

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DISTRIBUTION NETWORK RECONFIGURATION
FOR SMART GRID OPERATION

AYŞE AYBIKE ŞEKER
A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF ELECTRONICS ENGINEERING

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

AKILLI ŞEBEKELERİN İŞLETİLMESİ
İÇİN ELEKTRİK DAĞITIM
SİSTEMLERİNİN
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GEBZE
2021

GTÜ Fen Bilimleri Enstitüsü Yönetim Kurulu'nun 08/07/2021 tarih ve 2021/32 sayılı kararıyla oluşturulan jüri tarafından 04/08/2021 tarihinde tez savunma sınavı yapılan Ayşe Aybike Şeker'in tez çalışması Elektronik Mühendisliği Anabilim Dalında DOKTORA tezi olarak kabul edilmiştir.

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...../...../..... tarih ve/..... sayılı kararı.

SUMMARY

In power network, increasing demand, load variations, environmental concerns, renewable penetration, demand participation, and new technologies increase complexity of existing networks. Smart grid is emerged as an overall concept to control and monitor modern power networks with the help of advanced information and communication systems. In smart grid environment, distribution networks play an important role and its radial structure, unbalanced distributed loads, a great number of branches and nodes may cause challenges in network planning, state estimation, switching and load flow analysis.

Reconfiguration is used as a tool for planning and operation. Although a basic control action involves in reconfiguration; discrete nature of switches, many switching combinations and radiality constraint transform the problem into a mixed integer form.

In this thesis, first an analytical approach to reconfiguration problem is introduced for distributed load profiles. A sensitivity index based method is investigated for systems with spot loads. Then, a new method is developed for changed topology representation of a distribution network by bus-injection to branch-current (BIBC) matrix which has been introduced for load flow analysis of the distribution networks. The proposed method is tested using grid search algorithm which provides the exact solution. Effects of load modelling into distribution network reconfiguration is investigated with using voltage dependent and time varying loads. Finally, a metaheuristic method, Artificial Bee Colony (ABC) algorithm, is modified to solve problem for large systems. The solution methods from analytical to metaheuristic approaches are investigated and applied to distribution networks to obtain a reliable solution to reconfiguration problem.

Key Words: Distribution Network, Network Reconfiguration, BIBC Matrix, Smart Grid, Artificial Bee Colony Algorithm.

ÖZET

Güç şebekesinde artan talep, yüklerin çeşitliliği, çevresel kaygılar, yenilenebilir enerji kaynakların artırılması, talep katılımı ve yeni teknolojiler mevcut şebekelerin karmaşıklığını artırmaktadır. Akıllı şebeke, gelişmiş bilgi ve iletişim sistemlerinin yardımıyla modern güç ağlarını kontrol etmek ve izlemek amacıyla genel bir konsept olarak planlama ve işletmede verimli ve güvenilir çözümler sağlamak için ortaya çıkmıştır. Akıllı şebeke ortamında dağıtım sistemleri, tüketicilere tedarik sağlayan son kısım olduğu için önemli bir rol oynamaktadır. Radyal yapılar, dengesiz dağıtılmış yükler, çok sayıda dal ve düğüm nedeniyle planlama, durum tahmini, anahtarlama ve yük akışı analizlerinde zorluklarla karşılaşılabilir.

Rekonfigürasyon, şebekenin planlama ve işletmesinde kullanılan bir araçtır. Rekonfigürasyon temel bir kontrol eylemi, bir anahtarlama işlemi de olsa anahtarların ayrık doğası, birçok anahtarlama kombinasyonu ve radyallik kısıtlaması, işlemi karmaşık tam sayılı bir probleme dönüştürür.

Bu tezde, önce dağıtılmış yük profilleri için rekonfigürasyon problemine analitik bir yaklaşım tanıtılmıştır. Spot yüklere sahip sistemlerde hızlı çözüm elde etmek için duyarlılık indeksi tabanlı bir yöntem araştırılmıştır. Daha sonra anahtarlama işlemi için yeni bir yöntem geliştirilmiş ve sistemin topoloji değişiklikleri, yük akışı analizi için tanıtılan bara akımından hat akımı (BIBC) matrisinin modifiye edilmesiyle temsil edilmiştir. Önerilen yöntem, rekonfigürasyon problemine kesin çözüm sağlayan bir ızgara arama algoritması kullanılarak test edilmiştir. Yük modellemenin dağıtım şebekesinin yeniden yapılandırılmasına etkileri, gerilime bağlı ve zamanla değişen yükler kullanılarak araştırılmıştır. Son olarak, büyük şebekelerde yeniden yapılandırma problemini çözmek için metasezgisel yöntem olan Yapay Arı Kolonisi (YAK) algoritması geliştirilerek kullanılmıştır. Analitikten metasezgisel yaklaşımlara kadar uygulanabilecek çözüm yöntemleri geliştirilmiş ve rekonfigürasyon problemine güvenilir çözüm elde etmek için çeşitli dağıtım şebekelerine uygulanarak sonuçlar değerlendirilmiştir.

Anahtar Kelimeler: Dağıtım Şebekesi, Şebeke Yeniden Yapılandırması, BIBC Matrisi, Akıllı Şebeke, Yapay Arı Kolonisi Algoritması.

ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my advisor, Prof. Dr. Mehmet Hakan Hocaoglu to my co-advisor Dr. Tuba Gözel for the continuous support of my research, for their patience, motivation, and insightfulness. I am also grateful for the opportunities they provided me to join their team as a researcher in several projects which gave me a chance to widen my world both in research and in my personal life.

Beside my advisors, I would like to thank steering committee members of my thesis: Prof. Dr. Abdulkadir Balıkçı and Prof. Dr. Ahmet Fevzi Baba for their questions, advices, and feedbacks which helped me to widen my perspective during my PhD.

I am also thankful to my teammates for the long hours we worked together and for all fun we have had. In particular, I appreciate helps of Dr. Ahmet Köksoy and Onur Öztürk.

Finally, I would like to thank my parents and my precious sister for their endless support and love through my life and for their extra patience and understanding during my PhD.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u> <u>and Acronyms</u>	<u>Explanations</u>
ABC	: Artificial Bee Colony
ACO	: Ant Colony Optimization
ANN	: Artificial Neural Network
ASFLA	: Adaptive Shuffles Frogs Leaping Algorithm
BFOA	: Bacterial Foraging Optimization Algorithm
BIBC	: Bus Injection to Branch Current
DG	: Distributed Generation
FWA	: Fireworks Algorithm
GA	: Genetic Algorithm
GWO	: Grey Wolf Optimization
HSA	: Harmony Search Algorithm
ICSA	: Improved Cuckoo Search Algorithm
KCL	: Kirchhoff's Current Law
KVL	: Kirchhoff's Voltage Law
MABC	: Modified Artificial Bee Colony
PSO	: Particle Swarm Optimization
SA	: Simulated Annealing
SIM	: Sensitivity Index Method
SFS	: Stochastic Fractal Search

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1. INTRODUCTION

The smart grid is a modern electric power grid environment with improvement on efficiency and reliability through automated control, modern communications technics, metering technologies and modern energy management. Main goals of smart grid are to provide grid observability, improve power system performance and security, and reduce cost of operations, system maintenance, and planning.

The grid with intelligent functions is planned to detect, analyse, and restore disorders, incorporate with consumers, be resilient to security attacks, provide power quality, accommodate sustainable and local generation, optimize operation and maintenance cost by monitoring grid. Therefore, key elements of smart grid can be listed as fault and stability diagnosis, system restoration, reactive power control, distributed generation usage, demand side participation, and network reconfiguration.

As future grid contains more low carbon technologies like; photovoltaic panels, wind turbines, electric cars etc., grid should be analysed for effects of these technologies and unpredictable load profiles caused by them. Variability of renewable energy sources depends on meteorological conditions and they can vary hourly or even in minute by minute horizon [1]. So, during the day, the load profile fluctuates, and it may cause peak loadings at different times and feeder unbalance. As traditional grid has been designed for passive load demands that can be forecasted accurately and controllable distributed generators that can be turned on or off and operated continuously to deliver power, it has difficulty in managing new technologies including active load demands and variable generation of renewables. The transformation of power grid with increasing penetration of renewables, replacing conventional passive load with increasing demand side participation, development of energy storage systems made researchers to think about smart grid concept. Smart grid components like renewables, storages, demand side participation, and smart appliances increase uncertainty in both supply and demand as other components like sensors, smart meters and communications provide accurate information and better control [1]. Smart grid is emerged as an overall and better concept to control and monitor modern power networks with the help of advanced information and communication systems as it also provides efficient and reliable solutions for planning and operation.

Implementation of network operational or planning requirements such as; necessitate changes in configurations to transfer the loads to a different substation, ease the loading of equipment, and conduct planned maintenance etc. require for changes on topology of grid. These operations are called as network reconfiguration which is simply changing the topology of distribution network by opening or closing pre-installed switches, while keeping the radial structure of feeders intact. Reconfiguration needs an accurate representation of network topology as well as convenient load modelling and a fast response as one of the key elements of smart grid.

In fact, network reconfiguration can be used to reduce power losses to relieve overloads or to provide power to all customers in a fault or outage [2]. As well as, it has been used as a tool for planning and operation in normal state of network with renewables, storages and other emerging technologies, reconfiguration may also be useful for emergencies, accidents, attacks and weather-related disasters. Such disturbances may cause damages in distribution network which may take long hours to repair and provide energy back again [3]. Changing topology may increase network resiliency by providing the ability to tolerate, adapt and recover from disasters [4].

1.1. Literature Summary

Power distribution network reconfiguration is one of the most discussed problems in power grid optimisation in last forty years. Although a basic control action, a switching operation, involves in reconfiguration; discrete nature of switches, many switching combinations and radiality constraint transform the optimization problem into complex combinatorial non-differentiable form.

The distribution system should be operated at minimum cost that obtains radial configuration, serving all loads, coordinating overcurrent protective devices, keeping line, transformer and all other equipment current values and voltage magnitudes between limits [5]. Variation of loads in distribution network gives the opportunity to reconfigure the feeders during the day, week, months, or season to improve system quality.

The essential challenge of reconfiguration problem is to develop a switching procedure that ensures all loads are supplied and network remains radial. The switching operation in reconfiguration is mainly categorized in two types: branch

exchange and loop cutting. As branch exchange method performs in a radial system with opening and closing switch pairs, loop cutting opens switches in an initially meshed system until it becomes radial [6].

Extremely large combinatorial solution space is another challenge of reconfiguration. Methods require a very fast loss estimation technic for repeated and continuous evolution of these configurations [7].

Reconfiguration methods can be separated in two parts according to its purpose: single and multi-objective [8].

In the literature, most of the studies consider the reconfiguration problem as single objective of total active loss minimization. Even today, power loss minimization is the single most important objective. And constraints can be listed as current, voltage and radiality limits given as [9]:

$$\min \sum_{b=1}^{N_{br}} |I_b|^2 \cdot R_b \cdot K_b$$

Subject to constraints

$$K_b \cdot |I_b| < I_{max} \quad \text{current constraints}$$

$$V_{i_{max}} < V_i < V_{i_{min}} \quad \text{voltage constraints} \quad (1.1)$$

$$g_i(I, k) = 0 \quad \text{KCL}$$

$$g_v(V, k) = 0 \quad \text{KVL}$$

$$\varphi(k) = 0 \quad \text{radial topology constraints}$$

Here N_{br} is the number of closed branches, R_b, I_b, K_b are resistance, current and topological status of closed branch respectively. V_i is the voltage of bus i . $g_i(I, k)$ and $g_v(V, k)$ represent the Kirchhoff's voltage and current laws respectively.

The constraints are also given as penalty function as in [10]:

$$M = PL + p_1 \cdot f_v + p_2 \cdot f_c \quad (1.2)$$

Here, PL represents power loss, f_v and f_c are the penalty functions for bus voltage deviation and branch current limit. p_1 and p_2 are the penalty coefficients.

Other objective functions are also used as to minimize financial losses due to voltage sags without including cost due to power loss [11], combination of loss minimization and maximization of system load balancing [12], minimize cost for combination of several objectives as loss cost, switching cost, cost saved due to voltage profile improvement as [13]:

$$M = \min(LC + SWC - CIV) \quad (1.3)$$

Here, LC, SWC and CIV are for loss cost, switching cost and cost saved due to voltage improvement, respectively.

In the literature, some studies deal with more than one objective. In order to combine objectives different methods are used as weighted sum [14], [15], [16], [17], fuzzy [18]–[20], and pareto optimal [21]–[23] combination. As distribution networks become smart the reliability and power quality based objectives gain popularity. Pareto optimal multi objective methods are generally used in such problems. In multi objective methods, objectives are combined in terms of minimizing cost as in [21]:

$$M = \min \left(K_1 P_{loss} + K_2 Q_{loss} + \sum_{b=1}^{Nb} IC_b \right) \quad (1.4)$$

Here, reconfiguration is formulated as a pareto optimal multi-objective problem to minimize operating and total interruption costs. P_{loss} and Q_{loss} is for real and reactive power losses with cost coefficients K_1 and K_2 respect to minimize operation cost. IC_b is for interruption cost of bus b .

As conventional grid solutions fail to meet growing demand, expectations of consumers, security, and reliability the transformation to smart grid concept accelerated in last two decades. Penetration of distributed generation (DG), integration of energy storage systems, applications of communication technics, and growing stochastic grid environment make network reconfiguration problem more challenging.

In terms of solution methods, reconfiguration approaches can be separated into three categories: heuristic, metaheuristic, and mathematical optimization based methods [8]. Also, there are hybrid methods based on these three approaches.

Reconfiguration studies in literature are listed on Table 1.1. They are categorized by objective function, load flow approach and the method they use to solve reconfiguration problem. Furthermore, they are grouped for the type of solution approach.

In early studies for reconfiguration based on heuristics. Mainly two approaches are defined in switching decision: loop cutting and branch exchange. Loop cutting starts with closing all tie switches and make network meshed and then open switches until networks become radial while branch exchange closes a tie switch and open a sectionalizing switch from the loop each time to keep network radial. Merlin and Back is used it as a variation of branch and bound technique in their pioneer study for reconfiguration [8]. After them, loop cutting is used for line loss minimization with an improved heuristic approach [24], all switches are closed and then sequentially opened until a radial configuration is reached while an approximate formula used to estimate network losses. Another heuristic method using switch exchange is derived by Civanlar et al. [25]. A pair of switches are selected, one for opening and one for closing, to decrease line losses while remaining the network radial and all loads are supplied. Baran and Wu [2] follow the used approach by Civanlar and use reconfiguration for loss minimization and load balancing with a heuristic method. However, their spanning tree method does not ensure global optimal solution since algorithm depends on initial branch selection and does not examine all possible trees. Shirmohammadi and Hong [24] also described a heuristic technique to reduce resistive line losses that claims to reach optimum or near optimum solution of reconfiguration problem. Goswami and Basu [26] presented a heuristic algorithm based on optimal flow pattern which is determined by solving KVL and KCL equations of network and they limit the switch exchange operation by a single loop each time. McDermott et al. [5] starts their algorithm by opening all operable switches and then close the switches that causes least increase in objective function at each step. Kashem et al. [27] has been developed a two stage method. First it finds a loop which causes the maximum loss reduction with proposed loop loss reduction formula. Second stage determines the switching operation in that loop. The method proposed by Gomes et al. [28] starts with all tie switches are closed and opening criterion is based on total loss increase determined by a power flow program. In [29], multiple objectives that are real power loss, node voltage deviation and branch current loading, are considered and modelled with fuzzy sets. Abul'Wafa [30] proposes a method with two parts; first is to determine

best switching combination in all loops, second is performing load flows to calculate power loss and voltage profile of the best switching combination obtained in the first part. The author also uses branch current to bus injection matrix in power flow calculations. Although there are many other heuristic approaches that provide fast solutions with noncomplex calculations on practical networks, global optimal solution is yet to be established.

Deterministic methods that are listed on Table 1.1 as mathematical optimization based methods are applied to reconfiguration in limited extend. In [31], authors present a linearization of problem to solve with mixed integer linear programming. As losses does not represent in this study exactly they present a nonlinear formulization to solve the problem with mixed integer nonlinear programming in their next study [32]. In [33], reconfiguration is performed to minimise losses using mixed integer nonlinear programming method with Benders decomposition and optimal power flow. Although the study uses exact loss model, the fact that the problem is not convex in terms of continuous variables, it does not guarantee convergence to global solution. Another study [34] claims to guarantee global solution by using a new exact mixed integer nonlinear programming. As ability to reach global optimal solution of deterministic methods are discussed so far in studies, in [35] an exact solution for reconfiguration problem is introduced. A brute force search algorithm is used to make an exhaustive search to guarantee globally optimal solution under appropriate modelling assumptions for networks of moderate complexity.

The metaheuristic approaches are generally used to solve network reconfiguration problems. Several nature inspired metaheuristic algorithms have been proposed for reconfiguration. These are the ones that have been achieved so far; genetic algorithm [36]–[39], tabu search [10], [40], particle swarm optimization (PSO) [41]–[43], artificial bee colony (ABC) algorithm [44]–[46], ant colony algorithm (ACO) [47], [48], [49], harmony search algorithm (HSA) [50], bacterial foraging optimization algorithm (BFOA) [51], fireworks algorithm (FWA) [52], improved cuckoo search algorithm (ICSA) [53], selective firefly algorithm [54], adaptive shuffles frogs leaping algorithm (ASFLA) [55], hybrid grey wolf and particle swarm algorithm (GWO-PSO) [56], stochastic fractal search algorithm (SFS) [57].

In [38], a multi objective reconfiguration problem which minimize power loss, node voltage deviation and switching number is introduced. The objectives are transformed into fuzzy framework and solved using an adaptive genetic algorithm.

Another genetic algorithm based method [39] improved crossover operator of algorithm to generate radial configurations in order to minimize power loss and maximize system reliability. Simulated annealing (SA) based methods e.g., simplified line flow equations for SA [58], polynomial time cooling schedule based SA [59], hybrid tabu search and SA [60] are mainly used for loss minimization by reconfiguration. Artificial neural networks are also used in reconfiguration studies [61], [62]. ANN is preferred for changing load profiles that it can provide solutions without executing an iterative process. ACO based methods are used for loss minimization with penalty functions in [47] and load balancing in [48]. There are also several PSO based methods for reconfiguration studies e.g., discrete PSO algorithm for loss minimization and load balancing [41], PSO with graph theory [42] and hybrid fuzzy adaptive PSO [63] for loss minimization. Another population based method, artificial bee colony algorithm, is used for loss minimization in [46]. A comparison is performed in [44] between ABC and GA. In [45], a graph theory based discrete ABC algorithm is used to minimize voltage deviation index and maximize loadability margin of system by performing reconfiguration.

Metaheuristic methods overcome the weakness of heuristic methods as they are likely to converge global optima. Also, metaheuristic approaches are convenient to apply large networks for multi objectives. The disadvantages of metaheuristics can be count as accurate parameter tuning and complexity of algorithms.

Generally, in reconfiguration studies an optimal configuration is determined for a specific time point, but for realistic systems with time varying loads optimal time intervals and different reconfigurations may be considered within a specific time period. Variation of load during the time period is usually evaluated with different load types with different characteristics like residential, commercial and industrial [64]. Optimization for such systems generally solved with heuristic methods that focus on operation expenses minimization considering switching loss and deteriorations of switches lifespan [65]. Problems are also modelled as multi-objective considering placement of renewables [66]–[68], electric vehicles [69], load balancing [70], maximum voltage deviation etc. A number of reconfiguration studies used BIBC matrix for load flow calculations [52], [71].

Table 1.1: Studies on reconfiguration in literature.

Heuristic optimization based reconfiguration methods			
Writer	Objective	Load Flow	Method
Merlin and Back [8]	Loss minimization	Meshed and radial load flow	Branch and bound method
Civanlar et al. [25]	Loss minimization	Loss estimation formula	Branch exchange based heuristic method
Baran and Wu [2]	Loss minimization and load balancing	Forward backward load flow	Branch exchange based heuristic algorithm using approximate radial load flow methods
Shirmohammadi and Hong [72]	Loss minimization	Mesh and radial load flow	Sequential switch opening method
Goswami and Basu [26]	Loss minimization	Radial load flow	Switch exchange method: one tie line is closed first and a branch is opened to from the loop with minimum current
McDermott et al. [5]	Loss minimization	Radial load flow	Heuristic algorithm. All operable switches are open first.
Kashem et al. [27]	Loss minimization	Radial load flow	Branch exchange method based on minimal tree search with a loss exchange formula
Gomes et al. [28]	Loss minimization	Load flow	Sequential switch opening method starts with all switches closed.
Savier and Das [29]	Fuzzy multiobjective problem: minimum real power loss, maximum node voltage deviation, branch current loading.	Radial load flow	Branch exchange with heuristic algortihm
Wagner et al. [73]	Loss minimization	Gaus Siedel load flow	Linear programming and heuristic method comparision for uniformly distributed load
Abul'Wafa [30]	Loss minimizaiton	Radial load flow	Branch exchange heuristic algorithm using BIBC matrix

Table 1.2: Continuation.

Zhou et al. [74]	Number of switching minimization, load balancing	-	Combination of heuristic rules and fuzzy logic methods
Zhou et al. [75]	Operating cost minimization	Load flow	Heuristic method with sequential switch opening
Broadwater et al. [76]	Loss minimization subject to current, voltage, radiality constraints	Radial load flow	Branch exchange heuristic algorithm for time varying loads
Chen and Cho [77]	Energy loss minimization	Three phase radial load flow	Branch exchange based heuristic approach for hourly optimal switching
Bernardon et al. [78]	Weighted sum multiobjective	Radial load flow	Real time reconfiguration based on heuristic algorithm with DGs
Mathematical optimization based reconfiguration methods			
Writer	Objective	Load Flow	Method
Aoki et al. [79]	Loss minimization	Load flow	Reconfiguration based on recursive quadratic programming with uniformly distributed load
Wagner et al. [73]	Loss minimization	Load flow	Compares linear programming with optimal load flow and heuristic algorithms
Khodr et al. [33]	Loss minimization, load balancing	Radial load flow	Mixed integer nonlinear programming method with Benders decomposition and optimal power flow
Abur [80]	Loss minimization	Radial load flow	Linear programming-simplex method

Table 1.3: Continuation.

Jabr et al. [34]	Loss minimization	Radial load flow	Mixed integer convex programming in presence of DGs
Morton and Mareels [35]	Loss minimization	An equation using a sensitivity matrix	Brute force solution
Metaheuristic optimization based reconfiguration methods			
Writer	Objective	Load Flow	Method
Genetic algorithm (GA) based methods			
Nara et al. [36]	Loss minimization	Load flow	GA based method
Shin et al. [37]	Minimize Loss cost and Interruption cost	Load flow	Genetic Tabu search algorithm
Gupta et al. [38]	Minimization of real power loss, node voltage constraint violation, branch current constraint violation, swithcing number	Radial load flow	Fuzzy multiobjective formulation, modified GA with graph theory
Duan et al. [39]	Power loss minimization maximize system reliability (SAIDI, SAIFI, EENS)	Radial load flow	Improved crossover operator of GA which always generates radial configurations
Simulated annealing (SA) based methods			
Chang and Kuo [58]	Loss minimization	Radial load flow	Simplified line flow equations for SA
Jeon et al. [59]	Loss minimization	Radial load flow	Polynomial time cooling schedule based SA
Jeon and Kim [60]	Loss minimization	Radial load flow	Hybrid method: tabu search and SA
Artificial Neural Network (ANN) based methods			
Kashem et al. [61]	Loss minimization	-	ANN based method for optimum swithcing

Table 1.4: Continuation.

