DESIGN OF AN ADAPTIVE OVERCURRENT PROTECTION SYSTEM FOR MICROGRIDS

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Degree of Master of Science by Research

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DECLARATION

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ABSTRACT

Microgrids have been popularized in the past decade due to their ability to add distributed generation into the classic distribution systems. Protection problems are among several other problems that need solutions in order to extract the full capability of these novel networks. This research follows the branches of two major solutions, namely Adaptive protection, and Protection Optimization.

Adaptive protection implementation with a novel concept of clustering is studied and protection setting optimization is done using a novel hybrid nature-inspired algorithm. Two test system models are used to test the performance of the proposing method as final outcome being the operating time of relays due to different faults.

The selected algorithm proven to be effective than most other algorithms and the clustering approach for adaptive protection was able to reduce the number of adaptive groups.

Keywords— Adaptive Protection, Microgrid Protection, Protection Optimization, Directional Overcurrent Protection, Nature Inspired Optimization Algorithm, k-means Clustering

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LIST OF ABBREVIATIONS

CT	Current Transformer
CTI	Coordination Time Interval
DER	Distributed Energy Resources
DFIG	Doubly-Fed Induction Generators
DG	Distributed Generation
DOCR	Directional Overcurrent Relays
ECDG	Electronically Coupled Distributed Generation
ESS	Energy Storage Systems
IIDG	Inverter Interfaced Distributed Generation
VSC	Voltage Source Converter
LOG	Loss of Grid
LOM	Loss of Mains
MINLP	Mixed-Integer Non-Linear Programming
NIA	Nature-Inspired Algorithms
PCC	Point of Common Coupling
PS	Pickup Setting
SG	Synchronous Generator
SSC	Symmetrical Short Circuit
TDS	Time Dial Setting
WCMFO	Water Cycle - Moth Flame Optimization

1. Introduction

Microgrids have accumulated a considerable amount of interest within the past decade and turn out to be an essential asset in the power industry. The capability to incorporate sustainable energy generation methods into the distribution network is one of the vital reasons for microgrids recognition. A broad array of Distributed Generation (DG) technologies including, wind and other micro-turbine generation, photovoltaic generation along with energy storage, makes the microgrid more feasible in both grid-connected and islanded modes [1, 2].

There are several technical disputes to be confronted when trying to access the entire potential of microgrids, and protection is one of those challenging areas. Various solutions were introduced, driven by the development of protection techniques. Microgrids containing DG can cause variations in short circuit levels which is one of the main reasons for these protection challenges. The ability of microgrids to operate islanded of the main utility can make these variations more drastic. Also, the existence in different operating topologies can cause the protection selectivity much more complicated. Current state of research regarding these problems are discussed and novel solutions are proposed. Performance of these proposing methods are evaluated through simulation models and compared with other existing solutions.

1.1. Project Objectives and Scope

The main objective of the research is to design an optimized adaptive overcurrent protection system for a microgrid. Specific objectives can be listed as follows.

- Achieve Adaptive protection regardless of the network topology
- Incorporate Optimization Algorithms to provide a minimum operating time of relays and obtain optimal coordination

Proposing scheme will use adaptive protection methods to tackle the existence of different operating configurations. Novel optimization algorithm will be used to calculate protection settings while providing optimal selectivity and faster fault clearance.

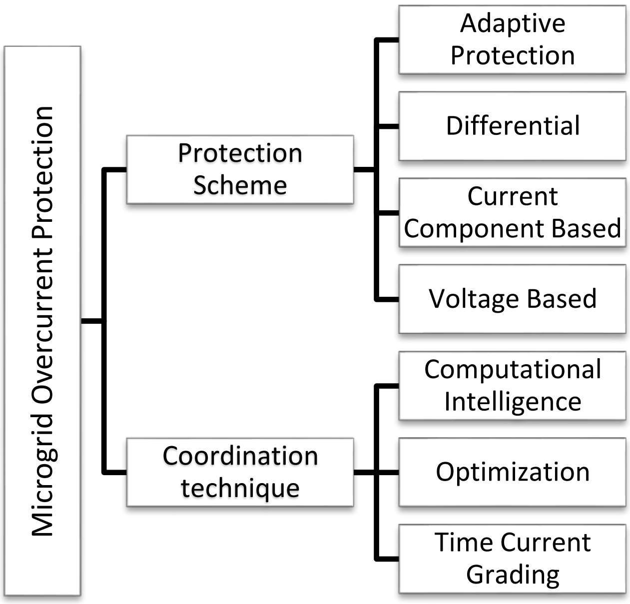


Figure 1.1 Characterization of Overcurrent Protection Methods

1.2. Distributed Generation techniques

Distributed Generations (DG) in microgrids use renewable and conventional energy sources. Intermittent nature of the renewable DGs (Wind, Photo-Voltaic Systems), require proper Energy Storage Systems (ESS) having fast response to provide an uninterrupted supply of electricity.

Two main types of distributed energy resources (DER) can be identified as electronically coupled or inverter interfaced, and rotating machine type generation. Electronically coupled distributed generation (ECDG) or Inverter interfaced distributed generation (IIDG) has AC-DC converters that create the interconnection between the energy source and the distribution network. These energy source technologies can range from solar photovoltaic (PV), wind turbine generation with inverter converter interface (Wind Type 4), Battery energy storage systems and even high-speed gas turbines with Voltage source converter (VSC) grid interface [3].

Rotating machine type DGs include squirrel cage and doubly fed type wind generation, diesel-fuelled generation and classic gas turbine generation.

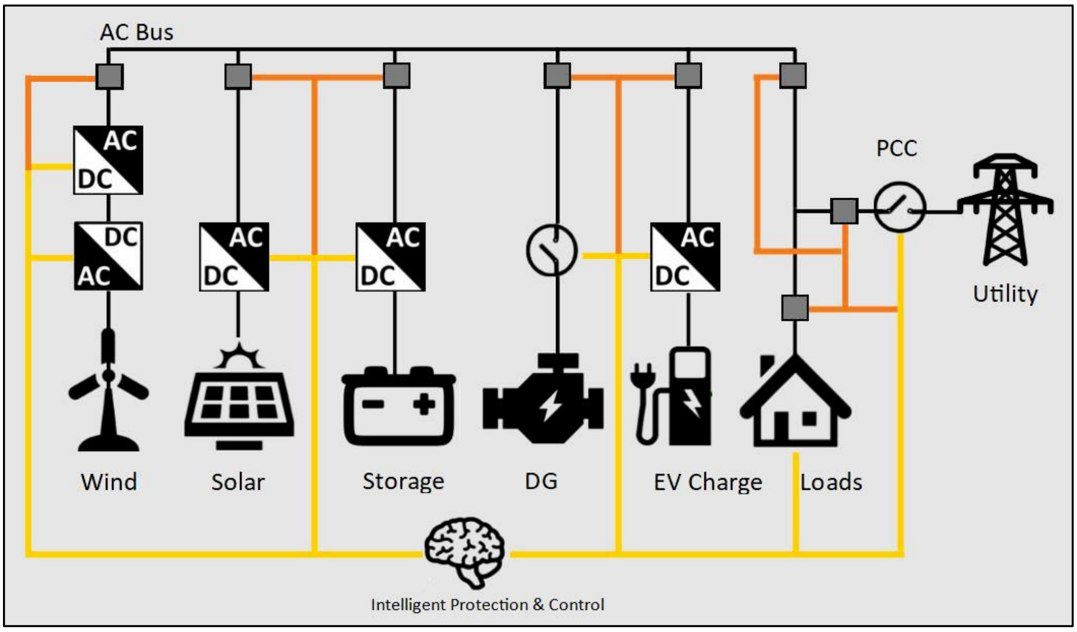


Figure 1.2 Typical Microgrid with Possible DG options

Table 1.1 Characteristics of microgrids.

Advantages	Disadvantages
Benefits the environment through the lack of greenhouse gas emission through low/zero-emission generation technologies	Separate control schemes are required to operate within both technical and economical limits
Through Islanding, microgrids can operate even during utility failures increasing the reliability levels	Use of battery-based energy storage systems can be expensive in both initiation and maintenance
Can contribute to peak shaving of the grid network by distributed generation during peak hours	Intermittent nature of the renewable energy sources
Used to electrify remote areas which have difficulties in connecting with the primary grid	Protection Challenges due to the distributed generation
An ideal solution for the CHP requirements of customers by increased overall energy efficiency	
The economic advantage of generating own electricity for a lower cost than from the main utility and even by exporting the energy back to the grid	

1.3. Protection problems in Microgrids

The existence of DG and different operating topologies mainly causes the technical challenges that microgrids face. Protection challenges can be identified as a major area that requires specialized solutions in order to manage efficient running microgrids.

1.3.1 Short Circuit Capacity

There are two critical levels in the variation of fault current as of the microgrid status shifts among grid-connected and islanded modes. During the islanded stage, short circuit capacity of the network is low, as the DGs have a much smaller capacity than the generation available in the utility grid. Due to this significant reduction of fault current as explained by the authors of [4], if the relay threshold values are selected according to the grid-connected mode, it will not be satisfactory for a fault occurred in the islanded mode. The short circuit current should be increased in this context to match with the settings, or the settings should be adjusted according to the topology. Both solutions have been attempted, and the second option is the main focus of this research. One method of increasing the fault current by adding a fault current source is discussed in [5].

1.3.2 Bidirectional Power Flows

Conventional distribution systems are radial with unidirectional power flow. Flow direction is from single or multiple sources at one end to the load at the opposite end. With the DG penetration of microgrids, this one-directional flow could change its direction according to the status of local generation and local consumption [6]. Because of this reverse power flow, magnitude, and direction of the fault current may change. This makes conventional protection coordination invalid, and the necessity for a directional protection element arises.

1.3.3 Unnecessary Tripping

Unnecessary tripping is also identified as selectivity issues or sympathetic tripping. When a fault occurs in a feeder powered by multiple sources; both utility and DG, each can contribute to the fault current. The problem occurs when a healthy portion of the system or a DG is disconnected due to the fault, instead of isolating the faulty feeder [7]. Unnecessary tripping creates a significant threat to the reliability of the network.

Example of this phenomena is illustrated in Figure 3 as relay R1 trips for a fault in the relay R2’s protection zone.

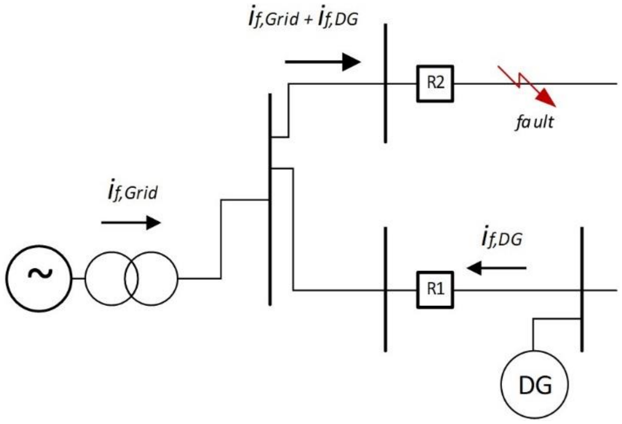
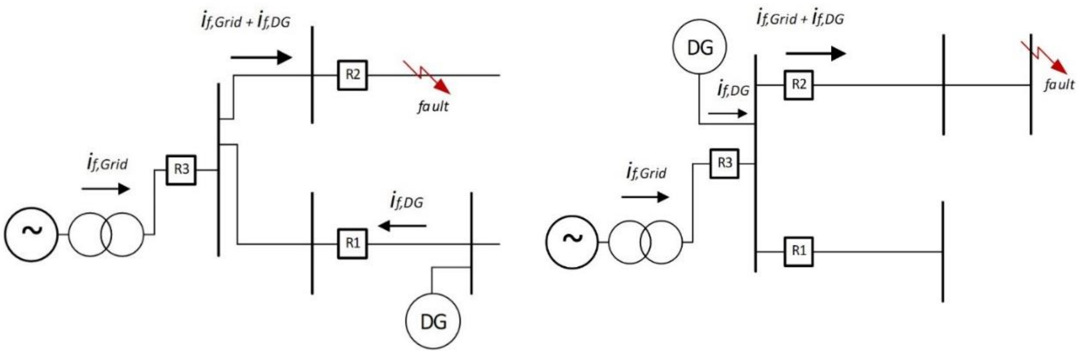


Figure 1.3 Unnecessary Tripping of Relay R1.

1.3.4 Under-Reach and Over-Reach

Under-reach, also known as Blinding of Protection, occurs from the grid fault current reduction due to the addition of DGs. As the fault current contribution decreases with the addition of DGs according to Figure 4 (a), the grid fault current may not be sufficient to trip the breaker associated with relay R3.

Overreach occurs with a fault occurring downstream of the DG connected bus, during the grid-connected operation. As per the scenario in Figure 4 (b), Relay R2 will operate for the fault beyond its zone due to the increased fault current when compared with a non-DG scenario.



(a) (b)

Figure 1.4 (a) The Underreach of Relay R3, (b) The Overreach of Relay R2.

1.3.5 Loss of Mains

Loss of mains (LOM) or Loss of Grid (LOG) scenario can be identified as losing the power from the parent grid. This can either be a disconnection from Point of common coupling (PCC) or a higher level. If it is from PCC, the microgrid becomes islanded and creates problems when DG cannot provide enough capacity to feed the local loads. Frequency stability and voltage dips can occur from the LOM [8]. In the other type of disconnection where a part of unenergized utility is connected with the DG fed microgrid, actions should be taken to either disconnect the DGs or switch to an islanded mode to prevent power from been fed back into the utility. A fast and reliable LOM detection method should be employed in order to cope with these scenarios effectively [9].

1.3.6 Integration of Various DG

Integration of a DG to a microgrid could increase the short circuit level associated with all of the network buses. The level of this increment will vary based upon location, size, and nature of the interconnecting DG [10]. Furthermore, the type of these DGs also contributes to this variation in a much diverse context. Synchronous DGs can contribute up to 5 times its rated current while PE interfaced DGs can only contribute up to 1.5 to 2 times to the short circuit capacity of the network [11]. Moreover, this value of short circuit current is pre-defined in the inverter control system [12]; therefore, different types of PE interfaces have different short circuit levels. Induction Generator based DGs also fall behind when providing short circuit current when compared to synchronous type DGs [13]. Diverse types of renewable DG source addition could further increase the complexity of varying short circuit level. As addressed by the authors of [14] two types of commonly used wind energy generation techniques, synchronous generator (SG) and doubly-fed induction generators (DFIG) has different symmetrical short circuit (SSC) characteristics with SG having about two times the value of DFIG for maximum short circuit capacity.

1.4. Thesis outline

The structure of the thesis is as follows. Chapter 2 summarizes basic protection scheme elements including the ones that are used in microgrids.

Chapter 3 presents the introduction to adaptive protection and its comparison with other existing methods. Different variations of adaptive protection implementations are discussed, and the identification of multiple topologies are followed through network item contingencies. Furthermore, the clustering methods are proposed to group similar topologies together to reduce the complexity of the adaptive settings.

In Chapter 4, the protection coordination problem and its proposed solutions throughout the years are discussed. Then it focuses on the most novel method of using computational intelligence to calculate optimized protection settings. Different variants of this method are presented, and the proposing method is introduced.

Chapter 5 presents the simulation models and process of the proposing protection system. Two main models are considered, and the process methodology is described until obtaining the results.

Chapter 6 presents simulation results and relevant discussion. Obtained relay settings are used in the system models to validate the accurate operation of protection under different faults.

Chapter 7 summarizes the conclusion and other prominent achievements in the research followed by recommendations for future improvements.

2. Microgrid Protection

Microgrids are usually looped or meshed systems with inherited DG. They can have many operating topologies including major modes of grid-connected or islanded modes as well as the line or other element contingencies. These possible network changes can cause short circuit level changes which require protection settings to be always kept in check.

2.1. Line Protection Overcurrent, Directional

Protection of the distribution level networks, including microgrids, are usually handled through six types of relays. Overcurrent, Distance, Voltage, Differential. The scope of this project is mainly focused online protection. Overcurrent and Distance are the most commonly used types for line protection. Out of these two, the overcurrent solution is more straightforward and cost-efficient. Even though it is the plainest option, it is more difficult to achieve protection of novel distribution networks with varying topologies and embedded generation.

Due to the meshed structure and the presence of DER in these networks, directional overcurrent relays (DOCR) are utilized more commonly. Directional Overcurrent relays are intended to measure the phasor difference between current and voltage, to identify the direction of current flow. The relay operates only if the fault is occurring in front of the relay. This directionality function is extremely important in a meshed system for correctly discriminate the origin of faults. Relays won't operate for fault currents in 'reverse' direction.

Four main properties of a protection system are sensitivity, selectivity, reliability, and speed. An ideal protection solution should satisfy all these characteristics.

Sensitivity is the ability to identify the minimum fault conditions as well as the moderate and severe faults. Sensitivity can be a major issue in microgrid scenarios with major changes in the short circuit current level. Pickup current setting of a relay is directly related to sensitivity and should be adjusted accordingly to provide protection at every fault level.

Selectivity is the perfect coordinated operation of primary and backup protection elements. For a fault, its primary relays should operate initially, and the backup protection should follow with the appropriate delay.

Reliability has two main sub qualities as dependability and security. Dependability is the characteristic ability to operate correctly during the required time. Security is the ability to mitigate unnecessary operations during nominal operating conditions. For example, the protection shouldn't get triggered by faults outside its zone and should have a tolerance on transients.

Speed is another significant factor in increasing the performance of a protection scheme. Faster fault clearance can ensure minimal damage to the network and equipment. Unnecessarily faster operations can cause undesired operations therefore appropriate tolerance levels should be defined.

