BBBC optimization algorithm has never been used to coordinate the transformers tap changers.

This chapter presented the overview of the BBBC algorithm. The operation of the BBBC algorithm is assessed in this chapter. The pseudo-code of the BBBC algorithm and the application of the BBBC algorithm for the coordination of transformers tap changers are presented as well.

The genealogy of the BBBC algorithm and the pseudo-code of the algorithm are discussed. The equations to generate new candidate solutions are presented. The BBBC algorithm is described to solve the coordination of transformer tap changers. This is followed by the conclusion chapter.

3.2 Genealogy of the Big Bang Big Crunch Algorithm

The BBBC algorithm is a popular algorithm inspired by one of the general relativity based cosmological theories confirmed by Sir Isaac Newton and Albert Einstein (two famous scientists) which stipulates that the universe was born in the “Big Bang” (BB) and may die in the “Big Crunch” (BC). In fact, the BB describes how the universe started and the BC describes how it will end as a result of creation.

The theory further articulates that, the universe is expanding because of BB and will not continue forever, instead, at some point in future, it will stop expanding and will collapse into itself. Everything will be pulling with it until it finally turns into the biggest black hole ever [14].

Scientists defined certain properties of the universe as density and compared them to critical density. It was observed that, if the density is higher than the critical density, an eventual collapse is highly possible. Originally, scientists believed that there were only two factors that had a major impact on the expansion of the universe, namely the gravitational force of attraction between all the galaxies and their outward momentum due to the BB. This was the beginning of the theory.

To explain this phenomenon, scientists had to accept the presence of an unknown entity, which they labelled ‘dark energy’. It is widely believed that this entity is pushing all galaxies further apart. With dark energy, and what little is known about it, there seems to be little room for the possibility of a BC.

The theory of BBBC algorithm also drew the attention of the National Aeronautics and Space Administration who found that the strength of dark energy in the universe is constant. Increasing dark energy strength would have reinforced the possibility of a BC. Even with static dark energy strength, an ever-expanding universe is still the most likely scenario. As a result, until data that contradicts these properties are collected, the BC will have to remain as a less favored theory.

In physics, the mass center of a distributed mass in space is the unique point where the weighted relative position of the distributed mass sums to zero. In the BBBC algorithm, the center of mass is the position including information on all positions and their costs, and it is close to positions that have better cost functions [15].

3.3 Operation and Advantage of Big Bang Big Crunch Algorithm

Inspired by the above-mentioned theory of universe evolution in 2006, Erol and Eksin proposed a new algorithm, namely, the BBBC algorithm [14]. The BBBC algorithm is divided into two main phases, namely the Big Bang Phase (BBP) and the Big Crunch Phase (BCP).

In the BBP phase as many optimization algorithms, the population N (Candidate solutions) is randomly distributed over the search space. Furthermore, this step is done once and the next step is the BCP, where a contraction procedure calculates the center of mass for all the candidate solutions. The BCP consists of two phases, the calculation of the center of mass or selection of fittest individual values for the minimal cost approach [14] and the creation of a new generation candidate around the center of mass.

3.4 Pseudo-code of the Big Bang Big Crunch Algorithm

According to [15] BBBC algorithm has gained significant popularity in recent years mainly due to its simplicity, low computational time and high convergence speed performance in solving optimization problems. Different algorithms and software such as MATLAB, DigSilent PowerFactory, and PSS/E have been developed to analyze complex data. The general pseudo-code of the algorithm is as follows:

Step a. Initial Population: Similar to other evolutionary algorithms such as GA [41], the initial candidates are uniformly spread uniformly across the search space.

Step b. Evaluation: Store the objective function and the corresponding candidate. The BBP is then followed by the BCP.

Step c. Big Crunch Phase: In this phase, select the fittest function as the center of mass or calculate the center of mass from fitness functions of each candidate in order to produce a weighted average point, which is called the “center of mass”. The following equation is used to calculate the center of mass:

$$x_{j,k}^{c} = \frac{\sum_{i=1}^{N} m_{j,k}^{i} * x_{j}^{i}}{\sum_{i=1}^{N} m_{j,k}^{i}} \quad \text{with} \quad m_{j,k}^{i} = \frac{1}{f_{j,k}^{i}} \tag{3.1}$$

where:

$x_{j,k}^{c}$ is the j[th] component of the center of mass.

x_{j}^{i} is the j[th] component of i[th] candidate.

$m_{j,k}^{i}$ is a value equal to the inverse of the $f_{j,k}^{i}$ fitness value of the i[th] candidate.

N is the total of all candidates (Population).

i, j are all natural integer numbers.

Step d. Big Bang Phase: The explosion produces new candidates that follow the normal distribution around the center of mass as shown in the following equation:

$$x_{j,k+1}^{new} = x_{j,k}^{c} + r * \alpha * \frac{(x_{max}^{j} - x_{min}^{j})}{k+1} \tag{3.2}$$

where:

$x_{j,k+1}^{new}$ is the new candidate.

$x_{j,k}^{c}$ is the center of mass calculated in Equation (3.1).

r is a random number from the standard normal distribution N (0, 1) with mean one.

α is a parameter that limits the search space.

x_{max}^{j} and x_{min}^{j} are respectively the upper and lower limits of the vector $x_{j,k}^{c}$.

k is the iteration number.

Although the standard deviation from Equation (3.2) can be set to a fixed value, the BBBC algorithm will produce better results if the standard deviation is set to decrease inversely with the current iteration. The equations of probability density functions for these normal distributions are defined by relations [42].

$$f(t,\alpha,\beta) = \frac{1}{\beta\sqrt{2\pi}} e^{-(\frac{t-\alpha}{\sqrt{2}.\beta})^2} \quad \text{With} \quad \alpha,\beta > 0,\ t \geq 0 \tag{3.3}$$

where:

α and β are the parameters of the considered distribution.

t is a variable and the function is calculated with equation.

$$F(t,\alpha,\beta) = \int_0^t f(t,\alpha,\beta)\ dt \tag{3.4}$$

Furthermore, in order to balance between the exploration and exploitation of the standard version of BBBC algorithm [40], in each BCP, the center of mass is selected by using either Equation (3.2) or the best individual as a starting point for the next BBP. By applying the best fit individual strategy, it is proposed that a comparison be made between the center of mass of the current iteration and the previous one. If there is some improvement in the current iteration center of mass, new populations are generated around this point; otherwise, the previous one is selected. In this way, the optimum solution can be found very quickly.

Step e. Termination: The center of mass is recalculated again after the BB explosion using the BC contraction phase. These explosion and contraction steps are repeated continuously until the termination criterion is met [43].

3.5 Pseudo-code of BBBC Algorithm for Coordination of Intertie Transformer Tap Changer

Form the operation of the BBBC algorithm, each step will be followed to solve the coordination of intertie transformer tap changers. Each step is followed individually in the module; Python programming language is used and applied on the PSS/E software. Each phase of the BBBC algorithm is subdivided into 4 and 2 steps respectively. The steps are explained below.