Salazar et al. [62]	Loss minimization	-	Improved ANN using clustering technique
Ant colony optimization (ACO) based methods			
Chang [47]	Loss minimization with penalty fuctions	-	ACO based method with capacitor placement
Wu et al. [81]	Loss minimization with feeder load balancing	-	ACO based algortihm with DGs
Particle swarm optimization (PSO) based methods			
Sivanagaraju et al. [41]	Loss minimization and load balancing	Radial load flow	Discrete PSO algortihm
Assadian et al. [42]	Loss minimization	Mesh load flow	PSO with graph theory
Niknam et al. [43]	Loss minimization	Radial-meshed load flow	Hybrid fuzzy adaptive PSO
Artificial bee colony (ABC) based algortihm			
Aman et al. [45]	Minimize Voltage Deviation index and maximize loadability margin	Radial load flow	Graph theory based Discrete ABC algothim
Linh and Anh [46]	Loss minimization	Load flow	ABC algorithm
Sulaima et al. [44]	Voltage profile improvement	Load flow	ABC and GA comparison

In conclusion, all optimization approaches for reconfiguration problems have pros and cons. Heuristic based approaches are widely implemented due to its ability to give fast reconfiguration results as it is based on operational experience. Methods based on sensitivity index also count as heuristic approach. Although heuristic methods are simple to formulate, they do not claim to reach global optima. [25], [82].

Metaheuristic methods takes longer time and have complex formulation but generally tend to find global optimum or near optimum of reconfiguration problem. The metaheuristic approaches are also suitable to find final reconfiguration of large system within acceptable time period.

On the other hand, mathematical optimization methods also called as deterministic methods that are used in reconfiguration studies are linear programming, nonlinear programming, quadratic programming, brute force etc. As discrete nature of switches and the radial operation of networks makes it difficult to represent in mathematical approaches, they have not been widely used in reconfiguration studies. In terms of global solution only a few of methods could claim to reach it while only one deterministic method guarantees the optimal solution.

1.2. Motivation

Reconfiguration is one of the most discussed problems in power system optimization in last forty years and generally methods have been implemented to use reconfiguration as a loss minimization technique. The essential challenges of reconfiguration problem are to decide a switching procedure that ensures all loads are supplied and network remains radial as well as a fast loss estimation with simple calculations. Therefore, the main objectives of this thesis are firstly to develop an analytical expression for reconfiguration, secondly to introduce a fast heuristic approach. Then the aim is to introduce a new switching procedure which overcomes radiality and continuity constraints and to provide power loss estimation with an analytical formula. Thereafter, it is planned to develop a grid search algorithm to obtain exact solution of reconfiguration problem and introduce a modified artificial bee colony algorithm to solve reconfiguration problem.

This study proposes reconfiguration solution methods that overcomes the essential challenges of problem. Although smart grid elements such as renewable

resources and energy storage units can be easily included in the analysis, this thesis is limited to developing reliable methods for reconfiguration in order to use in smart grid operation.

1.3. Thesis Outline

Chapters of thesis are introduced here.

In Chapter 1, distribution network reconfiguration problem is introduced, methods in literature are reviewed. Motivation of thesis is given.

Chapter 2 introduce an analytical approach for distribution networks with distributed load profile. Application of method is given in detail. After analysis and results, performance of method is discussed.

In Chapter 3, a heuristic method, a sensitivity index based approach to minimize power loss is developed. It is applied to 33 bus and 69 bus systems. Results of analysis are discussed in terms of reaching global optima, providing minimum power loss.

In Chapter 4, a new switching approach by modifying BIBC matrix is introduced. Power loss estimation with analytical formula before and after reconfiguration is able to make with proposed modification method.

In Chapter 5, grid search algorithm is used for reconfiguration problem. A recursive grid search is developed to try all possible switching combinations and reach the exact results for reconfiguration problem. Load modelling of distribution networks are examined with using static load model. Proposed method in Chapter 4 is applied to networks using grid search and results are discussed.

Chapter 6 gives a modification of ABC algorithm to solve reconfiguration problem and investigate its performance to reach optimal solution.

In Chapter 7, developed methods and the methods applied in literature are compared.

The conclusion is given in Chapter 8.

2. ANALYTICAL APPROACH FOR RECONFIGURATION

Analytical equations are described in this chapter to decide which loads or branches need to be transferred from one substation to another. Analysing the network with analytical approach gives opportunity to observe the effects of all system components from mathematical expressions. Analytical methods are introduced for problems as capacitor placement and distributed generator sizing and siting in distribution networks [83], [84]. Similarly, for reconfiguration an analytical method will contribute to comprehend the grid, analyse and offer better solution for grid's requirements and envisage the impacts of system parameters on grid.

In this chapter, a beginning of an analytical approach for reconfiguration problem is introduced for distributed loads and then the method is improved to apply sample systems.

2.1. Analytical expressions with distributed load profile

Analytical approach for network reconfiguration problem is developed for distributed load profiles to minimize system losses. Analysis are considered to be done for distributed load profiles initially for understanding the concept of state of art with analytical approach [85]. Distribution line for distributed parameters is modelled with the same resistance, R , and inductor, L , per unit values along the feeder and shunt capacitor is neglected. Loads are distributed along the line with the current density $Id(x)$. Length of line is assumed L and per unit impedance of line is $Z = R + jX$ ohm/km. The phasor current at point x is given in equation (2.1)

$$I(x) = \int_0^x Id(x)dx \quad (2.1)$$

Total power loss along line is given as equation (2.2).

$$P_{loss} = \int_0^L \left(\int_0^x Id(x)dx \right)^2 R dx \quad (2.2)$$

Expressions are derived for uniformly, increasing and centrally distributed load profiles as results are predictable. Line is supplied with two sources from two ends to decide location of a switch on the line for loss reduction.

Uniformly distributed load profile is presented in Figure 2.1. Assume a switch is located at point s on the feeder.

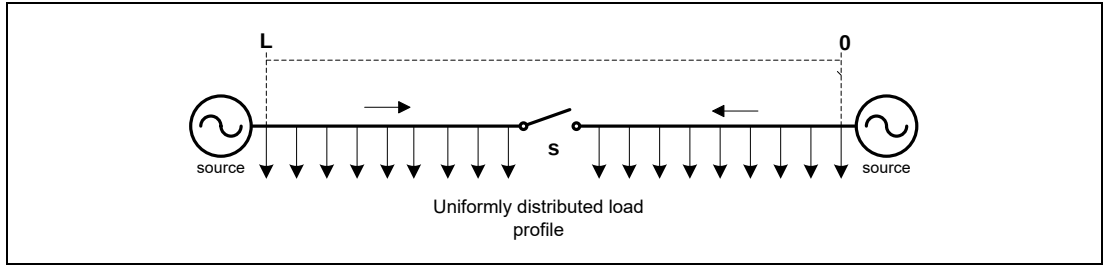


Figure 2.1: Uniformly distributed load profile.

Phasor current density for uniformly distributed load $Id_u(x)$ is a constant value as in equation (2.3) and total power loss is given in equation (2.4).

$$Id_u(x) = I \quad (2.3)$$

$$P_{loss_u}(x) = \int_0^s \left(\left| \int_0^s Id(x)dx \right| \right)^2 R dx + \int_0^{L-s} \left(\left| \int_0^{L-s} Id(x)dx \right| \right)^2 R dx \quad (2.4)$$

P_{loss_u} consists of two parts: loss from one source to switch s , and from other source to $(L - s)$. Equation (2.4) is simplified as in equation (2.5).

$$\begin{aligned} P_{loss_u}(x) &= \int_0^s \left(\left| \int_0^s Idx \right| \right)^2 R dx + \int_0^{L-s} \left(\left| \int_0^{L-s} Idx \right| \right)^2 R dx \\ &= \int_0^s s^2 I^2 R dx + \int_0^{L-s} (L - s)^2 I^2 R dx \\ &= s^3 I^2 R + (L - s)^3 I^2 R \\ &= I^2 R ((s)^3 + (L - s)^3) \end{aligned} \quad (2.5)$$

Derivative of loss expression with respect to s is given in (2.6) and it is set to zero as in equation (2.7) to obtain optimal location for the switch s .

$$\frac{dP_{loss_u}}{ds} = 3I^2RL(-L + 2s) \quad (2.6)$$

$$\frac{dP_{loss_u}}{ds} = 0 \quad (2.7)$$

Solution of equation (2.7) is given in (2.8). For a line with uniformly distributed load profile, location of switch to minimize power loss is given as:

$$s = \frac{L}{2} \quad (2.8)$$

Increasingly distributed load profile is presented in Figure 2.2. A switch is located at point s on the feeder. Phasor current density $Id_i(x)$ and total power loss is given in equation (2.9) and (2.10) respectively.

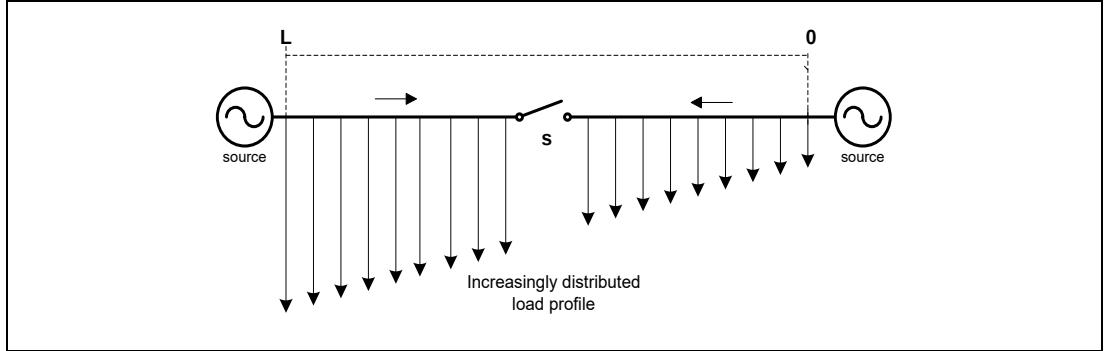


Figure 2.2: Increasingly distributed load profile.

$$Id_{i1}(x) = (L - x) I \quad Id_{i2}(x) = xI \quad (2.9)$$

$$P_{loss_i}(x) = \int_0^s \left(\left| \int_0^s Id_{i1}(x) dx \right| \right)^2 R dx + \int_0^{L-s} \left(\left| \int_0^{L-s} Id_{i2}(x) dx \right| \right)^2 R dx \quad (2.10)$$

Equation (2.11) is obtained by simplifying (2.10).

$$P_{loss_i}(x) = \frac{I^2 R}{4} ((s^3(s - 2L)^2) + ((L - s)^5)) \quad (2.11)$$

Derivative of total power loss respect to s is given in equation (2.12) and it is set to zero as in (2.13).

$$\frac{dP_{loss_i}}{ds} = -5L^4 + 20L^3s - 18L^2s^2 + 4Ls^3 \quad (2.12)$$

$$\frac{dP_{loss_i}}{ds} = 0 \quad (2.13)$$

Solution of equation (2.13) is given in (2.14). Here, location of switch s to minimize total power loss is calculated as:

$$s = 0.354L \quad (2.14)$$

Similarly, centrally distributed load profile is presented in Figure 2.3. A switch is located at point s on the feeder. Centrally distributed load phasor current density $Id_c(x)$ is and total power loss is given in equation (2.14) and (2.15) respectively.

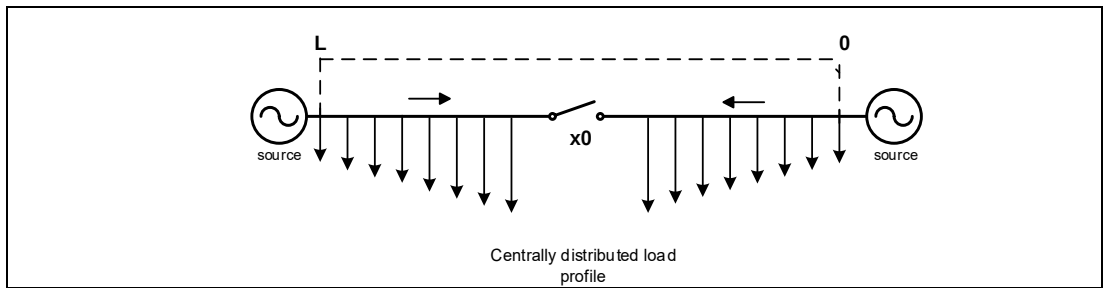


Figure 2.3: Centrally distributed load profile.

$$Id_c(x) = \begin{cases} Ix & 0 \leq x \leq L/2 \\ I(L - x) & L/2 \leq x \leq L \end{cases} \quad (2.14)$$

$$P_{loss_c}(x) = \int_0^s \left(\left| \int_0^s Id(x)dx \right| \right)^2 Rdx + \int_s^L \left(\left| \int_0^{L-s} Id(x)dx \right| \right)^2 Rdx \quad (2.15)$$

Total power loss of a line with centrally distributed load profile is simplified as in equation (2.16) and derivative of it respect to s is given in equation (2.17)

$$P_{loss_c}(x) = \int_0^s \left(\left| \int_0^s Ixdx \right| \right)^2 Rdx + \int_s^L \left(\left| \int_0^{L-s} I(L-x)dx \right| \right)^2 Rdx \quad (2.16)$$

$$\frac{dP_{loss_i}}{ds} = 0 \quad (2.17)$$

Solution of equation (2.17) gives the location of switch s to minimize total power loss of line as:

$$s = \frac{L}{2} \quad (2.18)$$

Results of switch location for a system with distributed loads are obtained. Power loss is expressed as a function of switch location. Derivative of loss respect to switch location provides the reconfiguration solution with minimum power loss. This study gives an insight for analytical solution to reconfiguration problem.

2.2. Application of analytical expressions with curve fitting

In real networks loads do not have distributed profile. Therefore, to apply this analytical approach for spot loads of a network, a procedure is developed [86]. To see how it works for a system with spot loads, flowchart of procedure is shown in Figure 2.4.

Algorithm starts with reading the system data and calculation of initial power loss. Loops on the system are identified. To calculate power loss with analytical equation and its derivation, spot loads are converted to a continuous function with using a curve fitting function. This is to create curves from branch current and resistance data. Once it is assumed all the current flow from the beginning of loop to

the end (last line is not connected) and a curve is fitted for branch currents. Then it is assumed all the current flows from the end of the loop (first line of loop is not connected) and a curve is fitted for branch currents. This is to get the branch current information in case this loop is opened from the point s . For line resistances same procedure is followed. Therefore, power loss expression could be written as a continuous function of x to make it possible to derive and find the $x=s$ value that makes power loss minimum. Here, x is between zero and length of loop and gives the location of switch to open, s . Then new power loss is calculated for the new configuration.

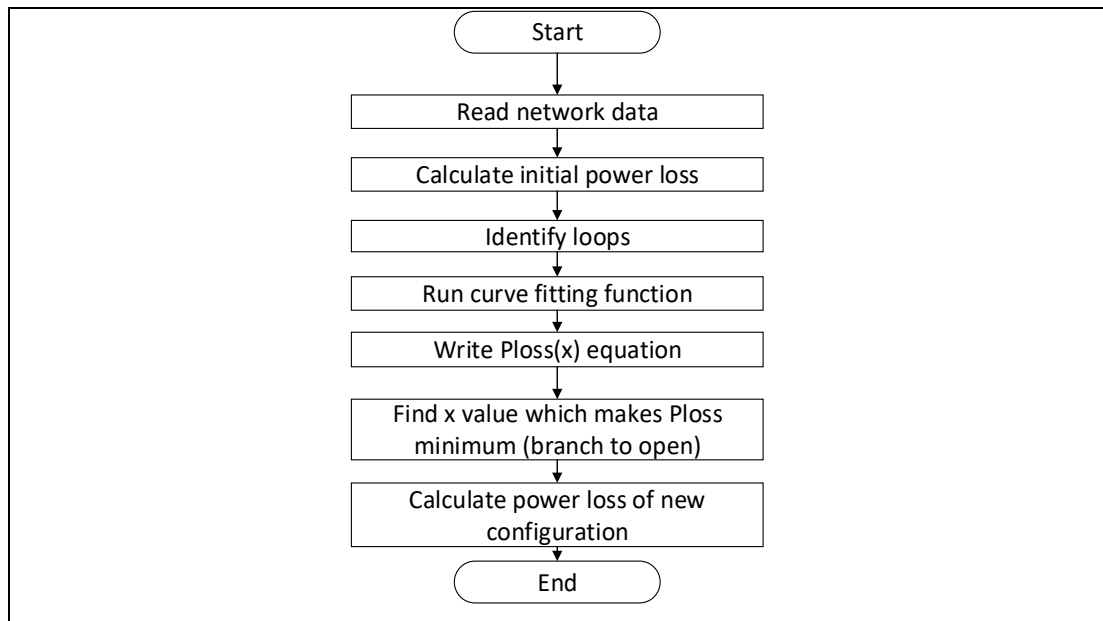


Figure 2.4: Flowchart of analytical approach.

A simple 8 bus system is given in Figure 2.5 to clarify this method. Here P_{loss1} is a constant value as it is sum of losses at each line. For the loop power losses are written as a function of x to apply analytical approach.

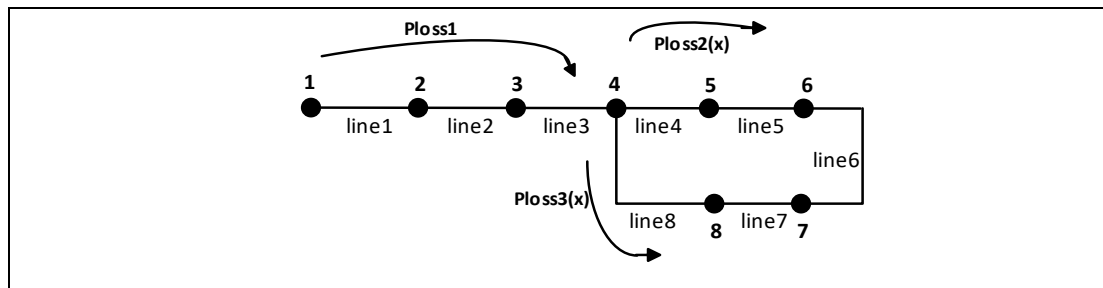


Figure 2.5: A sample 8 bus system.

Polynomial curves are fitted for discrete values of line currents and line resistances in a loop. Each line current is the sum of bus currents of the branch connected to that line. To write losses, $P_{loss2}(x)$ and $P_{loss3}(x)$, as a continuous function the system is represented in Figure 2.6 and Figure 2.7 showing direction of current flows, Branchcurrent1 and Branchcurrent2.

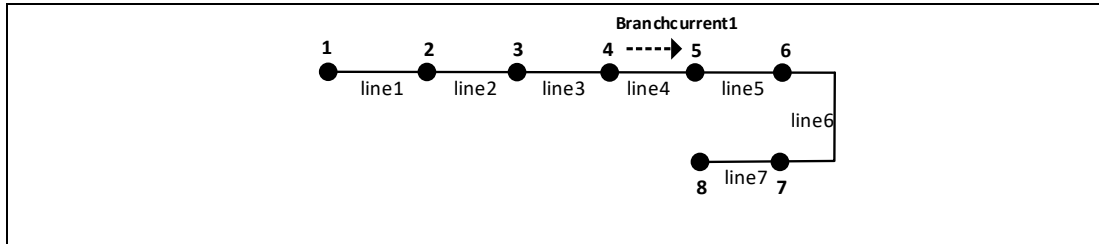


Figure 2.6: 8 bus system representation for BranchCurrent1.

For BranchCurrent1 it is assumed that line8 is not connected as in Figure 2.6. Data for BranchCurrent1 and resistances of lines, $Res1$, are given on Table 2.1.

Table 2.1: 8 bus system data for P_{loss2} .

	line4	line 5	line 6	line 7	line 8
$Res1$	$R4$	$R5$	$R6$	$R7$	$R8$
BranchCurrent1	$I5+I6+I7+I8$	$I6+I7+I8$	$I7+I8$	$I8$	0

Similarly, for BranchCurrent2 line 4 is not connected as in Figure 2.7 and the data to use for curve fitting is given on Table 2.2.

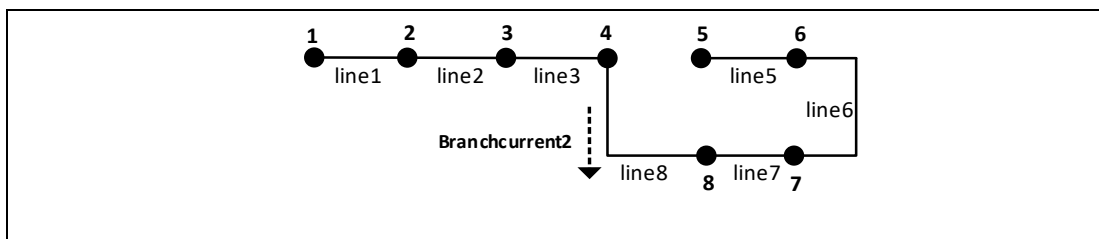


Figure 2.7: 8 bus system representation for BranchCurrent2.

Table 2.2: 8 bus system data for Ploss3.

	line 8	line 7	line 6	line 5	line 4
Res2	R8	R7	R6	R5	R4
BranchCurrent2	I8+I7+I6+I5	I7+I6+I5	I6+I5	I5	0

Power loss equation for Figure 2.5 can be written as follows:

$$Ploss(x) = Ploss1 + Ploss2(x) + Ploss3(x) \quad (2.19)$$

Ploss1 is given in equation (2.20).

$$\begin{aligned} Ploss1 = & R1(I2 + I3 + I4 + I5 + I6 + I7 + I8)^2 \\ & + R2(I3 + I4 + I5 + I6 + I7 + I8)^2 \\ & + R3(I4 + I5 + I6 + I7 + I8)^2 \end{aligned} \quad (2.20)$$

Ploss2(x) is defined in equation (2.21). Here, L is length of loop and power loss is written as a function of x which indicates a point on the loop. Res1(x) which is resistances of branches and BranchCurrent1(x) which represents currents of branches are obtained using equations (2.22) and (2.23) respectively as polynomial expressions.

$$Ploss2(x) = Res1(x)(BranchCurrent1(L - x))^2 \quad (2.21)$$

$$Res1(x) = a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0 \quad (2.22)$$

$$\begin{aligned} BranchCurrent1(l - x) \\ = b_n (l - x)^n + b_{n-1} (l - x)^{n-1} + \dots + b_1 (l - x) + b_0 \end{aligned} \quad (2.23)$$

Similarly, Ploss3 is given as

$$Ploss3(x) = Res2(x)(BranchCurrent2(x))^2 \quad (2.24)$$

where Res2 and Branch Current2 are written as

$$Res2(x) = c_n x^n + c_{n-1} x^{n-1} + \dots + c_1 x + c_0 \quad (2.25)$$

$$BranchCurrent2(x) = d_n(x)^n + d_{n-1}(x)^{n-1} + \dots + d_1(x) + d_0 \quad (2.26)$$

$$\frac{d}{dx} P_{loss}(x) = 0 \quad (2.27)$$

Solution of equation (2.27) is calculated using (2.19) to obtain switch location x which minimizes power loss. Decision of line to open is given by a condition check for given 8 bus system as

$$\begin{array}{llll} \text{if} & 0 \leq x < 1 & \text{open} & \text{line 4} \\ & 1 < x < 2 & \text{open} & \text{line 5} \\ & 2 < x < 3 & \text{open} & \text{line 6} \\ & 3 < x < 4 & \text{open} & \text{line 7} \\ & 4 < x \leq 5 & \text{open} & \text{line 8} \end{array} \quad (2.27)$$

For 8 bus system length of loop, L , is equal to 5 so x is between 0 and 5. If x is equal to 1, 2, 3 or 4 which are the locations of busses, related two lines are open and power loss is calculated for each. Results are compared and the line that make power loss minimum is chosen to open.

2.3. Analysis and Results

A 12 bus system [87] with one tie line from bus 2 to bus 12 is shown in Figure 2.8. It is assumed that line resistances and bus loads are equal. Loads are taken as current injections and branch currents of each line are calculated as sum of related bus loads. To implement proposed method, curves are fitted according to loop data on Table 2.3.

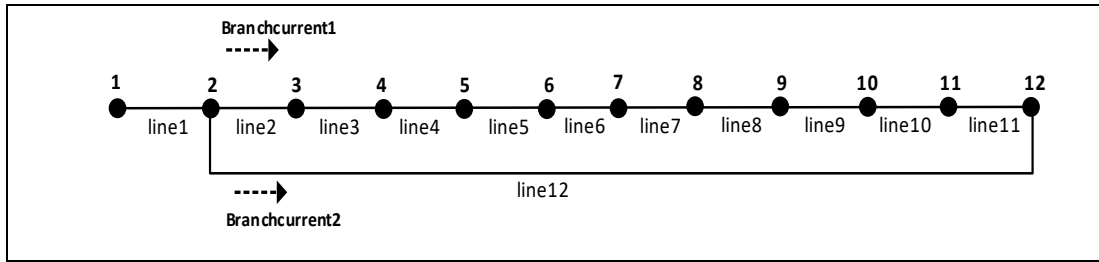


Figure 2.8: 12 bus system version I.