2.2. Primary and backup

Microgrid Primary relay can be identified as the one closest to the fault. There can be multiple primary relays for a fault each disconnecting a different section of the network to isolate the fault. Backup protection operates only if the fault is not cleared by the primary protection. Backup relays usually have time coordination with primary relays and if the fault persists beyond this pre-specified time, backup relays operate. Relay miscoordination can cause backup relays to operate prior to the primary relays and cause unnecessary disconnections leaving substantial portions of the network de-energized. Primary backup coordination is relatively easy in a radial network but for either meshed or DG sourced network it can be tedious. [15]

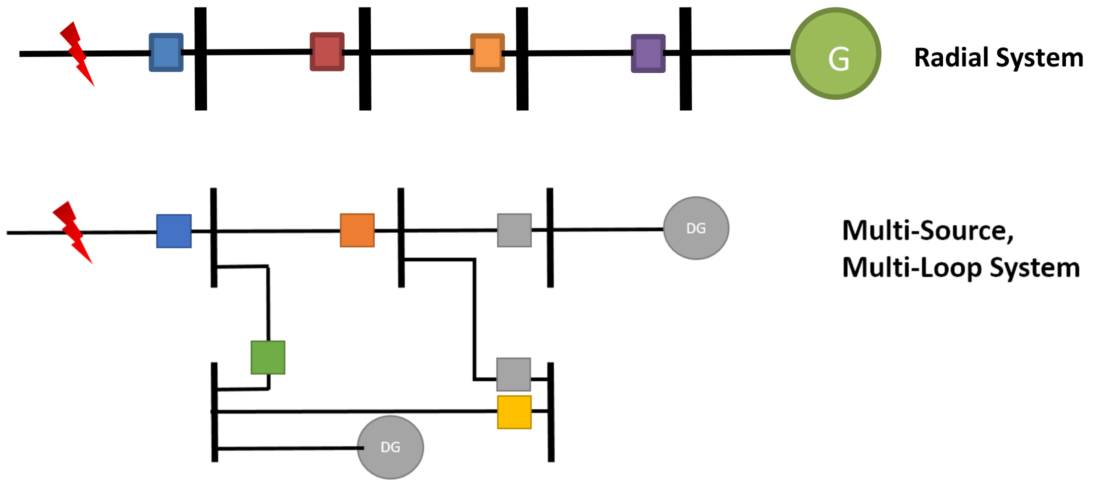


Figure 2.1 Radial and Meshed systems

2.3. Characteristic curves of relays

The operation of the overcurrent relay is governed by each of their characteristic curves. Inverse time curve is the widely used type with operating time increasing with the magnitude of the fault. There are standardized curves presented in the form of a mathematical model for relay operating time. Operating time of a relay can be expressed as in Equation 1 according to IEC 60255 standard. Parameters are also listed as in Table 2.1 and Table 2.2. There can even be custom curves developed by using different user-defined values instead of standard values [16].

$$t = \left[\frac{K_1}{\left(I_f/(PS \times CT_r)\right)^{K_3} - 1} + K_2\right] \times TDS \qquad (1)$$

Table 2.1 Relay Parameters

Symbol	Parameter
t	Operating time
TDS	Time Dial Setting
I_f	Fault Current
PS	Pickup Setting
CT_r	Current Transformer Ratio

Table 2.2 Standard Parameter values

Standard	Curve type	K_1	K_2	K_3
ANSI/IEEE	MI – moderately inverse	0.0515	0.1140	0.02
	VI – very inverse	19.61	0.491	2.0
	EI – extremely inverse	28.2	0.1217	2.0
	NI – normally inverse	5.95	0.18	2.0
	STI – short-time inverse	0.02394	0.01694	0.02
IEC-60255	SI – standard inverse	0.14	0	0.02
	VI – very inverse	13.5	0	1
	EI – extremely inverse	80	0	2
	STI – short-time inverse	0.05	0	0.04
	LTI – long-time inverse	120	0	1

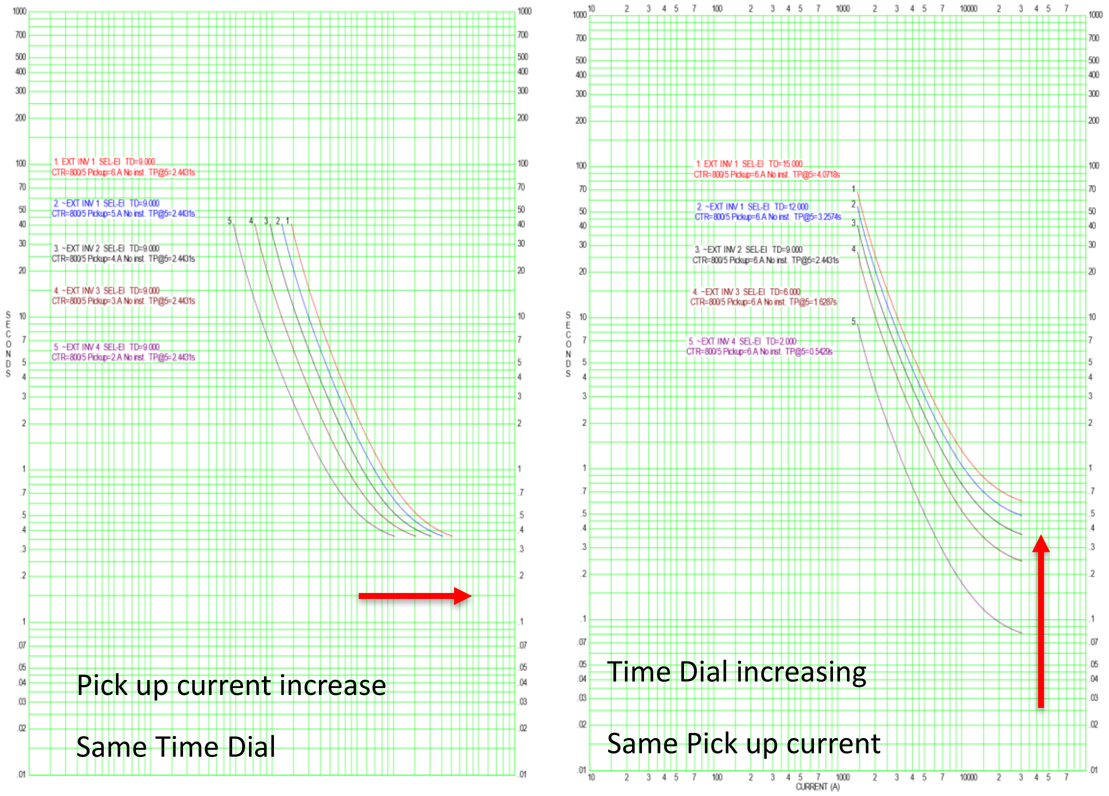


Figure 2.2 Time-Current Curve variation with variables

By varying these two variables we can change the operating time of a relay for specified current range. Considering different curve types can also provide a wide range of flexibility in setting operating times. But in this research only ‘Standard Inverse IEC curves’ are considered to avoid unnecessary complications.

3. Adaptive Protection

Adaptive Protection is defined as an online process of protection response modification in accordance with the network conditions. [17] An adaptive protection system design consists of a set of digital relays, a smart control system that monitors and responses to the network events, and communication infrastructure for the data transfer between processing and actuating pairs. There are several Communication-less protection methods proposed in the literature but with less feasibility in the modern meshed type microgrids. [18]

Apart from the adaptive protection, there are several other protection schemes that can be used with microgrid protection. Differential protection, Phasor Current-Based, Phasor Voltage-Based and Impedance Based are some of them. Adaptive Protection remains a popular solution among research due to its simplicity. There are also some drawbacks associated with these other schemes, such as differential methods can cause issues with unbalances and transients and current-based methods can mis operate with unsymmetrical loadings. A key obstacle of the adaptive scheme is that it requires prior knowledge on all possible configurations. But when applied to a microgrid it is not a major issue as the system is relatively small and the different topologies can be handled easily.

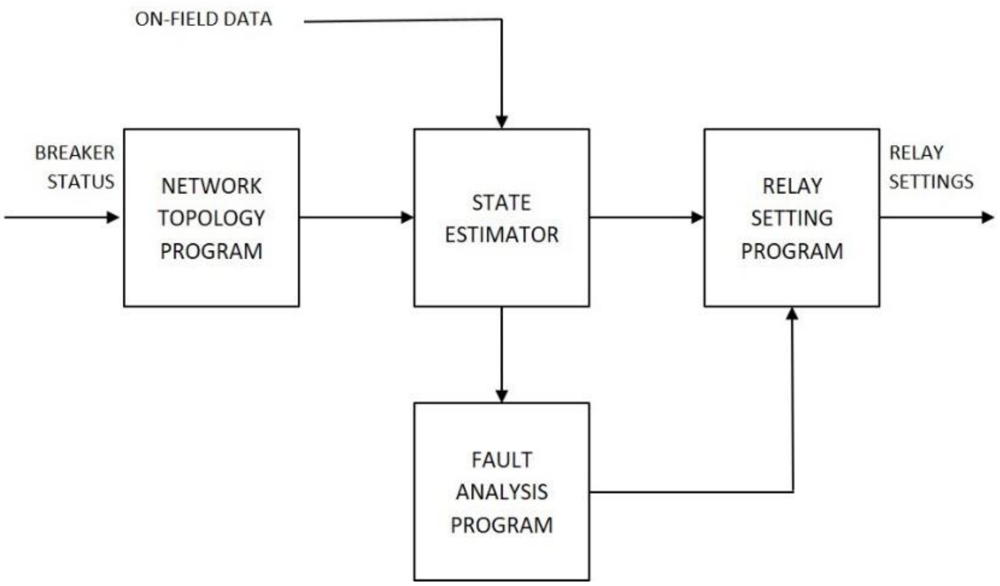


Figure 3.1 Simple Adaptive Protection Scheme.

3.1 Main Variants of adaptive protection

The following can be identified as the primary conditions to be satisfied for the practical execution of an adaptive protection scheme. Equipped with digital relays that accepts a wide range of tripping attributes and the switching of these settings should be possible via remote communication. The communication protocol should be compatible with standards such as IEC 61850.

One can either use offline analysis and have a set of pre-calculated relay settings which are applicable in the identified operating mode or revise the relay settings online according to the present topology. In the Offline method, a set of profound network topologies has to be identified and the respective protection settings for each state is recalled through an event table. Online calculation for an adaptive protection system is triggered by interruptions on distributed generations [19]. The above research did not take line contingencies into account when identifying the fault current variations. If that to be included this type of online protection calculation can be infeasible due to the higher number of uncertainties.

3.2. Network Topologies

Operating topologies can be identified by considering single contingencies. Each line, generator and transformer can be disconnected one at a time to obtain new topologies. While it is possible to identify more meaningful topologies by using double contingency, the obtained topologies are sufficient for validating the proposed design.

3.2.1. K- means Clustering

Clustering is a phenomenon used in data science, to group similar data objects. It is primarily a search function that is used to identify similar and dissimilar objects and group them accordingly [20]. Data clustering is vastly utilized in the fields of data mining and pattern recognition. There are several methods used to develop clusters such as hierarchical methods, partition methods, grid-based methods, model-based methods etc. The k-means clustering algorithm is a widely used method used for data clustering. The main objective of this algorithm is to minimize the distance from each data point to the centre of its cluster. Figure 3.2 illustrates the basic flowchart of k-means algorithm.

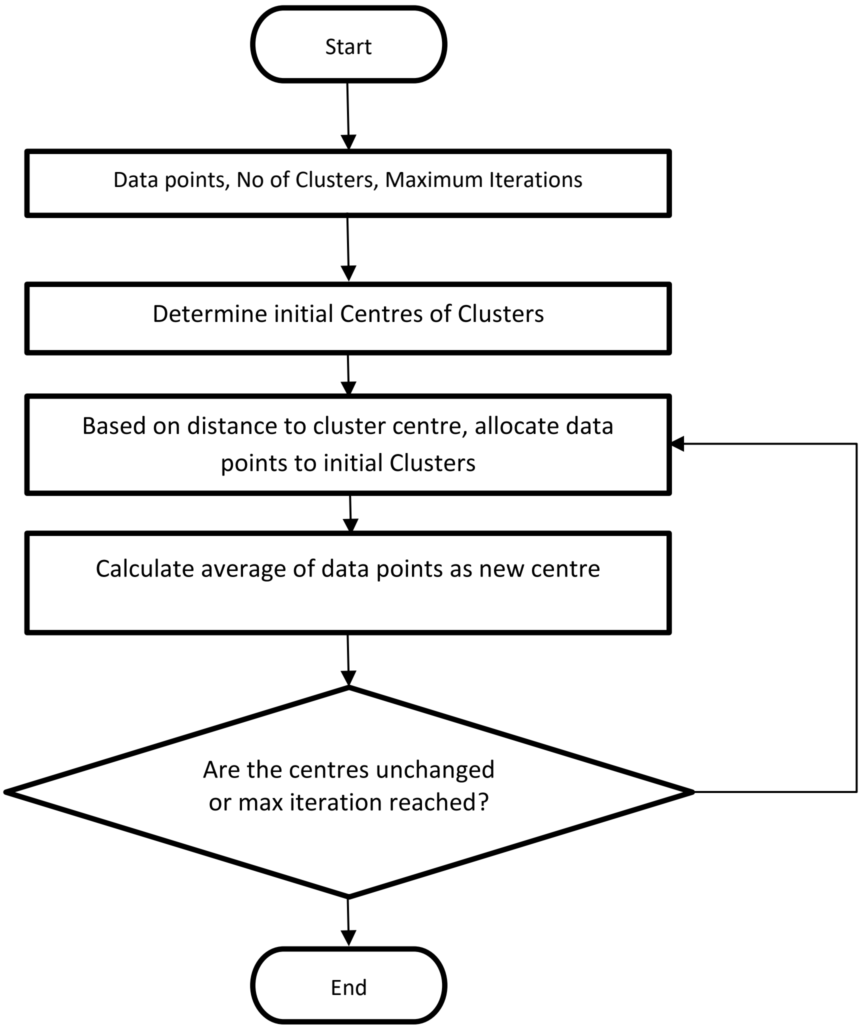


Figure 3.2 Flowchart of the k-means clustering algorithm

$$D_{ij} = \left[\sum_{m=1}^{d}\left(x_{im} - c_{jm}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

Equation 2 is used to calculate distances from every single data point to the closest centre. D_{ij} is the Distance between datapoint x and initial centre point c, where d is the number of dimensions in the selected space. After calculating the distances, the average of data in the whole cluster is calculated by equation 3. Here m is the dimension, j is the cluster no, n is the number of data points in the cluster.

$$a_{jm} = \frac{1}{n_j}\sum_{i=1}^{n_j} x_{im}\ ; m = 1,2, \ldots d \quad (3)$$

After that, the new averages are assigned as centres and the process is repeated until the desired iterations or there is no considerable change in centres between iterations.

4. Protection Coordination

Coordination of directional overcurrent relay becomes a critical issue in the meshed systems with distributed energy resources i.e. microgrids. This challenge has been confronted as early as 1988 [21]. Researchers were eager to find the ideal technique of getting protection relay settings. As the popularity of microgrids grew, which are inheritably multi-sourced and multi-loop in nature, the importance in the coordinated protection settings has also increased.

4.1. Different Coordination methods

Overcurrent relay coordination techniques are categorized in the literature as Conventional methods, Optimization techniques and the use of Computational Intelligence. Conventional methods consist of trial and error method and topological analysis.

The earliest of relay coordination approaches was trial and error method, which was also the most basic approach. It consists of tiresome manual calculations and takes many iterations to reach an acceptable relay setting. Slow convergence and the considerable number of iterations made this method very time-consuming. The topological analysis methods were introduced to reduce the iterations by using the "break-points" concept. Topological analysis occupies functional dependency and graph theory to identify the "breakpoints" which are used as optimum points to start the coordination process [21,22]. The solution obtained through topological analysis method is not the most optimal solution for relay settings.

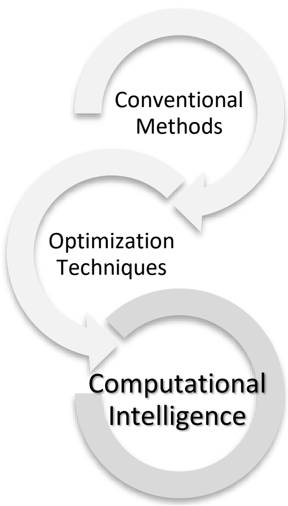


Figure 4.1 Evolution of coordination methods.

Optimization techniques are more advanced approach that eliminates the need for breakpoint formulation and can be used in both linear and non-linear methods. When using the linear problem formulation only a single variable is optimized (usually the Time Dial Setting) while other variable values (e.g. Pickup current) are assumed to be known. Pickup current values should be selected by prior experiences on fault and load data. Simplex methods, dual Simplex methods, and two-phase Simplex methods are some examples of linear optimization techniques. With the non-linear approach, more than one variable can be considered for the optimization. Mixed-integer non-linear programming (MINLP) is a popular method of solving non-linear optimization problems.

Computational Intelligence methods have become the present interest in many fields of research. Protection optimization is mainly done using Nature-inspired algorithms (NIA) that are specialized in solving optimization problems.

The other branches of computational intelligence techniques are not well reputed in solving optimization tasks. Neural Networks are able to learn and generalize from a given example hence specialized in model predictive applications. Fuzzy systems can solve uncertain problems based on a generalization of traditional logic. Nature-inspired algorithms can generate and evaluate a population of viable solutions for a given problem.

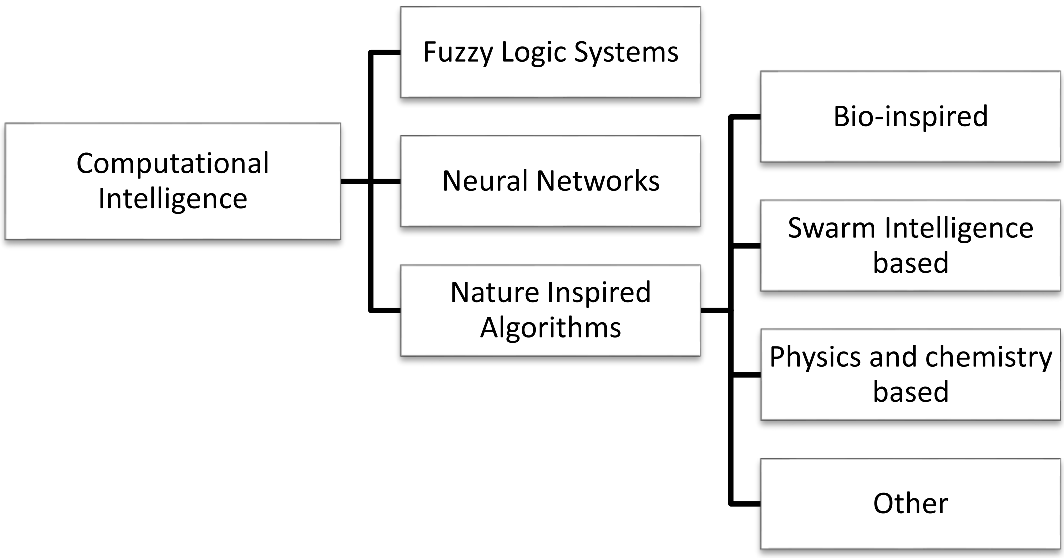


Figure 4.2 Classification of Computational Intelligence methods.

Within the recent years, more than hundreds of Nature inspired algorithms were developed. These NIAs are usually grouped in literature as Bio-inspired, Swarm intelligence-based, Physics and chemistry-based and Other. Several of these algorithms are Particle swarm optimization (PSO), Genetic algorithm (GA) which are more established algorithms. More recent algorithms such as Grey wolf optimization (GWO), Whale Optimization algorithm (WOA) have gathered the attention of the researchers.

4.2. Nature-Inspired Algorithms for Optimization

The NIAs are extensively being used primarily due to their dominance over other techniques. Some of the benefits can be listed as Simplicity, flexibility, Derivative-free mechanism, and Local optimum avoidance.

4.2.1 Different Objective Functions Used

Equation 4 presents the sum of operating times of relays for a defined fault. This is the most widespread objective function utilized by many of the literature [23, 24, 25]. Probability coefficient (w) is used to represent each fault occurrence probability.

$$min\ Z = \sum_{i=1}^{N} w_i t_i \tag{4}$$

Probability coefficient w is usually set as 1, which makes all faults to have equal rate of occurring. The considering three-phase ground fault for each primary protection zone can either be a near-bus fault (equation 5) [26, 27], or both near-bus and far-bus faults (equation 6) [28,29].

$$min\ Z_1 = \sum_{i=1}^{N} t_{i,near} \tag{5}$$

$$min\ Z_2 = \sum_{i=1}^{N_{near}} t_{i,near} + \sum_{j=1}^{N_{far}} t_{j,far} \tag{6}$$

A fault occurring at the beginning of a line near the relay is considered a near-end fault. This near end fault has the maximum short circuit current level for the considered relay. A far-end fault provides the minimum short circuit value for the considered relay while occurring at the furthest end of the line. Operating time for each near-end fault and far-end fault can be denoted as $t_{i,near}$ and $t_{j,far}$, respectively. When considering both near-end and far-end faults, the function is expected to become more generalized.

Third type of common objective function is sum of squares of the relay operating times, as in (7) [30, 31]. This is mainly used to minimize the backup relay operating times while prioritizing the primary operating times with the squares. The CTI constraints are included within the OF second summation term. Here Δt_j is for the relay coordination (8). The first term can be used alone for primary relay settings with coordination term included in the separate constraints (9).

$$min\, Z_3 = \sum_{i=1}^{N}(t_i)^2 + \sum_{j=1}^{M}(\Delta t_j - |\Delta t_j|)^2 \quad (7)$$

$$\Delta t_j = t_{j,k} - t_{i,k} - CTI \quad (8)$$

$$min\, Z_3 = \sum_{i=1}^{N}(t_i)^2 \quad (9)$$

It was found that these different objective functions do not make a considerable impact on the final results [32]. Therefore, the popular choice of using near end fault (Equation 5) has been used in the proposing scheme.

4.2.2 Different Algorithms Used

A large number of optimization algorithms have been used in relay coordination throughout the years. Some of those are tabularized below.