Step a. Initial Population: Create an initial population by randomly selecting (special Python function "shuffle") a set of 200 combination candidates (length of the population) from all feasible candidates (0.85-1.05) in a uniform manner (Combinations_with_replacement (total_tap, 4)). This simply means that we can have an event where we have a set of 4 combinations of the same value and this step is followed once. Then the special Python function is used to change the position of tap changers from 0.85 to 1.05 with a gap of 0.05.

Step b. Evaluation: Before the evaluation, all the fitness function values must be tabulated by randomly connecting the initial population on the grid, then obtaining the values of many populations (four for this problem) and the corresponding candidates.

After connecting all the population candidates on the system, the power flow is solved and all the constraints relative to the electrical devices are checked and validated. Then, each feasible candidate from the initial population is connected and disconnected until the last candidate and the objective function values are appended in an array called 'Loss'.

Step c. Big Crunch Phase: The fittest individual value among the feasible candidate could be selected as the center of mass by using the minimum objective function and this chosen solution is the best candidate for the first iteration in case the process stops. But for this case, the center of mass Equation (3.4) approaches are applied. And the center of mass is rounded to the nearest integer by using round Equation (3.1).

Step d. Big Bang Phase: Generate new individuals by using normal distribution. For a continuous variable optimization problem, add or subtract a normal random number whose value decreases between 0 and 1 as the iterations elapse. The new candidates are tabulated from the center of mass by using Equation (3.2).

Step e. Modification: Keep the fittest individual found so far in a separate place or as a member of the population.

Step f. Termination: Store current best solution and check if terminations criteria are met, then displays. "This is the best set of solutions corresponding on the fitness function of Fitness function". If not, repeat from step b until the termination a criterion is met, then displays "This is the best candidate solution corresponding on the fitness function of: Fitness function".

3.6 Advantages of the BBBC Algorithms

There are many type of algorithms, the choice of algorithm depends on the problem to be solved. For large systems, the metaheuristic algorithm can find the global solution in less iteration. This is the case of the BBBC algorithm which is a population-based evolutionary technique that has many keys advantages over other optimization techniques:

- It can easily be combined with more than algorithm.
- It can be adapted to complex engineering problems.
- It is sensitive to the nature of the objective function.
- It can converge quickly to the best solution.
- It does not require a binary conversion.

3.7 Conclusion

This chapter has discussed the BBBC algorithm and its advantages for solving power systems problems, by giving a review of the genealogy, the pseudo-code, and the graphical representation of the algorithm as well as the equation of the center of mass and creation of new generation. It is capital to understand what inspired the algorithm and how it works.

A lot of research has been conducted on solving power system issues using algorithms, with different conventions and evolutionary methods. The BBBC algorithm has some advantages over other metaheuristic algorithms. The objective functions are commonly to reduce the total active power, enhance voltage limit and decrease the costs of kilowatts per hour using different optimization methods.

The next chapter examines the theory on the assessment intertie transformer tap changers on the power flow in the corridor. The objective functions are to minimize the total system losses and the corresponding costs. The mathematical model used to solve the power systems optimization problem is presented.

Chapter 4: Formulating the Study of Coordination of Intertie Transformer Tap Changer Using BBBC Algorithm

4.1 Introduction

The previous chapter covered three main phases of the BBBC algorithm, namely the initial population, the evaluation of the objective function for each candidate and, finally, the new generation. It can be seen from Chapter 2 that the BBBC algorithm is mostly used to solve optimization problems: the optimal placement of DG in power systems, the reconfiguration of power systems, the stability of power systems, economic dispatch and power system control.

In this chapter, the theory on the coordination of transformers tap changers is evaluated in order to formulate transformer tap changers problem by clearly specifying the mathematical model of the objective function and all the constraints equations. The theory of Python errors is also covered.

Chapter 4 is divided into six sub-sections. These sub-sections will include the formulation of the problems; discussions on the impact of a combination of intertie transformers tap changers on the power system, the mathematical model of the transformer tap changer, and finally, the conclusions of the chapter.

4.2 Impact of Combinations of Intertie Transformer Tap Changers on Power Losses

There are many definitions of intertie transformers, but the one that fits the context of this study is: System intertie transformers connect extra high voltage transmission systems with voltages up to 800 kV together with the aim that both active and reactive power can be exchanged between the systems [44].

Normally, the insulation of the windings is graded. In separate windings transformers, tapings are placed at the neutral end of one of the windings. In auto-connected transformers, tapings are located in the phases of the low voltage side. See Figure. 6

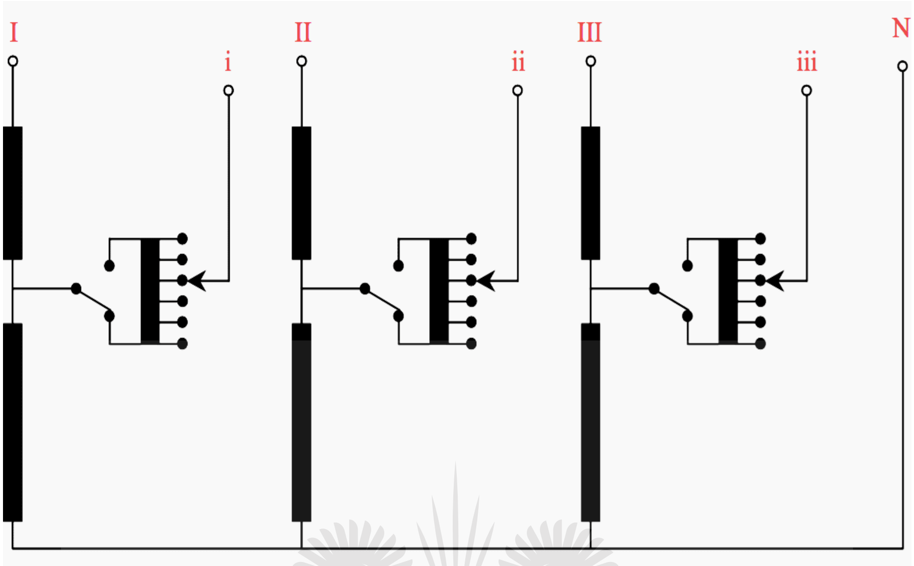

Figure 6: Auto-connected transformers tapping [44]

Tapings are sometimes located at the neutral points of auto-connected transformers, where the voltage level to earth and the voltage differences between the phases are lower than when the tapings are situated at the auto-tap [4444]. Small 'i' is the transformer tap, which can be connected or disconnected from the transformer, depending on the required output voltage and the constraints and capital 'I' stands for the transformer windings.