Curves of branch currents and line resistances as function of x is obtained by MATLAB curve fitting function “polyfit” and plotted as in Figure 2.9.

Table 2.3: Data I for 12 bus system version I.

	Res1 (pu)	BranchCurrent1	Res2 (pu)	BranchCurrent2
line2	0.00019	0.362	0.00019	0
line3	0.00019	0.3258	0.00019	0.0362
line4	0.00019	0.2896	0.00019	0.0724
line5	0.00019	0.2534	0.00019	0.1086
line6	0.00019	0.2172	0.00019	0.1448
line7	0.00019	0.181	0.00019	0.181
line8	0.00019	0.1448	0.00019	0.2172
line9	0.00019	0.1086	0.00019	0.2534
line10	0.00019	0.0724	0.00019	0.2896
line11	0.00019	0.0362	0.00019	0.3258
line12	0.00019	0	0.00019	0.362

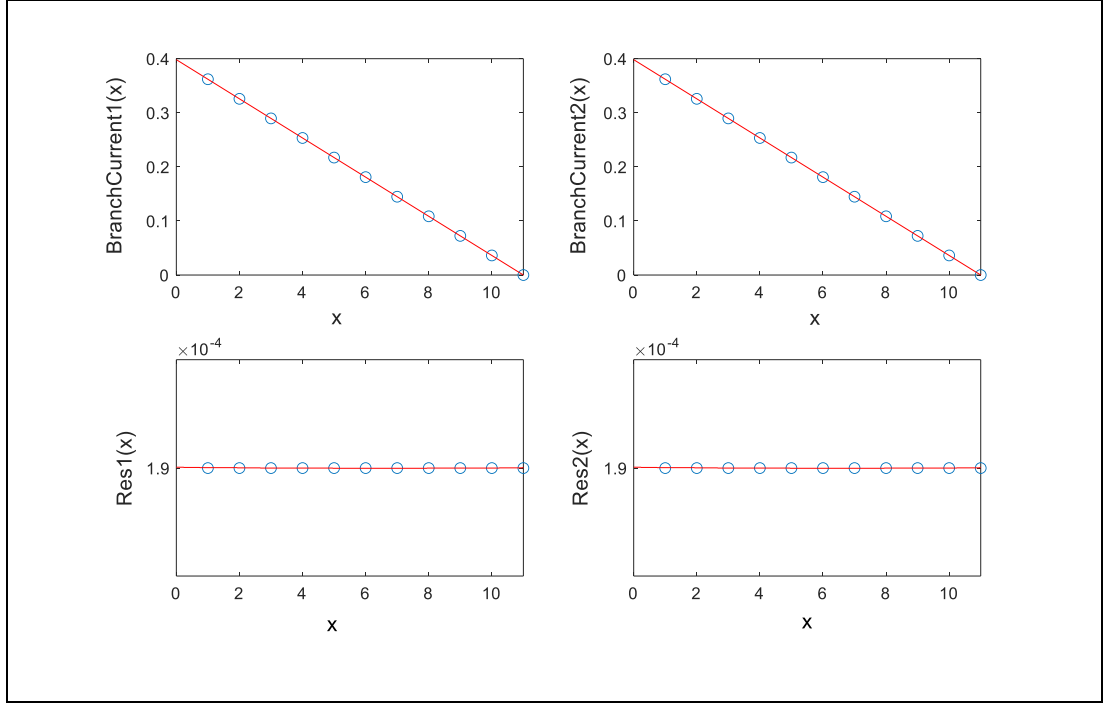


Figure 2.9: Branch currents and line resistances curves according the Table 2.3.

The loop has 11 lines and total power loss, $\text{Ploss}(x)$ function is written as takes its minimum value when $x=5.5$. In Figure 2.10, $\text{Ploss}(x)$ curve for the loop and the minimum value is shown. x is between $5 < x < 6$ which refers to line7, should be open to get minimum power loss.

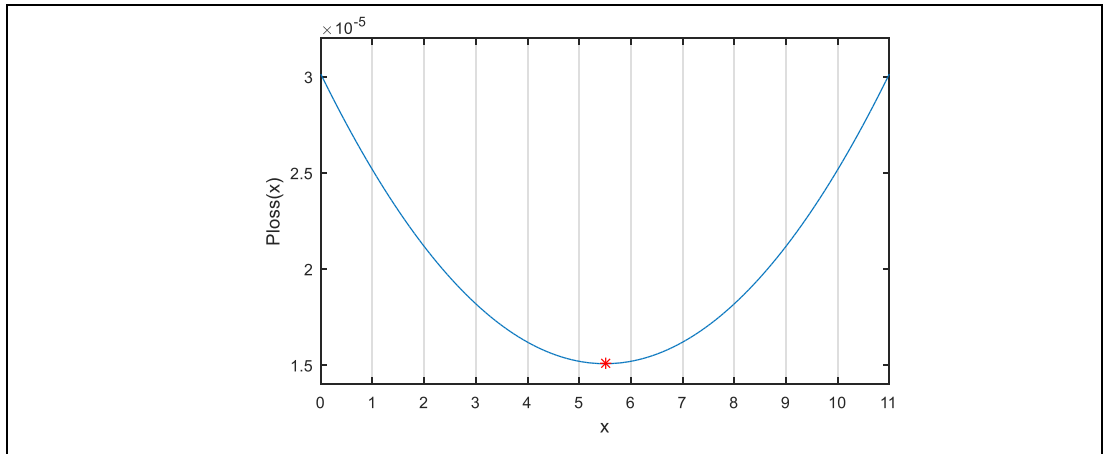


Figure 2.10: Power loss curve of 12 bus system version I with data I.

The same 12 bus system in Figure 2.8 with the following line resistance and branch current data is used to examine the method.

Table 2.4: Data II for 12-bus system version I.

	Res1 (pu)	BranchCurrent1	Res2 (pu)	BranchCurrent2
line2	0.000090	0.37500	0.000090	0
line3	0.000098	0.33500	0.000098	0.04000
line4	0.000173	0.28000	0.000173	0.09500
line5	0.000263	0.25000	0.000263	0.12500
line6	0.000090	0.23000	0.000090	0.14500
line7	0.000083	0.17500	0.000083	0.20000
line8	0.000364	0.13000	0.000364	0.24500
line9	0.000466	0.09000	0.000466	0.28500
line10	0.000239	0.05500	0.000239	0.32000
line11	0.000125	0.01500	0.000125	0.36000
line12	0.000102	0	0.000102	0.37500

The curves for branch currents and resistances are shown in Figure 2.11.

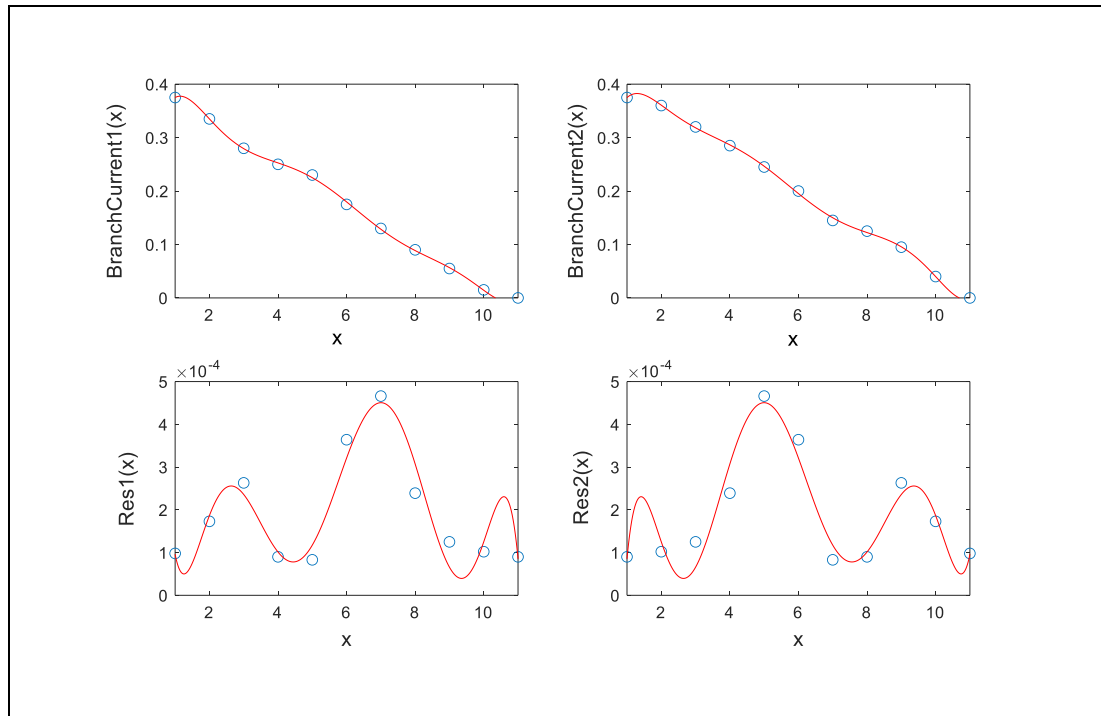


Figure 2.11: Branch currents and line resistances curves according the Table 2.4.

The extremum points for created power loss equation is shown in Figure 2.12. The points that make power loss negative aren't considered and $x=5.8$ has the minimum power loss among other solutions. The x value refers line7. With opening line7, new configuration gives the minimum power loss. After decision of new configuration of system power loss is calculated with Distribution Systems Power Flow Analysis Package (DSPFAP) [88]. Power loss for the base case, line12 does not exist (no loop), is 0.02069MW. Power loss of new configuration (line12 closed, line7 open) decrease to 0.00754MW.

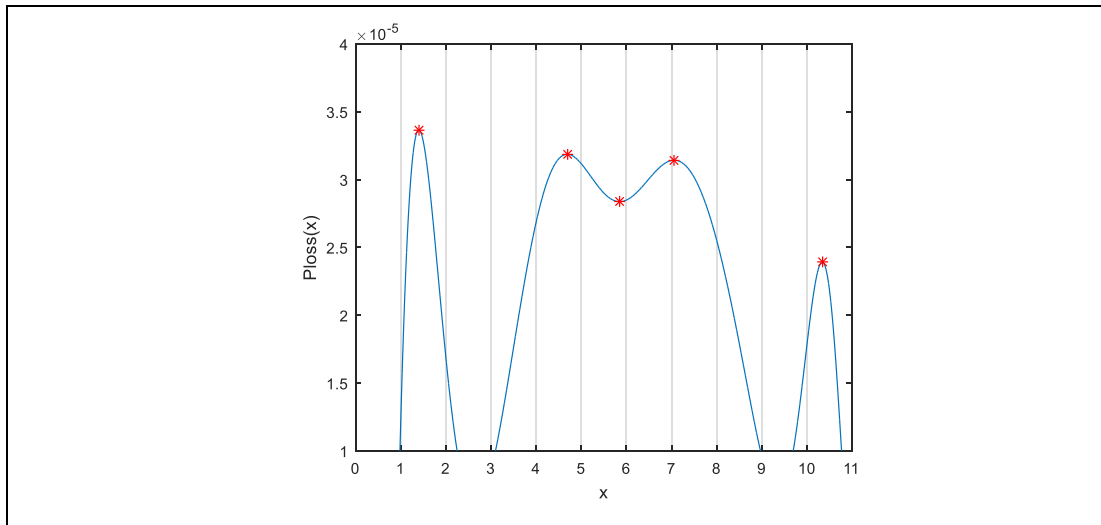


Figure 2.12: Power loss curve of 12 bus system version I with data II.

It is possible to deal loops as in Figure 2.13 in any system. Here, line8 has the sum of bus currents of bus 9, 10, 11 and 12.

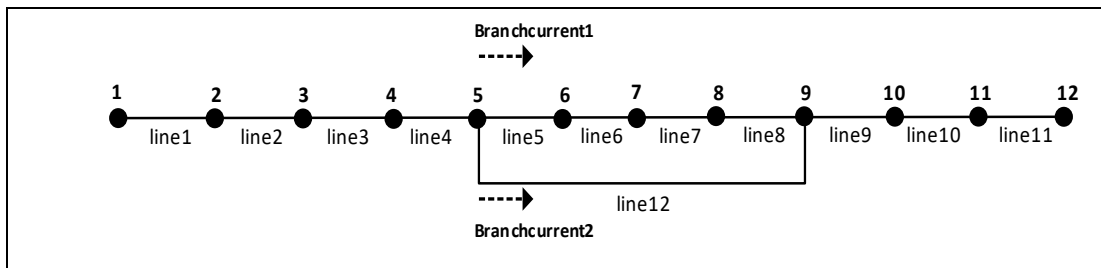


Figure 2.13: 12 bus system version II.

The branch current and line resistance data of the loop are shown in Figure 2.14. In Figure 2.15, $P_{loss}(x)$ takes the minimum value when $x=1.8$. And opening line 8 as solution refers, gives the largest decrease in power loss of system as 0.00481 MW.

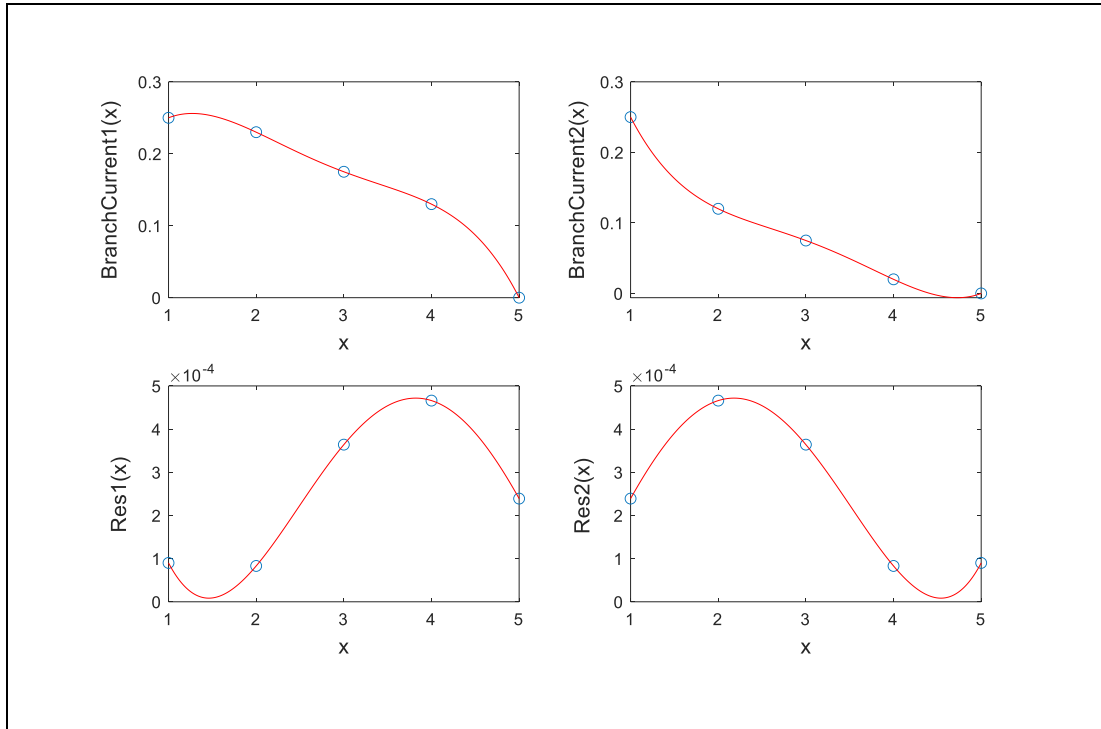


Figure 2.14: Branch currents and line resistances curves for 12 bus system version II.

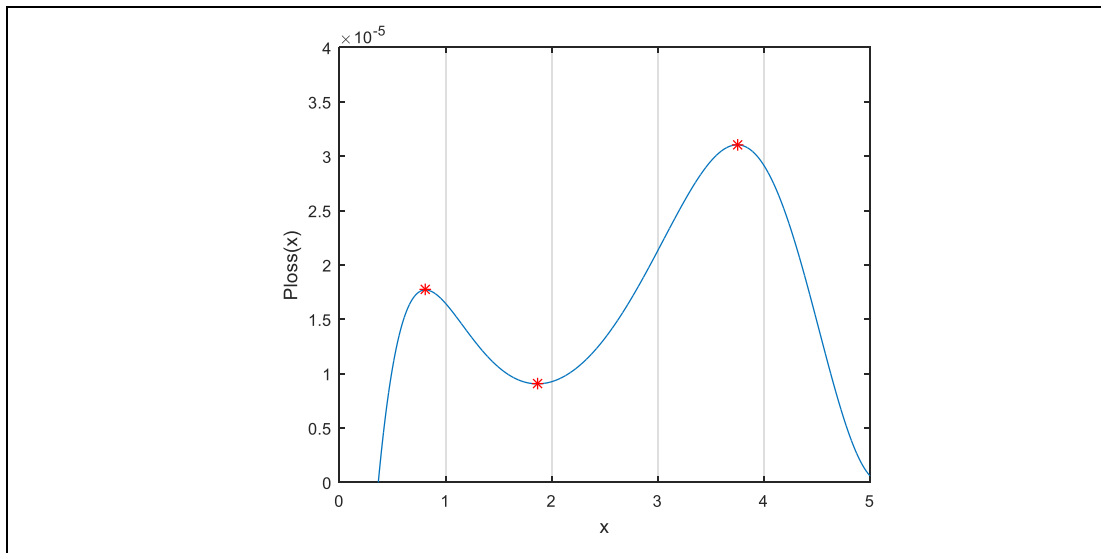


Figure 2.15: Power loss curve of 12 bus system version II.

Proposed analytical approach is applied for a 12 bus system with distributed loads and spot loads. For both cases it provides the new configuration with minimum power loss and results are confirmed by calculating power loss of all configurations.

2.4. Conclusion

The proposed method for reconfiguration problem is a study for an analytical approach. It is developed based on distributed load profiles and adapted to a system with spot loads. Distributed load profiles are used for understanding the concept of state-of-art with analytical approach. It is applicable as long as load and line data of system is represented as continuous functions.

However, the margin of error of the curve-fitting process to write the power loss function as an analytical expression takes this approach away from analyticity. It has been seen that it is a laborious task to make the power loss expression differentiable by making the line currents and resistances a continuous function depending on the length of the loops. In addition, it has been discovered that it is quite difficult to implement this method for more complex and large systems with multiple tie switches that may create multiple loops.

Nevertheless, developing a better curve fitting process with less error may give better results for larger system. Also, a sequential switching procedure for multiple loops may ease the implementation of method for more complex systems, left for future work.

3. SENSITIVITY INDEX BASED APPROACH FOR RECONFIGURATION

In the previous chapter, an analytical approach for reconfiguration problem is introduced. Loops are created by closing tie switches of system, then loads and line data on the loop is written as a continuous function. Curve fitting is done for spot loads and line resistances to rewrite power loss equation as a function of x which shows the position of tie switch. As results fall behind expectations of progress of method for larger networks, studies are carried out to develop a method with less calculation burden.

Heuristic approaches are based on technical criteria and try to find a solution by technical strategies. It has been widely used in reconfiguration studies mainly due to the reason that these methods always give fast reconfiguration results and are simple to formulate. However, heuristic approaches are not necessarily always reach the global optimum solution [8].

Here, a sensitivity index based heuristic method is examined to identify the position of the open switch in a loop. The main aim is to introduce a fast method with simple calculations that can be used for loss reduction where globally optimum solution is not necessarily needed. In [89], based on exact loss formula of Elgerd [90], an analytical method and loss sensitivity index method were developed to obtain the most appropriate location and size of distributed generators. The same loss index is decided to be used for placing tie switches, considering that bus powers have high impact on topology changes. As the index requires only one power flow to obtain networks information and have a basic formula with two components, it is expected to be convenient for a better heuristic method compare to previous studies in terms of calculation time and simplicity.

3.1. Sensitivity Index Method (SIM)

The real power loss in a system can be defined as in equation (3.1). It is known as exact loss formula [89].

$$P_{loss} = \sum_{k=1}^N \sum_{j=1}^N [\alpha_{kj}(P_k P_j + Q_k Q_j) + \beta_{kj}(Q_k P_j + P_k Q_j)] \quad (3.1)$$

Here P_j and Q_j are real and reactive power of bus j . N refers to bus number. α and β are given as follows:

$$\alpha_{kj} = \frac{r_{kj}}{V_k V_j} \cos(\delta_k - \delta_j) \quad \beta_{kj} = \frac{r_{kj}}{V_k V_j} \sin(\delta_k - \delta_j) \quad (3.2)$$

where $r_{kj} + jx_{kj} = Z_{kj}$ is the element kj of impedance matrix. V_k is voltage magnitude and δ_k is voltage angle of bus k . Equation (3.1) is expanded as in (3.3) to derivate respect to P_i .

$$\begin{aligned} P_{loss} = & \sum_{\substack{k=1 \\ k \neq i}}^N \sum_{\substack{j=1 \\ j \neq i}}^N [\alpha_{kj}(P_k P_j + Q_k Q_j) + \beta_{kj}(Q_k P_j + P_k Q_j)] \\ & + \sum_{\substack{k=1 \\ k \neq i}}^N [\alpha_{ki}(P_k P_i + Q_k Q_i) + \beta_{ki}(Q_k P_i + P_k Q_i)] \\ & + \sum_{\substack{j=1 \\ j \neq i}}^N [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j + P_i Q_j)] \\ & + [\alpha_{ii}(P_i P_i + Q_i Q_i) + \beta_{ii}(Q_i P_i + P_i Q_i)] \end{aligned} \quad (3.3)$$

Derivation steps of power loss equation (3.3) respect to active power of bus i is given through equation (3.4) - (3.6) as sensitivity index.

$$\frac{\partial P_{loss}}{\partial P_i} = \sum_{\substack{k=1 \\ k \neq i}}^N (\alpha_{ki} P_k - \beta_{ki} Q_k) + \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij} P_j - \beta_{ij} Q_j) + 2(\alpha_{ii} P_i) \quad (3.4)$$

Using $\cos(x) = \cos(-x)$ and $\sin(x) = \sin(-x)$ definitions and symmetrical characteristic of impedance matrix the derivation can be written as

$$\frac{\partial P_{loss}}{\partial P_i} = 2 \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij}P_j - \beta_{ij}Q_j) + 2(\alpha_{ii}P_i) \quad (3.5)$$

β_{ii} is equal to zero as $(\sin(\delta_i - \delta_i))$ is zero. Finally, the derivation is given in equation (3.6).

$$\frac{\partial P_{loss}}{\partial P_i} = 2 \sum_{j=i}^N (\alpha_{ij}P_j + \beta_{ij}Q_j) \quad (3.6)$$

This equation is derived for distributed generation (DG) allocation problem. Most sensitive bus is chosen as the location of DG to reduce related bus power and minimize power loss. In reconfiguration problem, it is used for meshed network considering bus power impact on network topology. Power loss sensitiveness of a bus is used for decision to open a branch in a meshed network. Line losses of branches which are connected to the most sensitive bus are compared and the one with smaller loss value is opened to obtain loss reduction.

To choose best topology that makes power loss minimum, all tie switches are closed, and power flow analysis is performed for fully meshed network. Sensitivity indices are evaluated for each bus using power flow results. A loop is chosen, and busses are ranked in descending order according to sensitivity indices. The most sensitive bus in a loop is identified and losses of lines connected to it are checked, the line with the lowest loss value is opened. These steps are shown in Figure 3.1 as a flowchart.