Table 4.1 Different NIA algorithms Used in Network Protection

Algorithm Name	Applied Model	Reference
Random Search Techniques (RST-2)	IEEE 3, 4, 6	D. Birla, 2006. [33]
Particle Swarm Optimization (PSO) and variants	IEEE 3, 4	J. C. Bansal 2008. [34]
Laplace Crossover Polynomial Mutation (LX-POL) Laplace Crossover Power Mutation (LX-PM)	IEEE 3, 4, 6, 14, 30	K. Deep, 2008. [35]
Differential Evolution (DE)	IEEE 3, 4, 6	R. Thangaraj, 2010. [36]
Modified Differential Evolution (MDE 1-5)	IEEE 3, 4, 6	R. Thangaraj, 2010. [37]
Harmony Search Algorithm (HSA)	IEEE 30	M. Barzegari, 2010. [38]
Genetic Algorithm (GA)	IEEE 3, 4, 6	Uthitsunthorn, 2010. [39]
Seeker Algorithm SA	IEEE 3, 8	T. Amraee, 2012. [26]
Teaching and Learning Based Optimization (TLBO)	IEEE 3, 4, 6	M. Singh, 2013. [40]

Black Hole Algorithm (BHA)	33- Bus Radial	N. Ghaffarzadeh, 2015. [41]
Biogeography-based optimization (BBO) and BBO-LP linear programming	IEEE 3, 4, 8	A. Albasri (2015). [42]
Cuckoo optimization algorithm (COA)	Custom MG	A. Ahmarinejad, 2016. [43]
Backtracking Search Algorithm (BSA)	IEEE 6, 8, 16	Bouchekara, 2016. [44]
Bacteria Foraging Algorithm (BFA)	IEEE 3, 4, 6	S. Adhikari, 2016. [45]
Electromagnetic field optimization (EFO)	IEEE 8, 9, 15	H. Bouchekara, 2017. [46]
Firefly Algorithm (FA)	IEEE 3, 4, 6, 8	M. Sulaiman, 2018. [47]
Grey Wolf Optimization (GWO)	IEEE 6, 30	Kim, C.H, 2018. [48]
Nature-Inspired Root Tree Algorithm (NIRT)	Custom MG	A. Wadood, 2018. [49]
Water Cycle Algorithm (WCA)	IEEE 15, 30	A. A. El-Fergany 2019. [50]

The algorithms are used in either linear or non-linear problem formulation. In linear scenarios, only a single variable is considered in the optimization usually the Time Dial Setting (TDS). In these types of linear cases, the other variables namely Pick-up Setting and the Curve type are pre-selected using either conventional methods or previous experiences [49]. In non-linear formulation, multiple variables can be included in the optimization. Usually, both TDS and PS are optimized simultaneously. [51] Sometimes even the operating relay time-current curve type is considered in the optimization to achieve a more dynamic protection solution. [52]

4.2.3 Multi-Objective Optimization

Multi-Objective Optimization (MOO) is required when there are multiple number of objectives to be improved. When performing a multi optimization simultaneously, compromises are being made in order to achieve the optimal set of solutions. This set of solutions is called the Pareto front.

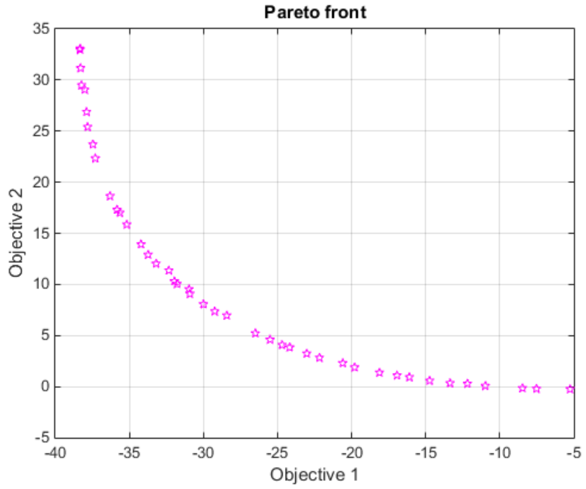


Figure 4.3 Pareto front for a problem with two objectives.

In attaining the required Pareto front solution there are two popular methods as Multi-Objective Decision Making (MODM) practices and Multi-objective optimization techniques. When using the MODM method, the multi-objective problem is converted into a single objective model usually through the weighted sum method [53]. Different weights are assigned according to the importance of the objective and added together to formulate a single objective function. At each run of the optimization algorithm, it will provide a solution from its respective Pareto optimal solution set.

Multi-objective optimization technique utilizes a special multi-objective version of the metaheuristic algorithm. Most of the novel optimization algorithms have their own multi-objective version proposed by the literature. This method is not widely used due to their long execution times and larger standard deviation of the solution vector. They usually exhibit weaker algorithm performance when compared with its single objective counterpart [54]

4.2.4 Constraint Handling

When solving an optimization problem there can be constraints that limit the feasible solution space. The constraints shouldn't be violated for a feasible solution. There are two main types of constraints as equality constraints and inequality constraints.

$$\min f(x)$$

$$g_i(x) \leq 0 \quad i = 1, \dots \ , q \tag{10}$$

$$h_j(x) = 0 \quad j = 1, \dots \ , m \tag{11}$$

For the above optimization of f(x) there are q number of inequality constraints g(x) and m number of equality constraints h(x) (equation 10, 11).

Optimization algorithms handle constraints in different ways. Some algorithms have inherited constraint handling where it only requires defining the equality and inequality constraint functions. For example, the genetic algorithm (GA) can perform constrained optimization without any modification of the usual input syntax. Some algorithms cannot process constrained optimization problems and need to use modifications in input data to obtain a feasible solution set. i.e. Particle Swarm Optimization (PSO).

4.2.5 Penalty Method

Penalty function method of constraint handling is a more popular option in constrained optimization. Penalty function method transforms the constrained problem into an unconstrained one through modification of main objective function. This can be done in two ways as additive method and multiplicative method. The additive method is the more popular option which adds a penalty function to the main objective function.

$$f(x) = \begin{cases} f(x) \, ; if \ no \ violations \ occur \\ \quad f(x) + p(x) \, ; otherwise \end{cases} \tag{12}$$

If no violations occur, penalty function p(x) will be zero and when violations occur it will be positive for minimization problems and vice versa.

4.3 Performance of Algorithms

Different optimization algorithms can produce different optimized datasets as output values. Better the algorithm performance, more optimal the results will be. To identify the degree of optimization for a problem, its objective function value can be used as a performance indicator. As an example, for a minimization problem, the algorithm that can produce the minimum objective function value can be considered as the best performing algorithm.

Following Table 4.2 presents objective function values from different algorithms for three test systems. It is evident that more novel algorithms have lower objective function values, indicating better performance. It is also evident that hybrid algorithms such as Immune Algorithm and Particle Swarm Optimization (IA-PSO) have better performance than its normal counterpart (Immune Algorithm IA).

Table 4.2 Comparison of Objective function values

Algorithm	IEEE 3-bus	IEEE 4-bus	IEEE 6-bus
GA [34]	5.07616	3.85874	13.7996
SOMA [34]	8.01016	3.78922	26.1495
SOMGA [34]	4.78989	3.67453	10.3578
RST2 [34]	4.83543	3.70502	10.6192
PSO [29]	4.78066	3.65240	8.1245
DE [55]	4.84218	3.67744	10.6272
MDE-4 [55]	4.78067	3.66749	10.3812
MDE-5 [55]	4.78060	3.66940	10.3514
LX-POL [55]	4.82650	3.57490	10.6028
LX-PM [56]	4.82860	3.58300	10.6219
OCDE2 [56]	4.78060	3.66742	10.3286
TLBO [29]	5.33490	5.58900	23.7878
SASOS [55]	4.72010	3.55330	9.8948
IA [29]	-	3.6758	9.3468
IA-PSO [29]	-	3.1239	7.6722

These hybrid algorithms are created by combining two or more primary algorithms. They can utilize the best features of combining algorithms to enhance the overall search efficiency to obtain the solution. The proposing scheme will also use a hybrid algorithm to get a better solution set.

5. Simulations on Test model Systems

Two system models were used in simulating the protection scheme. A generic microgrid model with six busses, Grid connection and three Distributed generations was the first test model. The second model was a modified IEEE 14 bus system which uses the 33kV distribution section of standard IEEE 14-bus network.

5.1 Six Bus Generic Microgrid

The six-bus generic microgrid model consists of 7 lines, 14 relays, 2 synchronous generators, 1 wind generator, 3 general loads and 1 utility connection.

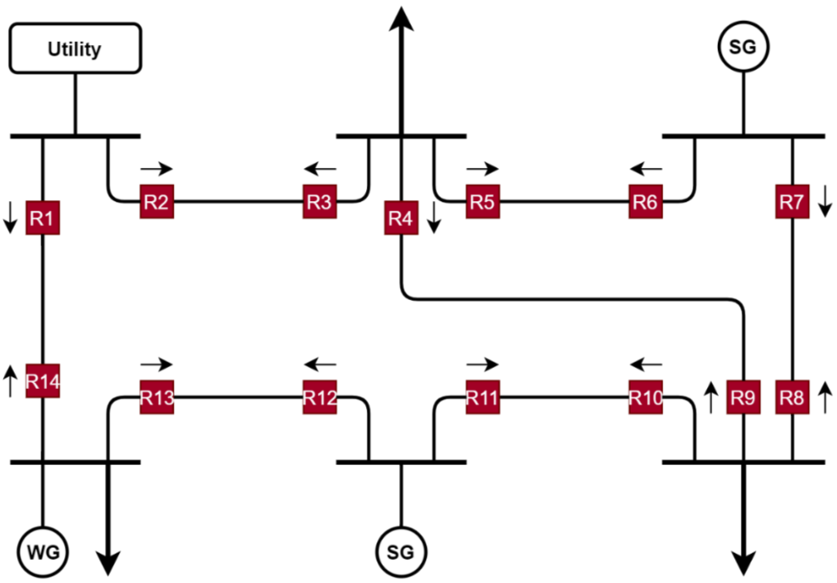


Figure 5.1 Schematic view of Generic Six bus microgrid.

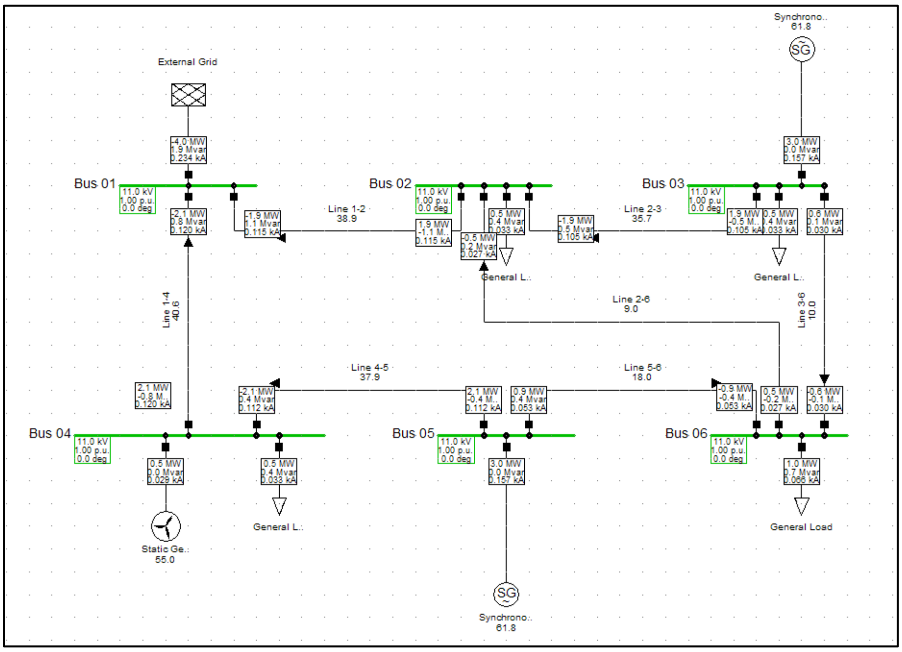


Figure 5.2 Simulation model Generic Six bus microgrid.

This six-bus generic microgrid was used to simulate the performance of different algorithms.

5.1.1 System Parameters

System parameters of each element in the used model are listed in Table 5.1 to Table 5.5.

Table 5.1 System External Grid Data

Bus Type	SL
Angle	0 deg
Voltage SetPoint	1 p.u
Max Short Circuit Power	100 MVA

Table 5.2 System Line Model XLPE-CU 3x95 11kV

Rated Voltage	11 kV
Rated Current in air	1 kA
Nominal Frequency	50 Hz
AC Resistance 1,2 Sequence	0.193 Ohm/km
AC Resistance Zero Sequence	1 Ohm/km
Inductance 1,2 Sequence	0.31831 mH/km
Inductance Zero Sequence	3.183099 mH/km
Capacitance 1,2 Sequence	0.35969 uF/km
Length	0.1 km (Line 2-6, 0.3 km)

Table 5.3 Synchronous Machine Model Data

Bus Type	PQ
Nominal Apparent Power	4.855 MVA
Nominal Voltage	11 kV
Power Factor	0.8
Synchronous Reactance xd	1.5 p.u
Synchronous Reactance xq	0.75 p.u
Transient Reactance	0.256 p.u
Subtransient Reactance	0.168 p.u
Stator Resistance	0.0504 p.u
Zero sequence Reactance x0	0.1 p.u
Zero sequence Resistance r0	0 p.u
Negative Sequence Reactance x2	0.2 p.u
Negative Sequence Resistance r2	0 p.u
Machine type IEC 60909	Salient Pole Series 1

Table 5.4 Static Generator Model Data

Category	Wind Generator
Bus Type	PQ
Nominal Apparent Power	1 MVA
Nominal Voltage	11 kV
Power Factor	0.8
Sub transient Short-Circuit Level	1 MVA
Transient Short-Circuit Level	1 MVA
R to X’’ Ratio	0.1

Table 5.5 General Load Model Data

Active Power	0.5 MW (Bus 6 – 1 MW)
Power Factor	0.8
Voltage	1 p.u
Technology	3PH PH-E
Balanced/Unbalanced	Balanced

5.1.2 Load Flow Analysis

The microgrid was modelled using DigSILENT PowerFactory. Balanced, positive sequence load flow calculations are done to get the load currents through each relay. These load currents are used for the calculation of lower limits of pickup setting (PS) for each relay. Results from this load flow analysis are presented in Table 5.6.

Table 5.6 Load Flow Analysis

Relay No	Islanded Current (A)	Grid-Connected Current (A)	CT Ratio
1	48	120	600/5
2	48	115	600/5
3	48	115	600/5
4	9	27	100/5
5	45	105	600/5
6	45	105	600/5
7	68	30	300/5
8	68	30	300/5
9	9	27	80/5
10	114	53	600/5
11	114	53	500/5
12	45	112	500/5
13	45	112	500/5
14	48	120	600/5

5.2 Modified IEEE 14 Bus System

The 33kV Distribution section of the IEEE 14 bus system was used as another test model to verify the protection solution [57]. As shown in figure 5.3 the 33kV section is connected with a high voltage section through transformers from bus 6 and bus 9. When disconnected from these links, the distribution section acts as an islanded microgrid. There is only one Synchronous generator in the original 33kV section but in order to in produce, the DG penetration of the system two of the same type generation was added to Bus 13 and Bus 9.

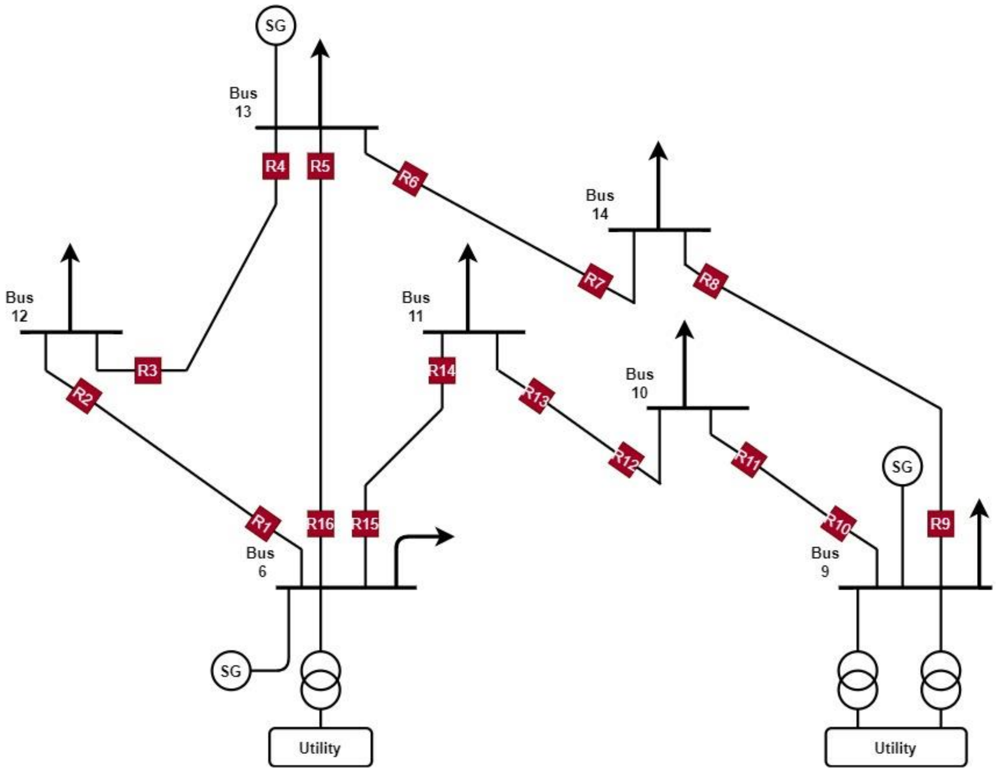


Figure 5.3 Schematic view of Modified 14 bus microgrid.

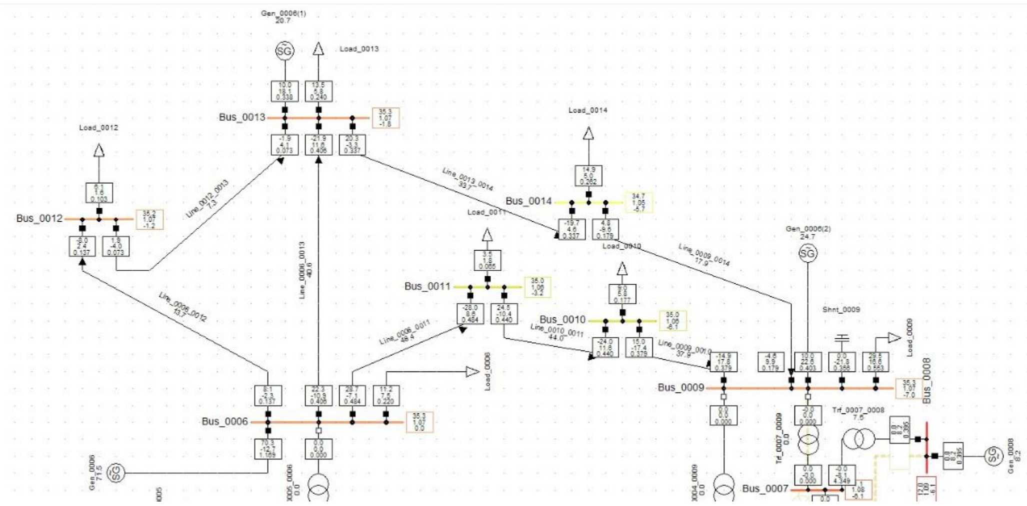


Figure 5.4 Simulation model of Modified 14 bus microgrid.

This modified 14 bus system was used to simulate the ability to use optimized settings in an adaptive manner.