4.3 Problem Formulation for General Optimization

The active power losses on power systems vary in load depending on the resistive power losses, and this can be written as $P_{loss} = I^2R$ during the network planning or power system design phases. Power utilities need to set the transformer's taps at an optimal position, although it should be noted that the life span of the transformer may be greatly affected.

Optimization can be defined as the process of finding the best solution to maximize or minimize a given objective function under given constraints. The solution obtained is called the optimal solution. In most cases, the constraints to which the objective function can be subject are categorized as boundary, equality and inequality constraints. However, some objective functions are not subject to any constraints; in this case, the optimization problem is identified as an unconstrained problem.

The optimization problem can be a single-objective optimization or multi-objective optimization involving multiple objective functions. Thus, the single-objective optimization problem can be seen as a particular case of a multi-objective optimization problem having only one objective function. The general mathematical formulation of a multi-objective optimization problem is given as:

$$\min or \max f(X) = \{f_1(X),\ f_2(X), f_3(X), \ldots, f_{kobj}(X)\} \tag{4.1}$$

Subject to:

$$ec_n(X) = 0, \qquad n = 1, \ldots, k_{ec} \tag{4.2}$$

$$ic_n(X) \leq 0, \qquad n = 1, \ldots, k_{ic} \tag{4.3}$$

$$X = \{ X_{kv}^{min}, X_{kv}^{max}\} \qquad n = 1, \ldots, k_v \tag{4.4}$$

where:

$f_1, f_2, f_3, \ldots,$ and f_{kobj}	are different objective functions to be optimized.
ec_n and ic_n	are the equality and inequality constraints respectively.
X^{min} and X^{max}	are the minimal and maximal values of the bounded variable X.
k_{ec}, k_{ic}, k_v	are a set of equality, inequality and boundary constraints respectively.

Optimization problems can also be categorized as linear or non-linear. A linear optimization problem has linear objective function(s) and constraints while a non-linear optimization problem has at least one non-linear objective function or constraint [45]. Optimization problems can also be classified according to the type of variables present in the objective functions or constraints.

In the event that all variables are real numbers, the optimization problem is defined as a continuous optimization problem. If all the variables are discrete numbers or binary numbers, the problem is defined as an integer programming problem. When both discrete and real numbers are included, the optimization problem is defined as a mixed-integer programming problem [46]. From the description above, it can be seen that the choice of any optimization algorithm depends on the type of optimization problem.

The optimization problems can be addressed in two parts: the first part is to determine the initial solution and the corresponding objective function, and the second part is to increase the value of the objective function to obtain an optimal solution [47]. All optimization algorithms have in common the initial solution also called the starting solution. This can be either a single based initial solution [48] or a population based initial solution. The choice of this solution is based on a few easy evaluations of the objective function. Some methods are available [49].

In this section, the formulation of the problem is presented. Growth in demographics and technological progress mean rising demand for electricity. However, the energy supply by power utilities is insufficient. Therefore the reduction of power losses in power systems and corresponding costs is an issue of utmost importance. So instead of constructing new lines or placing DGs, transformers can be coordinated at their optimal tap positions to achieve the objectives function of reducing power losses.

In order to investigate how to improve the efficiency and cost savings of power generation of power systems, utilities may coordinate the transformer taps. The highest and lowest relative power losses and their associated costs can be formulated as a non-linear problem. The difference between these losses is referred to as net power losses, and it is used to demonstrate the importance of using the BBBC algorithm for an optimization problem.

4.4 Problem Formulation of the Coordination of Intertie Transformer Tap Changer

The aim of a meta-heuristic optimization algorithm is to search all the possible solution which meets the objective function while satisfying the specified constraints. However, for large-scale problems as a power system problem, the evaluating space depends on the population size and iteration number.

The problem of finding the lowest and highest relative power losses and their associated costs can be formulated as a non-linear problem. The difference between the best and the worst active power losses is referred to as net power losses, and is used to demonstrate the importance of using the BBBC algorithm for assessing the coordination of intertie transformer tap changers.

4.4.1 Decision Variables

The decision variable is the quantity that the decision-maker controls. So, there is a decision variable for every optimization problem. The decision variable for this problem is the location of the transformer tap.

t_1 is the tap changer setting of transformer 1.

t_2 is the tap changer setting of transformer 2.

t_3 is the tap changer setting of transformer 3.

t_4 is the tap changer setting of transformer 4.

Sign Restrictions:

$t_1, t_2, t_3, t_4 > 0$

4.4.2 Objective Functions

4.4.2.1 Power Losses:

The objective functions of minimizing the overall power losses of the system are given by the following equations.

$$P_{loss} = \sum_{i=1}^{n} \left(\frac{P_i^2 + Q_i^2}{V_i^2}\right) * r_i = \sum_{i=1}^{n} |I|_i^2 * R_i = \sum_{k=1}^{n} P_{k,loss} \tag{4.5}$$

where:

P_{loss} is the active power loss.

P_i, is the i[th] branch active power.

Q_i, is the i[th] branch reactive power.

V_i, is the i[th] branch voltage.

r_i is the i[th] branch of the internal resistance.

$P_{k,loss}$ is the individual k line loss and k the line between i and j buses.

R_i is the resistance of individual network connections branches.

This equation can also be used as mathematic model of the objective function

$$P_{loss(int)} = \left\{\frac{V_2' - V_1'}{[t_{p1}^2(R_{p1} + jX_{p1}) + (R_{s1} + jX_{s1})] + Z_{line} + [(R_{s2} + jX_{s2}) + t_{p2}^2(R_{p2} + jX_{p2})]}\right\}^2 * R_{line} \tag{4.6}$$

t_{p1} is the turns ratio of transformer 1.

R_{p1} is the resistance of the primary winding of transformer 1.

X_{p1} is the leakage reactance of the primary winding of transformer 1.

R_{s1} is the resistance of the secondary winding of transformer 1.

X_{s1} is the reactance of the secondary winding of transformer 1.

t_2 is the turns ratio of transformer 2.

R_{p2} is the resistance of the primary winding of transformer 2.

X_{p2} is the leakage reactance of the primary winding of transformer 2.

R_{s2} is the resistance of secondary winding of transformer 2.

4.4.2.2 Cost of Losses:

The cost of generating power is a crucial factor. Reducing the power losses reduces the cost of generating power and saves the power systems equipment. At peak demand, when there is a high power demand and high power loss, the monetary value of savings can be calculated from [50].

$$C_{loss} = MW_{pkloss} * 8760 * llf * AALRMCG_n * \sum_{1}^{39} \frac{(1+r_{ppi})^n}{(1+r_{ppi})^n} \quad [51] \qquad (4.7)$$

where:

C_{loss}	is the net present value (NPV) of losses over a 25-year period in rand.
MW_{pkloss}	is the value of losses in MW calculated at the time of system peak.
$AALRMCG_n$	is the annual average long run marginal cost of generation in $/MWh in year.
llf	is the loss load factor.
r_{ppi}	is the producer price index inflation rate in % in year n.
r_{ndr}	is the nominal discount rate in %.
n	is the total number of years.