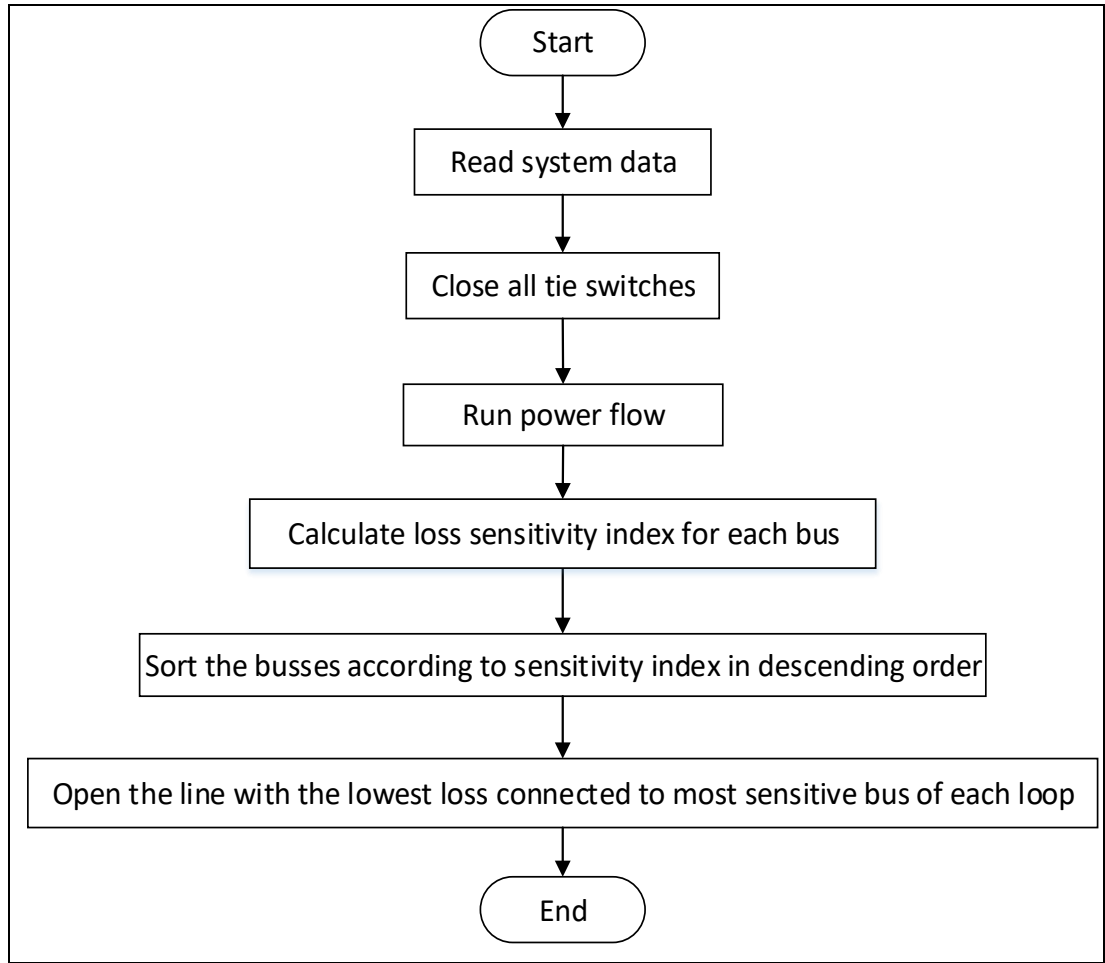


Figure 3.1: Flowchart of sensitivity index based algorithm for reconfiguration.

3.2. Analysis and Results

The algorithm for sensitivity index based approach is applied to 12 bus [87], 33 bus [2] and 69 bus [91] systems. All tie switches of systems are closed, and loops are created. Then, a power flow analysis is performed using MATPOWER [92]. Sensitivity index is calculated for each bus and loops are evaluated individually to obtain results.

3.2.1. 12 Bus System

12 bus system is used for reconfiguration analysis. The system is modified with several tie lines to create loops. Loads are assumed to be equal at each bus and line

parameters are taken identical for initial analysis. 12 bus system with one loop is shown in Figure 3.2.

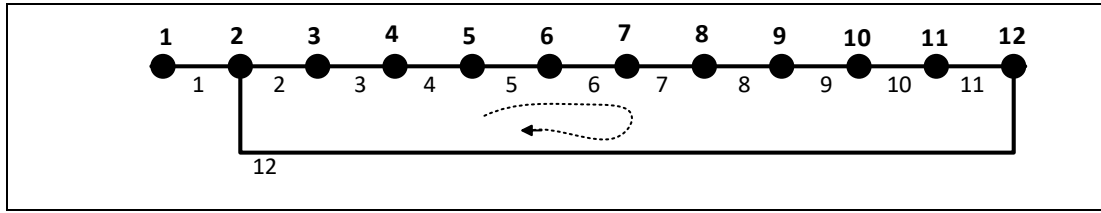


Figure 3.2: A sample system 12bus_1.

Sensitivity index value of each bus is shown in Figure 3.3. The most sensitive bus is 8 and lines connected to bus 8 are line 7 and 8. The line with smaller loss value as shown on the table in Figure 3.3, line 7 is opened. As the loads and line values are equal, system is separated two equal branches by opening line 7.

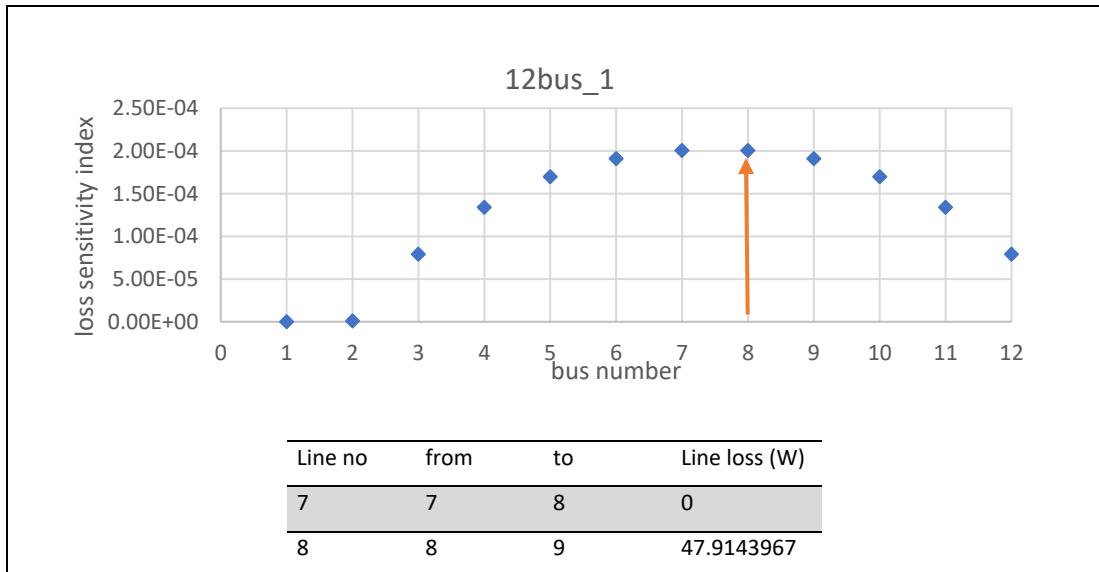


Figure 3.3: Reconfiguration result of 12bus_1 system.

Two lines as tie lines are added to 12 bus system to create 2 different loops. A power flow is performed for this topology of system. Sensitivity index values are compared within selected loop.

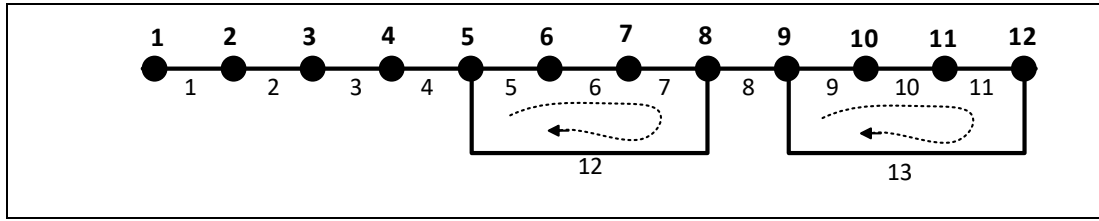


Figure 3.4: A sample system 12bus_2.

In Figure 3.5 and Figure 3.6 results of loop 12 and 13 is given. The loop created by adding line 12 includes bus 5, 6, 7 and 8. The most sensitive one among them is bus 8, and the line with smaller loss value is 7 as given in Figure 3.5. Similarly, for loop 13 the most sensitive bus is 11 among bus 9, 10, 11 and 12. The lines connected to bus 11 is line 10 and line 11. The one with smaller loss value is line 11 as shown in Figure 3.6.

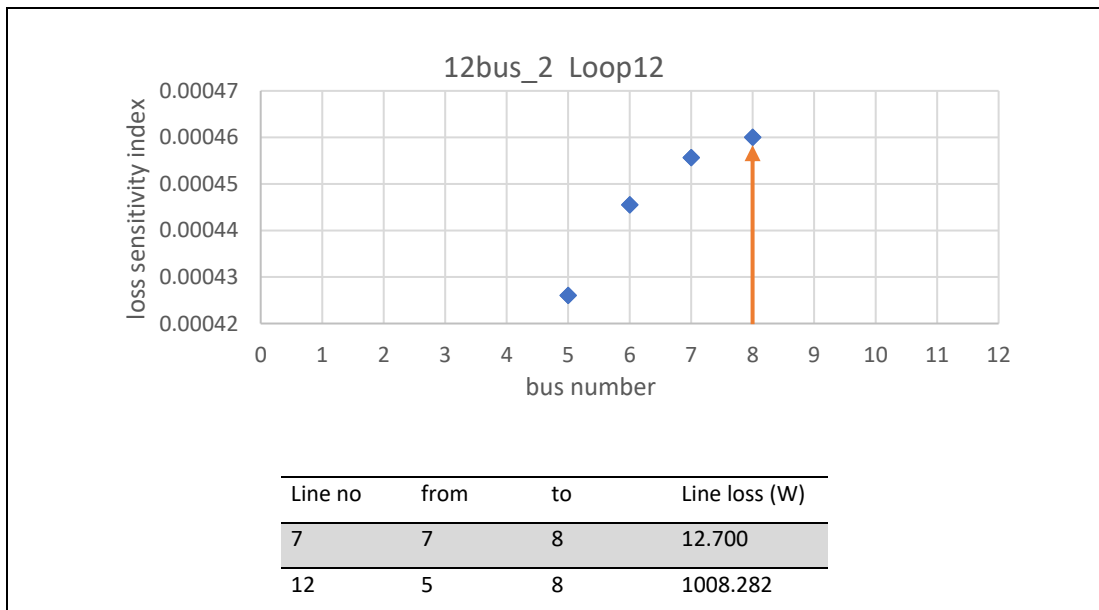


Figure 3.5: Reconfiguration result of 12bus_2 system for Loop12.

First, system has become meshed by closing tie switches 12 and 13. Then sensitivity index is calculated to decide which line to open. The new configuration to minimize total power loss for Figure 3.4 is obtained by opening line 7 and 11. By performing this switching, system remains radial in final configuration.

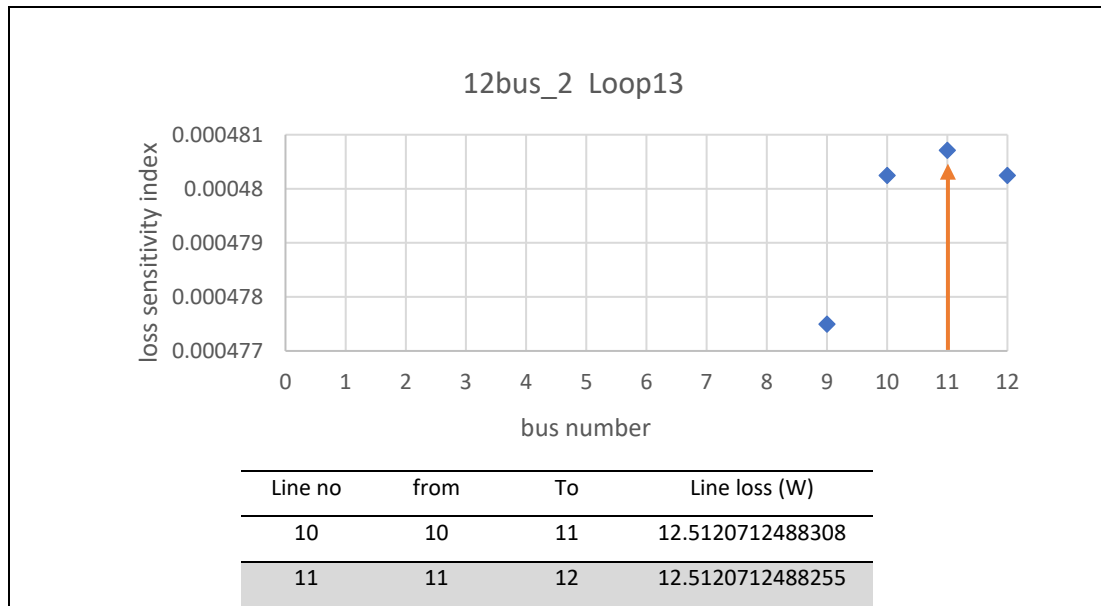


Figure 3.6: Reconfiguration result of 12bus_2 system for Loop13.

In distribution networks, location of tie switches is commonly created loops in a loop as in Figure 3.7. As the power flow is performed for mesh system, loops are considered as shown by dotted lines in figure. For example, loop 13, which is formed by closing line 13, consist of buses 2, 5, 6, and 7.

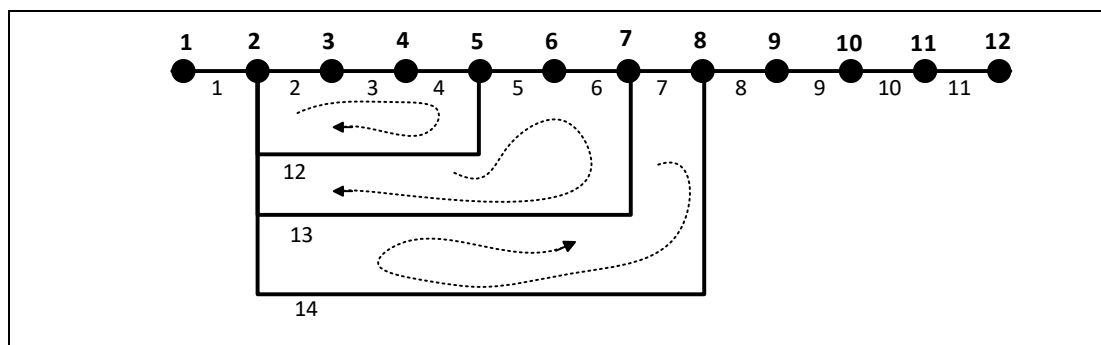


Figure 3.7: A sample system 12bus_3.

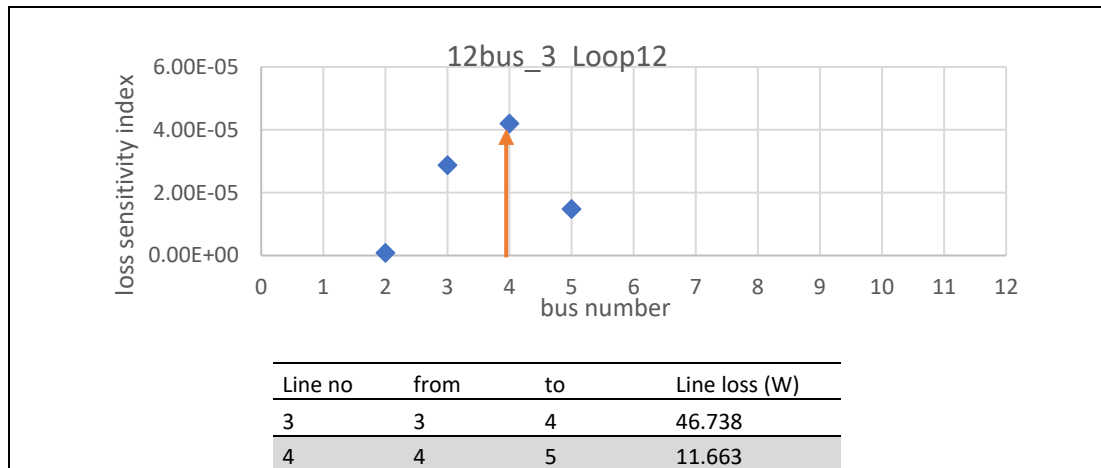


Figure 3.8: Reconfiguration result of 12bus_3 system for Loop12.

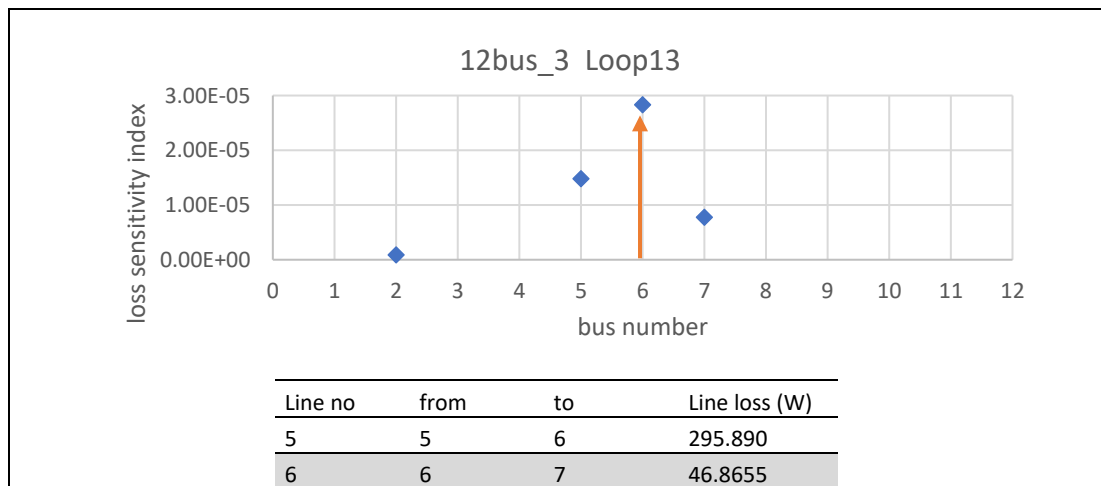


Figure 3.9: Reconfiguration result of 12bus_3 system for Loop13.

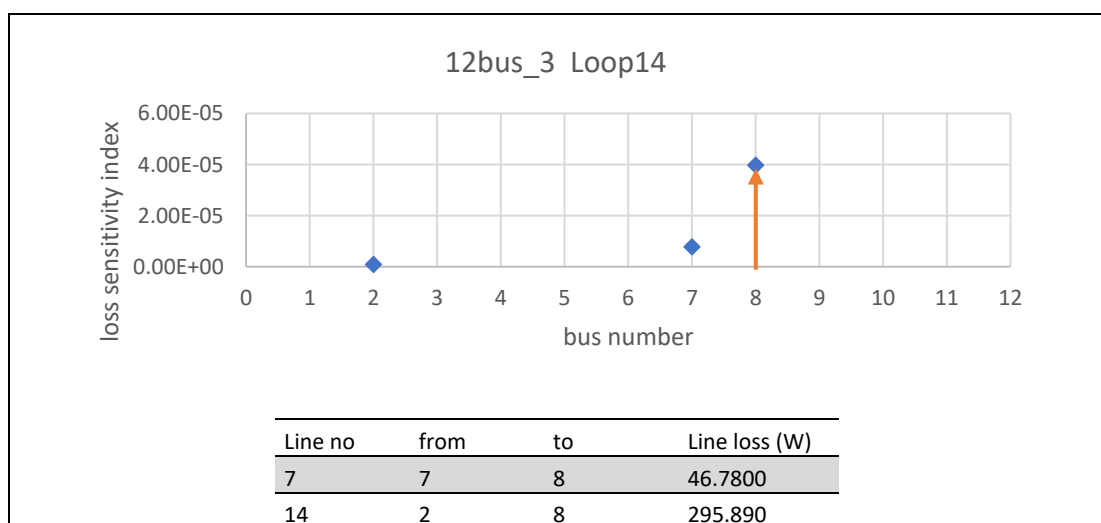


Figure 3.10: Reconfiguration result of 12bus_3 system for Loop14.

and line 36 which is same as the tie switch is opened. Switch 34 is forms the Loop5 and line 14 is opened to reduce losses. Tie switches 36 and 37 remains open which means reducing power losses by closing them is not likely to happen.

Results of SIM is also given in Figure 3.12. The graphics give the sensitivity index values of busses in each loop as tables show the line data connected to the most sensitive bus.

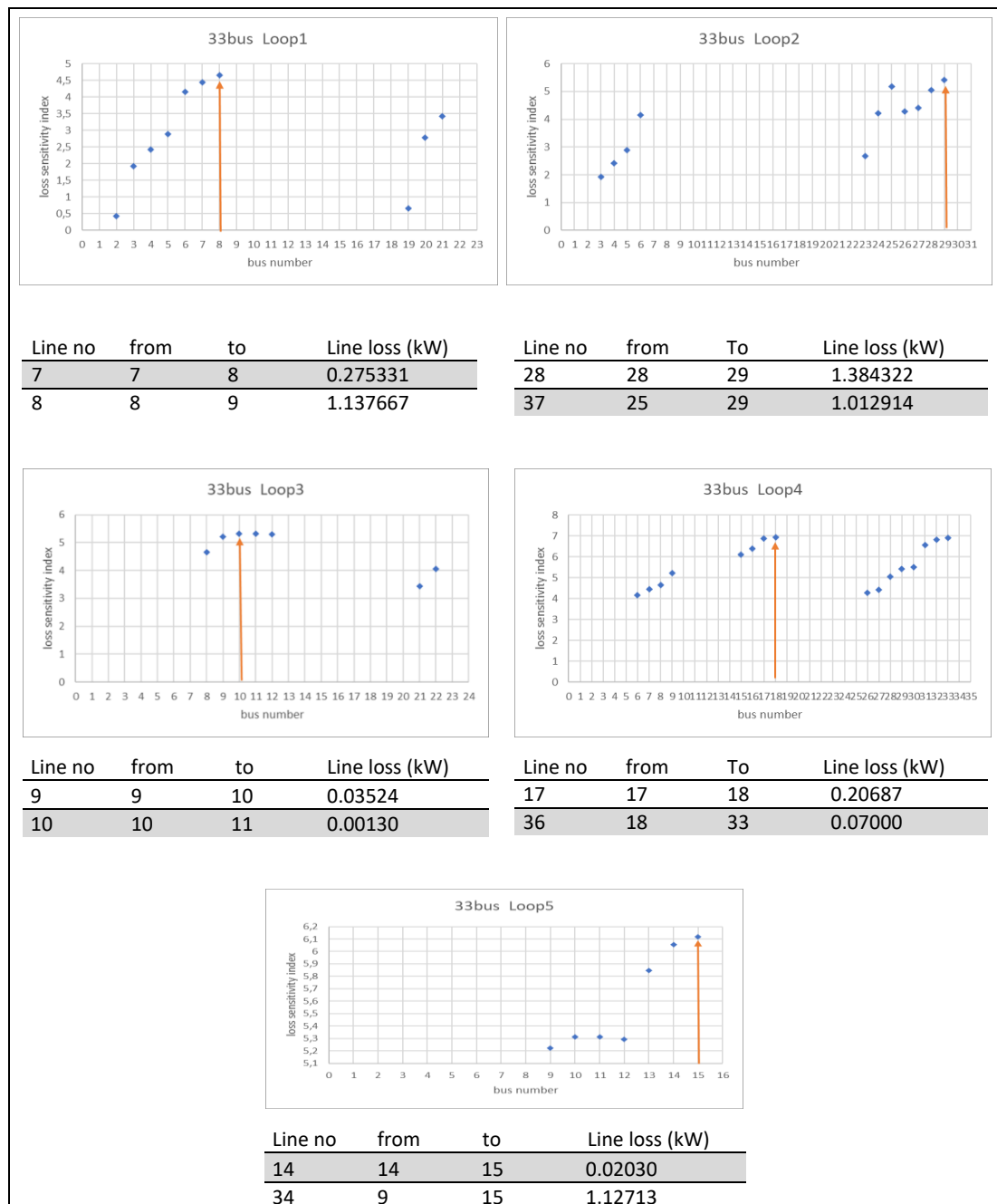


Figure 3.12: Reconfiguration results of 33 bus system with SIM.