5.2.1 System Parameters

Table 5.7 System Line Data

Bus No 1	Bus No 2	Resistance p.u	Reactance p.u
6	12	0.12291	0.25581
12	13	0.22092	0.19988
13	14	0.17093	0.34802
14	9	0.12711	0.27038
9	10	0.03181	0.0845
10	11	0.08205	0.19207
11	6	0.09498	0.1989

Table 5.8 System Generator Data

Bus Type	PV
Nominal Apparent Power	100 MVA
Nominal Voltage	33 kV
Power Factor	1
Synchronous Reactance xd	2 p.u
Synchronous Reactance xq	2 p.u
Transient Reactance	0.3 p.u
Sub transient Reactance	0.2 p.u
Stator Resistance	0.0 p.u
Zero sequence Reactance x0	0.1 p.u
Zero sequence Resistance r0	0 p.u
Negative Sequence Reactance x2	0.2 p.u
Negative Sequence Resistance r2	0 p.u
Machine type IEC 60909	Salient Pole Series 1

Table 5.9 System Load Data

Bus No	MW	MVAR
6	15.68	10.50
9	41.30	23.24
10	12.60	8.12
11	4.90	2.52
12	8.54	2.24
13	18.90	8.12
14	20.86	7.00

5.2.2 Single Element Contingencies

In order to represent the variation of topologies, single element contingencies for Modified 14 Bus system was considered. New topologies are obtained by disconnecting each Line, generator, and utility connection one at a time (Table 5.10).

Eight topologies are obtained by disconnecting one line at a time. Ninth topology is the one with everything connected. Three more topologies can be obtained by disconnecting each generator and final topology is where utility connection is disconnected.

Table 5.10 System Topologies Considered

Topology No	Disconnected Element
1	Line 6-12
2	Line 12-13
3	Line 13-6
4	Line 13-14
5	Line 14-9
6	Line 9-10
7	Line 10-11
8	Line 6-11
9	none
10	Gen - Bus 13
11	Gen - Bus 9
12	Gen - Bus 6
13	Utility

5.2.3 Load Flow Analysis

Load Flow analysis is done for each topology to obtain current flowing through each relay at nominal operation. These values are used as lower limits when calculating pickup settings of the relays. These values are indicated in Table 5.11. CT ratios are also indicated in the table and all current values in the table are in amperes.

Table 5.11 Load Flow Analysis

Relay No	**T01**	**T02**	**T03**	**T04**	**T05**	**T06**	**T07**	**T08**	**T09**	**T10**	**T11**	**T12**	**T13**	**CT Ratio**
1	-	104	227	70	119	88	99	103	93	130	98	93	137	1500/5
2	-	-104	-227	-70	-119	-88	-99	-103	-93	-130	-98	-93	-137	500/5
3	-105	-	162	-36	56	-35	-40	43	-37	25	-40	-17	73	500/5
4	105	-	-162	36	-56	35	40	-43	37	-25	40	17	-73	1500/5
5	-305	-206	-	-99	-33	-192	-240	-259	-214	-301	-236	-175	-406	1600/5
6	117	129	81	-	268	108	154	174	128	89	157	115	337	1250/5
7	-117	-129	-81	-	-268	-108	-154	-174	-128	-89	-157	-115	-337	600/5
8	-144	-134	-203	-265	-	-153	-118	-110	-135	-184	-106	-147	179	750/5
9	144	134	203	265	-	153	118	110	135	184	106	147	-179	1500/5
10	145	146	149	157	162	-	176	242	146	149	108	135	-379	2000/5
11	-145	-146	-149	-157	-162	-	-176	-242	-146	-149	-108	-135	379	1000/5
12	-93	-87	-127	-152	-24	-183	-	65	-87	-62	-116	-53	-440	1500/5
13	93	87	127	152	24	183	-	-65	87	62	116	53	440	1000/5
14	-140	-138	-176	-200	-84	-248	-65	-	-139	-116	-175	-115	-484	800/5
15	144	138	176	200	84	248	65	-	139	116	175	115	484	2000/5
16	305	206	-	99	330	192	240	259	214	301	236	175	406	2000/5

5.3 Short Circuit Analysis

Problem formulation for optimization requires short circuit current values through each relay. Short circuit analysis is done for the test system model according to IEC60909 due to the presence of distributed generation.[58].

5.3.1 Near-end Faults and Far-end Faults

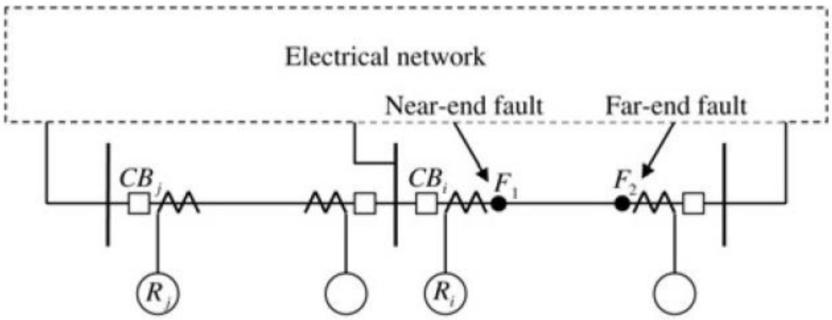


Figure 5.5 Near-end and Far-end Faults [59]

Faults occurring on a line can initiate at any location of the total length of the line. When a relay is concerned the faults can occur from just after the relay to the furthest end from the relay. When DOCRs are used for line protection, near-end faults and far-end faults of a specific relay can be identified as in figure 5.5. Considering relay R_i, its near end fault is a fault occurring at point F_1. This is simply the maximum fault current which can be achieved by a fault. As when the fault moves further away, the impedance of the line causes the current to decrease. Far end fault is a fault occurring at point F_2 where the minimum fault current can be achieved.

5.3.2 Fault analysis of Simulation Models

Three Phase to ground faults are considered as they have the maximum short circuit value. Near end faults are taken as the maximum fault current value while the far-end fault current is considered as the minimum.

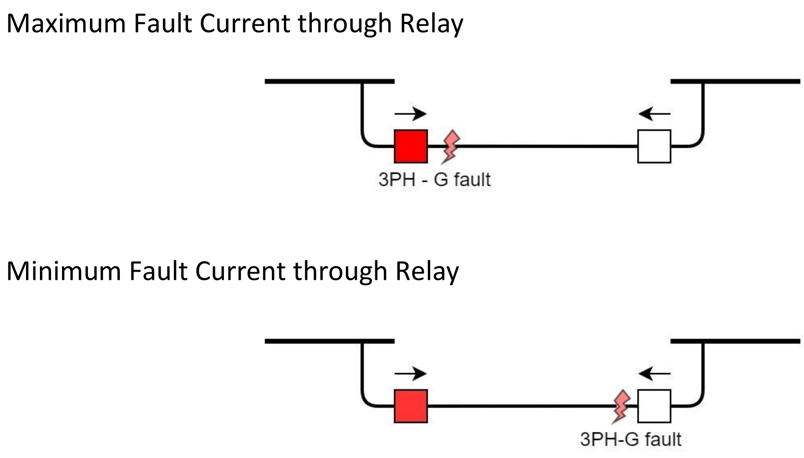


Figure 5.6 Maximum and Minimum 3ph Faults

Primary and backup pairs have been identified and fault currents through each primary/backup pair is recorded for the relay coordination process.

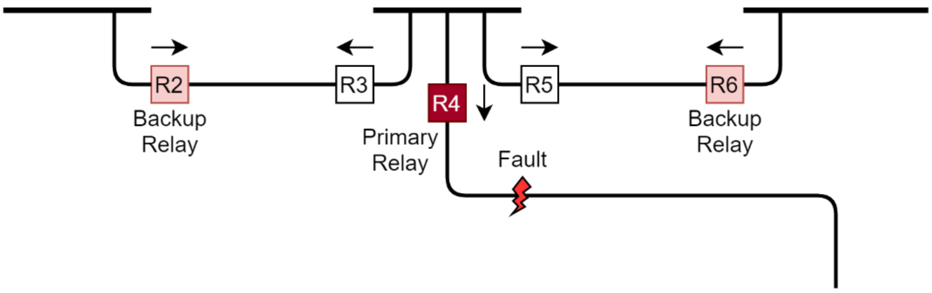


Figure 5.7 Primary and Backup Relays

5.3.2.1 Short Circuit analysis of Generic Six bus microgrid

For the Generic 6 Bus system, short circuit analysis was done for both islanded and grid-connected modes. All primary backup relay pair was considered and both near-end and far-end 3ph fault values were recorded. Table 5.12 presents the fault analysis for primary faults and Table 5.13 presents primary and backup currents for near-end faults.

Table 5.12 Primary Fault Currents

Relay No	**Islanded**		**Grid Connected**	
	Primary 3ph near end Fault Current (A)	Primary 3ph far end Fault Current (A)	Primary 3ph near end Fault Current (A)	Primary 3ph far end Fault Current (A)
1	1737	1107	6950	5296
2	1597	967	6815	5163
3	2385	1750	3359	1760
4	2691	417	7419	1641
5	1590	706	6153	3891
6	2654	1763	4607	2366
7	2287	1397	5433	3186
8	1961	1073	5305	3060
9	2940	661	6848	1091
10	1776	1141	4728	3125
11	2220	1582	5376	3762
12	2727	2086	4685	3078
13	1264	634	5435	3822
14	2244	1610	3217	1620

Table 5.13 Primary and Backup Pairs

Relay		**Islanded 3ph near end Fault Current (A)**		**Grid Connected 3ph near end Fault Current (A)**	
Primary	Backup	Primary	Backup	Primary	Backup
1	3	1737	1737	6950	1727
2	14	1597	1597	6815	1587
3	9	2385	635	3359	1026
3	6	2385	1750	3359	2333
4	2	2691	953	7419	5125
4	6	2691	1738	7419	2303
5	2	1590	957	6153	5136
5	9	1590	633	6153	1019
6	8	2654	1055	4607	3014
7	5	2287	688	5433	3846
8	4	1961	389	5305	1569
8	11	1961	1572	5305	3736
9	7	2940	1373	6848	3123
9	11	2940	1568	6848	3725
10	4	1776	391	4728	1576
10	7	1776	1384	4728	3153
11	13	2220	621	5376	3789
12	10	2727	1128	4685	3092
13	1	1264	1094	5435	5265
14	12	2244	2074	3217	3046

5.3.2.2 Short Circuit analysis of Modified 14 Bus system

For the Modified 14 Bus system, short circuit analysis was done for all selected topologies. All primary backup relay pair was considered and both near-end and far-end 3ph fault values were recorded. Table 5.14 presents the fault analysis for Topology no 1. All other topologies data can be found in Appendix A.

Table 5.14 Primary and Backup Fault Currents for Topology 1

Primary Relay no	Backup Relay no	3ph near--end primary (kA)	3ph near--end backup (kA)	3ph far--end primary (kA)	3ph far-end backup (kA)
1	5				
1	14				
2	4				
3	1	0.000	0.000	0.000	0.000
4	16	17.707	7.116	4.999	2.009
4	7	17.707	2.200	4.999	0.621
5	3	10.811	0.000	5.864	0.000
5	7	10.811	2.228	5.864	0.873
6	16	15.415	7.051	3.752	1.479
6	3	15.415	0.000	3.752	0.000
7	9	4.805	4.805	2.268	2.268
8	6	3.699	3.699	2.123	2.123
9	11	19.591	2.655	4.891	0.411
10	8	19.378	2.085	10.219	0.983
11	13	3.442	3.442	2.749	2.749
12	10	10.057	10.057	4.753	4.753
13	15	5.923	5.923	3.466	3.466
14	12	4.699	4.699	2.764	2.764
15	5	19.177	5.706	6.006	1.660
15	2	19.177	0.000	6.006	0.000
16	14	16.311	2.710	7.319	0.965
16	2	16.311	0.000	7.319	0.000

5.4 Optimization Algorithm Implementation

Optimization algorithm implementation can be separated into two areas as objective function formulation and constraint formulation. Relay operating time is the main consideration of the optimization and minimization approach is used

5.4.1 Objective function formulation

Objective function formulation can be considered the basic stage of the optimization process. As described in the section 4.2.1 summation of the relay operating times are used to form the objective function. The final goal is to minimize this summation, subjected to different constraints.

$$T = \frac{K_1 \times \boldsymbol{TDS}}{\left(I_f/(\boldsymbol{I_{pickup}})\right)^{K_2} - 1} \tag{13}$$

From the equation for operating time of a relay, Time Dial Setting and Pickup Setting are considered variables. They are called as decision variables and the final solution is to find the optimal set of values for these decision variables. As for the curve type, IEC standard inverse curves are selected.

$$min\, Z = \sum_{i=1}^{N} f_i \tag{14}$$

Summation of all relay operating times for maximum short circuit currents is taken as discussed in section 4.2.1. Fault current values are substituted from the short circuit analysis and the time-current curve type was taken as standard inverse. For minimization, we get a function of TDS and PS (equation 15).

$$\min Z = f(TDS_1, TDS_2, .., TDS_N, PS_1, PS_2, .., PS_N) \tag{15}$$

5.4.2 Constraint formulation

There are two types of constraints applied in the optimization process to achieve an accurate set of solutions. They are Decision variable Bounds and Functional constraints.

Decision Variable Bounds are applied to the decision variables according to their physical limitations. TDS values are limited between 0.05 and 1.1 according to relay manufacturer limitations and PS values are bound between overload currents and minimum fault currents [25, 26, 60] (Equations 16 – 20).

$$TDS_i^{min} \leq TDS_i \leq TDS_i^{max} \tag{16}$$

$$0.05 \leq \ TDS_i \ \leq 1.1 \tag{17}$$

$$I_{pickup}^{min} \leq \ I_{pickup} \ \leq \ I_{pickup}^{max} \tag{18}$$

$$I_{pickup}^{min} = 1.5 \times I_{load} \tag{19}$$

$$I_{pickup}^{max} = \frac{2}{3} \times I_{fault,\,min} \tag{20}$$

Functional Constraints are used to keep the coordination between primary and backup relays. Operation time difference between a primary relay and a backup relay is set to be greater than the coordination time interval (equation 21). CTI value was selected as 0.2s (equation 22).

$$t_{j,k} - t_{i,k} \geq CTI \tag{21}$$

$$t_{backup} - t_{primary} \geq 0.2 \tag{22}$$

Fault clearing limits are also added as functional constraints (equation 23). The allowable time period for a relay is set as between 0.05 s to 1 s (equation 24). This allows relays to clear faults within safe time limits.

$$t_i^{min} \leq \ t_{i,op} \ \leq \ t_i^{max} \tag{23}$$

$$0.05 \leq \ t_{i,op} \ \leq 1.00 \tag{24}$$

5.4.3 Optimization Algorithm Implementation for Test Systems

Optimization problem formulation for each system is done by forming both objective function and constraint function. Short circuit data and load flow data is used in this formulation while the problem is solved to find the best set of values for the decision variables.

5.4.3.1 Six Bus Generic Microgrid

This system has a total of 14 relays therefore with two variables per each relay makes the total decision variables to 28. An objective function is formed by taking the summation of maximum fault operating times of each relay (equation 25). Short circuit data from section 5.3.2.1 was used in formulating the function. Objective function MATLAB codes can be found in the Appendix B.

$$min\ Z = \sum_{i=1}^{N} T_{i,near} \tag{25}$$

$$= \frac{K_1 \times TDS(1)}{\left(I_f(1)/\left(I_{pickup}(1)\right)\right)^{K_2}-1} + \frac{K_1 \times TDS(2)}{\left(I_f(2)/\left(I_{pickup}(2)\right)\right)^{K_2}-1} + \cdots + \frac{K_1 \times TDS(14)}{\left(I_f(14)/\left(I_{pickup}(14)\right)\right)^{K_2}-1}$$

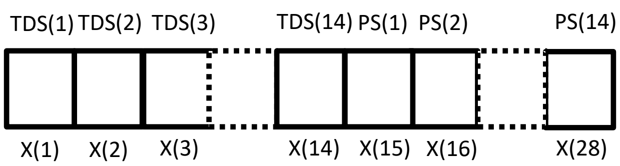


Figure 5.8 Decision Variables Array for Six Bus System

Decision variable array structure for MATLAB implementation is illustrated in Figure 5.8. Constraint functions are formulated with the short circuit data from section 5.3.2.1. Relay operating time limits are also included in the main constraint function. These inequality constraint MATLAB codes are included in Appendix B.

Different Algorithms have been used to compare the performance of algorithms and to select the best performing one. Table 5.15 presents the algorithms that have been used.

Table 5.15 Optimization Algorithms Used for Comparison

Algorithm	Reference
Modified Particle Swarm Optimization (PSO)	K. Masuda, 2010. [61]
Mine Blast Algorithm (MBA)	A. Sadollah, 2013. [62]
Water Cycle Algorithm (WCA)	H. Eskandar, 2012. [63]
Whale Optimization Algorithm (WOA)	S. Mirjalili, 2016. [64]
Sine Cosine Algorithm (SCA)	S. Mirjalili, 2016. [65]
Grey Wolf Algorithm (GWO)	A. Lewis, 2014. [66]
Neural Network Algorithm (NNA)	A. Sadollah, 2018. [67]
Particle Swarm-Gravitational Search Algorithm (PSGSA)	S. Z. M. Hashim, 2010. [68]
Particle Swarm-Grey Wolf Algorithm (PSGWO)	N. Singh, 2017. [69]
Water Cycle - Moth Flame Algorithm (WCMFO)	S. Khalilpourazari, 2019. [70]

5.4.3.2 Modified 14 Bus System

This system has a total of 16 relays therefore with two variables per each relay makes the total decision variables to 32. An objective function is formed by taking the summation of maximum fault operating times of each relay (equation 26). Objective function MATLAB codes can be found in Appendix E.

$$min\, Z = \sum_{i=1}^{N} T_{i,near}$$

$$= \frac{K_1 \times TDS(1)}{\left(I_f(1)/\left(I_{pickup}(1)\right)\right)^{K_2} - 1} + \frac{K_1 \times TDS(2)}{\left(I_f(2)/\left(I_{pickup}(2)\right)\right)^{K_2} - 1} + \cdots + \frac{K_1 \times TDS(16)}{\left(I_f(16)/\left(I_{pickup}(16)\right)\right)^{K_2} - 1} \quad (26)$$

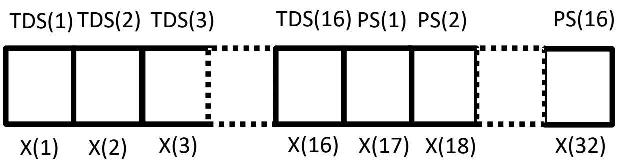


Figure 5.9 Decision Variables Array for Modified 14 Bus System

Constraint functions are formulated with the short circuit data from section 5.3.2.1. Relay operating time limits are also included in the main constraint function. These inequality constraint MATLAB codes are included in Appendix E.

6. Results and Discussion

Optimization is run on MATLAB software to obtain the best data set for the decision variables. These obtained relay settings are then put into the equations and the validity of operating time for the faults are observed. The settings are further applied to the DigSILENT simulation model and relay time-current curves are also obtained.

6.1 Six Bus Microgrid

For the Six Bus microgrid system, ten different algorithms were used to obtain ten different solution sets. Most optimal solution will be the solution with the lowest objective function value.

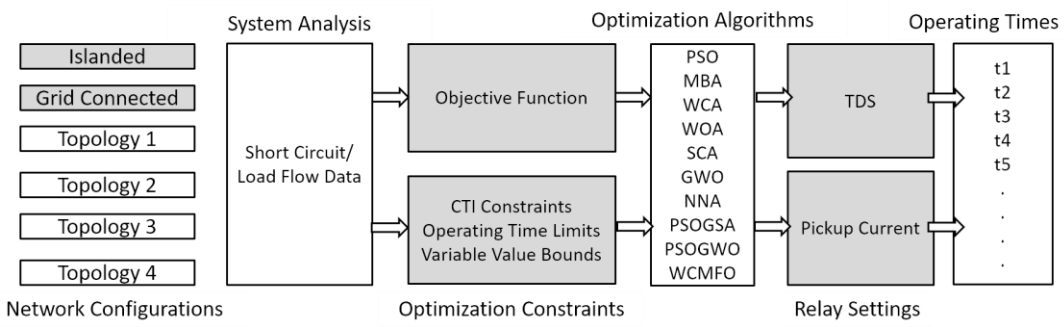


Figure 6.1 Simulation Methodology

6.1.1 Relay Settings by different algorithms

The solution obtained by each algorithm is compared according to their objective function value to determine the best performing algorithm. Detailed results tables are available in Appendix C. It was found that out of all the considering algorithms, Water Cycle Moth Flame Optimization Algorithm had the best performing solution set. Table 6.1 presents the Relay settings and operating times for both islanded and grid-connected modes of operation.