4.4.3 Constraints

4.4.3.1 Equality Constraints

The coordination of transformers tap changers can reduce line losses and enhance voltage limits. However, the loadability and the capacity of the transmission and distribution systems must not be exceeded. The equation of powers generation of each bus is given by the following equations.

- **Active power generation of generator buses**

$$P_{Gi} - P_{Di} = \sum_{i=1}^{39} V_i * V_j \{G_{ij}.cos(\delta i - \delta j) \pm B_{ij}.sin(\delta i - \delta j)\} = P_{loss(i)} \qquad (4.8)$$

- **Reactive power balance in the network**

$$Q_{Gi} - Q_{Di} = \sum_{i=1}^{39} V_i * V_j\{G_{ij}.cos(\delta i - \delta j) \pm B_{ij}.sin(\delta i - \delta j)\} = Q_{loss(i)} \quad (4.9)$$

- **Complex power generation of generator buses**

$$S_{Gi} - S_{Di} = \sum_{i=1}^{39} V_i * V_j\{G_{ij}.cos(\delta i - \delta j) \pm B_{ij}.sin(\delta i - \delta j)\} = S_{loss(i)} \quad (4.10)$$

- **The real power balance equation and reactive power balance are:**

P_i and Q_i are defined as:

$$P_i = V_i.\sum_{j=1}^{39} V_j\{G_{ij}.cos(\delta i - \delta j) + B_{ij}.sin(\delta i - \delta j)\} \quad (4.11)$$

$$Q_i = V_i.\sum_{j=1}^{39} V_j\{G_{ij}.cos(\delta i - \delta j) - B_{ij}.sin(\delta i - \delta j)\} \quad (4.12)$$

where:

Q_{Gi}, Q_{Di} and $Q_{loss\,(i)}$ are respectively the generation, demand and loss power at node i.

P_{Gi}, P_{Di} and $P_{loss\,(i)}$ are respectively the active power generation, active power demand and loss power at node i.

S_{Gi}, S_{Di} and $S_{loss\,(i)}$ are respectively the complex power generation, complex power demand and complex loss power at node i.

V_i , V_j and δi , δj are respectively voltages and corresponding angles at bus i and j.

G_{ij}, B_{ij} are reluctance and admittance between node i and j.

4.4.3.2 Inequality Constraints

- **Generator**

Active and reactive power inequalities: The total generation must be between the minimum and maximum power in order to avoid power violations, as seen in the following inequalities.

$$P_{i,\ min} \leq P_i \leq P_{i,\ max} \quad (4.13)$$

$$Q_{i,\ min} \leq Q_i \leq Q_{i,\ max} \quad (4.14)$$

- **Branch**

The Line Capacity Limits S_i in MVA, power flow of lines should be greater and less than respectively zero and maximum $S_{i,max}$ permitted power of line due to line thermal capacity. Zero power is excluded because there is no need for optimization at no load.

$$0 < \sum_{i=1}^{n} S_i \leq \sum_{i=1}^{n} S_{i,max} \quad \text{where } S_i = P_i \pm jQ_i \tag{4.15}$$

Active power and reactive power are all inequality equations.

- **Load**

The bus voltages should be within the ranges of minimum and maximum voltages with an acceptable tolerance of 0.05 pu.

$$V_{min} \leq V_i \leq V_{max} \quad With \;\; V_i = \pm 0.05\, pu \tag{4.16}$$

- **Swing bus**

The capacity of the swing bus must be less than the power base capacity.

$$MVA \leq 100 \tag{4.17}$$

- **Transformer tap changer**

$$t_{x\,min} \leq t_i \leq t_{x\,max} \quad \text{with } \; x \in N \tag{4.18}$$

where:

N is the number of tap-setting transformer branches

- **Transformer efficiency constraint**

The transformer efficiency is required to be greater than a pre-specified value named maximum efficiency

$$\frac{P_o + P_c + P_{cu}}{P_o} \geq n_m \tag{4.19}$$

n_m is the maximum efficiency.

P_o is the output power.

P_c, P_{cu} are respectively the copper and core power losses.

There are two important parameters that determine the size of the candidate to be evaluated, namely the size of the population and the number of iterations. The following formula gives the total number of evaluated candidates.

$$Total\ candidate = Population\ size * Total\ iteration \quad (4.20)$$

4.5 Conclusion

In this chapter, the theory on the coordination of transformer tap changers was discussed, focusing on the formulation of the problem on transformer tap changers by explaining the mathematical model of the objective function and examining all the constraints. The decision variables and objective functions were also specified.

The coordination of transformer tap changers is an optimization problem. This problem was formulated in terms of decision variables, objective functions, and constraints. The chapter has proven that the turn ratio of the transformer tap changer can influence the power losses and the associated life-cycle costs.

In the next chapter, the methodology of the study will be presented. Two case studies are presented, one on the IEEE 39 bus systems and the other on the Eskom systems. The software used for simulations is PSS/E and the code is written in Python programming language.

Chapter 5: Cases Studies of Coordination of Intertie Transformer Tap Changer

5.1 Introduction

The previous chapter discussed the fundamental knowledge of how to deal with the coordination of the transformer tap changers. The problem was formulated and, the decision variables, the objective functions of power losses and the associated costs were examined. This has been done by clearly specifying the limitations.

This chapter discusses the methodology of the study. The IEEE 39 bus and Eskom testing systems are used to demonstrate the impact of the BBBC algorithm on the coordination of transformer tap changers. A relationship between PSS/E and Python is established for the simulation of the program.

The BBBC algorithm is written on Python to support the investigation. The data is analyzed using the IEEE and Eskom systems. The method and tools used for this research are presented to provide further information and explanation on the coordination of tap changers and the software used for the simulation.

5.2 Case Study 1: IEEE 39 Bus System

The IEEE 39 bus testing system ' power line and transformer corridor parameters are modeled in PSS/E. The system was used to test the program developed in Python language. The transformer tap changer of the area shown in Figure 7 was coordinated to support the deficiency of power in that area.

5.2.1 Topology of IEEE 39 Bus Systems

Power system network topology analysis is a basic function of the Energy Management System (EMS). As the name implies, the IEEE 39 bus system consists of 39 busses and is also known as the '10-machine New-England Power System'. The swing bus is represented by generator 39 and the busses with generators are known as generator busses, which are busses from 30 to 38, while the rest are the non-generator busses or load busses. There are 12 transformers connect on the grid.

5.2.2 Modified IEEE 39 Bus Systems for the Case Study

The transformers that can be coordinated are chosen on the basis of the objective function to be achieved for a specific period of time, and the area affected. For testing purpose, an intertie transformer (345/765 kV) with a length of 571 km was constructed between busses 7 and 6. The aim is to evacuate power from the generation source in the vicinity of bus 6, with an intention to support the area around bus 7. Power line and transformer corridor parameters for the 39 bus system are modeled in PSS/E [52].