In new configuration of 33 bus system, branches 7, 10, 14, 36, and 37 are opened. Power loss of 33 bus system is 202.67 kW for base configuration, and after reconfiguration it becomes 142.0 kW. Bus voltage profile of 33 bus system before and after reconfiguration is given in Figure 3.13. Minimum bus voltage is improved from 0.91 pu to 0.93 pu.

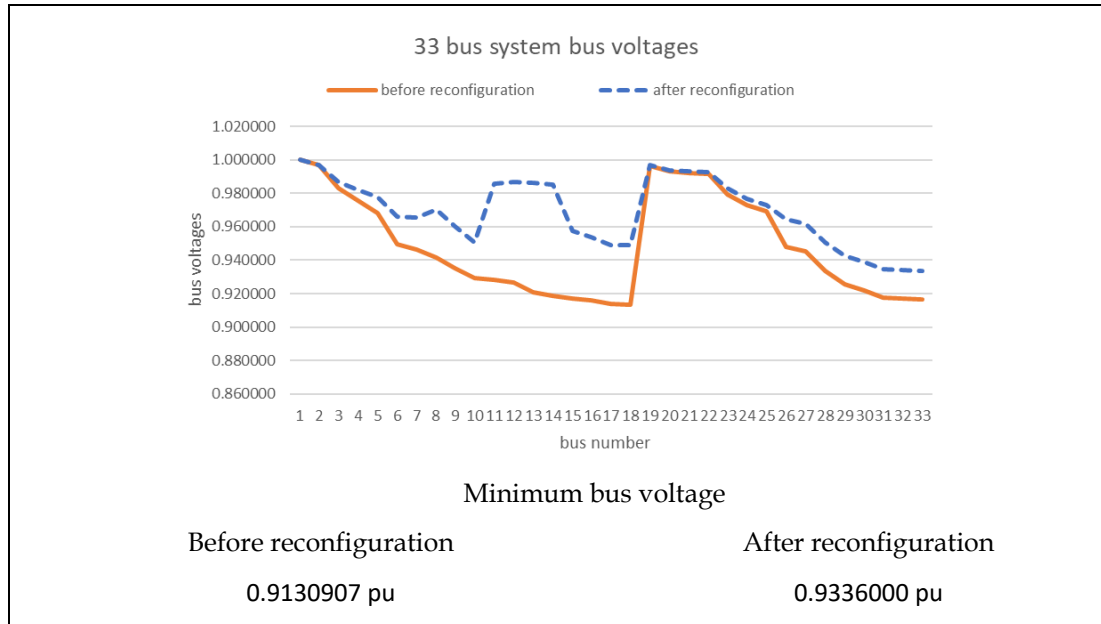


Figure 3.13: Bus voltages of 33 bus system for SIM.

SIM provides solution to reconfiguration problem with reducing power loss 30% and improving voltage profile for 33 bus system.

3.2.3. 69-Bus System

69 bus system has 5 tie switches as shown in Figure 3.14. First a power flow analysis of system is done after all tie switches is closed, then sensitivity index is calculated for each bus.

Sensitivity index of busses in each loop are identified and plotted. The most sensitive ones and lines related to it are given in Figure 3.15.

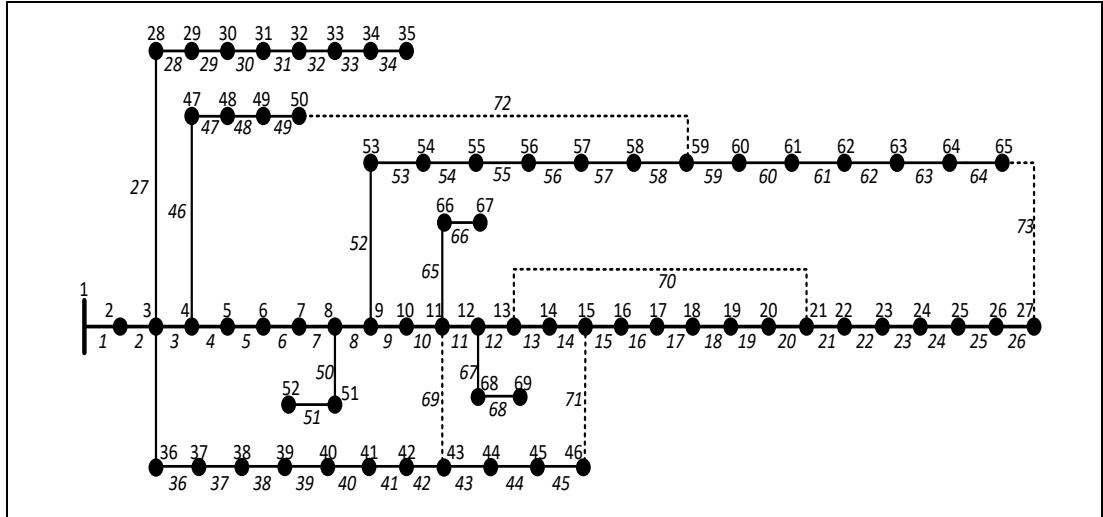


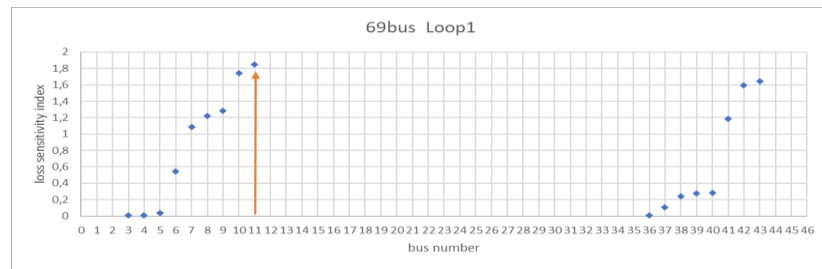
Figure 3.14: 69 bus system.

Loop1 is formed by closing tie switch 69 and the most sensitive bus for this loop is identified as 11. The lines 10 and 69 are connected to the most sensitive bus and the one with smaller loss value, line 69 is opened. Loop 2 is formed by closing tie switch 71 and the most sensitive bus of the loop is 13. Losses of line 12 and 13 are compared and line 13 is opened due to its lower line loss value. Loop 3, Loop4, and Loop 5 are formed by closing tie switches 70, 73, and 72. Same steps are followed and most sensitive buses of Loop 3, 4 and 5 are identified as 21, 61, and 59 respectively. Line loss values connected to the most sensitive bus are compared in each loop and final configuration is obtained.

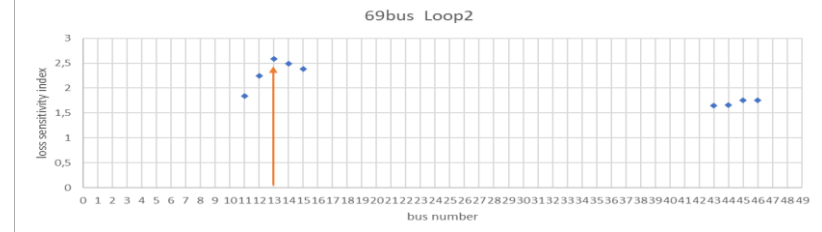
The new configuration for 69 bus to minimize total power has lines 13, 20, 58, 61, and 60 open instead of line 69, 70, 71, 72, 73.

Power loss of 69 bus system is 224.9 kW for base configuration, and after reconfiguration it becomes 104.87 kW.

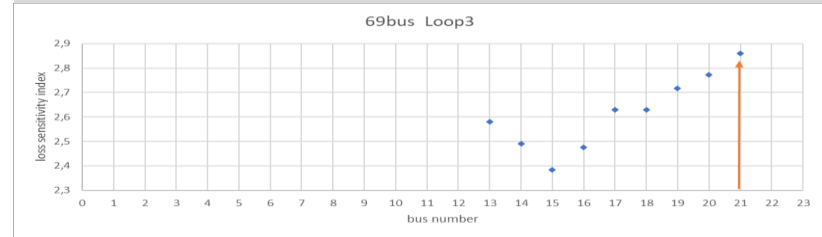
Bus voltages before and after reconfiguration is given in Figure 3.16. Minimum bus voltage is improved from 0.90 to 0.94 pu.



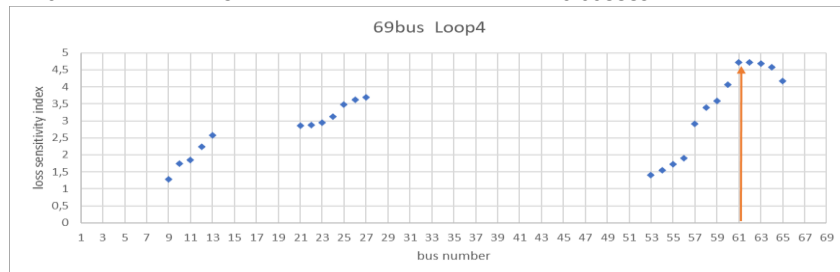
Line no	from	to	Line loss (kW)
10	10	11	0.392259
69	11	43	0.302775



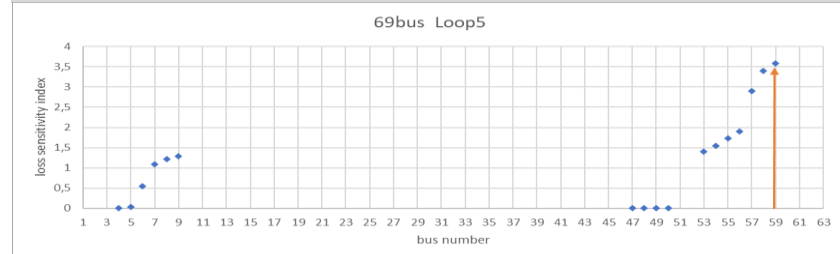
Line no	from	to	Line loss (kW)
12	12	13	0.762
13	13	14	0.091



Line no	from	to	lineloss
20	20	21	0.17302
70	13	21	0.608889



Line no	from	to	Line loss (kW)
60	60	61	6.969
61	61	62	0.007



Line no	from	to	Line loss (kW)
58	58	59	0.81113
72	50	59	12.526738

Figure 3.15: Reconfiguration result of 69 bus system with SIM.

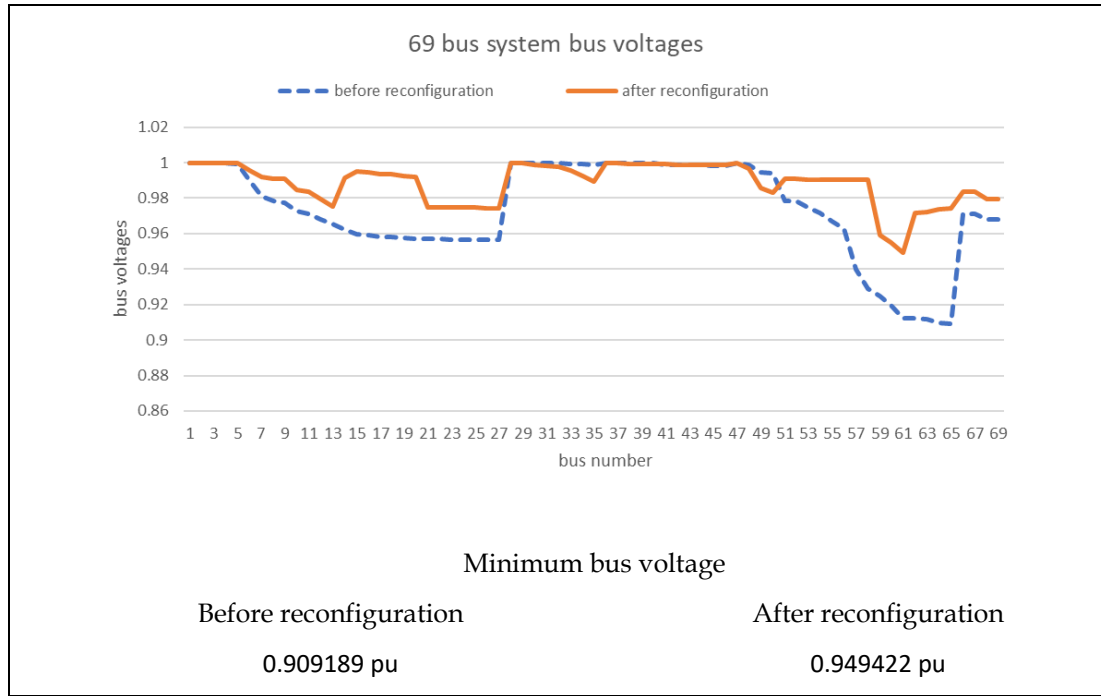


Figure 3.16: Bus voltages of 69 bus system.

Power loss of 69 bus system is reduced by 53% with the new configuration obtained by SIM. And reconfiguration provides an improvement on bus voltages.

3.3. Conclusion

A sensitivity index derived from exact loss formula is used to decide a better configuration for distribution network with less power loss. Once all tie switches in a system is closed and sensitivity index is calculated for all buses. The most sensitive bus in a loop is obtained and one of the branches connected to sensitive bus is opened. The branch to open selected as the one which has lower loss value. Analysis with sensitivity index approach is applied to 33 bus and 69 bus systems which are commonly used in literature. Results show that total power loss is reduced 30% for 33 bus system and 53% for 69 bus system and voltage profile is improved for both systems. Although such reduction in loss may be satisfying under certain conditions but this does not prove the method can reach global optimal solution. Reconfiguration results depend on the initial topology of the system and some possible configurations may be neglected for this reason. However, it can be said that the advantage of this method is obtaining a configuration that reduces the power loss can be reached with

noncomplex and fast calculations. It only needs one power flow to obtain initial bus voltages of system and calculate sensitivity index to reach reconfiguration results.

A bus sensitivity index is implemented for reconfiguration problem considering bus power effect on topology changes. However, a line sensitivity index that calculates power loss sensitiveness of branches may have been considered as a more effective solution method in future studies.

Moreover, the studies in literature as given on Table 1.1, present various configurations and total power loss results for 33 bus and 69 bus systems which claims to be the optimal solution and solution method. However, in order to evaluate these results in the literature, there is a need for a method that reaches the final result by trying all configurations. In chapter 5, a method is developed that tries all configurations and finds the exact solution of reconfiguration problem that minimizes power loss.

4. BUS INJECTION TO BRANCH CURRENT (BIBC) MATRIX MODIFICATION FOR RECONFIGURATION

The difficulty of applying distributed load profile based analytical approach in complex and large systems is seen in the first chapter. It is also realised that sensitivity index approach may not give the optimum result due to the dependence of the system's initial topology. Therefore, in this chapter, it is aimed to present a solution approach to the reconfiguration problem by using an analytical power loss expression, which is suitable for spot loads and includes system topology information.

In reconfiguration problem, besides its large combinatorial solution space and discrete nature of switches, changing switch status on/off with certain constraints such as radiality and continuity and representing the changed topology for further analysis are the main challenges. Most of the studies first randomly change the switch status on or off and check if the new network ensures the radial structure and continuity then, reorder the network data for power flow calculations and loss estimation. Therefore, infeasible switching operations are created and then eliminated with further controls that causes computational burden. Moreover, power loss calculations with load flow analysis are time-consuming.

Introduction of Bus Injection to Branch to Branch Current (BIBC) matrix for power flow analysis [93] and presentation of an analytical formula for power loss estimation using BIBC matrix [84] constituted the motivation of this chapter. A method is introduced for BIBC matrix modification to reflect the network topology changes which also make it possible to calculate power loss analytically.

4.1. Analytical Power Loss Calculation for Distribution Networks

Total power loss of a system can be calculated using branch currents and line resistances. Branch current and bus current injection relationship is obtained by applying KCL. Loads are assumed as constant currents. Branch currents vector B is obtained with bus current injections vector I and bus-injection to branch-current matrix $BIBC$ as in equation (4.1) [88].

$$[B]_{nb} = [BIBC]_{nb \times (n-1)} [I]_{(n-1) \times 1} \quad (4.1)$$

Here, n is number of buses, nb is number of branches, I is bus current injection vector excluding swing bus. Total power loss can be written by using R_i for the resistance of branch i and B_i for branch currents as [84]:

$$P_{loss} = \sum_{i=1}^{nb} |B_i|^2 R_i = [R]^T [BIBC][I]|^2 \quad (4.2)$$

BIBC is the matrix that shows the relationship between bus current injections (I) and branch currents (B).

To use equation (4.2) in reconfiguration, changes on system topology should be represented in the equation. Although bus current injections remain constant for the new configuration, BIBC matrix which represents the branch currents is changed. Resistance vector also need to be revised for the removed and added lines. The changes are shown in (4.3) with revised resistance vector as rR and reconfigured BIBC matrix as $rBIBC$.

$$P_{loss_r} = [rR]^T [rBIBC][I]|^2 \quad (4.3)$$

P_{loss_r} provides the power loss of reconfigured network and rR is achieved with exchanging the line resistance of removed branch with the added one. Modifying $BIBC$ matrix and building $rBIBC$ matrix will be detailed in Section 4.2.

4.1.1. BIBC matrix

Proposed BIBC matrix modification method is developed with the knowledge of forming BIBC matrix for radial networks and meshed networks. Therefore, in this section, forming BIBC matrix is explained in detail on a sample network. In Figure 4.1, a 6 bus system is given. Branch currents for 6 bus system can be obtained as in equation (4.4).

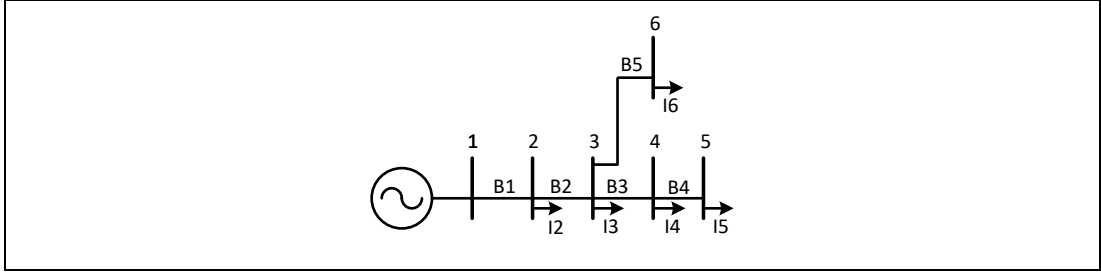


Figure 4.1: A radial distribution network.

$$\begin{aligned}
 B_5 &= I_6 \\
 B_4 &= I_5 \\
 B_3 &= I_4 + I_5 \\
 B_2 &= I_3 + I_4 + I_5 + I_6 \\
 B_1 &= I_2 + I_3 + I_4 + I_5 + I_6
 \end{aligned} \tag{4.4}$$

As it can be seen in Figure 4.1, branch currents can be stated with bus current injections. Branch 5 is connected to bus 6 in the sample network and its current is given as current of 6th bus in (4.4). Similarly, branch 4 only carries the current of 5th bus. Bus 4 and 5 is connected to branch 3 therefore, branch current B_3 is sum of bus current 4 and 5. Sum of bus currents 3, 4, 5, and 6 give the current of Branch 2. Finally, current of first branch is sum of all bus currents of whole network. Bus injections to branch current matrix, BIBC is written according to equation (4.4) and given in (4.5) [93].

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \tag{4.5}$$

Steps of building BIBC matrix with network bus and line data is given in Figure 4.2. Demonstration of BIBC building steps is given in Figure 4.3 for each branch sequentially.

Step 1. Create a matrix of size nb x (n-1) and set all elements of the matrix to zero.
(The columns of matrix represent buses other than swing bus).

Step 2. Assign 1 to k.

Step 3. Detect bus i and j which are connected to line k.

Step 4. Copy bus i column to bus j column.

Step 5. Set kth row of bus j column to "1".

Step 6. Repeat steps from 3 to 5 for each line of the system to create BIBC matrix.

Figure 4.2: Steps of building BIBC matrix.

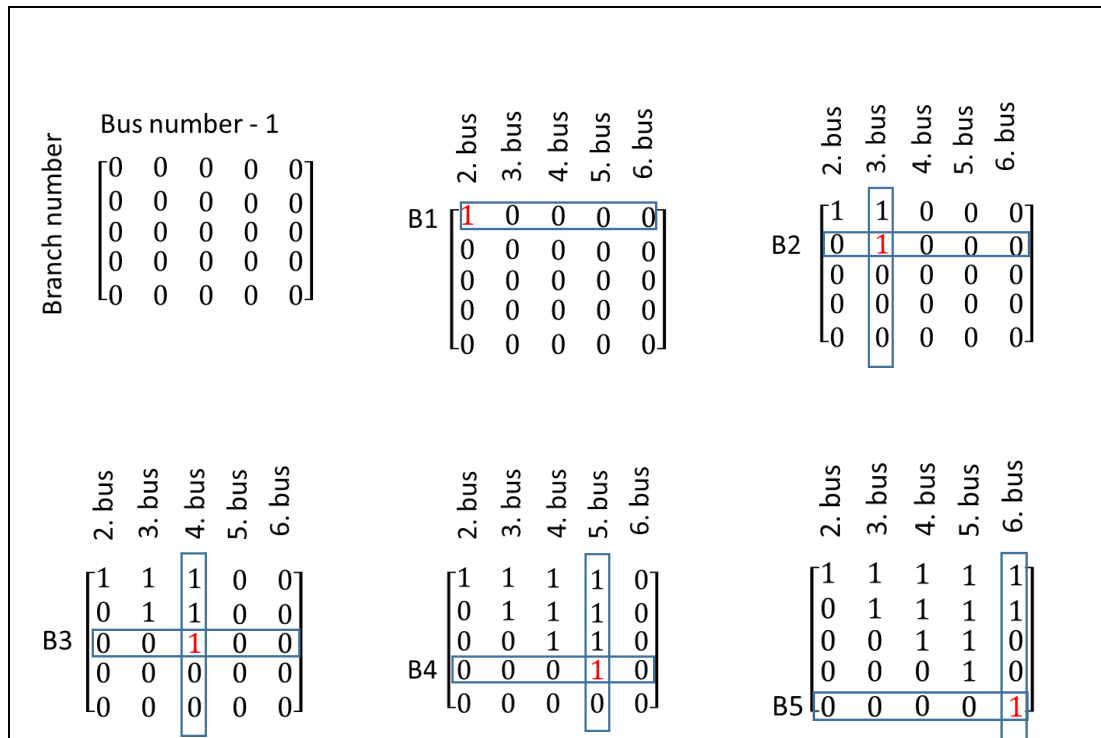


Figure 4.3: Demonstration of BIBC matrix steps.

First matrix in Figure 4.3 represents the Step 1 on Figure 4.2 . Starting from the first branch, second bus column is copied to third and related row is set to 1 by following Step 4 and 5. For branch 3 which is connected to bus 3 and 4 as detected in Step 3, 3. bus column is copied to 4. bus column and 3rd row of that column is set to 1

as in the 4th matrix given in figure. Steps from 3 to 5 is repeated for B4 and B5 to complete the BIBC matrix.

4.1.2. BIBC matrix for mesh system

In some distribution networks, feeders with heavy loads can be supported with another feeder and mesh systems are created. BIBC matrix is developed again for such closed systems [93]. A mesh system with one loop is shown in Figure 4.4.

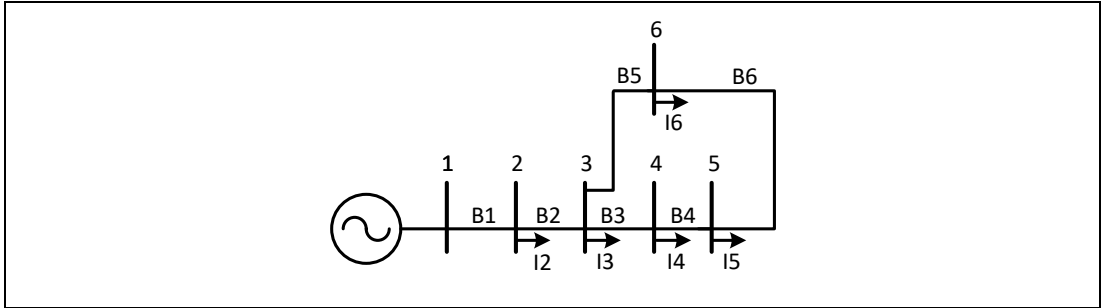


Figure 4.4: A mesh system.