Table 6.1 Results from WCMFO Algorithm

Relay No	Islanded			Grid Connected		
	TDS	I_{pick}	T (s)	TDS	I_{pick}	T (s)
1	0.05	548.4	0.3241	0.31	313.08	0.6825
2	0.06	427.2	0.296	0.18	900.77	0.6137
3	0.05	847	0.3625	0.05	1194	0.3349
4	0.06	193.2	0.1506	0.37	35.1	0.4626
5	0.07	278.87	0.2863	0.14	979.2	0.5155
6	0.06	854.4	0.3544	0.06	1200	0.3188
7	0.07	600	0.3566	0.16	595.1	0.4958
8	0.07	465.1	0.3136	0.15	404.3	0.4026
9	0.11	160	0.2624	0.19	159.83	0.346
10	0.07	519.05	0.3737	0.1	1018.68	0.4612
11	0.06	732	0.3526	0.12	894.88	0.4785
12	0.06	1000	0.395	0.23	145.6	0.4404
13	0.1	188.85	0.3436	0.16	764.59	0.5517
14	0.06	729.6	0.3447	0.05	1034.14	0.3049
OF Value	4.5161			6.4092		

Not all the algorithms handle the given problem constraints accurately. Table 6.2 provides constraint violations by each algorithm. The selected algorithm had no constraint violations when obtaining the optimal solution set.

Table 6.2 Constraint Handling of Different Algorithms

Algorithm	Constraint handling Method	Islanded		Grid Connected	
		Time Limit Violations	CTI Violations	Time Limit Violations	CTI Violations
PSO	Penalty	1	2	2	8
MBA	Penalty	0	0	0	4
WCA	Penalty	0	0	0	1
WOA	Penalty	0	0	0	0
SCA	Penalty	0	4	0	9
GWO	Direct	0	0	0	0
NNA	Direct	0	0	0	0
PSOGSA	Direct	0	0	0	0
PSOGWO	Direct	0	0	0	0
WCMFO	Direct	0	0	0	0

Primary and backup relay operating times from the selected solution set is given in Table 6.3. It is evident that no coordination time violates the given 0.2 s minimum limit.

Table 6.3 Primary/ Backup Relay Operation with settings from WCMFO

Relay Pairs		Islanded max fault		CTI (s)	Grid max fault		CTI (s)
Primary	Backup	Primary (A)	Backup (A)		Primary (A)	Backup (A)	
1	3	1737	1737	0.20	6950	1727	0.26
2	14	1597	1597	0.20	6815	1587	0.20
3	9	2385	635	0.20	3359	1026	0.38
3	6	2385	1750	0.20	3359	2333	0.31
4	2	2691	953	0.34	7419	5125	0.25
4	6	2691	1738	0.42	7419	2303	0.20
5	2	1590	957	0.20	6153	5136	0.20
5	9	1590	633	0.28	6153	1019	0.20
6	8	2654	1055	0.20	4607	3014	0.20
7	5	2287	688	0.20	5433	3846	0.20
8	4	1961	389	0.26	5305	1569	0.26
8	11	1961	1572	0.20	5305	3736	0.20
9	7	2940	1373	0.32	6848	3123	0.32
9	11	2940	1568	0.25	6848	3725	0.26
10	4	1776	391	0.20	4728	1576	0.20
10	7	1776	1384	0.20	4728	3153	0.20
11	13	2220	621	0.20	5376	3789	0.20
12	10	2727	1128	0.20	4685	3092	0.20
13	1	1264	1094	0.20	5435	5265	0.20
14	12	2244	2074	0.20	3217	3046	0.20

Percentage reduction of relay operating times for the maximum faults are given in Table 6.4 and Table 6.5. Reduction is calculated from both average and worst-case scenarios in terms of the selected algorithm. There is a reduction of 20%-40% from average operating times in Islanded mode and a reduction of 10%-30% in Grid-Connected mode.

Table 6.4 Reduction of Operating times in Islanded mode

R	WCMFO Results	Average Operating Time	Maximum Operating Time	% reduction from avg	% reduction from max
1	0.3241	0.4239	0.5965	24	46
2	0.2960	0.4081	0.6260	27	53
3	0.3625	0.4840	0.6818	25	47
4	0.1506	0.2793	0.4401	46	66
5	0.2863	0.4001	0.5855	28	51
6	0.3544	0.5183	0.7982	32	56
7	0.3566	0.5282	0.692	32	48
8	0.3136	0.4749	0.8841	34	65
9	0.2624	0.4088	0.5486	36	52
10	0.3737	0.5230	0.8100	29	54
11	0.3526	0.5152	0.8281	32	57
12	0.3950	0.5635	0.8109	30	51
13	0.3436	0.449	0.6252	23	45
14	0.3447	0.4802	0.7248	28	52

Table 6.5 Reduction of Operating times in Grid-Connected mode

R	WCMFO Results	Average Operating Time	Maximum Operating Time	% reduction from avg	% reduction from max
1	0.6825	0.7507	0.8604	9	21
2	0.6137	0.7438	0.8530	17	28
3	0.3349	0.4660	0.7454	28	55
4	0.4626	0.5402	0.7136	14	35
5	0.5155	0.6495	0.8782	21	41
6	0.3188	0.4369	0.6824	27	53
7	0.4958	0.6161	0.8369	20	41
8	0.4026	0.5144	0.8703	22	54
9	0.3460	0.4541	0.6147	24	44
10	0.4612	0.6008	0.8993	23	49
11	0.4785	0.5974	0.8381	20	43
12	0.4404	0.5521	0.8116	20	46
13	0.5517	0.6716	0.8351	18	34
14	0.3049	0.4947	0.7591	38	60

6.1.2 Relay Time-Current Curves

Several Time-current curves for different relays in both modes are presented in figure 6.2 to 6.5. Faults are created at 50% of line length primary and backup relay operation is considered. It is visible that all primary backup pairs operate with perfect coordination

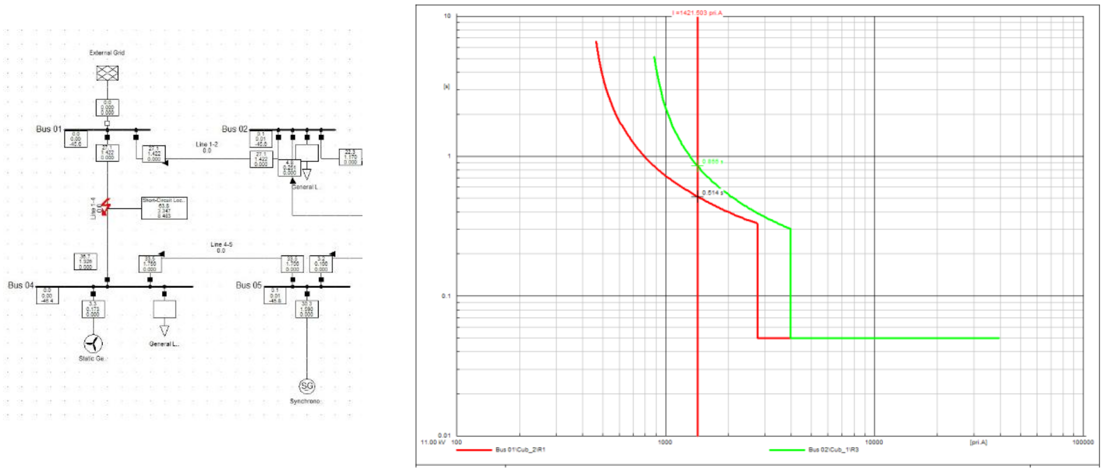


Figure 6.2 Three Phase fault 50% Line 1-4 Islanded Mode

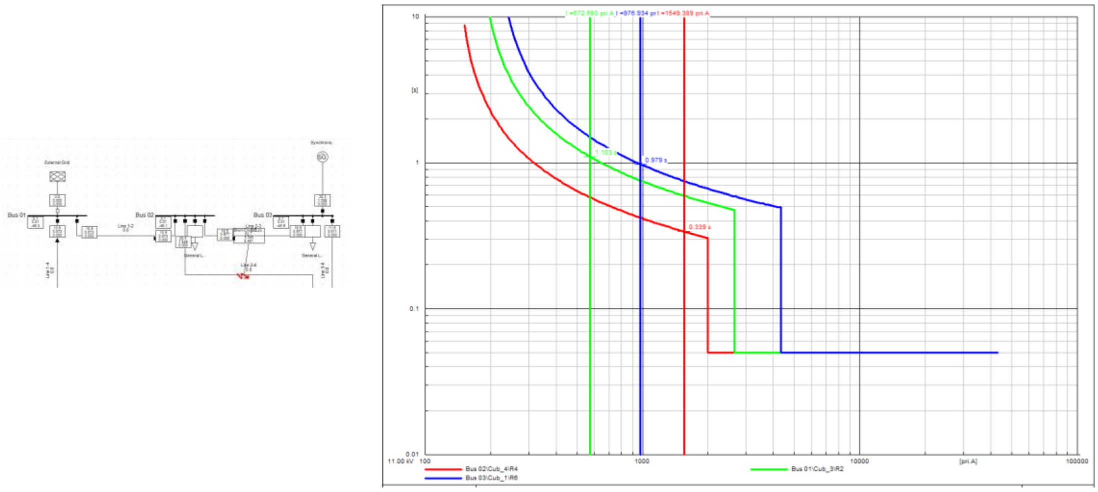


Figure 6.3 Three Phase fault 50% Line 2-6 Islanded Mode

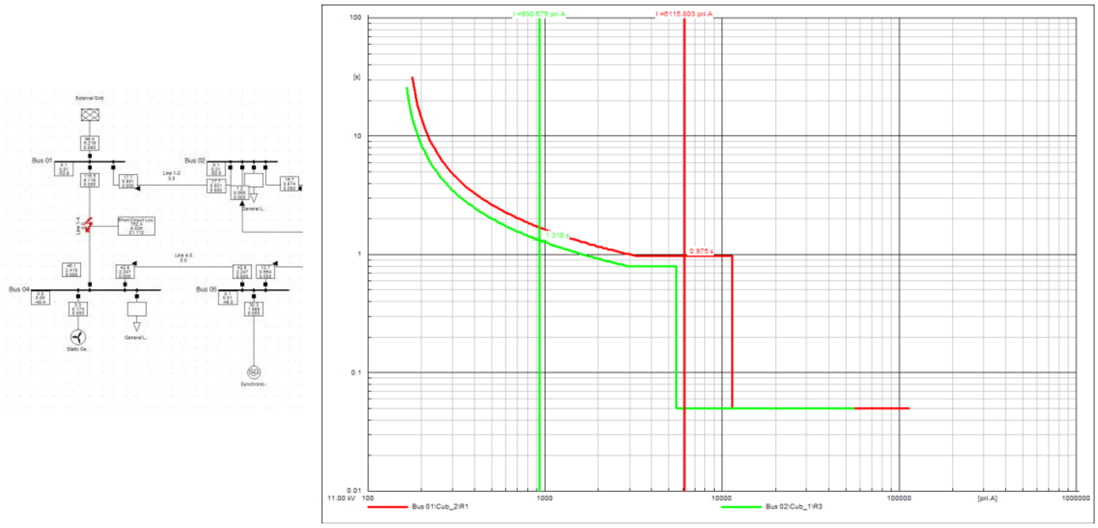


Figure 6.4 Three Phase fault 50% Line 1-4 Grid Connected Mode

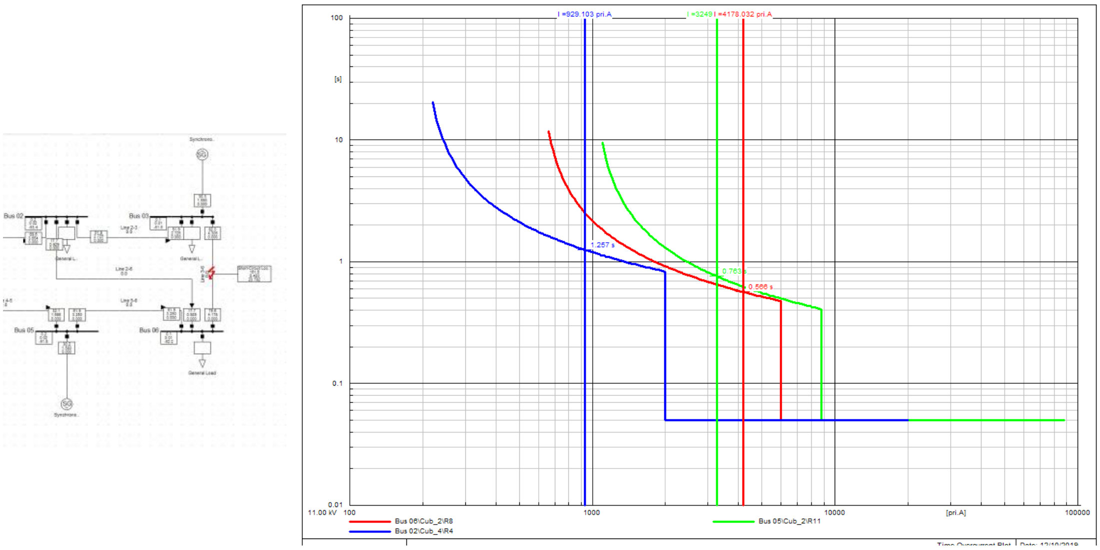


Figure 6.5 Three Phase fault 50% Line 3-6 Grid Connected Mode

6.1.3 WCMFO Algorithm

Hybrid Water Cycle - Moth Flame Optimization algorithm (WCMFO) is a combination of two primary algorithms namely Water cycle optimization algorithm and moth flame optimization algorithm.

Water Cycle optimization algorithm is a novel optimization algorithm inspired by the flow of water streams towards the sea. Figure 6.6 illustrates a simple schematic of the algorithm composition.

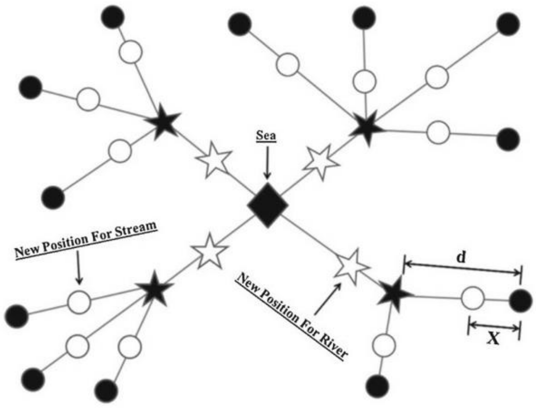


Figure 6.6 WCA Schematic Diagram.[63]

Moth Flame optimization algorithm is inspired by the flying patterns of moths around a light source. Figure 6.7 illustrates the fly patterns used for the algorithm. Combination of these algorithms make a high-performance metaheuristic algorithm. Pseudo code of the WCMFO algorithm is included in Appendix D.

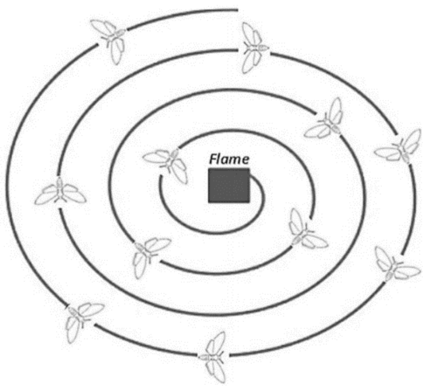


Figure 6.7 Fly patterns of Moths around Light

6.2 Modified IEEE 14 bus system

In the modified IEEE 14 bus system model, optimization was done using the WCMFO algorithm for different operating topologies. Instead of calculating different set for each and every topology, clustering was used to identify similar topologies and they were given a same set of protection settings.

6.2.1 Clustering for Adaptive protection

As described in Section 5.2.2 there are 13 topologies under consideration. Most industrial overcurrent relays have facilities to save at least four setting groups. Here the available 13 topologies are divided into four clusters according to their short circuit levels.

Standard Deviation of each relays short circuit current during different topologies are considered the clustering factor. Following Figure 6.8 provides the deviation of short circuit value from its mean value for each topology. Topology no 9 is separated into its own cluster and topologies 1, 2, 4, 5, 6, 7, 8 are grouped into another cluster. Remaining two clusters are selected as topologies 3, 11 and topologies 10, 12, 13. Table 6.6 presents the Grouping of topologies into clusters.

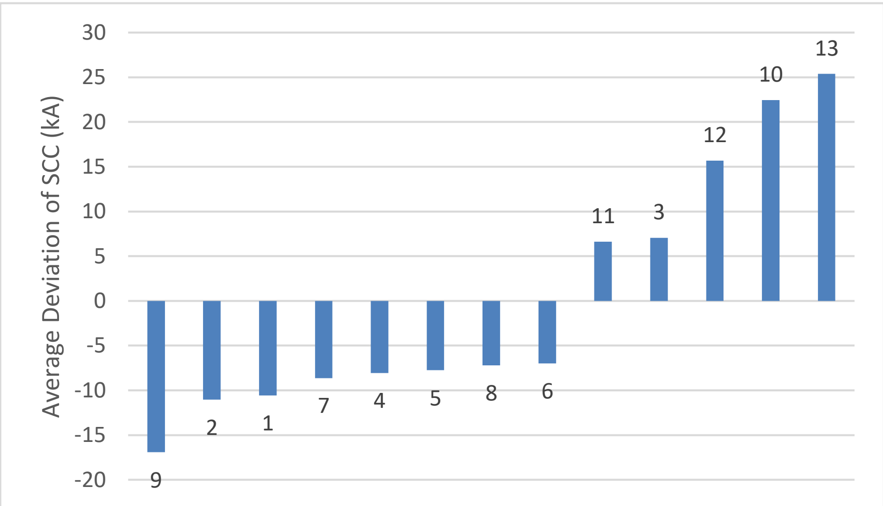


Figure 6.8 Mean Short Circuit Level Variation of Topologies

Table 6.6 Topologies Divided into Clusters

Cluster 1	Cluster 2	Cluster 3	Cluster 4
Topology 9	Topology 1	Topology 3	Topology 10
	Topology 2	Topology 11	Topology 12
	Topology 4		Topology 13
	Topology 5		
	Topology 6		
	Topology 7		
	Topology 8		

6.2.2 Relay Settings for Each Cluster

Relay settings for each cluster is calculated using WCMFO algorithm. Several changes from the previous model method had to be made in order to cope with the clustering.

Objective function was formed with the maximum currents of the set of topologies belonging to the relevant cluster. When imposing constraints, some topologies had similar constraints which had to be put only once effectively reducing the number of constraints. Minimum and maximum operating times constraints were also imposed for the minimum and maximum fault values considering the whole cluster. Decision variable bounds were set considering all the values ranging throughout the cluster. MATLAB code written for the Cluster 4 can be found in Appendix E.