Firstly, the intertie line has a total resistance per-unit of 0.0063 pu, a reactance of 0.036 pu, a line charging capacitance of 12.0138 pu and a continuous rating of 1251 MVA. The leakage reactance of the transformer was set at 0.0075 pu, and the tap changer settings ranged from 0.85 pu to 1.05 pu. The following Figure 6 shows the modified IEEE 39 bus system.

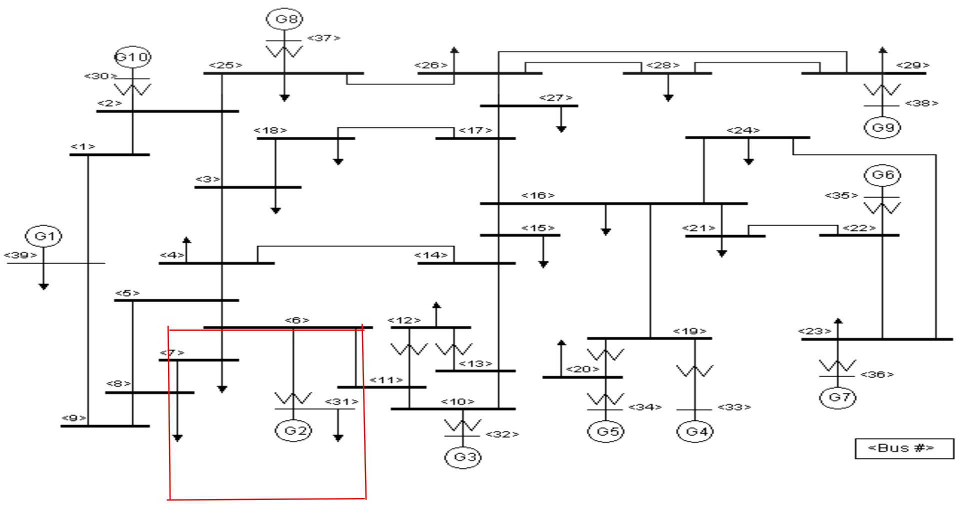

Figure 7: Single line diagram of the IEEE 39 bus systems [53]

5.3 Case Study 2: Eskom System

A portion of the Eskom system was used for further testing of the program developed in Python language and simulated on PSS/E. The corridor was built from the Alpha to Beta substation and the parameters of the intertie line are shown in the next section.

5.3.1 Eskom System Data

A second case study was based on the Eskom transmission network with the portion of interest shown in Figure 7. A 435 km intertie connecting the Alpha and Beta substations is shown. The intertie is built at 765 kV, with 400/765 kV step-up transformers at the Alpha substation and 765/400 kV step-down transformers at the Beta substation. The Alpha Beta line has a total resistance of 0.0081 pu, a reactance of 0.02101 pu, a line charging capacitance of 10.2645 Siemen and a continuous rating of 5558 MVA. The transformer tap changer turn ratios range from 0.85 pu to 1.05 pu.

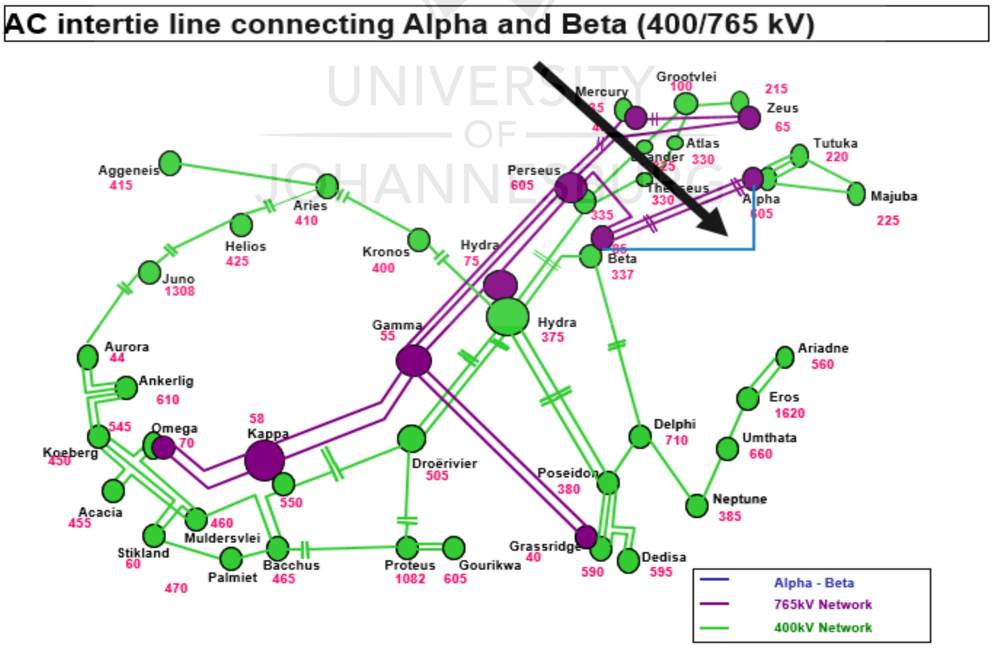

Figure 8: Portion of the network showing the Alpha Beta 765 kV line [54]

5.3.2 Assumptions of the Study

To assess the economic value of active power losses, the following general assumptions are made [55]:

- The Annual Average Long Run Marginal Cost of Generation (AALRMCG) values in Table 2 are used to calculate the monetary value of the savings in losses.
- The loss load factor is assumed to be 0.53.
- The period of evaluation shall be 25 years.
- Nominal amounts are used in the justification.
- The base year is 2018.
- The nominal discount rate of 12.2% is being assumed.
- The values of inflation in the form of the producer price index (PPI) used in the assessment are assumed to be 6%.
- Corporate tax is 28%.

Table 2: Nominal values of annual average long run marginal cost of generation [55]

Year	Nominal Value ($/MWh)	Year	Nominal Value ($/MWh)	Year	Nominal Value ($/MWh)	Year	Nominal Value ($/MWh)
2019	34.00	**2025**	48.62	**2031**	68.98	**2037**	97.84
2020	36.33	**2026**	51.55	**2032**	73.19	**2038**	103.71
2021	38.51	**2027**	54.63	**2033**	77.50	**2039**	109.94
2022	40.99	**2028**	57.91	**2034**	82.15	**2040**	116.54
2023	43.45	**2029**	61.39	**2035**	87.08	**2041**	123.52
2024	45.87	**2030**	65.07	**2036**	92.30	**2042**	130.94

In the optimization problem studied here, the solution space consists of combinations of pairs of tap changers settings to interconnect the transformers at the ends of the intertie. With 20 possible settings for each transformer tap changer; there are 116280 possible combination pairs in the search space. The BBBC algorithm can therefore be used in this case as the possible optimal solutions are few.