In distribution networks the current drawn from slack bus does not change when a loop is formed. But added line data must be included in the system. Although it does not affect it, but new lines created must also be included in the system. In the example distribution system shown in Figure 4.4, tie switch at line 6 is closed and a loop is created. Currents of bus 5 and 6 is rewritten considering new added line, B_6 as in equation (4.6).

$$I'_5 = I_5 + B_6 \quad I'_6 = I_6 - B_6 \quad (4.6)$$

Line currents can be written on BIBC matrix as in equation (4.7)

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 + B_6 \\ I_6 - B_6 \end{bmatrix} \quad (4.7)$$

Equation (4.7) is rearranged as in (4.8).

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} B_6 \\ -B_6 \end{bmatrix} \quad (4.8)$$

Finally, BIBC matrix for mesh systems is given in equation (4.9).

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ B_6 \end{bmatrix} \quad (4.9)$$

In general form it can also be written as

$$\begin{bmatrix} B \\ B_{new} \end{bmatrix} = [BIBC] \cdot \begin{bmatrix} I \\ B_{new} \end{bmatrix} \quad (4.10)$$

Steps of forming BIBC matrix for mesh system is given in Figure 4.5.

- Step 1. Create a matrix of size nb x (n-1) and set all the elements of the matrix to zero.
(The columns of matrix represent buses other than swing bus).
- Step 2. Assign 1 to k.
- Step 3. Detect bus i and j which are connected to line k.
- Step 4. If line k does not make a loop, copy bus i column to bus j column and set kth row of bus j column to “1”.
- Step 5. If line k creates a loop, subtract bus i column from bus j column and copy to kth column. Set kth row of kth column to “1”.
- Step 6. Repeat steps from 3 to 5 for each line of the system to create BIBC matrix for mesh system.

Figure 4.5: Steps of building BIBC matrix for mesh systems.

4.2. Modification of BIBC matrix

A method is developed to modify BIBC matrix in order to use it in reconfiguration studies and estimate power loss with an analytical expression [94]. Topology change of a distribution network is reflected to BIBC matrix. To change configuration of a network a tie switch is closed, a loop is formed, and a sectionalizing switch is opened to satisfy radiality. Bus current injections do not change when a loop is formed, but new branch should be added to network. Similarly, to keep system radial existing branch will need to be removed by opening a switch. As bus injections do not change, BIBC matrix will need to be modified to calculate power loss with equation (4.3) for the new network configuration.

In Figure 4.6 (a) a six bus system with one tie line between bus 4 and 6 is given and it is used to explain BIBC matrix modification process. First, BIBC matrix and branch currents of the six bus system is given in (4.11).

$$[B] = [BIBC][I]$$

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (4.11)$$

BIBC matrix is also given as a table in Figure 4.6 (b) to explain further steps clearly.

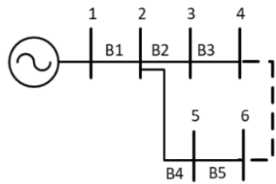
	<table><tr><th></th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th></tr><tr><td>B1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr><tr><td>B2</td><td>0</td><td>1</td><td>1</td><td>0</td><td>0</td></tr><tr><td>B3</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td></tr><tr><td>B4</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td></tr><tr><td>B5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td></tr></table>		12	13	14	15	16	B1	1	1	1	1	1	B2	0	1	1	0	0	B3	0	0	1	0	0	B4	0	0	0	1	1	B5	0	0	0	0	1
	12	13	14	15	16																																
B1	1	1	1	1	1																																
B2	0	1	1	0	0																																
B3	0	0	1	0	0																																
B4	0	0	0	1	1																																
B5	0	0	0	0	1																																
(a)	(b)																																				

Figure 4.6: 6-bus system base configuration (a) and BIBC matrix (b).

Here, branch to close B_{cl} is defined as B_6 . A loop is formed as in Figure 4.7 (a). After adding B_6 , current injections of bus 4 and 6 is redefined in equation (4.12) as

explained in previous section in detail. B_6 is also represented on table in Figure 4.7 (b).

$$I'_4 = I_4 + B_6 \quad I'_6 = I_6 - B_6 \quad (4.12)$$

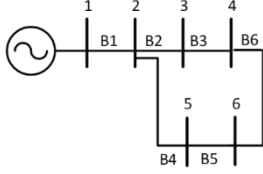
	<table><tr><th></th><th>I2</th><th>I3</th><th>I4</th><th>I5</th><th>I6</th><th>B6</th></tr><tr><td>B1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td></tr><tr><td>B2</td><td>0</td><td>1</td><td>1</td><td>0</td><td>0</td><td>1</td></tr><tr><td>B3</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>1</td></tr><tr><td>B4</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>-1</td></tr><tr><td>B5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>-1</td></tr><tr><td>B6</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td></tr></table>		I2	I3	I4	I5	I6	B6	B1	1	1	1	1	1	0	B2	0	1	1	0	0	1	B3	0	0	1	0	0	1	B4	0	0	0	1	1	-1	B5	0	0	0	0	1	-1	B6	0	0	0	0	0	1
	I2	I3	I4	I5	I6	B6																																												
B1	1	1	1	1	1	0																																												
B2	0	1	1	0	0	1																																												
B3	0	0	1	0	0	1																																												
B4	0	0	0	1	1	-1																																												
B5	0	0	0	0	1	-1																																												
B6	0	0	0	0	0	1																																												
(a)	(b)																																																	

Figure 4.7: 6-bus system mesh configuration (a) and BIBC matrix (b)

Nonzero rows of B_6 column gives the information of branches which formed a loop. The branch to open, B_{op} , can be selected from one of the branches B_2, B_3, B_4, B_5 or B_6 itself to keep system radial. If branch 4 is opened, B_4 row should be equal to zero as in equation (4.13). Equation (4.14) show that B_6 is equal to sum of injection currents of bus 5 and 6.

$$B_4 = I_5 + I_6 - B_6 = 0 \quad (4.13)$$

$$B_6 = I_5 + I_6 \quad (4.14)$$

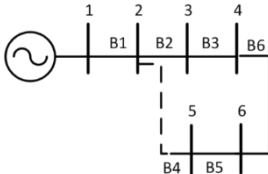
	<table><tr><td></td><td>I2</td><td>I3</td><td>I4</td><td>I5</td><td>I6</td><td><i>B6</i></td></tr><tr><td>B1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td></tr><tr><td>B2</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr><tr><td>B3</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td></tr><tr><td>B4</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>-1</td></tr><tr><td>B5</td><td>0</td><td>0</td><td>0</td><td>-1</td><td>0</td><td>-1</td></tr><tr><td><i>B6</i></td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td></tr></table>		I2	I3	I4	I5	I6	<i>B6</i>	B1	1	1	1	1	1	0	B2	0	1	1	1	1	1	B3	0	0	1	1	1	1	B4	0	0	0	0	0	-1	B5	0	0	0	-1	0	-1	<i>B6</i>	0	0	0	1	1	1
	I2	I3	I4	I5	I6	<i>B6</i>																																												
B1	1	1	1	1	1	0																																												
B2	0	1	1	1	1	1																																												
B3	0	0	1	1	1	1																																												
B4	0	0	0	0	0	-1																																												
B5	0	0	0	-1	0	-1																																												
<i>B6</i>	0	0	0	1	1	1																																												
(a)	(b)																																																	

Figure 4.8: 6-bus system new configuration (a) and BIBC matrix (b).

BIBC matrix is updated with using equation (4.14). Branches those formed a loop are affected with added line. Opened branch, fourth row of BIBC matrix, become

zero as in Figure 4.8 (b). Negative value on fifth row indicates power flow direction is changed on fifth branch, B_5 . Closed branch B_6 is replaced with opened one, B_4 , on BIBC matrix. Branch currents of new configuration as in Figure 4.8 (a) are given by equation (4.15).

$$[rB] = [rBIBC][I]$$

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_6 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (4.15)$$

BIBC modification procedure can be implemented as follows: Branch to close, B_{cl} , between bus j and k is selected. A temporary vector, tmp , is obtained with subtracting I_k column of BIBC from I_j column $([I_j] - [I_k])$. To keep radiality one of the branches of the loop should be opened (B_{op}). In BIBC matrix, an XOR operation is performed between B_{op} row and the nonzero rows of tmp that give the branches of the loop. Finally, in $rBIBC$ matrix name of the opened branch is changed with closed one B_{cl} .

Figure 4.9 represents the BIBC modification steps for system in Figure 4.6 (a), Branch to close (B_{cl}), B_6 , is connected between bus 4 and bus 6. The tmp vector is obtained by subtracting columns of BIBC matrix as in Figure 4.9. B_4 is selected as branch to open B_{op} and XOR operation is done between B_4 row and nonzero rows of BIBC matrix which are B_2, B_3, B_5 . Opened branch B_4 is changed to closed branch B_6 and the $rBIBC$ matrix is obtained as in figure below.

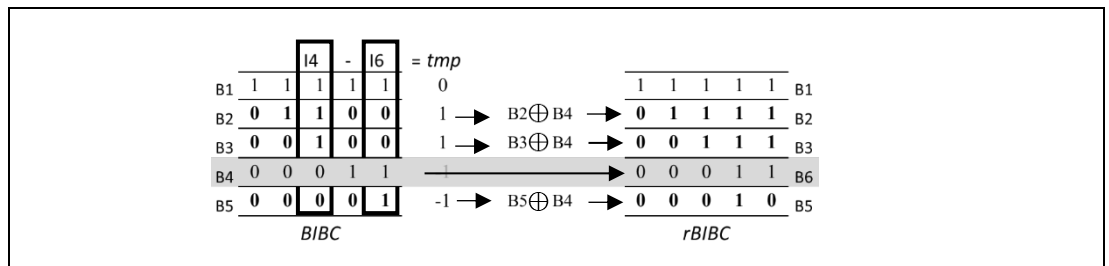


Figure 4.9: BIBC and rBIBC matrix.

Modification methodology of BIBC matrix, can be implemented using pseudo code given below:

Step 1. Determine branch to close B_{cl} between bus j and bus k .

Step 2. Build a temporary vector. Nonzero rows give the branch numbers of loop:

$$tmp = |BIBC(:, j - 1) - BIBC(:, k - 1)|$$

Step 3. Choose branch to open B_{op} in the loop using tmp vector.
 Make $tmp(op) = 0$.

Step 4. Form $[rBIBC]$ by performing XOR logical operation between open branch row $BIBC(op, :)$ and each row of BIBC matrix where $tmp = 1$

Step 5. Exchange the open branch B_{op} with closed branch B_{cl} in the branch current vector $[B]$ to obtain new branch current vector $[rB]$ of the new configuration.

Figure 4.10: BIBC matrix modification steps.

4.3. Conclusion

In this chapter, a matrix modification methodology developed for switching operation of reconfiguration problem. BIBC matrix which provides network topology information is used to represent network topology before and after reconfiguration. With BIBC matrix modification methodology, changes on network are reflected to matrix which enable us to use the analytical formula to calculate power loss after any topology change. This allows to use the same analytical power loss estimation after reconfiguration with modified BIBC matrix. When a line added, and another is removed in reconfiguration process, line data of network changes. Proposed method overcome ordering problem of lines after any topology change for further power flow analysis. Resistance vector of analytical power loss estimation formula can be modified only by replacing removed line with the added one. One of the advantages of proposed method is that once a tie switch is closed the modification procedure gives us the line numbers on the formed loop. This feature of method eliminates the need for radiality and continuity check of network branches. Therefore, it never creates infeasible topology for network.

Proposed BIBC matrix modification method requires a search algorithm to systematically apply it on networks. In chapter 5, a grid search algorithm is introduced for reconfiguration problem and switching operations by BIBC modification method.

5. GRID SEARCH ALGORITHM FOR RECONFIGURATION

Grid search, which is one of direct search method, aims to divide the search space into grids and to reach the lowest value by evaluating objective function for all grid points [95]. It has been used for many disciplines including power systems e.g. in distributed generation allocation problem [85]. In this chapter an objective function is defined to minimize power loss by reconfiguration. Introduced BIBC modification method in chapter 4 is integrated to algorithm in order to analyse several systems. As BIBC modification method provides all possible switching options, grid search algorithm is used to examine all of them systematically to obtain the exact results of problem.

5.1. Problem Formulation

The use of reconfiguration to obtain minimum power loss can be obtained as in equation (5.1) where P_{loss} is for the total loss of network, B_i is the current of i^{th} branch. Subject to voltage, current and radial topology constraints as in equation (5.2). Current of each branch (B_i) must be under its permissible limit. Voltage magnitude (V_i) at each node must be between pre-defined range.

In reconfiguration studies, majority of search methods for the best network topology are based on heuristic algorithms as considerable number of switching and discrete nature of switch increase complexity of the problem.

$$\min P_{loss} = \sum_{i=1}^{nb} |B_i|^2 R_i \quad (5.1)$$

$$\begin{aligned} B_i &< B_{max} \\ V_{min} &< V_i < V_{max} \\ &radial\ network\ structure \end{aligned} \quad (5.2)$$

However, grid search algorithm is the only method that allows to examine all possible switching combinations in a network thus ensures the exact solution. In grid search, tie switches number of the network, k , number of tie switches which are included in reconfiguration, n , are identified, all possible tie switch combinations are listed, and search process starts. Tie switch combinations are listed as vectors to enable choosing how many of those are used for reconfiguration. Once a tie switch is closed and the first candidate branch in the loop is opened, second tie switch is closed, and the first candidate branch of the new loop is opened, and this is repeated until the last tie switch. After the last tie switch is closed, all branches in the loop are opened one by one and power loss is calculated. Then algorithm starts to go back to the first loop step by step. At each step the whole topology of network changes due to new formed loops. Grid search is performed by a recursive function to ensure all combinations are examined. Proposed method, changing the network topology with BIBC modification, provides feasible switching combinations at each step through its capability of keeping system radial and operable without additional checking for radiality or continuity.

Steps of algorithm is given in Figure 5.1. BIBC modification process within grid search algorithm is detailed step by step. First system data is read, BIBC matrix is created, and tie switches are identified. Considering operational limitations number of switches to be included in reconfiguration is decided and combinations are listed. For every combination vector following steps are repeated. cl is counter for branch to close is set to 1 and first tie switch is closed in step 3. In next step tmp vector is created using BIBC matrix modification method and branches to open are identified. op is counter of branch to open and it is set to 1. First branch on the tmp vector that created the loop is opened in step 5. In step 6, $rBIBC$ and rR are calculated. Step 7 is for recursive search process. If all branches to close are not tried, cl counter is increased and algorithm turns to step 3 to close next tie switch and follow the same steps until step 7. When branch to close counter reach its limit that means the last loop is created and each branch in the loops is to be opened one by one and power loss is calculated. Then the algorithm decrease branch to close counter to go back previous loop and to open second branch in that loop. Steps from 4 to 7 are again repeated until all combinations are tried. This allows the algorithm examine power loss for each possible topology. These steps are also given as a flowchart in Figure 5.2.

Step 1. Read system data, create BIBC matrix, identify number of tie switches, k .

Step 2. Decide number of switches to close, n . List combinations $\binom{k}{n}$.

Repeat for each combination vector

Step 3. Choose branch to close B_{cl} , $cl = 1..n$

Step 4. Close branch B_{cl} , create tmp vector.

Step 5. Open branch B_{op} , $op = 1..length(tmp)$

Step 6. Calculate $rBIBC$ and rR

Step 7. **if** $cl \neq n$ **do**

$cl = cl + 1$, turn 3

else if $op \neq length(tmp)$ **do**

Calculate power loss for new configuration

$op = op + 1$, turn 5

else

Calculate power loss for new configuration

$cl = cl - 1$, turn 3

end

Step 8. Choose the configuration with minimum power loss as solution.

Figure 5.1: Grid search algorithm steps for reconfiguration.

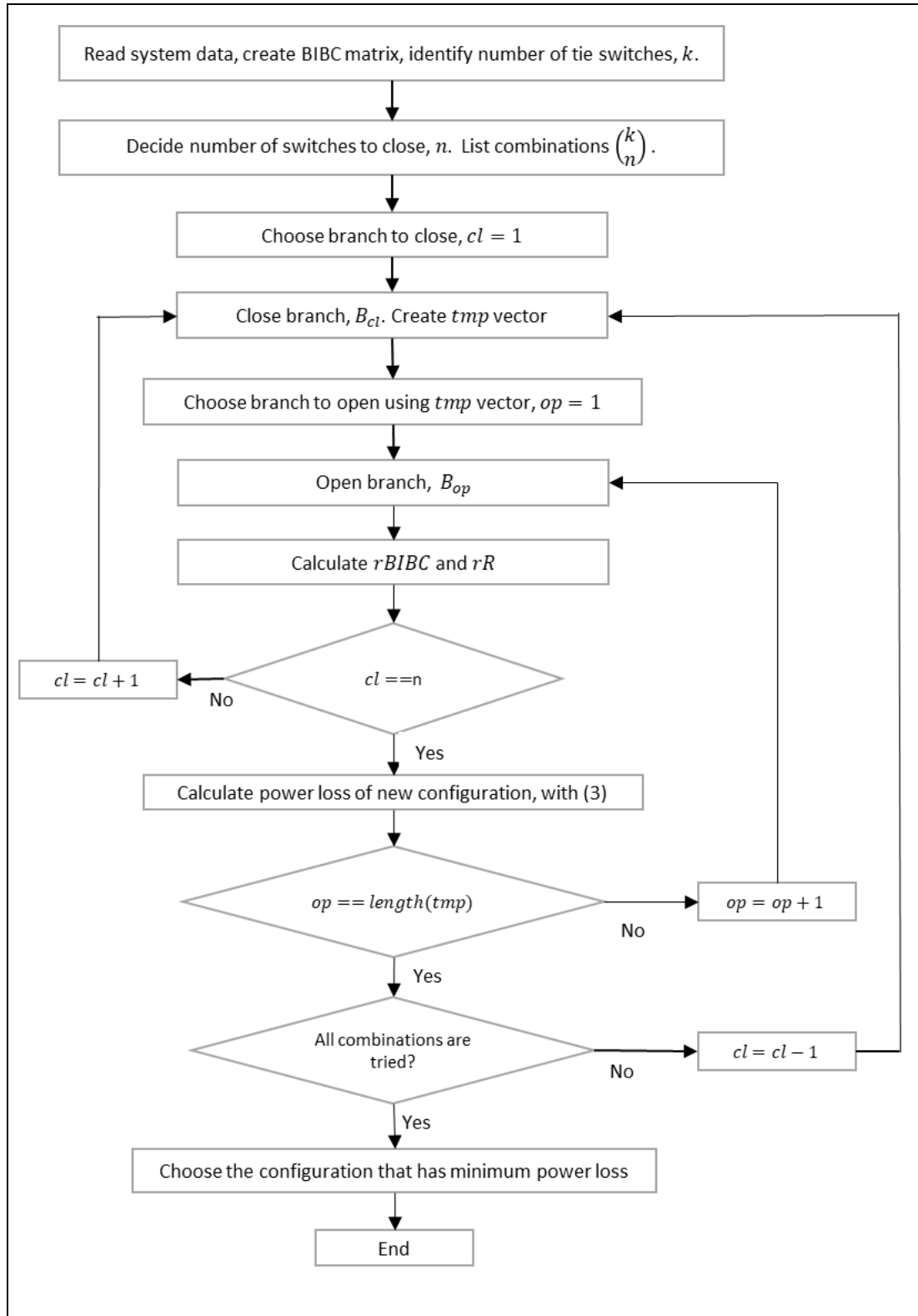


Figure 5.2: Flowchart of grid search algorithm.

5.2. Distribution Network Load Modelling

Loads with different characteristics and types may be present in real distribution networks. As proposed method with analytical formula takes network loads as constant current injections, conventional power flow studies in literature generally assume loads as constant power. To investigate effect of load characteristics in reconfiguration studies, in this chapter static load modelling is considered, and analysis for distribution system with different load characteristics are performed. A backward-forward sweep method [96] for distribution systems power flow analysis is used to compare reconfiguration results with the proposed method.

5.2.1. Static Load Model

Static load model is commonly expressed in a polynomial or an exponential form. Here, voltage dependent static load model for active and reactive load powers are represented in exponential form as:

$$P = P_0 \left(\frac{V}{V_0} \right)^{np} \quad Q = Q_0 \left(\frac{V}{V_0} \right)^{nq} \quad (5.3)$$

Where P_0 and Q_0 are real and reactive load powers at nominal voltage V_0 . V is bus voltage. np and nq indicate load exponents. Different values of load exponents represent specific loads like pumps, fans, motors, lightening etc.[97]. For example, $np = nq = 1$ indicates a constant current load and it is used in power flow analysis to calculate power loss and compare results with the proposed method that uses analytical formulation. Lower or upper values of np , nq present different load characteristics that might be connected to distribution system. In distribution networks loads with similar characteristics are grouped and defined as residential, commercial, and industrial load types.

5.2.2. Time Varying Load Model

Distribution networks for different load types with variation in time are also considered in this study. A distribution system with residential, commercial, and industrial load types is generated. Each load type has specific load profile for considered time period. Characteristics of different load types, varying in time, is also modelled as voltage dependent active and reactive powers. Different np, nq values might apply for the loads of the same network during different seasons, weeks, or days. Even day and night characteristics of a distribution system might be different in real distribution networks as shown in Table 5.1 [98].

Table 5.1: Example data for voltage dependent loads.

Load type	Summer/day		Summer/night		Winter/day		Winter/night	
	np	nq	np	nq	np	nq	np	nq
Residential	0.72	2.96	0.92	4.04	1.04	4.19	1.30	4.38
Commercial	1.25	3.50	0.99	3.95	1.50	3.15	1.51	3.40
Industrial	0.18	6.00	0.18	6.00	0.18	6.00	0.18	6.00

5.3. Analysis and Results

Reconfiguration process using proposed BIBC matrix modification is applied to test systems. 33 bus system [2] and 69 bus test system [91] are used to demonstrate the validity and reliability of proposed method. In grid search algorithm two approaches are used to estimate power loss with proposed analytical formula and power flow based method:

Grid Search 1 (GS-1): Grid search for proposed method calculates power loss of system using analytical equation given in equations (4.2) and (4.3). Topology changes are represented with $rBIBC$ matrix and line data changes with rR vector. Here, system loads are assumed to be constant current injections.

Grid Search 2 (GS-2): A backward-forward sweep method is used for power flow analysis to calculate power loss. System loads are modelled with voltage

dependent formula given in equation (5.3). Even though the *rBIBC* matrix is used for changing topology, line data of systems need to be reordered appropriately for power flow calculations.

5.3.1. Reconfiguration for 33 Bus System

Grid search is applied to 33 bus system. Normally open branches between related buses are detected by reading system data as 33 (8-21), 34 (9-15), 35 (12-22), 36 (18-33) and 37 (25-29). Total active and reactive loads of base system are 3715 kW and 2300 kVAr respectively. Power loss is calculated for the base case as 176.62 kW. In loss calculation GS-1 uses analytical equation (4.3) and GS-2 runs backward-forward sweep algorithm for power flow analysis for system loads with different load exponents.

First, BIBC matrix is formed, then combinations of tie switches are listed. For 33 bus system all tie switched are involved in reconfiguration process and algorithm starts to search. Assume the first tie switch combination is [33 34 35 36 37]. Branch 33 is closed, *tmp* vector is calculated using BIBC matrix to identify branches in the formed loop. The first branch in the loop is identified using *tmp* and opened. BIBC matrix is modified then, second tie switch on the line 34 is turned off, second loop is formed and first branch in second loop is opened. BIBC matrix is modified and same steps are repeated for branch 35 and 36. As the last branch 37 is closed, the last loop is formed, the first branch in the loop is opened, BIBC matrix is modified, and power loss is calculated. Then, all the branches in the last loop are opened one by one and power loss is calculated. Grid search runs recursively, so the algorithm goes one loop back after calculating power losses by opening each branch of last loop and open the next branch in the previous loop. Same search order is repeated for the last loop. Here, recursive function enables to repeat same steps for every branch in each loop. BIBC modification process make it possible that grid search algorithm effectively searches all solution space. Thus, power loss for completely changed system topology for each closed-opened branch pair can be calculated.