Table 6.7 Relay Settings Obtained for each Cluster

R	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	TDS	PS	TDS	PS	TDS	PS	TDS	PS
1	0.08	1711.42	0.09	1576.85	0.10	1265.38	0.14	1156.82
2	0.13	239.39	0.11	359.43	0.24	178.62	0.16	132.91
3	0.18	147.70	0.22	102.49	0.14	266.47	0.25	196.44
4	0.09	1340.67	0.09	1242.76	0.14	1110.95	0.18	390.24
5	0.15	410.37	0.13	770.48	0.12	1063.73	0.22	320.01
6	0.12	802.59	0.13	702.75	0.05	1883.52	0.11	1411.36
7	0.11	526.09	0.14	369.22	0.15	452.22	0.22	351.05
8	0.09	616.25	0.09	652.10	0.07	969.47	0.20	364.91
9	0.07	1884.25	0.20	414.33	0.19	638.61	0.10	1928.79
10	0.07	3652.03	0.07	3928.06	0.08	3403.79	0.12	2552.65
11	0.14	240.39	0.20	247.74	0.23	230.61	0.12	673.40
12	0.05	2648.40	0.05	2716.60	0.07	2199.05	0.10	1781.16
13	0.05	1875.58	0.07	1761.16	0.32	203.20	0.05	1978.00
14	0.19	238.89	0.24	160.00	0.13	469.85	0.18	520.16
15	0.05	2993.00	0.05	3462.17	0.09	2741.14	0.06	2604.80
16	0.19	405.03	0.19	513.51	0.20	526.91	0.10	2043.25
OF	4.7193		5.5123		6.6272		7.7457	

6.2.3 Relay Time Current Curves

Following figures 6.9 to 6.17 presents Specified Relay operations both primary and backup for a 3ph fault at 50% of the line's length.

Cluster 1 Settings

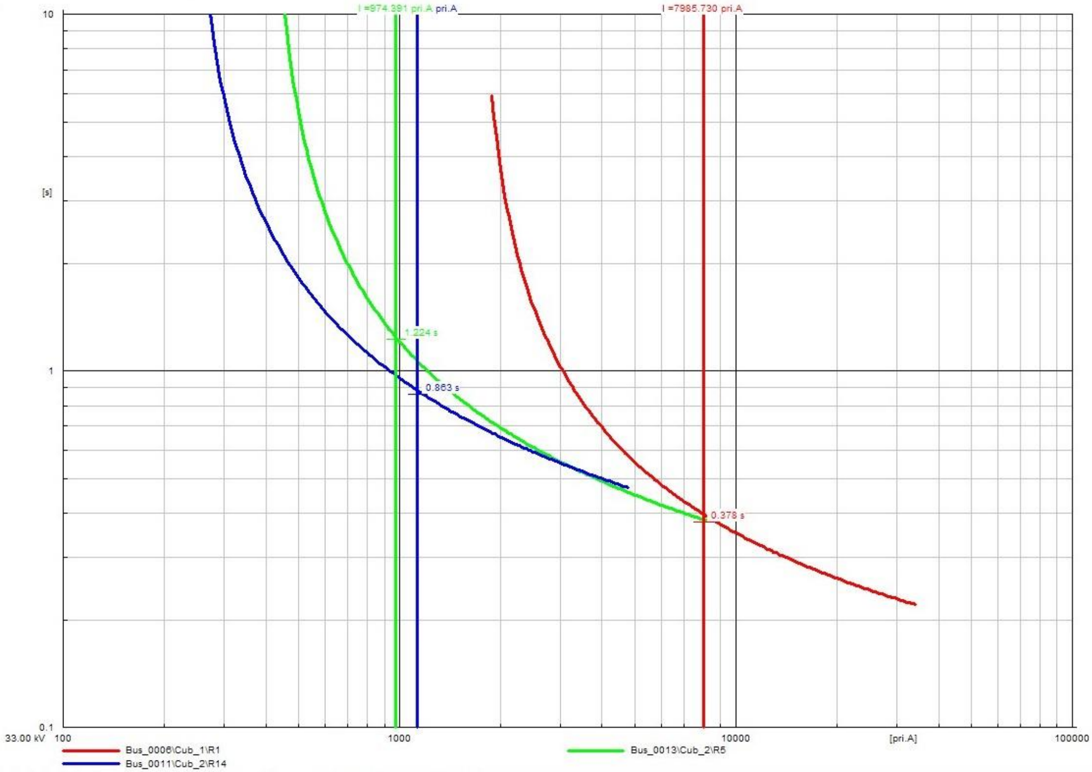


Figure 6.9 Topology 9 R1 Primary operation with Backup R5 & R14

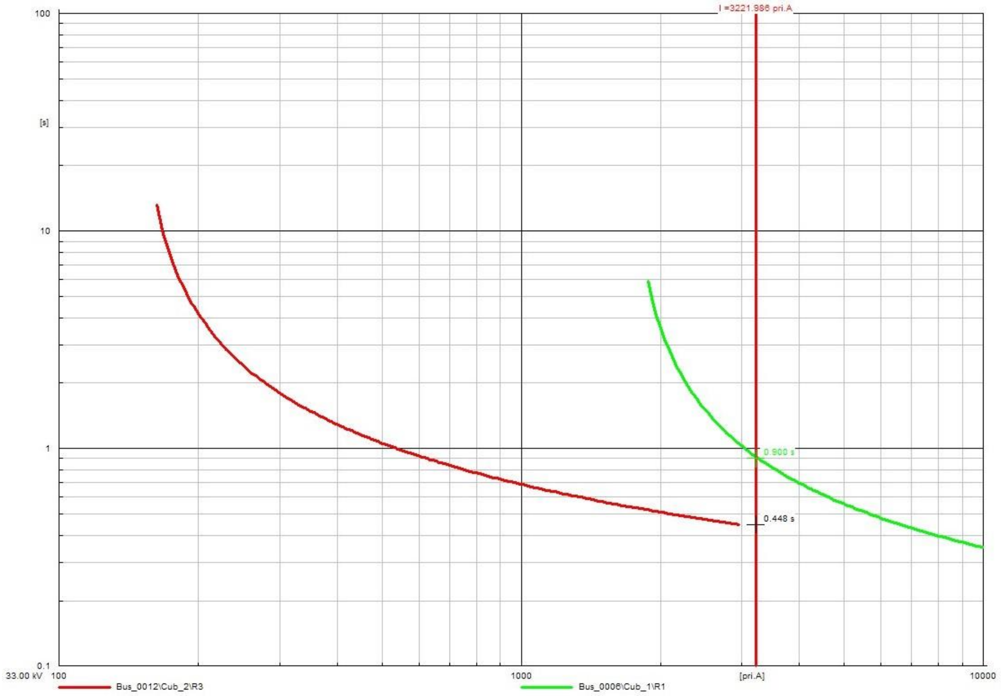


Figure 6.10 Topology 9 R3 Primary operation with Backup R1

Cluster 2 Settings

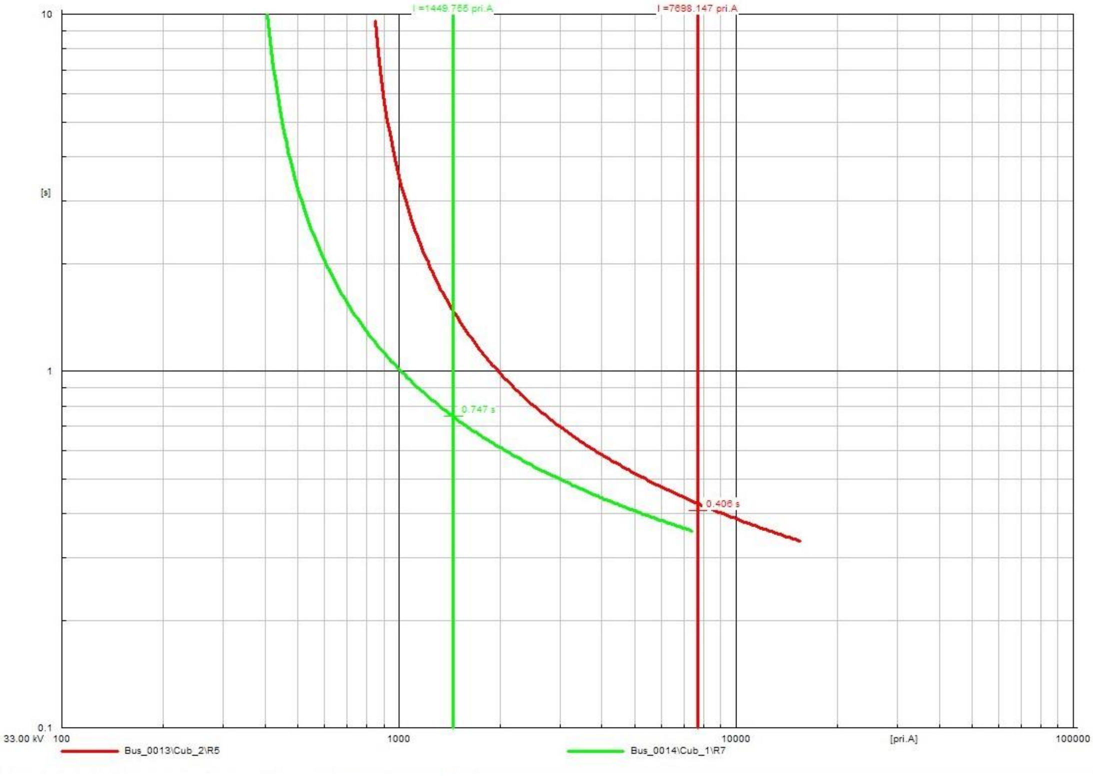


Figure 6.11 Topology 2 R5 Primary operation with Backup R7

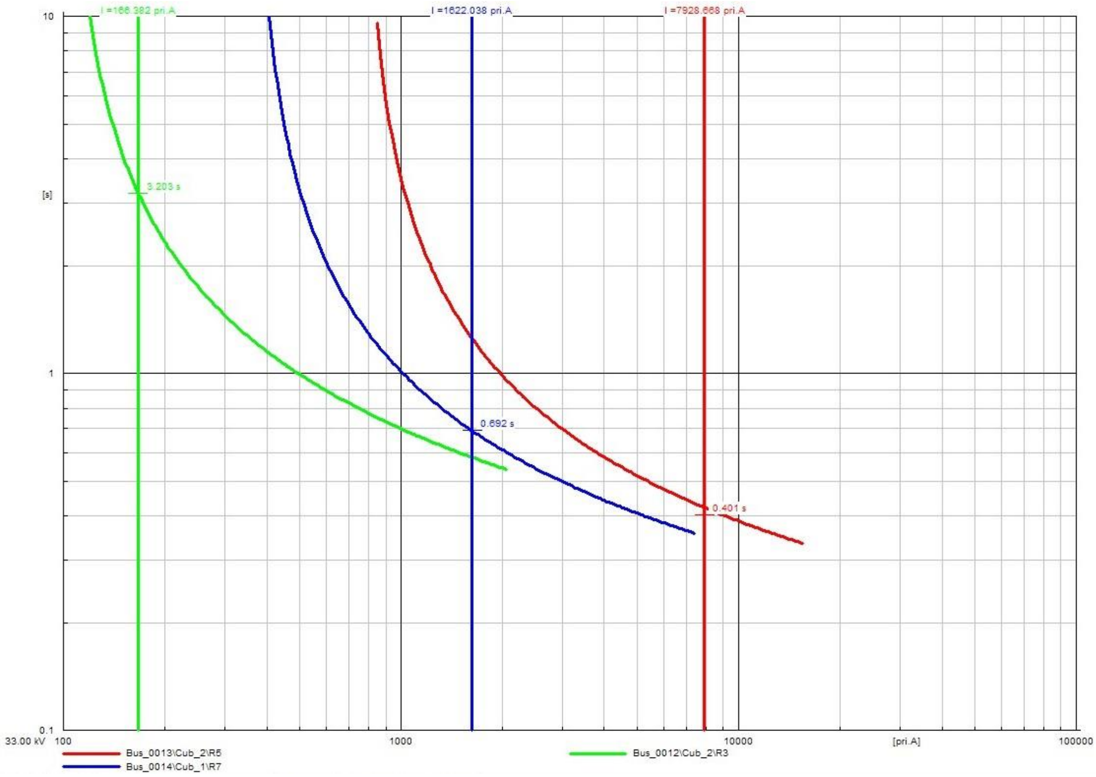


Figure 6.12 Topology 7 R5 Primary operation with Backup R7 & R3

Cluster 3 Settings

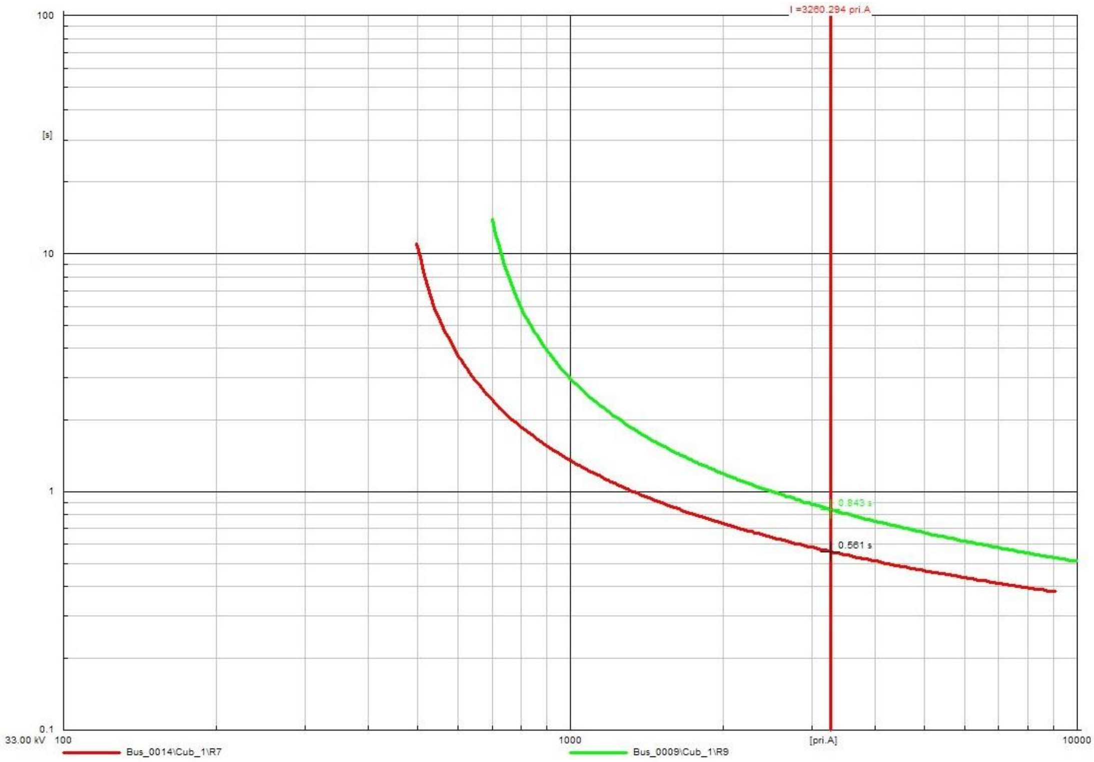


Figure 6.13 Topology 3 R7 Primary operation with Backup R9

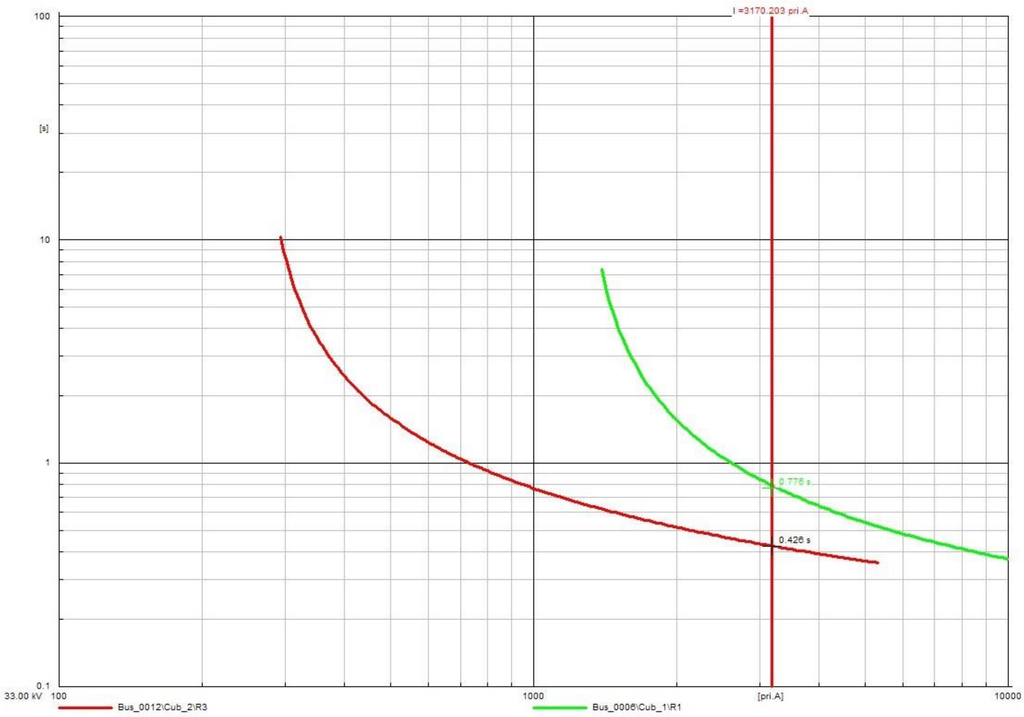


Figure 6.14 Topology 11 R3 Primary operation with Backup R1

Cluster 4 Settings

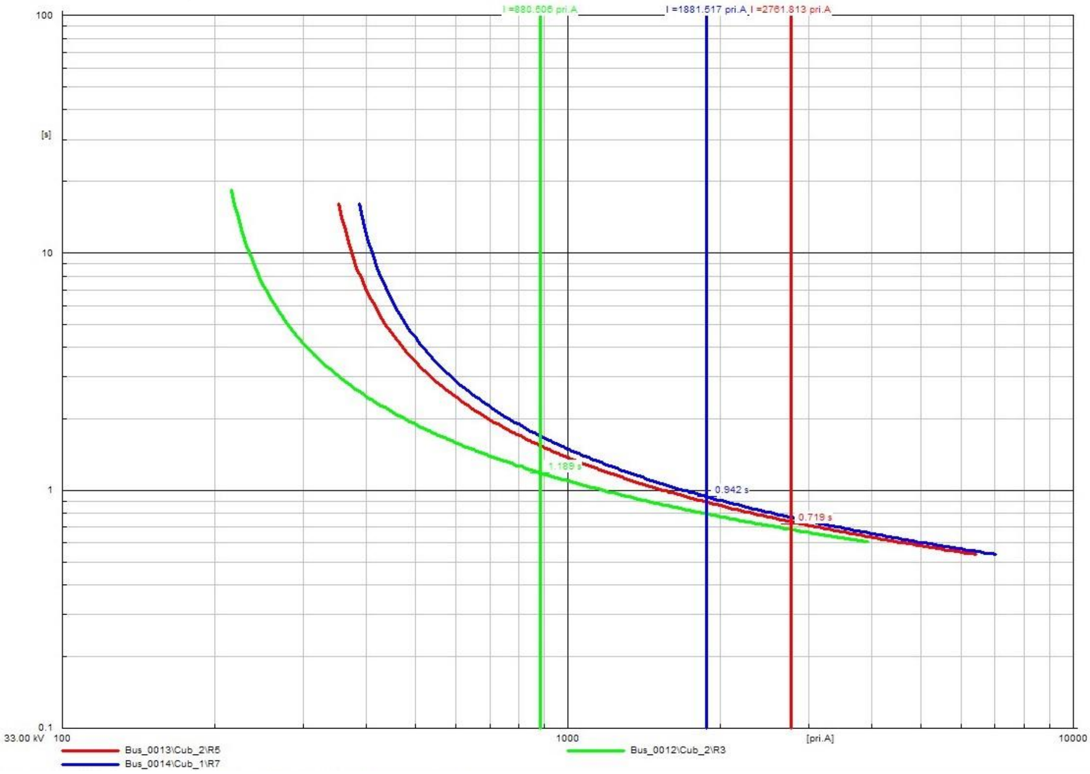


Figure 6.15 Topology 10 R13 Primary operation with Backup R14 &R3

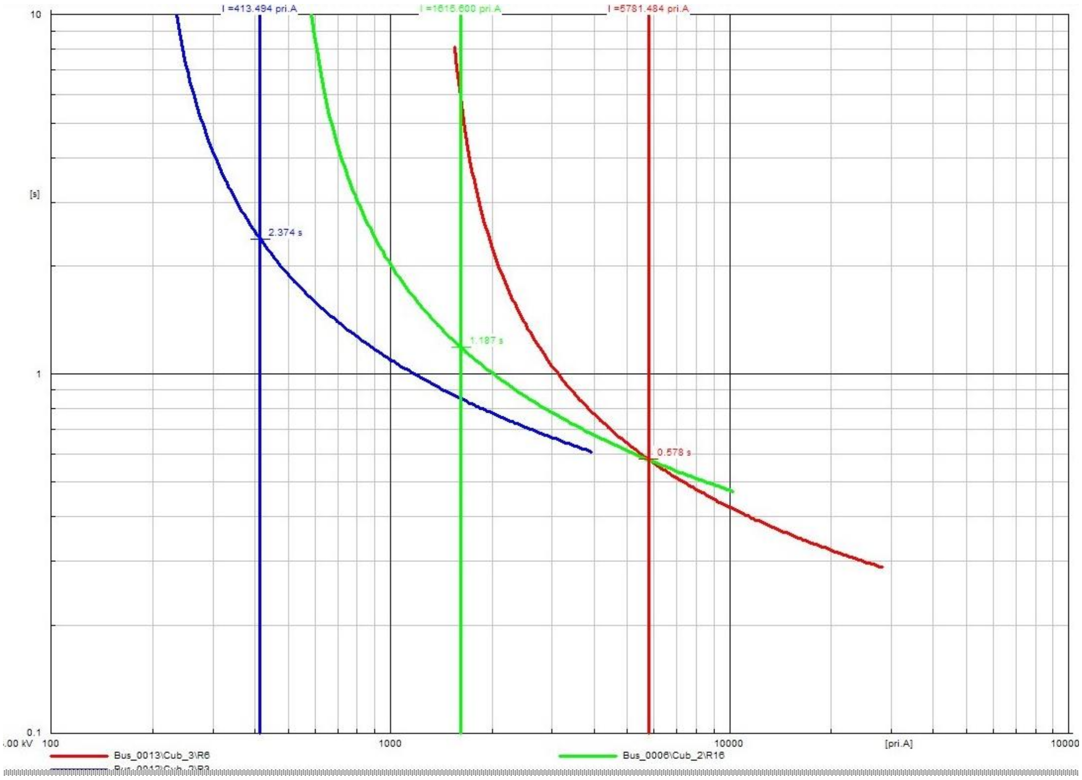


Figure 6.16 Topology 12 R6 Primary operation with Backup R16 &R3

Full data on fault clearing times can be found in Appendix F. Appendix data are calculated for the two extremes as near-end 3ph fault and far- end 3ph fault while the above graphs are obtained for the middle value of a 3ph fault at middle of the line.