5.4 Conclusion

For this study, the BBBC algorithm is coded using Python programming language, which is simply the main command of PSS/E. This software is used to draw the IEEE 39-bus testing system and, the Eskom system testing is used to test the transformer tap changers, Nominal values of Annual Average Long Run Marginal Cost of Generation is determined for future.

IEEE 39 bus and Eskom testing systems are system used for optimization problems. In order to support an area, the new corridor can be built into the testing system. It is better to use Python programming language (Popular and simple) than other languages that can work with PSS/E.

In the next chapter, the results of the simulation are presented and discussed. Two case studies are explored, namely the IEEE 39 bus system and the Eskom system. These results, which will be presented in the form of figures, present the system of active power variation with respect to the combination of transformer tap changers.

Chapter 6: Results and Discussion

6.1 Introduction

The previous chapter discusses the method of coordinating transformers tap changers using the BBBC algorithm. Two case studies were taken into account to test the algorithm namely, the IEEE 39 bus and the Eskom testing systems. The first one is mostly used because it is easily accessible compared to the second one which is available for Eskom users.

The results of the simulation are presented and discussed in this chapter. The reduction of active power losses is presented and the associated life-cycle costs are provided to determine the monetary value of the active power losses. The sum of the total system losses is used as a reference value, and the highest and the lowest values of power losses are calculated on the basis of the selected transformer tap changers combinations, as carefully selected by the algorithm. Although these values may vary accordingly, they are recorded in order to examine potential savings in power losses. The results are later compared to those discussed in the literature review.

This chapter discusses the variation in the relative active power losses and the variation in lifecycle costs calculated for both the IEEE 39 bus system and the Eskom power grid. The methods used to obtain results are those presented in the previous chapter. The conclusions are finally drawn in the last section of this chapter.

6.2 Case Study 1: Results from IEEE 39 Bus Testing System

6.2.1 Apparent Power Flow in the Corridor

Figure 8 shows the variation of the apparent power flow in the corridors, and this is plotted against the combinations of transformer tap changers. A population of 100 candidates generated from 4 transformers with 21 tap positions is evaluated. There are 50 iterations that generate a total of 5000 combinations.

It can be observed from Figure 8 that by coordinating a combination of transformer tap changers using the BBBC algorithm, the intertie load ranges from the highest value of 381.29 MVA to the lowest value of 189.58 MVA, as the iteration elapses. The potential difference between these extremes values is 191.71 MVA. These illustrations show that there is a variation in the apparent power flow when the transformer tap changer is coordinated. These results were obtained from two studies that examined the use of tap changers as a solution for insufficient power supply.

The first paper [56] showed that the optimal positions of transformer tap changer need to be determined in order to deal with discrete states of the power system over a long period of time, including annual light-loads, peak-loads and emergency conditions. It was also noted that the generator bus and auxiliary bus voltages were within the 5% limits allowed. In the second study [12] the operation of an Off-LTC transformer had an impact on the feeder voltage profile, power losses and the maintenance of the feeder voltage within limits.

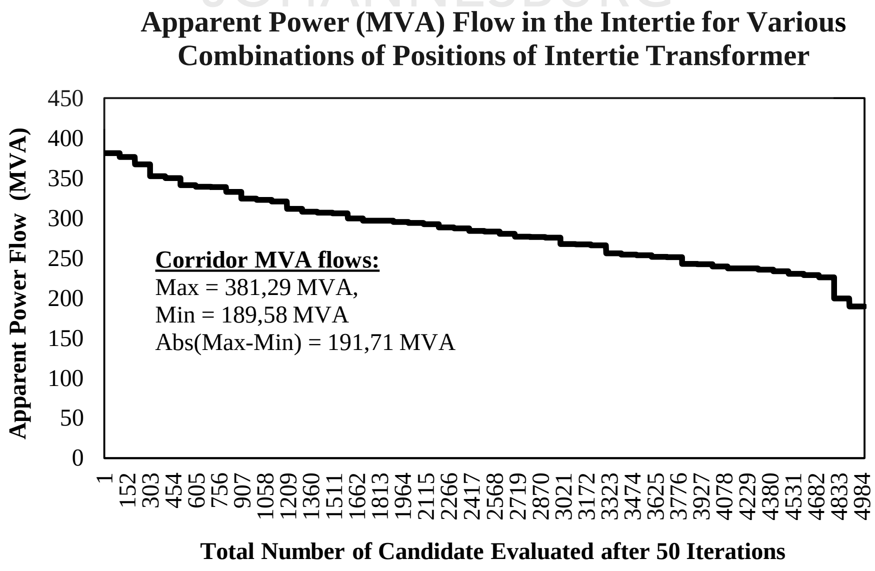

Figure 9: Apparent power (MVA) flow in the intertie for various candidates

6.2.2 Variation Relative Active Power Losses

Figure 10 shows the variation in relative savings in active power losses (MW) for different set of combinations of transformer tap changers**.** The observation made is that the active power loss varies from the highest value of 23.34 MW to the lowest value of -2.14 MW, depending on the coordination of the transformer tap changers of the selected transformers. The negative power means that the net power savings are less than the actual power. The difference between these extremes values is 25.48 MW. The results show the evolution of the initial population to the new generation using the BBBC algorithm.

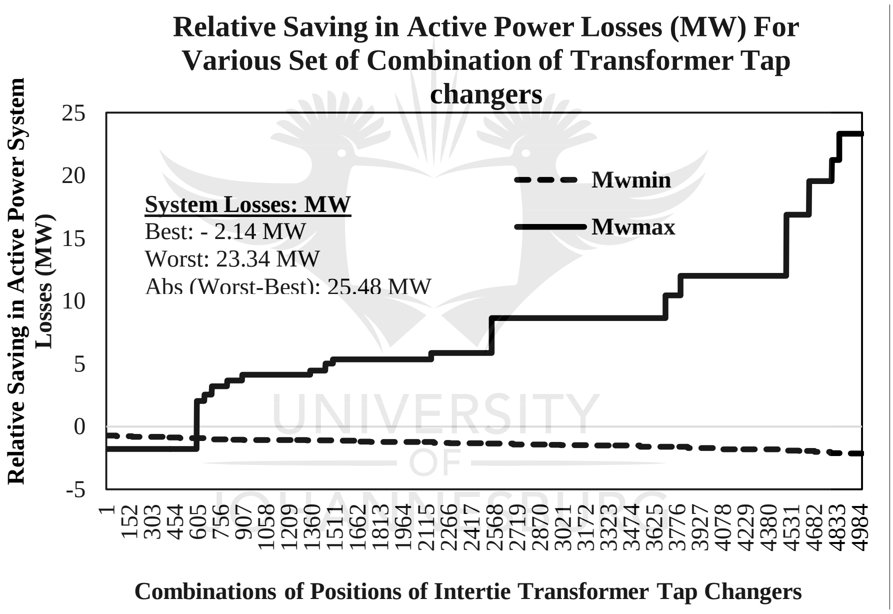

Figure 10: Variation relative active power losses with number of candidates

6.2.3 Cost of Active Power Losses

In order to quantify the benefits as a result of reduced active power losses, the life-cycle costs were calculated, and the results are shown in Figure 11. The variation in life-cycle cost of active power losses for different combinations are plotted for various iterations and are shown in Figure 11. The costs that can be relatively saved are $ - 4.28 million and the costs that could be relatively lost are $ 46.68 million, which represent potential savings of $ 50.96

million through the careful selection of the transformer tap changers combinations using the BBBC algorithm.