The optimal open branch configurations for GS-1 and GS-2 are given on Table 5.2. Proposed BIBC modification method is used in both. In GS-1 power loss

calculated with analytical formula assuming loads are constant current injections. For GS-2, power flow analysis is run for voltage dependent static load models. Here exponents for load models are chosen as a wide range from 0 to 5 to compare final configurations, power losses before and after reconfiguration with the proposed method GS-1. The row where $np = nq = 1$ at GS-2 results is for constant current load and gives the same results with GS-1 as expected.

In literature most of the studies calculate base power loss of 33 bus system as 202.67 kW and optimal configuration as 7-9-14-32-37 which reduces power loss to 139 kW. Minimum bus voltage is 0.913 pu and 0.937 pu before and after reconfiguration respectively [5], [31]. Same base power loss is achieved with constant power load model ($np = nq = 0$) and exact results obtained via GS-2 is given on Table 5.2. Configuration of 7-9-14-28-32 reduces losses to 135.38 kW where minimum bus voltage is 0.915 pu after reconfiguration.

Final configuration is the same for most of load exponents values, but power loss differs from proposed method GS-1. As voltage dependency increase with higher values of load exponents as 4 to 5 final reconfigurations are changed to 7-9-14-31-37. Yet those higher values of load exponents are not typical load characteristics of distribution systems, changing open branch 31 with 32 also does not cause a big difference in power loss as well as topology. So, the variation in power loss value depends on the load model rather than the configuration here.

After all, 33 bus system provides the same final configuration as GS-1 for load exponents values from 1 to 3.5 and only one branch changes in final configuration with very small loss reduction for other load exponents. For constant power load model, mostly used in literature, final configuration is same with GS-1 although the exact GS-2 results show that power loss reaches its minimum with a very small reduction when open branch 37 is changed with 28.

In final configuration for higher values of load exponents, 4 to 5, although they are not typical loads for distribution systems, only open branch 32 changes to 31 which do not cause a big topology change or power loss reduction.

In conclusion, results of reconfiguration for a wide range of power exponents which represent different load types final configuration only differs in one switch. Line 28 or 31 instead of 32 cause very small difference in final power loss and final topology.

Results for 33 bus system shows proposed method GS-1 with constant current load type approach represents distribution system well and get the results 9 times faster than the GS-2.

Table 5.2: 33 bus system reconfiguration results.

GS-1				
Load model	Final configuration	Power loss before reconfiguration (kW)	Power loss after reconfiguration (kW)	CPU time (s)
constant current	7-9-14-32-37	176.37	127.36	19
GS-2				
Load exponents	Final configuration	Power loss before reconfiguration (kW)	Power loss after reconfiguration (kW)	CPU time (s)
np=nq=0				
constant power	7-9-14-28-32	202.676	135.385	
np=nq=0.5	7-9-14-28-32	188.676	131.474	
np=nq=1				
constant current	7-9-14-32-37	176.628	127.371	
np=nq=1.5	7-9-14-32-37	166.124	122.556	~ 170
np=nq=2	7-9-14-32-37	156.872	118.121	
np=nq=2.5	7-9-14-32-37	148.649	114.021	
np=nq=3	7-9-14-32-37	141.279	110.216	
np=nq=3.5	7-9-14-32-37	134.634	106.676	
np=nq=4	7-9-14-31-37	128.611	103.201	
np=nq=4.5	7-9-14-31-37	123.118	99.917	
np=nq=5	7-9-14-31-37	118.087	96.856	

5.3.2. Reconfiguration for 69 Bus System

In 69 bus system, normally open switches are on the branches 69 (11-43), 70 (13-21), 71 (15-46), 72 (50-59), 73 (27-65). Total active and reactive loads of base system are 3802 kW and 2694 kVAr respectively. Active and reactive load levels of 69 bus system are very close to each other. Thus, 69 bus test system is introduced in a capacitor allocation problem in the literature. In order to investigate effects of load types to reconfiguration in such a system, loads are considered only residential, only commercial and only industrial using voltage dependent load formula. Load exponents are chosen from Table 5.1 for summer season as in Table 5.3 for GS-2. Also, reconfiguration for the system with constant current and constant power loads is taken into account to compare results with proposed method and studies in literature respectively.

Final configuration obtained with GS-1 is 14-55-61-69-70. For the constant current loads shown on Table 5.3, GS-2 gives same power loss of 90.79 kW as GS-1. The difference in final configuration is not essential because it occurs due to sensitive calculations that changes with second open branch. Power loss is changed from 90.7965 to 90.7982 kW by opening branch 58 to 55 respectively. GS-1 assumes all bus voltages equal to 1, GS-2 calculates them with power flow analysis which in the end affects final configuration with a very small loss difference. Thus, the final configuration for GS-1 and GS-2 can be accepted as the same due to the unremarkable loss change of 0.0017 kW.

69 bus system has variety of optimal configuration results in literature [8]. The ones with the same power loss of 224.9 kW, have different final power loss values in the range between 96.1 kW and 99.6 kW after reconfiguration. To compare with literature, minimum power loss for constant power load model is calculated in GS-2 as 93.44 kW and final configuration is 14-58-61-69-70. A few numbers of the studies in literature could reached the same configuration with higher final loss value.

Reconfiguration results for 69 bus system with only residential, commercial, or industrial load have the same final configuration and only one branch, 13 instead of 14, is different from GS-1 solution.

Changing open branch 14 to 13 in GS-1 gives the minimum power loss as 90.87 which is 0.08 kW higher than the exact solution. Therefore, the unlike final configuration can be assumed identical due to very small difference.

Analysis with voltage dependent load modelling shows that final configurations slightly differ for different load types. Therefore, distribution network loads can be modelled as constant current injections. As reactive load exponent n_q difference is not essential, active load exponent n_p can be defined as 1 for realistic distribution system load modelling.

Eventually with the negligible final configuration differences for different load types, in terms of speed, proposed method outperforms with 16 times faster calculation speed for 69 bus system.

Table 5.3: 69 bus system reconfiguration results.

GS-1				
Load model	Final configuration	Power loss before reconfiguration (kW)	Power loss after reconfiguration (kW)	CPU time (s)
constant current	14-55-61-69-70	191.50	90.79	216
GS-2				
Load exponents	Final configuration	Power loss before reconfiguration (kW)	Power loss after reconfiguration (kW)	CPU time (s)
$n_p=n_q=0$ constant power	14-58-61-69-70	224.99	93.44	3341
$n_p=n_q=1$ constant current	14-58-61-69-70	191.50	90.79	3429
$n_p=0.72$ $n_q=2.96$ residential	13-55-61-69-70	181.01	89.39	3580
$n_p=1.25$ $n_q=3.50$ commercial	13-55-61-69-70	168.46	87.69	3660
$n_p=0.18$ $n_q=6.00$ industrial	13-55-61-69-70	175.09	87.74	3700

5.3.3. Reconfiguration for Networks with Time Varying Loads

In smart grid, application of smart meters, communication skills, real time information improve the control capability of networks. With penetration of renewables, integration of storage units, and demand participation, changes on topology of network are required for smart grid operation. So, reconfiguration might be made yearly, monthly, daily, or hourly. Although, switching cost, life of switches and calculation time limits do not always provide an opportunity to make optimal switching for each time step, in general daily reconfiguration is performed.

Here, reconfiguration is performed for 24 hours period. 33 bus system is reorganized with time varying loads. Base active power values of loads at each bus is given in Figure 5.3. All loads operate at 0.98 power factor. Hourly varied loads are generated using profiles given in Figure 5.4. Base powers are taken as peak values of given time period, 24 hours. Industrial and commercial loads reach their peak values in working hours and residential loads in the evening as expected. For each configuration power loss is calculated for each hour. Sum of power losses for 24 hours is taken as total power loss of the day for a configuration. The configuration that gives the minimum total power loss is decided as the optimal configuration for the day.

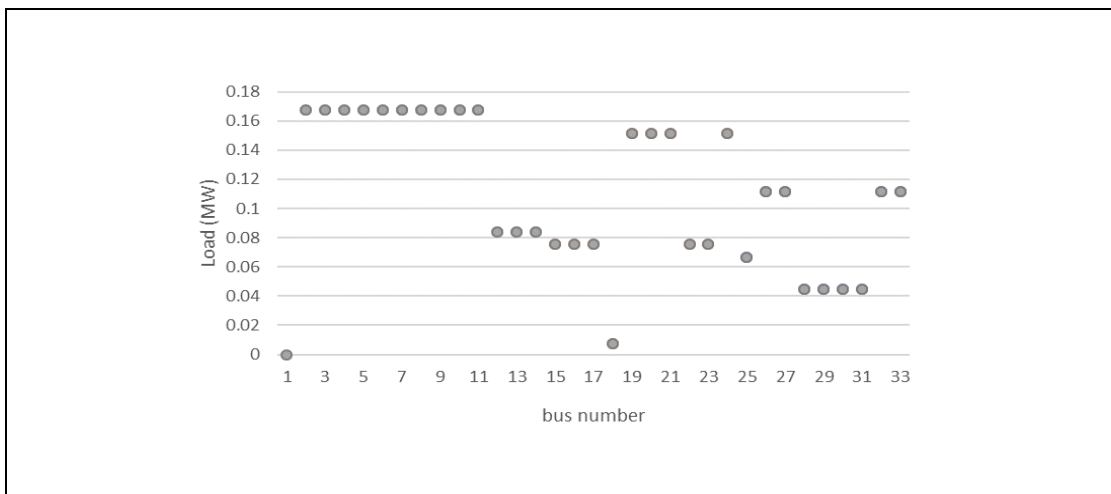


Figure 5.3: 33 bus system load distribution.

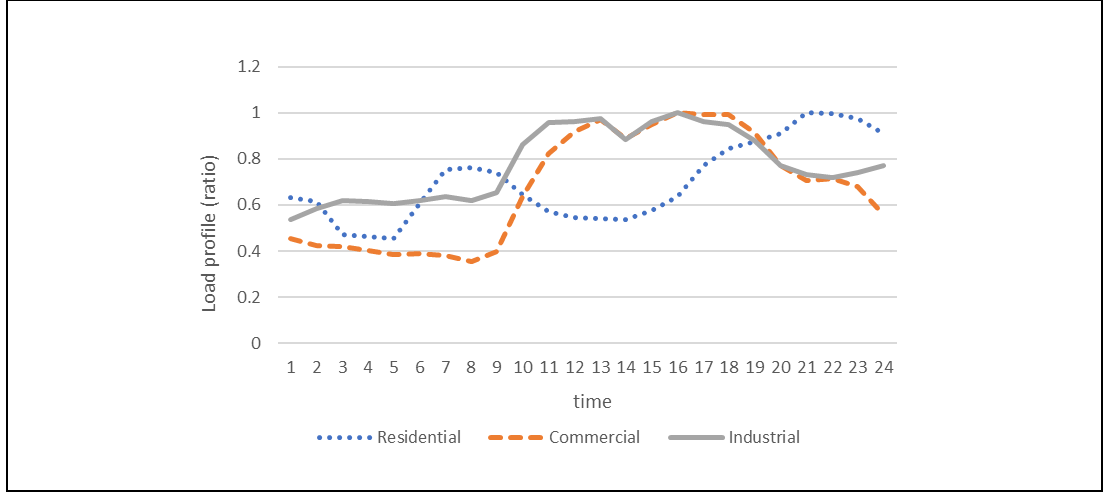


Figure 5.4: 33 bus system load profile.

Assume there is k number of possible configurations for the system. Grid search estimates power loss, $Ploss_i(t)$ for a specific time. Total power loss of each configuration, $TotalPowerLoss_i$, for the given time period can be calculated as follows:

$$TotalPowerLoss_i = \int_0^t Ploss_i(t) dt \quad i = 1..k \quad (5.4)$$

The configuration that causes total power loss minimum is accepted as final configuration for the system.

In studies with time varying loads, reconfiguration problem approach generally is cost minimization rather than only power loss minimization. For a given time period, number of switching, cost of switching operation, switching time interval decision are main concerns of cost calculation beside power loss minimization. However, in this study reconfiguration with time varying loads is examined to see the effects of load modelling into reconfiguration and to validate efficiency of proposed method. For this reason, system loads given in

Figure 5.3 are assumed only residential, commercial or industrial and load profiles in Figure 5.4 are used to obtain reconfiguration results both with GS-1 and GS-2 as given in Table 5.4. Different load types with different load exponents for day and night of seasons are given in Table 5.1. GS-2 is run for each case.

Table 5.4: Reconfiguration results of system with time varying loads.

GS-1						
Load type		Final configuration	Power loss before reconfiguration (kW)	Power loss after reconfiguration (kW)	CPU time (s)	
residential		9-14-16-27-33	1438.40	875.01	588.1	
commercial		9-14-16-27-33	1400.10	851.73	590.6	
industrial		9-14-16-27-33	1720.50	1046.60	585.1	
GS-2						
Load type	Season	Load exponent	Final configuration	Power loss before re-configuration (kW)	Power loss after re-configuration (kW)	CPU time (s)
residential	summer/day	np=0.72 nq=2.96	9-14-16-27-33	1453.40	877.75	3732.7
	summer/night	np=0.92 nq=4.04				
	winter/day	np=1.04 nq=4.19	9-14-16-27-33	1422.30	870.48	3726.2
	winter/night	np=1.30 nq=4.38				
commercial	summer/day	np=0.72 nq=2.96	9-14-16-27-33	1374.00	846.08	3720.9
	summer/night	np=0.92 nq=4.04				
	winter/day	np=1.04 nq=4.19	9-14-16-27-33	1351.50	840.20	3766.6
	winter/night	np=1.30 nq=4.38				
industrial	summer/day	np=0.18 nq=6.00	9-14-15-28-33	1814.90	1068.32	3880.5
	summer/night					
	winter/day					
	winter/night					

Results for residential and commercial load type give the same configuration as in GS-1. Although the final configuration for system with only industrial loads is different in GS-1 and GS-2, changed open branches does not cause a big topology variation.

As all possible configurations for every time step is calculated with proposed method, results for each time step or any time interval can also be obtained within given calculation times in Table 5.4. Proposed method GS-1 is around 6 times faster than GS-1.

5.4. Conclusion

In literature, decision of switch to close/open, control of radiality/continuity, parameter setting of the method, calculation time of power flow analysis, convergence of heuristic or metaheuristic algorithms to local optima are the main challenges of reconfiguration problem. Proposed BIBC matrix modification does not only provide the new topology of network after reconfiguration but also provides the knowledge of formed loop, changed current flow direction. Thus, it enables to examine all switching options with a well organized grid search algorithm without any need to further radiality/continuity check or parameter setting and it gives the exact reconfiguration result which minimize power loss. As proposed method GS-1 assumes network loads as constant current, to compare results and validates method's effectiveness, a sweep based power flow algorithm, GS-2, is also used in analysis to investigate effect of different load types using voltage dependent load model.

For 33 bus and 69 bus system with various load types, final configurations are identical or very similar to proposed method GS-1 as presented in section 5.3.1. Results show that constant current load model which is used in GS-1 confidently represents distribution network loads.

Moreover, the 33 bus system is analysed with time varying residential, commercial and industrial loads in section 5.3.3. Time dependent loads have varying load exponents both daily and seasonally. The final configuration to minimize power loss for a day is determined with using GS-1 and GS2. The configuration which decreases sum of 24 hours power loss to minimum is selected as the best daily topology of the network. Change in load type do not affect daily reconfiguration results too. Only there is a small topology difference for a network with only industrial loads. Proposed method used in GS-1 with constant current load modelling is validated for a network with time varying loads.

The results demonstrate the effectiveness of proposed approach for residential and commercial loads by using various load exponents for voltage dependent loads in GS-2 analysis which give the same final configuration with the GS-1. Although, effects of various reactive load exponents might not be essential because distribution system loads commonly operate with power factors close to 1 which cause small

values of reactive power, the difference in final configuration for industrial loads may occur due to very high reactive load exponent with an almost zero active load exponent. Overall, various load types are considered separately to see the difference with the constant current load approach in the proposed method. In actual distribution networks with load types of residential, commercial, and industrial together, proposed method is applicable as discussed above.

In terms of calculation time, according to analysis of 33 bus, 69 bus system and system with time varying loads, as number of possible switching options increase, spent time to examine all also gets longer. Proposed method with grid search finds the final network topology of 33 bus system with minimum power loss in almost 20 seconds while calculation time rise to 216 seconds for 69 bus system. Yet in any case, compare to results with power flow analysis, calculation time of proposed method GS-1, is 9 times faster for 33 bus system, 16 times faster for 69 bus system and almost 7 times faster for system with time varying loads. While grid search is convenient to be used as an exact solution method in distribution network reconfiguration for 33 bus and 69 bus systems, it may not be possible to achieve results in reasonable duration for larger and more complicated systems. Proposed BIBC modification method for network topology change allows to estimate power loss with analytical expression instead of power flow analysis and it is possible to implement the method in any other search algorithms to shorten the execution time.

6. MODIFIED ARTIFICIAL BEE COLONY (MABC) ALGORITHM FOR RECONFIGURATION

The exact solution for reconfiguration problem using a grid search algorithm is introduced in previous chapter. Although grid search with proposed switching procedure and loss estimation solves the reconfiguration problem in reasonable duration, it may take longer than expected as systems become large scale or more complex. Therefore, reconfiguration problem is solved with several metaheuristic algorithms in literature e.g. GA is largely used in reconfiguration problem solution because of its ability to find global optimal or near optimal solution for large scale combinatorial optimization problems [36]–[39]. Another population based algorithm PSO which is based on behaviour of flock of bird or school of fish is used in reconfiguration studies for loss minimization. It is implemented as in original PSO or modified discrete version [41], [42], [63]. An optimization technique inspired by behaviour of ants, ACO, is used in reconfiguration problems for loss minimization and load balancing [47], [48]. Population based algorithms head towards the optimal solution from a population of possible solutions in a given search space [99]. The main advantages of metaheuristic algorithms are providing good solutions and being applicable to large scale systems [100].

There are several studies in literature that solve reconfiguration problem with ABC algorithm considering loss minimization [46], [101], [102], voltage profile improvement and system loadability maximization [45]. Some of these studies able to reach global optimal solution while the others converge to near optimal solution.

In this chapter, Artificial Bee Colony (ABC) algorithm is used to solve reconfiguration problem to minimize power loss of network. ABC is chosen because it gives effective and efficient solution, it is easy to code, and it has limited parameters to tune. At the beginning ABC algorithm is explained in detail and then a modified version of ABC is introduced for discrete nature of reconfiguration problem.

6.1. ABC Algorithm

The artificial bee colony algorithm approach is established from foraging behaviour of real honeybees. ABC is introduced by Karaboga [103] as a new heuristic method for solving multidimensional optimization problems. It was proposed for unconstrained problems, and then another version is published for constrained optimization problems [104]. Later on, a modified version of ABC algorithm is published for constrained problems [105].

The algorithm designed according to real honey bee swarm which has three kinds of bees: employed bees, onlooker bees, and scout bees [105], [106].

- Employed bees: Randomly search for food source positions (solutions) and share the information of nectar amount of source by dancing with bees waiting in the hive. Duration of dance depends on the nectar amount (fitness value) of food source.
- Onlooker bees: Watch dances of employed bees and chose a food source position according to quality of it.
- Scout bees: When a food source is abandoned, its employed bee becomes a scout and starts to search for a new food source randomly [106].

Onlookers are placed on food sources by using probability based selection, as the nectar amount increases on source onlooker bees prefer that source too. Scout bees are the explorers and have no guidance while looking for food. That creates the possibility of both low and rich quality sources may be discovered. In ABC one of employed bee is selected as the scout bee and this selection is controlled by a parameter “limit”. If the food source (solution) is not improved by a predetermined number of trials, its employed bee abandons the source, and it converts to a scout. So “limit” is the number of trials before leaving a food source [103].

In ABC algorithm employed bees’ number is equal to onlooker bees’ number. At initialization step a randomly distributed population of solutions is generated. Each solution x_i ($i = 1, 2, \dots, E_b$) is a D-dimensional vector. Here E_b is the number of employed bees and D is the number of optimization parameter. After initialization the population of the positions (solutions) is subjected to repeated cycles $cycle = 1, 2, \dots, MCN$ of the search process of the employed, onlooker and scout bees. Then, an

employed bee produces a modification on the position (solution) in her memory depending on the local information (visual information) and tests the nectar amount (fitness value) of the new source (modified solution). If the nectar amount of the modified solution is higher than the previous one the bee memorizes the new position and forgets old one. Otherwise, she keeps the position of previous one in her memory. After all employed bees complete the search process; they share the nectar information of the food source and their positions information with the onlooker bees on the dance area. An onlooker bee evaluates the nectar information taken from all employed bees and chooses a food source with a probability related to its nectar amount. Same procedure is applied as in the case of employed bee.

Pseudo-code of main body of ABC algorithm [105]:

```

Step 1. Initialization
Step 2. Evaluation
Step 3. cycle = 1
Step 4. repeat
Step 5. Employed Bees Phase
Step 6. Calculate Probabilities for Onlookers
Step 7. Onlooker Bees Phase
Step 8. Scout Bees Phase
Step 9. Memorize the best solution achieved so far
Step 10. cycle = cycle + 1
Step 11. until cycle =Maximum Cycle Number

```

Figure 6.1: Steps of ABC algorithm.

Equation (6.1) is given to calculate probability value related with that food source.

$$p_i = \frac{fitness_i}{\sum_{i=0}^{E_b} fitness_i} \quad (6.1)$$

Here, $fitness_i$ is the fitness value of the solution i and E_b is the number of food source positions (solution) in other words, half of the colony which is equal to number of employed bees.

Onlooker bees select their food source among the high value of p_i . They produce a neighbour food source position $i+1$ to the selected one i , then compare nectar amounts (fitness values) of neighbour and previous position. And the same selection criterion used by employed bees is applied to onlooker bees. This is repeated until all onlookers are distributed. If a solution does not improve for a predetermined number of time (limit), its employed bee abandon this solution and she becomes a scout and search for a new random food source position. Once the new position is determined, next ABC algorithm cycle starts.

Neighbour food source position is determined with the equation (6.2)

$$x_{ij}^{new} = x_{ij}^{old} + u(x_{ij}^{old} - x_{kj}) \quad (6.2)$$

where $k \neq i$ and both $i, k \in \{1, 2, \dots, E_b\}$. u is a random number between $[-1, 1]$ and $j \in \{1, 2, \dots, D\}$. When the food source position is abandoned, its employed bee becomes a scout. Scout produces a new food source position as follows:

$$x_i^{j(new)} = minx_i^j + u(maxx_i^j - minx_i^j) \quad (6.3)$$

where u is a number between $[-1, 1]$.

ABC algorithm has three control parameters: 1) the colony size CS. 2) limit value 3) maximum cycle number MCN.

6.2. MABC Algorithm for Reconfiguration Problem

ABC algorithm given in previous section is designed for continuous problems. Discrete nature of switches in reconfiguration needs a different neighbourhood function for employed and onlooker bee phases of ABC. In [102], a discrete version of ABC for reconfiguration problem is introduced. The neighbourhood process is

developed for graph theory based topology change strategy with radiality and continuity constraints.

Here, a new neighbourhood strategy for discretization of ABC algorithm is introduced for proposed BIBC matrix modification based topology change strategy which overcomes the constraint of keeping network radial as well as providing power to all loads.