Red curve represents the primary relay time current curve and the respective primary current is represented in the red vertical line. Operating time for this primary current is at the intersection point and the time value is also labelled. Green curves are backup relay curves and when there is more than one backup relay considered, blue curve also represents the backup curve. Backup fault currents are represented in vertical lines of relevant colour and the intersection points are the backup operating times.

It is evident that settings group for each cluster is valid for all topologies belonging to that cluster. This clustering approach vastly reduces the number of adaptive stages while grouping the similar topologies.

7. Conclusion and future work

7.1. Conclusion

Microgrid Protection solution research has emerged due to the ineffectiveness of classic protection schemes. Two main areas of microgrid protection was identified as the existence of multiple operating modes and the difficulty of relay coordination due to the multi-sourced and multi-loop network architecture. Identified solutions were the use of adaptive protection and using a Computational intelligence-based relay setting optimization method.

Adaptive protection by Pre-Calculated relay settings was selected in this approach as a more practical method of incorporating optimization algorithms for microgrid protection. If the settings calculation to be done online, it would require online short circuit data. Even at this stage the short circuit data would not be a direct measurement rather would end up being a pre-stored value. Therefore, a collection of short circuit data for several meaningful topologies is a necessity for protection optimization. Also, the optimization algorithms take several minutes to run therefore real time setting calculation is not feasible.

From the first test model, water cycle-moth flame (WCMFO) hybrid Algorithm Provided considerable reduction in operating time for the considered microgrid model out of other algorithms compared. Reduction of 20%-40% from avg. operating times was recorded in Islanded mode. Reduction of 10%-30% from avg. operating times was recorded in Grid Connected mode. Also, WCMFO settings had no violations in coordination and maximum fault clearance constraints. Relay operating times didn't exceed 1s and primary /backup coordination didn't violate the minimum limit of 0.2s.

Second Test system was used to employ the adaptability of the scheme. Network element single contingencies were used to define operating topologies. Clustering was used to group similar topologies together in terms of the short circuit current. Settings were obtained for each cluster using the WCMFO algorithm and validated for each topology within the cluster.

It was evident that even with a large number of topologies, the number of required setting groups can be managed by the use of clustering. Final relay operating times obtained by the settings were well within the initialized constraints. Coordination times did not go below the 0.2 s margin and the fault operating times didn't exceed 1s for the primary protection.

7.2. Limitations of the Study

The Proposing scheme is mainly focused on overcurrent line protection of microgrid networks. Hence it is only successful for line faults occurring in the network. Also, the protection optimization is mainly done for ground faults. Therefore, minimum fault clearance cannot be guaranteed for line faults. All the considering faults were occurring within the system; therefore, relay operation coordination may get disrupted by faults outside of the microgrid.

7.3. Future work

The proposing optimized adaptive protection system is validated on two system models. There are several areas identified in both emphasizing the validity and improving the performance.

Protection scheme can be further improved as mentioned below.

- Testing on More Network Topologies

  Two or three network element contingencies can be used to create more network topologies which can be used to test the optimization performance for wider range of topologies. Number of clusters may need to be increased to occupy a large number of topologies. Review on relay specifications indicated that there are relays which can set up to eight setting groups. Therefore, cluster size can even go up to even 8.

- Application on different system models

Same as more topologies, the scheme can be applied to different network models to test the functionality. More complex networks can be a challenge to optimize and compromises may need to be made.

- Integrating the Curve Type as a variable

Here the relay characteristic was fixed to the IEC standard time-current curve. By setting the curve type as a variable, more flexible optimization can be obtained for complex systems.

- Possibility of extending beyond Overcurrent protection

The same adaptive and optimization approach can be extended to other protection types beyond overcurrent protection. But distance or impedance-based protection may not be suitable as their feasibility in microgrids are incredibly low. If the microgrid can be equipped with phasor measuring units, current or voltage phasor-based protection can be implemented as adaptive protection. Instead of the short circuit levels, in phasor levels at each type of fault can be used to generate the adaptive setting. Even optimization can be included by defining an appropriate constraint set.

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APPENDIX A- Modified 14 Bus System Short-circuit analysis

Topology 1

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5				
1	14				
2	4				
3	1	0.000	0.000	0.000	0.000
4	16	17.707	7.116	4.999	2.009
4	7	17.707	2.200	4.999	0.621
5	3	10.811	0.000	5.864	0.000
5	7	10.811	2.228	5.864	0.873
6	16	15.415	7.051	3.752	1.479
6	3	15.415	0.000	3.752	0.000
7	9	4.805	4.805	2.268	2.268
8	6	3.699	3.699	2.123	2.123
9	11	19.591	2.655	4.891	0.411
10	8	19.378	2.085	10.219	0.983
11	13	3.442	3.442	2.749	2.749
12	10	10.057	10.057	4.753	4.753
13	15	5.923	5.923	3.466	3.466
14	12	4.699	4.699	2.764	2.764
15	5	19.177	5.706	6.006	1.660
15	2	19.177	0.000	6.006	0.000
16	14	16.311	2.710	7.319	0.965
16	2	16.311	0.000	7.319	0.000

Topology 2

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	21.601	5.656	5.285	1.384
1	14	21.601	2.662	5.285	0.651
2	4	0.000	0.000	0.000	0.000
3	1				
4	16				
4	7				
5	3	10.811	0.000	5.864	0.000
5	7	10.811	2.228	5.864	0.873
6	16	15.415	7.051	3.752	1.479
6	3	15.415	0.000	3.752	0.000
7	9	4.805	4.805	2.268	2.268
8	6	3.699	3.699	2.123	2.123
9	11	19.591	2.655	4.891	0.411
10	8	19.378	2.085	10.219	0.983
11	13	3.442	3.442	2.749	2.749
12	10	10.057	10.057	4.753	4.753
13	15	5.923	5.923	3.466	3.466
14	12	4.699	4.699	2.764	2.764
15	5	19.177	5.706	6.006	1.660
15	2	19.177	0.000	6.006	0.000
16	14	16.311	2.710	7.319	0.965
16	2	16.311	0.000	7.319	0.000

Topology 3

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	16.286	0.000	4.884	0.000
1	14	16.286	2.804	4.884	0.749
2	4	4.255	4.255	2.541	2.541
3	1	4.816	4.816	2.793	2.793
4	16	10.892	0.000	4.311	0.000
4	7	10.892	2.369	4.311	0.834
5	3				
5	7				
6	16	11.022	0.000	3.465	0.000
6	3	11.022	2.717	3.465	0.730
7	9	4.854	4.854	2.416	2.416
8	6	3.421	3.421	2.140	2.140
9	11	19.571	2.641	4.940	0.549
10	8	19.399	2.108	10.250	1.069
11	13	3.354	3.354	2.729	2.729
12	10	10.088	10.088	4.787	4.787
13	15	5.596	5.596	3.375	3.375
14	12	4.734	4.734	2.887	2.887
15	5	15.922	0.000	5.670	0.000
15	2	15.922	2.482	5.670	0.819
16	14				
16	2				

Topology 4

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	20.654	4.479	4.790	-0.942
1	14	20.654	2.792	4.790	0.938
2	4	4.192	4.192	1.255	1.255
3	1	4.712	4.712	1.768	1.768
4	16	15.091	6.600	4.263	0.984
4	7	15.091	0.000	4.263	0.000
5	3	10.264	1.699	4.714	-1.150
5	7	10.264	0.000	4.714	0.000
6	16				
6	3				
7	9				
8	6	0.000	0.000	0.000	0.000
9	11	19.834	2.860	4.990	0.719
10	8	17.481	0.000	9.740	0.000
11	13	3.552	3.552	2.951	2.951
12	10	9.595	9.595	4.701	4.701
13	15	6.004	6.004	3.574	3.574
14	12	4.650	4.650	2.889	2.889
15	5	19.289	4.572	6.088	1.506
15	2	19.289	1.170	6.088	0.386
16	14	17.572	2.839	6.810	1.464
16	2	17.572	1.150	6.810	-1.699

Topology 5

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	20.654	4.479	4.790	-0.942
1	14	20.654	2.792	4.790	0.938
2	4	4.192	4.192	1.255	1.255
3	1	4.712	4.712	1.768	1.768
4	16	15.091	6.600	4.263	0.984
4	7	15.091	0.000	4.263	0.000
5	3	10.264	1.699	4.714	-1.150
5	7	10.264	0.000	4.714	0.000
6	16	16.520	6.542	3.902	1.545
6	3	16.520	1.674	3.902	0.396
7	9	0.000	0.000	0.000	0.000
8	6				
9	11				
10	8	17.481	0.000	9.740	0.000
11	13	3.552	3.552	2.951	2.951
12	10	9.595	9.595	4.701	4.701
13	15	6.004	6.004	3.574	3.574
14	12	4.650	4.650	2.889	2.889
15	5	19.289	4.572	6.088	1.506
15	2	19.289	1.170	6.088	0.386
16	14	17.572	2.839	6.810	1.464
16	2	17.572	1.150	6.810	-1.699

Topology 6

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	18.703	5.111	4.674	-0.466
1	14	18.703	0.000	4.674	0.000
2	4	4.307	4.307	1.407	1.407
3	1	4.599	4.599	1.622	1.622
4	16	16.728	5.994	4.381	0.494
4	7	16.728	2.299	4.381	0.855
5	3	12.369	1.542	5.343	-1.316
5	7	12.369	2.325	5.343	1.337
6	16	15.866	5.970	3.832	1.372
6	3	15.866	1.528	3.832	0.351
7	9	4.714	4.714	2.362	2.362
8	6	3.780	3.780	2.315	2.315
9	11	17.273	0.000	4.796	0.000
10	8				
11	13				
12	10	0.000	0.000	0.000	0.000
13	15	6.155	6.155	3.721	3.721
14	12	0.000	0.000	0.000	0.000
15	5	20.092	5.180	6.240	1.609
15	2	20.092	1.326	6.240	0.412
16	14	15.109	0.000	6.210	0.000
16	2	15.109	1.316	6.210	-1.542

Topology 7

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	18.703	5.111	4.674	-0.466
1	14	18.703	0.000	4.674	0.000
2	4	4.307	4.307	1.407	1.407
3	1	4.599	4.599	1.622	1.622
4	16	16.728	5.994	4.381	0.494
4	7	16.728	2.299	4.381	0.855
5	3	12.369	1.542	5.343	-1.316
5	7	12.369	2.325	5.343	1.337
6	16	15.866	5.970	3.832	1.372
6	3	15.866	1.528	3.832	0.351
7	9	4.714	4.714	2.362	2.362
8	6	3.780	3.780	2.315	2.315
9	11	17.273	0.000	4.796	0.000
10	8	19.709	2.283	10.436	1.209
11	13	0.000	0.000	0.000	0.000
12	10				
13	15				
14	12	0.000	0.000	0.000	0.000
15	5	20.092	5.180	6.240	1.609
15	2	20.092	1.326	6.240	0.412
16	14	15.109	0.000	6.210	0.000
16	2	15.109	1.316	6.210	-1.542

Topology 8

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	18.703	5.111	4.674	-0.466
1	14	18.703	0.000	4.674	0.000
2	4	4.307	4.307	1.407	1.407
3	1	4.599	4.599	1.622	1.622
4	16	16.728	5.994	4.381	0.494
4	7	16.728	2.299	4.381	0.855
5	3	12.369	1.542	5.343	-1.316
5	7	12.369	2.325	5.343	1.337
6	16	15.866	5.970	3.832	1.372
6	3	15.866	1.528	3.832	0.351
7	9	4.714	4.714	2.362	2.362
8	6	3.780	3.780	2.315	2.315
9	11	17.273	0.000	4.796	0.000
10	8	19.709	2.283	10.436	1.209
11	13	0.000	0.000	0.000	0.000
12	10	10.272	10.272	4.930	4.930
13	15	0.000	0.000	0.000	0.000
14	12				
15	5				
15	2				
16	14	15.109	0.000	6.210	0.000
16	2	15.109	1.316	6.210	-1.542

Topology 9

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	20.906	4.941	4.826	-0.660
1	14	20.906	2.643	4.826	0.806
2	4	4.350	4.350	1.375	1.375
3	1	4.747	4.747	1.726	1.726
4	16	17.001	6.397	4.425	0.696
4	7	17.001	2.171	4.425	0.733
5	3	12.348	1.648	5.195	-1.272
5	7	12.348	2.196	5.195	1.005
6	16	16.308	6.357	3.794	1.276
6	3	16.308	1.627	3.794	0.327
7	9	4.798	4.798	2.240	2.240
8	6	3.740	3.740	2.121	2.121
9	11	19.594	2.657	4.884	0.390
10	8	19.375	2.081	10.215	0.970
11	13	3.455	3.455	2.752	2.752
12	10	10.052	10.052	4.748	4.748
13	15	5.971	5.971	3.479	3.479
14	12	4.694	4.694	2.744	2.744
15	5	19.750	5.028	6.056	1.433
15	2	19.750	1.287	6.056	0.367
16	14	17.487	2.689	6.627	1.130
16	2	17.487	1.272	6.627	-1.648

Topology 10

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	17.141	1.250	4.341	1.999
1	14	17.141	2.535	4.341	0.937
2	4	3.132	3.132	0.406	0.406
3	1	4.270	4.270	1.709	1.709
4	16	8.659	6.476	3.183	2.045
4	7	8.659	2.193	3.183	1.139
5	3	3.875	1.667	1.380	-0.309
5	7	3.875	2.211	1.380	1.684
6	16	8.096	6.462	2.972	2.372
6	3	8.096	1.654	2.972	0.607
7	9	4.709	4.709	2.235	2.235
8	6	2.935	2.935	1.570	1.570
9	11	19.165	2.312	4.795	0.138
10	8	18.730	1.530	9.965	0.580
11	13	3.145	3.145	2.402	2.402
12	10	9.808	9.808	4.626	4.626
13	15	5.401	5.401	3.168	3.168
14	12	4.572	4.572	2.618	2.618
15	5	15.147	1.314	5.473	0.191
15	2	15.147	0.336	5.473	0.049
16	14	16.403	2.565	6.616	1.130
16	2	16.403	0.309	6.616	-1.667

Topology 11

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	20.047	4.771	4.757	-0.646
1	14	20.047	2.117	4.757	0.626
2	4	4.295	4.295	1.327	1.327
3	1	4.679	4.679	1.667	1.667
4	16	16.495	6.176	4.368	0.681
4	7	16.495	1.849	4.368	0.591
5	3	11.997	1.590	5.012	-1.227
5	7	11.997	1.868	5.012	0.634
6	16	16.046	6.132	3.733	1.131
6	3	16.046	1.569	3.733	0.290
7	9	4.086	4.086	1.913	1.913
8	6	3.679	3.679	2.108	2.108
9	11	11.849	2.672	4.151	0.727
10	8	11.381	2.081	7.390	1.270
11	13	3.374	3.374	2.731	2.731
12	10	7.303	7.303	3.947	3.947
13	15	5.856	5.856	3.398	3.398
14	12	3.906	3.906	2.203	2.203
15	5	19.326	4.849	5.940	1.343
15	2	19.326	1.241	5.940	0.344
16	14	16.729	2.150	6.394	0.748
16	2	16.729	1.227	6.394	-1.590

Topology 12

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	13.358	5.001	4.059	-0.626
1	14	13.358	2.642	4.059	1.106
2	4	4.026	4.026	1.353	1.353
3	1	3.996	3.996	1.166	1.166
4	16	14.816	4.257	4.096	0.598
4	7	14.816	2.070	4.096	0.787
5	3	11.724	1.089	5.173	-1.286
5	7	11.724	2.087	5.173	0.984
6	16	13.773	4.253	3.589	0.791
6	3	13.773	1.089	3.589	0.202
7	9	4.705	4.705	2.130	2.130
8	6	3.539	3.539	1.899	1.899
9	11	18.933	2.162	4.790	0.150
10	8	18.965	1.857	10.028	0.803
11	13	2.945	2.945	2.244	2.244
12	10	9.869	9.869	4.646	4.646
13	15	4.918	4.918	2.967	2.967
14	12	4.593	4.593	2.710	2.710
15	5	12.104	5.061	4.978	2.079
15	2	12.104	1.295	4.978	0.532
16	14	9.715	2.672	4.417	1.590
16	2	9.715	1.286	4.417	-1.089

Topology 13

Primary Relay	Backup Relay	3ph near-end primary (kA)	3ph near-end backup (kA)	3ph far-end primary (kA)	3ph far-end backup (kA)
1	5	15.752	4.900	4.358	-0.488
1	14	15.752	2.370	4.358	0.850
2	4	4.138	4.138	1.339	1.339
3	1	4.289	4.289	1.379	1.379
4	16	15.448	5.073	4.210	0.489
4	7	15.448	1.871	4.210	0.661
5	3	11.755	1.302	5.096	-1.260
5	7	11.755	1.888	5.096	0.785
6	16	14.750	5.053	3.671	0.969
6	3	14.750	1.293	3.671	0.248
7	9	4.011	4.011	1.929	1.929
8	6	3.619	3.619	2.107	2.107
9	11	11.184	2.661	4.073	0.677
10	8	10.703	2.082	7.135	1.263
11	13	3.272	3.272	2.717	2.717
12	10	7.055	7.055	3.935	3.935
13	15	5.403	5.403	3.293	3.293
14	12	3.898	3.898	2.440	2.440
15	5	14.751	4.964	5.473	1.636
15	2	14.751	1.271	5.473	0.419
16	14	12.231	2.400	5.255	1.086
16	2	12.231	1.260	5.255	-1.302