The negative cost means that the cost of net power savings is less than the cost of actual power. This means that by choosing the worst combination of transformer tap changers, there is a possibility of power utilities losing up to $ 50.96 million. This will significantly decrease the economics of the power utility.

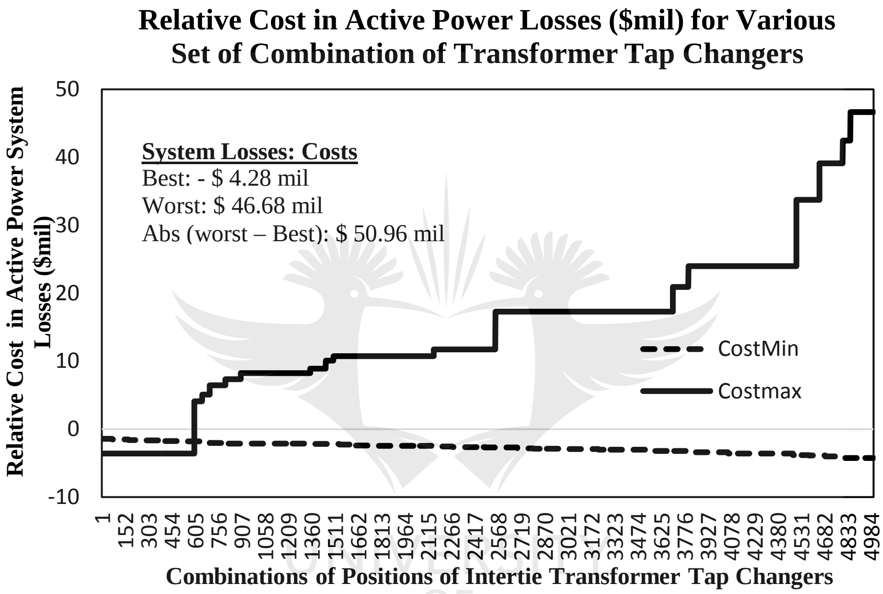

Figure 11: Relative life-cycle cost of saving in active power losses for various candidates

6.3 Case Study 2: Results from Eskom System

6.3.1 Apparent Power Flow in the Corridor

Figure 12 shows the variation in the apparent power flow for the different MVA, depending on the combinations of transformer tap changers. Similarly, for the Eskom case study, a population of 100 candidates has been evaluated with 50 iterations for a total of 5000 candidates. These also include combinations of 4 transformers in 21 tap positions. It was noted that there is a change in power flow, ranging from the highest value of 2255.63 MVA to the lowest value 1153.33 MVA.

The potential difference between these extreme values is 1103.30 MVA. The apparent power flow is also plotted in Figure 12 to show the variation of the apparent power flow in the corridors. This difference indicates that there is an appreciable impact on the amount of apparent power flows when coordinating transformer tap changers using the BBBC algorithm. This observation is supported by studies reported in [12, 56, 57].

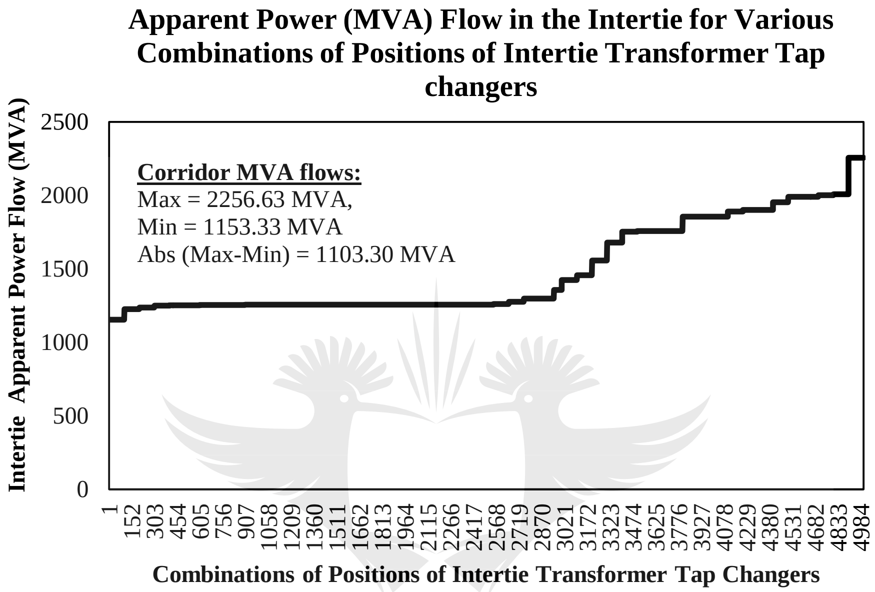

Figure 12: Apparent power (MVA) flow in the intertie for various candidates

6.3.2 Active Power Losses

An observation made in Figure 13 is that depending on the coordination of the transformer tap changers of the selected transformers, the active power loss varies from the highest value of 29.68 MW to the lowest value of -34.51 MW. The difference between the calculated active power losses is 64.19 MW. The negative power implies that the net power savings is less than the actual power. These results show an evolution from the initial population to the new generation. Figure 13 provides an implicit explanation of the variation in actual power losses and the linear line of the actual power.