Tie switches in a network is given as a vector. Assume there are five tie switches in network and food source position which presents solution i is given as

$$x_{ij}^{old} = [x_{i1} \ x_{i2} \ x_{i3} \ x_{i4} \ x_{i5}] \quad (6.4)$$

Here i is for solution number which is between 1 and E_b (employed bee number). j is for optimization parameters and it is between 1 and 5 for a system with 5 tie switches as in (6.4). Neighbour food source position for i^{th} employed bee can be obtained by modifying each tie switch. As any change on a single tie switch affects the whole system topology, decision of next tie switch to open depends on the previous one to satisfy constraints of network: radiality and continuity. Food source modification process is given in Figure 6.2.

```

Step 1: Calculate fitness for solution,  $x^{old}$ 
Step 2:  $j = 1$ 
Step 3: Repeat
Step 4: Close tie switch  $x_{ij}$ , form a loop.
Step 5: Open a switch,  $k_{ij}$ , randomly from the loop.
Step 6: Calculate fitness for solution,  $x^{new}$ .
Step 7: if  $fitness_{x^{new}} > fitness_{x^{old}}$ 
            $x_{ij} = k_{ij}$ 
       else
            $x_{ij} = x_{ij}$ 
       end
Step 8:  $j = j + 1$ 
Step 9: Until  $j = D$ 

```

Figure 6.2: Proposed ABC neighbourhood process for reconfiguration.

Proposed modified ABC algorithm is developed using proposed BIBC modification method which is introduced in Chapter 4. In given neighbourhood process when a tie switch is closed in Step 4, BIBC modification method starts, and branch numbers of formed loop is identified to be randomly selected in Step 5. Analytical power loss equation (4.1) is used for power loss estimation to calculate objective function of problem.

The modification process is explained with an example on Table 6.1. First solution is defined as base case tie switches of system. For each optimization parameter which is 5 switches in this example, same procedure is repeated. First tie switch x_{11} is closed and a random switch, k_{11} , from the formed loop is opened. Fitness of x^{new} is calculated and a greedy selection is made. For $j = 1$ fitness of new solution is greater and switch x_{11} is replaced with k_{11} for new solution. For $j = 2$ switch previous configuration is taken as x^{old} , second tie switch x_{12} is closed, and a random switch k_{12} is open from the formed loop. Fitness value of new solution is not improved thus, second switch of solution remain same as x_{12} . This process is followed until the last tie switch and modified solution is obtained.

Table 6.1: An example of proposed ABC neighbourhood process.

Switch number	x^{old}	Condition	x^{new}
$j = 1$	$[x_{11} \ x_{12} \ x_{13} \ x_{14} \ x_{15}]$	$fitness_{x^{new}} > fitness_{x^{old}}$	$[k_{11} \ x_{12} \ x_{13} \ x_{14} \ x_{15}]$
$j = 2$	$[k_{11} \ x_{12} \ x_{13} \ x_{14} \ x_{15}]$	$fitness_{x^{new}} < fitness_{x^{old}}$	$[k_{11} \ x_{12} \ x_{13} \ x_{14} \ x_{15}]$
$j = 3$	$[k_{11} \ x_{12} \ x_{13} \ x_{14} \ x_{15}]$	$fitness_{x^{new}} > fitness_{x^{old}}$	$[k_{11} \ x_{12} \ k_{13} \ x_{14} \ x_{15}]$
$j = 4$	$[k_{11} \ x_{12} \ k_{13} \ x_{14} \ x_{15}]$	$fitness_{x^{new}} > fitness_{x^{old}}$	$[k_{11} \ x_{12} \ k_{13} \ k_{14} \ x_{15}]$
$j = 5$	$[k_{11} \ x_{12} \ k_{13} \ k_{14} \ x_{15}]$	$fitness_{x^{new}} < fitness_{x^{old}}$	$[k_{11} \ x_{12} \ k_{13} \ k_{14} \ x_{15}]$

Proposed neighbourhood process is both applied in employed and onlooker bee phases of ABC. Flow chart of modified ABC algorithm for reconfiguration is given in Figure 6.3. Flowchart provides main steps of algorithm considering colony size, maximum cycle number and limit parameters.

6.3. Analysis and Results

In reconfiguration problem with objective of reducing power losses of networks there are two main manners: switching procedure and power loss estimation. Proposed MABC algorithm uses proposed BIBC modification method for switching and analytical power loss equation (4.1) for loss estimation. As introduced and proved in Chapter 4, BIBC modification method does not require any constraints for radiality and continuity. Also, it enables to estimate power loss with an analytical formula instead of power flow analysis after any topological change.

Proposed modified ABC algorithm is applied to 33 bus and 69 bus systems. ABC parameters are chosen as 100 for iteration number and 10 for colony size. Larger values of colony size do not improve the search process or decrease the convergence iteration thus it is selected twice as many as the number of tie switches in the system. Iteration number is selected large enough to obtain convergence graphics of algorithm.

Generally, initial colony of metaheuristic algorithms have significant impact on reaching global optima and convergence. Starting the search from a better point increase the chance to obtain global optimal solution in shorter time. The performance of proposed MABC algorithm is compared under 2 different case. The colony is initialised as:

Case 1: Initial colony is taken as network's normally open tie switches.

Case 2: Initial colony is chosen with a previous knowledge based on heuristic approach results obtained with SIM in chapter 2.

It is expected to reach solution with less iteration in Case 2 than in Case1. Therefore, MABC algorithm is tested on 33 bus and 69 bus systems for two cases and convergence of algorithm is investigated.

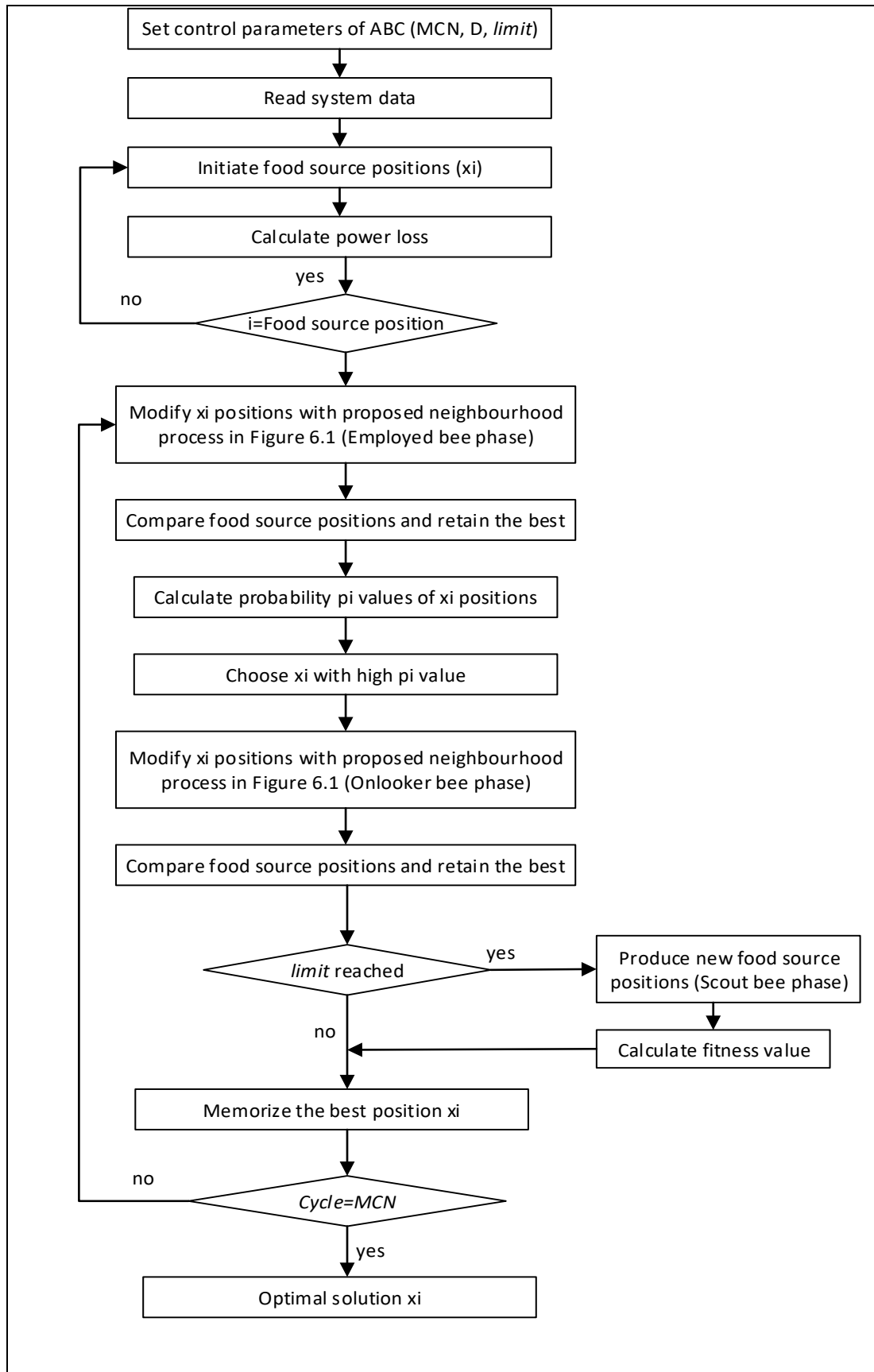


Figure 6.3: Flow chart of modified ABC algorithm for reconfiguration.

In 33 bus system, the initial solution is selected as system's tie switches (33, 34, 35, 36, 37) in Case 1. For Case 2, the configuration (7, 10, 14, 36, 37) that obtained in Chapter 2 with sensitivity index method, SIM, is chosen as initial colony. Proposed modified ABC algorithm reached global optima for both cases as given on Table 6.2.

Table 6.2: Modified ABC results of 33 bus system.

	Initial network	MABC
Open switches	33-34-35-36-37	7-9-14-32-37
Power loss (kW)	176.37	127.36

The algorithm is run several times and 10 of them including the best and worst convergence curves are given in Figure 6.4 and Figure 6.5 for Case 1 and Case 2 respectively.

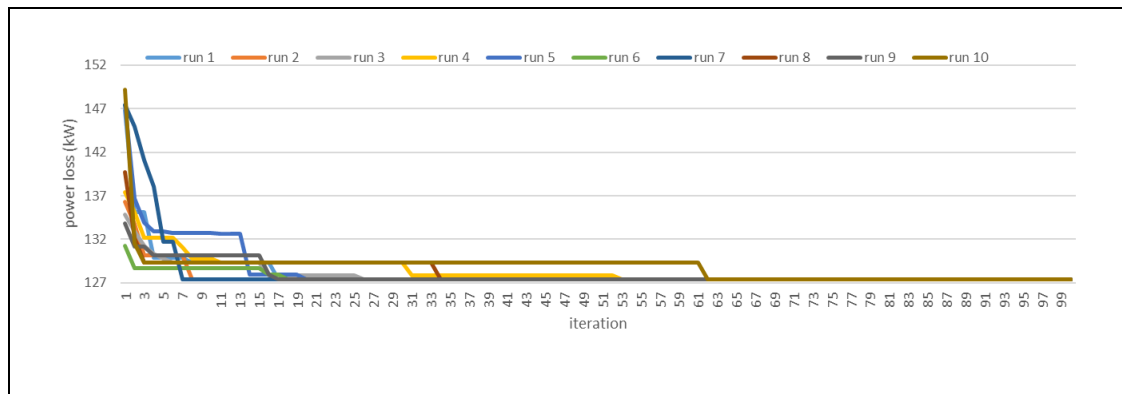


Figure 6.4: Case 1 convergence curves of ABC for 33 bus system.

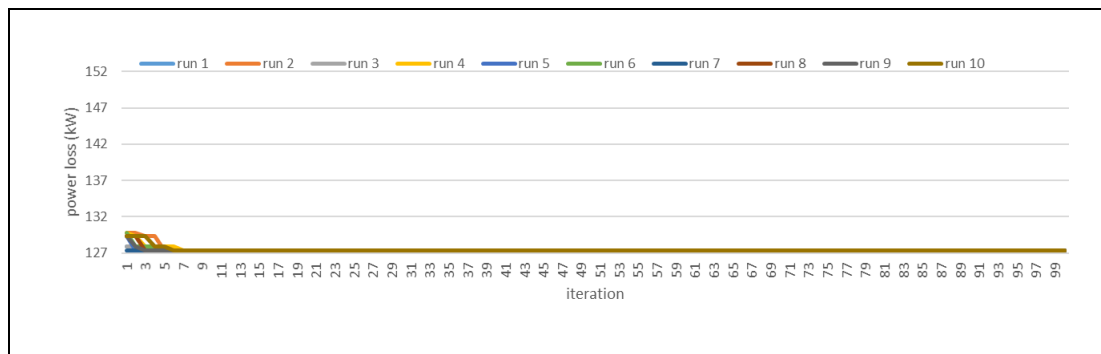


Figure 6.5: Case 2 convergence curves of ABC for 33 bus system.

Performance of algorithm in terms of iteration number to reach optimal solution is improved with a better initialization as expected. For example, while the iteration 9 is the best value in Case 1, it is the worst value for Case 2.

Similarly, MABC algorithm is run for two cases for 69 bus system. Case 1 use the system's tie switches (69, 70, 71, 72, 73) as initial colony while Case 2 starts search process with the result of SIM (13, 20, 58, 61, 69). In Table 6.3, reconfiguration results for 69 bus system is given. Although final power loss is same for Case 1 and 2, final configuration may change in several runs for Case 1. Second open switch takes values between 55 and 58 which does not cause change in power loss in three decimals. For Case 2 the same open switch is obtained as 58 in all runs.

The algorithm is run several times for 69 bus system and 10 of them including the best and worst convergence curves are given in Figure 6.6 and Figure 6.7 for Case 1 and Case 2 respectively.

Table 6.3: Modified ABC results of 69 bus system.

	Initial network	MABC
Open switches	69-70-71-72-73	14-58-61-69-70
Power loss (kW)	191.50	90.79

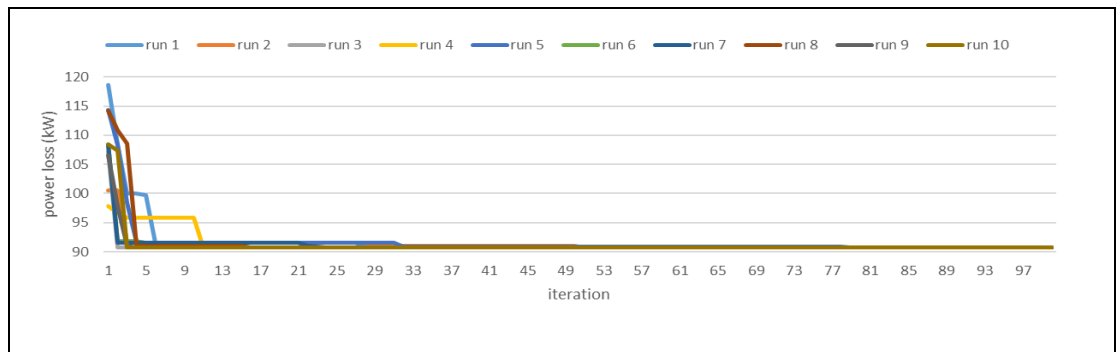


Figure 6.6: Case 1 convergence curves of ABC for 69 bus system.

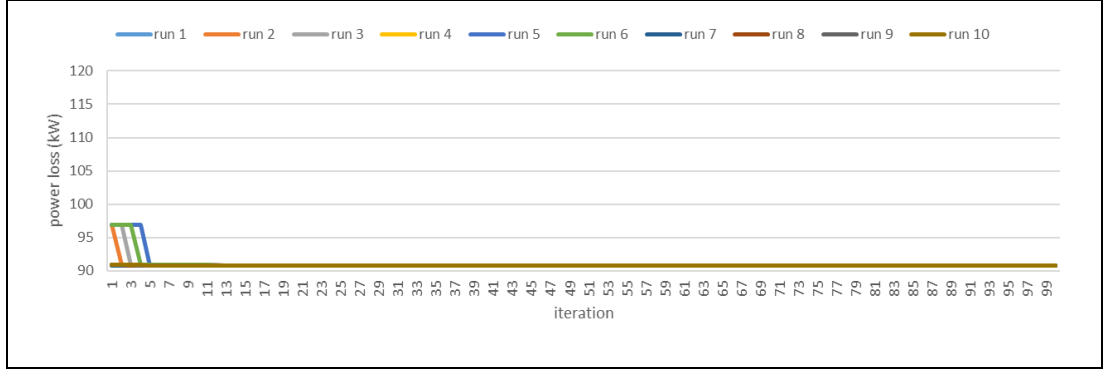


Figure 6.7: Case 2 convergence curves of ABC for 69 bus system.

For Case 1, the best iteration that finds the optimal configuration that minimizes power loss is 2 while the worst one is iteration 51. For Case 2, starting the search with a better initialized colony improved convergence of MABC algorithm as seen in Figure 6.7. Algorithm finds the optimal configuration of 69 bus system in 5 iterations in the worst case.

6.4. Conclusion

In this chapter, a metaheuristic approach for reconfiguration problem is presented. MABC algorithm is used to minimize power loss of network by reconfiguration. In literature, ABC algorithm is used for the first time in reconfiguration problem in [101] to minimize power loss of several systems and obtained results are very close to global optima. Another study [102] is proposed a discrete ABC algorithm, and compare convergence performance of it with conventional ABC. Also, the reason for developing a discrete approach is explained as continuous optimization technics cannot lead the global solution because tie switches represent the integer numbers and rounding-off position of solutions at neighbour mutation procedure may also results slow convergence. With the same concerns here, ABC algorithm is modified to obtain a better performance for discrete nature of reconfiguration problem. Due to a different method than other studies in literature used in changing network topology here, a new modification method is introduced. Optimal solution is achieved for 33 bus and 69 bus systems. Convergence of proposed modified ABC algorithm is investigated under two different case by selecting different starting points e.g., normally open tie switches for Case 1 and a

heuristic knowledge for Case 2. As a well-known fact a better initial colony which means starting the search process from a point close to the solution, improves performance of algorithm to reach optimal solution with less iterations. Result of proposed SIM is taken as initial colony in modified ABC and results are obtained to show improvement in convergence of algorithm.

In conclusion, proposed modification in neighbourhood process improved algorithm by means of reaching global solution as it only generates feasible mutated solutions by using proposed BIBC modification method. Also, faster convergence is achieved using SIM for initial colony.

7. CONCLUSION

In this thesis various methods for reconfiguration problem are examined for smart grid operation. As increasing demand, variation of loads, environmental concerns, renewable penetration, demand participation, and new technologies increase complexity of networks, smart grid concept offers fast and reliable solutions for network planning and operation. Reconfiguration is an important tool to make necessitate changes in configurations to transfer the loads to a different substation, ease the loading of equipment, reduce power losses to relieve overloads or to provide power to all customers in faults, outages, emergencies, accidents, attacks and weather-related disasters. Therefore, reconfiguration requires an accurate representation of network topology, convenient load modelling and a fast response as one of the key elements of smart grid.

In chapter 2, an initial study of analytical approach is introduced for reconfiguration problem. The aim is to reduce power loss of network by changing its topology. First, power loss expression is written for a system with distributed load profile. Loss is rephrased for a system supplied by identical sources from two end which represents a loop. A tie switch is needed to open to keep system radial and reduce power loss. As system assumed to have distributed parameters, power loss is written as a function of length which represents the location of switch. Derivation of loss expression respect to switch position gives the location of switch that makes power loss minimum. Then, to be able to apply analytical approach for systems with spot loads, line and load parameters of the system is expressed as continuous functions of length by curve fitting. It has been concluded that the method is applicable only when load and line data of system can be represented as continuous functions. However, curve fitting process moves away the approach from analyticity also to write power loss expression as a continuous function is a laborious task which makes the approach quite difficult to implement on complex and large systems.

In chapter 3, a heuristic approach SIM is introduced based on a sensitivity index, to find optimal configuration of network to reduce power loss. A sensitivity index which is derived from exact loss formula for distributed generator allocation is used considering impact of bus powers on topology changes. Loop cutting method is used to change topology of network by closing all tie switches at first. Sensitive bus of each

loop is identified and the branch with lower loss value which is connected to the most sensitive bus is opened. As the solution is obtained with only one power flow and index calculation, SIM can be defined as a noncomplex and fast approach. Results shows that SIM is able to reach near optimal solution but does not guarantee the global optimal one due to results dependency on the initial topology or network. Yet, SIM can be satisfying under certain conditions that require power loss reduction and it provides a near optimal solution very fast that can be used as an initial population of any metaheuristic algorithm.

In chapter 4, a solution is presented for one of the challenges in reconfiguration studies: topology representation. BIBC matrix is used to represent topology of a network and a method is introduced for BIBC matrix modification to represent network topology changes. The reason for choosing BIBC matrix for topology representation is that it provides an opportunity to calculate power loss of a network with analytical expression. Here a version of branch exchange method is used. BIBC matrix is modified according to information of closed and opened switch pairs. The most important advantage of this method is that BIBC modification process provides the branches that forms a loop to decide which branch to open. This feature of method resolves the radiality and continuity constraints of reconfiguration problem. Thus, considering the method only needs initial network data, it is suitable to apply on any distribution network and use with any search method or metaheuristic optimization algorithm.

In chapter 5, proposed BIBC modification method has implemented on distribution network reconfiguration problem to obtain exact solution. The analytical expression is used to calculate power loss based on BIBC matrix and bus current injections. Reconfigured topology and power loss of network is obtained with proposed modification method of BIBC matrix which ensures radiality and continuity of system. Final configuration for the minimum power loss is reached with a grid search algorithm that examines all possible switching operations using a recursive function. Proposed method with analytical power loss expression assumes system loads as constant current injections. Thus, validation of method is verified by analysing systems with voltage dependent load models using sweep algorithm based power flow analysis. Voltage dependent static load models with various load exponents are examined to see the effect of load types on reconfiguration. As distribution system

loads operate at power factor close to unity, higher reactive load exponents do not affect results substantially. According to the results, constant current approach used in proposed method with analytical loss expression could represent most of the distribution network loads. In addition, the method is improved for systems with time varying loads and analysis are performed to obtain the best configuration. Reconfiguration is performed daily for different load types and effects of them are investigated.

In terms of runtime of this exact method, although calculation time certainly depends on the system topology rather than the size of network, a small system with same number of switches that creates longer loops may have the equal possible switching options of a big system with same number of switches which creates very small loops, it is verified that using proposed analytical loss calculation formula instead of power flow analysis (considering the exact solution method examines each possible switching option), substantially reduce the calculation time. Furthermore, as proposed method enables examining all switching options which is an exhaustive search in an acceptable runtime, it gives an opportunity for new methods using metaheuristics to verify validity of their algorithm with exact solution of reconfiguration problem.

In chapter 6, a metaheuristic algorithm ABC is modified to solve reconfiguration problem. Although exact solutions are obtained with grid search, still there is a need of a faster solution for large systems. Conventional ABC algorithm is developed for continuous problems thus it requires a modification for discrete nature of switches in its neighbourhood stage. A procedure is introduced to modify neighbour solutions using BIBC matrix modification and required randomness of ABC algorithm. Then, modified algorithm MABC is run for two cases. Initial colony which is initial points to start search process are chosen as normally open tie switches for first case, and the solution obtained with SIM in chapter 3 for the second case. Convergence of algorithm is investigated for both cases and it has been verified that SIM is able to improve runtime of any metaheuristic algorithm.

This thesis presents a heuristic (SIM), two mathematical (analytical, grid search) and a metaheuristic (MABC) approaches for reconfiguration problem solution. Although analytical approach has not meet expectations, it still has potential to be improved in further studies. As a heuristic approach, SIM, do not only reach the near

optimal solution but also come to forefront comparing to the other methods introduced in literature. Moreover, SIM has been proposed to be used in metaheuristic approaches and its impact on convergence of MABC algorithm has been proved. The exact result of reconfiguration is obtained using grid search algorithm and results obtained with other methods are verified. Yet, there are still many works to be done. For smart grid operation, beside fast and reliable reconfiguration methods, the environment with DGs, storages and demand participation etc. needs to be consider in network representation and analysis. From this point of view, we believe these methods can be improved considering elements of smart grid and multi objective approaches can be considered to answer needs of grid.

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BIOGRAPHY

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APPENDICES

Appendix A: Journal Article and Conference Proceeding Based on the Thesis

Şeker A. A., Gözel T., Hocaoglu M. H., (2021), “BIBC Matrix Modification for Network Topology Changes: Reconfiguration Problem Implementation”, *Energies*, 14(10), 2738.

Seker A. A., Gözel T., Hocaoglu M.H., (2018), “An Initial Study of Analytical Approach for Reconfiguration”, *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 1-6, Sarajevo, Bosnia and Herzegovina, 21-25 October.