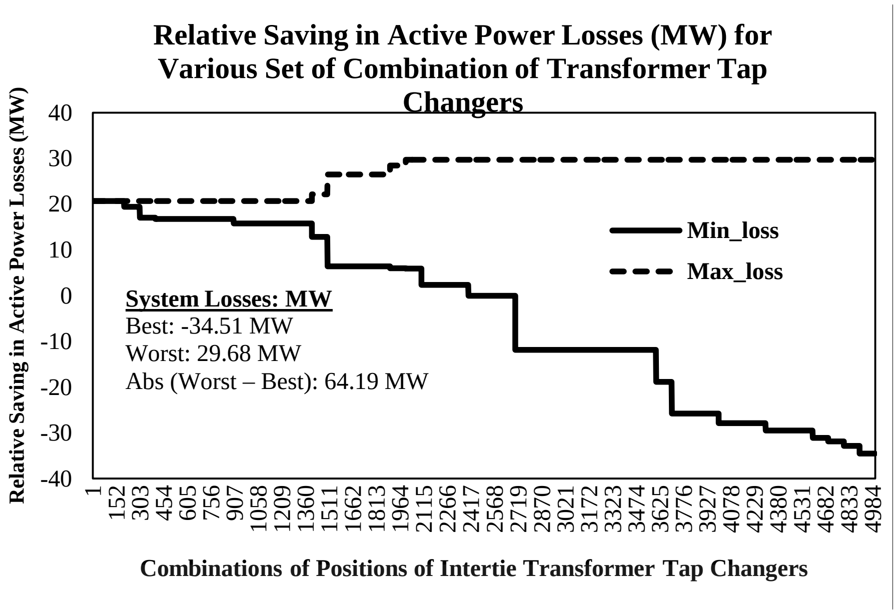

Figure 13: Variation of relative active power losses for various candidates

6.3.3 Cost of Active Power Losses

The variation in the life-cycle costs of active power losses for different iterations with various combinations is shown in Figure 14. The highest calculated savings amount to $ 59.36 million and the lowest relative savings amount to $ -69.02 million, representing potential saving of $ 128.38 million thanks to the careful selection of the combination of transformer tap changer using the BBBC algorithm. The negative cost implies that the net power savings are less than the actual cost of power.

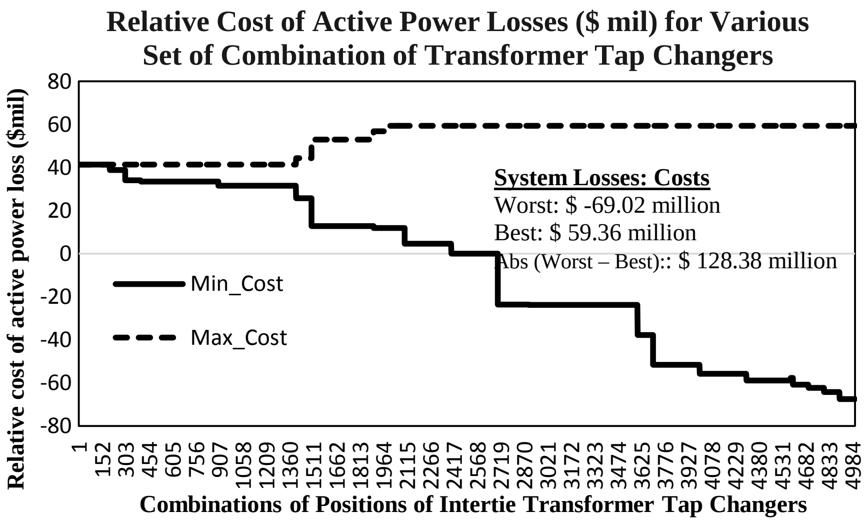

Figure 14: Relative life-cycle cost of saving in active power losses for various candidates

6.4 Conclusion

In this chapter, the results of the simulation were presented and the apparent power flow in the corridor was recorded. In order to determine the potential difference in power losses for each system, the highest and the lowest values of power losses were recorded. The associated life-cycle costs of power losses have also been determined.

The results of this study show that there is value in coordinating transformer tap changers using the meta-heuristic BBBC algorithm. In addition, with the use of the BBBC algorithm, this method has the potential to improve the selection of transformer tap changers in order to reduce the power flow in the system and active power losses.

In the next chapter, the findings of the study are discussed and recommendations are given. The question of coordinating of transformer tap changers for the reduction of active power losses will be answered. The aim, the objectives of the study, conclusions and future studies are made.

Chapter 7: Conclusion and Proposal for Future Studies

7.1 Problem Statement and Research Gap

One of the challenges of the power system is the large amount of power losses. There are two categories of power losses: technical and non-technical losses. Technical losses are the losses that occur on the transmission and distribution lines, transformer windings and the capacitors of the power system. Active power losses are caused by resistive components and reactive power losses are caused by reactive components.

A literature review was conducted to identify and examine various studies on the impact of transformer tap changers. The authors examined the tap changers of transformers directly connected to generators in order to minimize the deviations of the system bus voltages. Another study investigated the impact of the parameters of high voltage transmission lines interconnecting transformers and concluded that transformer reactance values needed to be carefully selected.

The aim of this dissertation was to assess the impact of the coordination of transformers tap changers in order to meet the objective functions of reducing the overall amount of technical active power losses and the corresponding life costs.

7.2 Aim and Objectives

In view of the above, the main aim of this study is to assess the impact of the coordination of intertie transformer tap changers in order to reduce the overall amount of technical active power losses and the corresponding life-cycle costs. The specific objectives of this research were as follows:

- To demonstrate the impact of the combination of transformer tap changers on the apparent power loading of the intertie line, a program is developed in Python programming language. This program used the BBBC algorithm and the code is directed to the Power System Simulator for Engineering (PSS/E).
- To assess the impact of coordinating a combination of transformer tap changers on the amount of active power losses of the power system. A module is developed from the program to determine the amount of active power losses with the corresponding candidate for each combination.
- To assess the impact of coordinating a combination of transformer tap changers on the lifecycle costs of the system' active power losses. Similarly, a module recording the corresponding life-cycle costs of the active power losses will be added to the program.

7.3 Findings and Conclusion

7.3.1 Findings

The studies have shown that

- The coordination of the transformer tap changer using the BBBC algorithm lead to different amounts of apparent power flow in the intertie. They cause different power sharing profiles between the intertie and the rest of the grid.

- The coordination of the transformer tap changers using the BBBC algorithm lead to different amounts of active power losses for each combination. This is one more proven method for power utility companies to reduce the active power losses.

- The coordination of the transformer tap changers using the BBBC algorithm lead to different life-cycle costs of technical active power losses associated with various combinations.

7.3.2 Conclusion

The study has demonstrated that the choice of the combination of transformer tap changer settings has a tangible impact on the amount of power flowing inside the intertie and facilitates the exchange of real and apparent power between different areas of a power system. A careful choice of the combinations of interties transformer tap changers should be made, as there are choices that may have superior techno-economic benefits in terms of grid efficiency.

7.4 Proposal for Future Studies

As demonstrated by this study, the effectiveness of application of BBBC algorithm has been shown to deal with the coordination of transformer tap changers ratio in order to achieve the objectives function of reducing the overall amount of technical active power losses and their corresponding life-costs and enhancing the total voltage limits in the electrical system.

In the future, more research needs to be done to investigate the coordination of the transformer tap changers using HBBBC algorithm. Moreover, the final candidates must furthermore satisfy the geographical condition. This project can help customers to participate more effectively in the market not only by making more efficient use of their energy but also by enabling to sell back their excess electricity to utility companies. Other research may also focus on the use of some metaheuristic algorithm (HBBBC) for intertie transformer tap changers and compare the results with those obtained in this dissertation.

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