APPENDIX B- MATLAB Codes of Optimization Algorithms Six Bus system

PSO optimization algorithm for grid connected mode

```
function y = func1(x,scale_factor)
k(1)=0.14;
k(2)=0.02;

%%grid connected
y = k(1) *( (x(1)*0.01/((6950/120/x(15))^k(2)-1))+...
            (x(2)*0.01/((6815/120/x(16))^k(2)-1))+...
            (x(3)*0.01/((3359/120/x(17))^k(2)-1))+...
            (x(4)*0.01/((7419/20/x(18))^k(2)-1))+...
            (x(5)*0.01/((6153/120/x(19))^k(2)-1))+...
            (x(6)*0.01/((4607/120/x(20))^k(2)-1))+...
            (x(7)*0.01/((5433/60/x(21))^k(2)-1))+...
            (x(8)*0.01/((5305/60/x(22))^k(2)-1))+...
            (x(9)*0.01/((6848/16/x(23))^k(2)-1))+...
            (x(10)*0.01/((4728/120/x(24))^k(2)-1))+...
            (x(11)*0.01/((5376/100/x(25))^k(2)-1))+...
            (x(12)*0.01/((4685/100/x(26))^k(2)-1))+...
            (x(13)*0.01/((5435/100/x(27))^k(2)-1))+...
            (x(14)*0.01/((3217/120/x(28))^k(2)-1)));


penalty = 0.0;
[h,g] = constr(x);
for i = 1:length(h)
if h(i)~=0
penalty = penalty + h(i)^2;
end
end
for i = 1:length(g)
if g(i)>0
penalty = penalty + g(i)^3;
end
end
y = y+penalty*scale_factor;

function [h,g] = constr(x)
h(1) = 0;
k(1)=0.14;
k(2)=0.02;
cti=0.2;


% %----------------------------------Grid Connected------------------%
g(1) = cti + k(1)*(x(1)*0.01/((6950/120/x(15))^k(2)-1) - x(3)*0.01/((1727/120/x(17))^k(2)-1)) ;
g(2) = cti + k(1)*(x(2)*0.01/((6815/120/x(16))^k(2)-1) - x(14)*0.01/((1587/120/x(28))^k(2)-1)) ;
g(3) = cti + k(1)*(x(3)*0.01/((3359/120/x(17))^k(2)-1) - x(9)*0.01/((1026/16/x(23))^k(2)-1)) ;
g(4) = cti + k(1)*(x(3)*0.01/((3359/120/x(17))^k(2)-1) - x(6)*0.01/((2333/120/x(20))^k(2)-1)) ;
g(5) = cti + k(1)*(x(4)*0.01/((7419/20/x(18))^k(2)-1) - x(2)*0.01/((5125/120/x(16))^k(2)-1)) ;
g(6) = cti + k(1)*(x(4)*0.01/((7419/20/x(18))^k(2)-1) - x(6)*0.01/((2303/120/x(20))^k(2)-1)) ;
g(7) = cti + k(1)*(x(5)*0.01/((6153/120/x(19))^k(2)-1) - x(2)*0.01/((5136/120/x(16))^k(2)-1)) ;
g(8) = cti + k(1)*(x(5)*0.01/((6153/120/x(19))^k(2)-1) - x(9)*0.01/((1019/16/x(23))^k(2)-1)) ;
g(9) = cti + k(1)*(x(6)*0.01/((4607/120/x(20))^k(2)-1) - x(8)*0.01/((3014/60/x(22))^k(2)-1)) ;
g(10) = cti + k(1)*(x(7)*0.01/((5433/60/x(21))^k(2)-1) - x(5)*0.01/((3846/120/x(19))^k(2)-1)) ;
g(11) = cti + k(1)*(x(8)*0.01/((5305/60/x(22))^k(2)-1) - x(4)*0.01/((1569/20/x(18))^k(2)-1)) ;
g(12) = cti + k(1)*(x(8)*0.01/((5305/60/x(22))^k(2)-1) - x(11)*0.01/((3736/100/x(25))^k(2)-1)) ;
g(13) = cti + k(1)*(x(9)*0.01/((6848/16/x(23))^k(2)-1) - x(7)*0.01/((3123/60/x(21))^k(2)-1));
g(14) = cti + k(1)*(x(9)*0.01/((6848/16/x(23))^k(2)-1) - x(11)*0.01/((3725/100/x(25))^k(2)-1));
g(15) = cti + k(1)*(x(10)*0.01/((4728/120/x(24))^k(2)-1) - x(4)*0.01/((1576/20/x(18))^k(2)-1)) ;
g(16) = cti + k(1)*(x(10)*0.01/((4728/120/x(24))^k(2)-1) - x(7)*0.01/((3153/60/x(21))^k(2)-1)) ;
g(17) = cti + k(1)*(x(11)*0.01/((5376/100/x(25))^k(2)-1) - x(13)*0.01/((3789/100/x(27))^k(2)-1)) ;
g(18) = cti + k(1)*(x(12)*0.01/((4685/100/x(26))^k(2)-1) - x(10)*0.01/((3092/120/x(24))^k(2)-1)) ;
g(19) = cti+ k(1)*(x(13)*0.01/((5435/100/x(27))^k(2)-1) - x(1)*0.01/((5265/120/x(15))^k(2)-1)) ;
g(20) = cti + k(1)*(x(14)*0.01/((3217/120/x(28))^k(2)-1) - x(12)*0.01/((3046/100/x(26))^k(2)-1));

%max far end current less than 1s
 g(21) =            (k(1)*x(1)*0.01/((5296/120/x(15))^k(2)-1))-1.0 ;...
 g(22) =            (k(1)*x(2)*0.01/((5163/120/x(16))^k(2)-1))-1.0 ;...
 g(23) =            (k(1)*x(3)*0.01/((1760/120/x(17))^k(2)-1))-1.0 ;...
 g(24) =            (k(1)*x(4)*0.01/((1641/20/x(18))^k(2)-1))-1.0 ;...
 g(25) =            (k(1)*x(5)*0.01/((3891/120/x(19))^k(2)-1))-1.0 ;...
 g(26) =            (k(1)*x(6)*0.01/((2366/120/x(20))^k(2)-1))-1.0 ;...
 g(27) =            (k(1)*x(7)*0.01/((3186/60/x(21))^k(2)-1))-1.0 ;...
 g(28) =            (k(1)*x(8)*0.01/((3060/60/x(22))^k(2)-1))-1.0 ;...
 g(29) =            (k(1)*x(9)*0.01/((1091/16/x(23))^k(2)-1))-1.0 ;...
 g(30) =            (k(1)*x(10)*0.01/((3125/120/x(24))^k(2)-1))-1.0 ;...
 g(31) =            (k(1)*x(11)*0.01/((3762/100/x(25))^k(2)-1))-1.0 ;...
 g(32) =            (k(1)*x(12)*0.01/((3078/100/x(26))^k(2)-1))-1.0 ;...
 g(33) =            (k(1)*x(13)*0.01/((3822/100/x(27))^k(2)-1))-1.0 ;...
 g(34) =            (k(1)*x(14)*0.01/((1620/120/x(28))^k(2)-1))-1.0 ;...
```

```
%max current greater than 0.05s
 g(35) =0.05-(k(1)*x(1)*0.01/((6950/120/x(15))^k(2)-1)) ;...
 g(36) =0.05-(k(1)*x(2)*0.01/((6815/120/x(16))^k(2)-1)) ;...
 g(37) =0.05-(k(1)*x(3)*0.01/((3359/120/x(17))^k(2)-1)) ;...
 g(38) =0.05-(k(1)*x(4)*0.01/((7419/20/x(18))^k(2)-1)) ;...
 g(39) =0.05-(k(1)*x(5)*0.01/((6153/120/x(19))^k(2)-1)) ;...
 g(40) =0.05-(k(1)*x(6)*0.01/((4607/120/x(20))^k(2)-1)) ;...
 g(41) =0.05-(k(1)*x(7)*0.01/((5433/60/x(21))^k(2)-1)) ;...
 g(42) =0.05-(k(1)*x(8)*0.01/((5305/60/x(22))^k(2)-1)) ;...
 g(43) =0.05-(k(1)*x(9)*0.01/((6848/16/x(23))^k(2)-1)) ;...
 g(44) =0.05-(k(1)*x(10)*0.01/((4728/120/x(24))^k(2)-1)) ;...
 g(45) =0.05-(k(1)*x(11)*0.01/((5376/100/x(25))^k(2)-1)) ;...
 g(46) =0.05-(k(1)*x(12)*0.01/((4685/100/x(26))^k(2)-1)) ;...
 g(47) =0.05-(k(1)*x(13)*0.01/((5435/100/x(27))^k(2)-1)) ;...
 g(48) =0.05-(k(1)*x(14)*0.01/((3217/120/x(28))^k(2)-1)) ;

clear all
clc
format long
pop = 100;
phi_1 = 1.05;
phi_2 = 1.1;
nmax = 8000;
scale_factor = 100000;
weight = linspace(1,0.3,nmax);
%grid connected bounds
lb = [5 5 5 5 5 5 5 5 5 5 5 5 5 5 1.3 1.246 1.246 1.755 1.138 1.138 1 1 2.194 1 1 1.456 1.456
1.3];
ub = [110 110 110 110 110 110 110 110 110 110 110 110 110 110 9.467 8.44 9.95 10 8.16 10 10 10 10
8.489 10 10 7.747 8.944];

for i = 1:length(lb)
for j = 1:pop
x(i,j) = lb(i) + (ub(i)-lb(i))*rand;
v(i,j) = 0;
end
end
for i = 1:pop
fitness(i) = func1(x(:,i),scale_factor);
pbest(i) = fitness(i);
px(i,:) = x(:,i);
end
[gbest, location] = min(fitness);
gx = x(:,location);
for i = 1:nmax
for j = 1:pop
v(:,j) = weight(i)*v(:,j) + phi_1*rand*(px(j,:)'-x(:,j))+ phi_2*rand*(gx-x(:,j));
x(:,j) = x(:,j) + v(:,j);
for k = 1:length(x(:,j))
if x(k,j) < lb(k) || x(k,j) > ub(k)
x(k,j) = lb(k) + (ub(k)-lb(k))*rand;
end
end
fitness(j) = func1(x(:,j),scale_factor);
if fitness(j) < pbest(j)
pbest(j) = fitness(j);
px(j,:) = x(:,j);
end
end
[gbest, location] = min(pbest);
gx = x(:,location);
[gx' gbest];

fprintf('%3d %8.3f %8.3f %8.3f %8.3f % 8.3f\n',i,gx,gbest)
end
```

APPENDIX C - Generic Six Bus Microgrid Results

Islanded Mode Operation – Relay Settings

Relay	PSO		MBA		WCA		WOA		SCA		GWO		NNA		PSOGSA		PSOGWO		WCMFO	
No	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}
1	0.16	286.38	0.21	147.35	0.13	304.33	0.16	243.75	0.06	544.99	0.06	548.07	0.05	548.4	0.05	548.4	0.05	548.21	0.05	548.4
2	0.15	238.38	0.24	121.68	0.08	426.95	0.13	244.74	0.1	348.65	0.1	280.59	0.06	418.35	0.05	427.2	0.06	423.09	0.06	427.2
3	0.12	703.28	0.12	617.44	0.11	633.78	0.2	272.94	0.11	356.79	0.07	751.74	0.16	199.35	0.07	678.8	0.05	851.91	0.05	847
4	0.17	133.3	0.11	184.74	0.17	76.26	0.27	43.44	0.08	193.2	0.22	48.88	0.07	185.79	0.11	102.53	0.13	81.55	0.06	193.2
5	0.13	266.33	0.21	140.8	0.16	169.05	0.13	241.18	0.12	276.4	0.09	307	0.07	307.2	0.06	307.2	0.06	306.7	0.07	278.87
6	0.26	276.18	0.23	255.08	0.23	218.2	0.21	316.7	0.14	197.46	0.21	149.5	0.07	854.06	0.11	458.79	0.06	854.4	0.06	854.4
7	0.15	441.72	0.16	453.55	0.21	188.44	0.25	183.98	0.14	554.33	0.25	122.2	0.08	571.35	0.07	600	0.07	598.63	0.07	600
8	0.37	111.06	0.22	180.21	0.1	474.78	0.21	193.87	0.07	478.05	0.12	332.69	0.07	489.52	0.08	430.02	0.08	411.59	0.07	465.1
9	0.27	106.42	0.31	56.64	0.25	64.98	0.21	111.78	0.29	57.95	0.21	56.18	0.13	159.99	0.17	99.39	0.28	20.62	0.11	160
10	0.13	435.6	0.28	165.49	0.14	262.79	0.17	287.61	0.12	443.71	0.08	549.39	0.07	548.94	0.06	549.6	0.06	544.52	0.07	519.05
11	0.21	377.42	0.21	275.28	0.15	327.48	0.16	415.47	0.08	717.66	0.07	729.35	0.06	716.72	0.06	732	0.06	732	0.06	732
12	0.22	402.28	0.27	281.06	0.08	877.02	0.18	403.84	0.11	818.28	0.24	192.76	0.08	901.76	0.07	818.1	0.06	999.84	0.06	1000
13	0.17	202.76	0.14	216.92	0.19	101.93	0.15	180.08	0.17	154.57	0.09	239.68	0.08	245.89	0.08	246	0.08	245.86	0.1	188.85
14	0.17	311.97	0.3	129.87	0.07	698.96	0.19	234.87	0.16	321.8	0.11	438.7	0.16	181.91	0.05	729.6	0.06	729.02	0.06	729.6
OF Value		9.0421		8.76		6.8984		8.1165		6.5451		6.151		4.9311		4.8748		4.7287		4.5161

Grid Connected Mode Operation – Relay Settings

Relay	PSO		MBA		WCA		WOA		SCA		GWO		NNA		PSOGSA		PSOGWO		WCMFO	
No	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}	TDS	I_{pick}
1	0.25	695.63	0.25	959.58	0.44	208.33	0.29	551.58	0.4	240.98	0.34	343.28	0.17	1136.04	0.2	987.36	0.18	1124.75	0.31	313.08
2	0.3	625.89	0.27	807.32	0.25	775.28	0.29	628.32	0.45	149.52	0.27	582.42	0.18	1012.77	0.2	797.24	0.29	363.1	0.18	900.77
3	0.18	472.3	0.19	467.26	0.27	271.66	0.15	602.2	0.05	1194	0.05	1183.41	0.05	1133.94	0.05	1175.87	0.05	1160.5	0.05	1194
4	0.35	149.49	0.41	91.07	0.46	70.21	0.3	163.4	0.49	75.75	0.36	48.64	0.23	199.96	0.25	135.54	0.39	35.18	0.37	35.1
5	0.28	671.13	0.33	377.76	0.23	694.37	0.23	717.67	0.19	537.38	0.36	146.58	0.16	936.85	0.15	894.38	0.14	964.48	0.14	979.2
6	0.23	469.73	0.28	262.34	0.09	1200	0.12	790.38	0.1	1200	0.07	1165.18	0.06	1200	0.06	1200	0.06	1200	0.06	1200
7	0.32	391.38	0.42	171.98	0.26	452.7	0.31	320.39	0.24	85.44	0.23	319.2	0.18	591.97	0.2	399.44	0.17	590.07	0.16	595.1
8	0.42	209.43	0.36	173.21	0.23	285.6	0.21	353.46	0.23	221.62	0.24	144.4	0.12	599.98	0.12	585.69	0.15	421.18	0.15	404.3
9	0.37	114.57	0.41	62.92	0.27	141.52	0.3	141.31	0.22	56.59	0.27	113.57	0.21	160	0.28	75.83	0.37	35.29	0.19	159.83
10	0.33	389.89	0.32	292.91	0.16	1009.73	0.22	575.21	0.13	643.06	0.11	1017.41	0.12	1018.68	0.15	508.66	0.25	160.32	0.1	1018.68
11	0.32	389.26	0.28	440.12	0.24	385.55	0.22	509.17	0.21	472.22	0.28	202.3	0.12	852.92	0.14	802.71	0.13	997.24	0.12	894.88
12	0.22	582.27	0.23	544.48	0.34	266.3	0.2	566.6	0.16	320.51	0.23	172.66	0.13	1000	0.08	996.13	0.08	994.17	0.23	145.6
13	0.27	505.33	0.32	395.63	0.32	274.4	0.21	665.1	0.35	256.25	0.21	595.1	0.17	638.77	0.2	521.24	0.18	658.79	0.16	764.59
14	0.18	453.15	0.25	294.48	0.34	156.36	0.16	550.36	0.06	1073.28	0.06	1059.29	0.2	321.3	0.05	1047.89	0.05	1063.61	0.05	1034.14
OF Value		10.5585		10.4152		9.6264		8.9947		7.5196		7.3155		6.9065		6.4385		6.6997		6.4092

Islanded Mode Relay Operating times

Relay	PSO	MBA	WCA	WOA	SCA	GWO	NNA	PSOGSA	PSOGWO	WCMFO
1	0.5965	0.5912	0.5324	0.5596	0.3456	0.3408	0.3098	0.3198	0.3191	0.3241
2	0.5301	0.626	0.4129	0.4899	0.4496	0.4034	0.2985	0.2866	0.2883	0.296
3	0.6818	0.6037	0.5555	0.6436	0.4125	0.3912	0.4433	0.3874	0.358	0.3625
4	0.3931	0.2798	0.3217	0.4401	0.1993	0.3614	0.1667	0.2325	0.2474	0.1506
5	0.4979	0.5855	0.4771	0.4792	0.472	0.3747	0.2858	0.271	0.2715	0.2863
6	0.7982	0.658	0.6269	0.6728	0.3662	0.5036	0.4053	0.4461	0.3518	0.3544
7	0.6489	0.692	0.5683	0.6709	0.6731	0.5699	0.3876	0.3573	0.3571	0.3566
8	0.8841	0.6313	0.4626	0.6333	0.3242	0.4551	0.3328	0.3811	0.3311	0.3136
9	0.5486	0.5244	0.4448	0.441	0.4989	0.3581	0.3	0.3303	0.3796	0.2624
10	0.6499	0.81	0.5151	0.6442	0.5981	0.4912	0.4107	0.3749	0.3626	0.3737
11	0.8281	0.6916	0.5412	0.6567	0.4668	0.4505	0.3689	0.3989	0.3966	0.3526
12	0.7777	0.8109	0.4787	0.6651	0.6243	0.6046	0.4725	0.4145	0.3912	0.395
13	0.6252	0.5309	0.5282	0.5388	0.5613	0.3704	0.3196	0.3364	0.3352	0.3436
14	0.5821	0.7248	0.4327	0.5813	0.5532	0.476	0.4296	0.338	0.3393	0.3447
OF Value	9.0421	8.76	6.8984	8.1165	6.5451	6.151	4.9311	4.8748	4.7287	4.5161

Grid Connected Mode Relay Operating times

R	PSO	MBA	WCA	WOA	SCA	GWO	NNA	PSOGSA	PSOGWO	WCMFO
1	0.7478	0.8604	0.8505	0.7836	0.8038	0.7707	0.6285	0.7071	0.6718	0.6825
2	0.853	0.8517	0.7977	0.8186	0.7908	0.7537	0.6544	0.6398	0.665	0.6137
3	0.6173	0.668	0.7454	0.5989	0.3665	0.3545	0.3188	0.33	0.3261	0.3349
4	0.6067	0.6294	0.6658	0.5278	0.7136	0.474	0.4228	0.4129	0.4867	0.4626
5	0.8782	0.8071	0.7196	0.7314	0.5424	0.6537	0.5706	0.5391	0.5372	0.5155
6	0.6824	0.6574	0.4641	0.4872	0.5017	0.3324	0.2997	0.2949	0.3306	0.3188
7	0.8369	0.8204	0.7215	0.7406	0.3907	0.5513	0.5641	0.5162	0.5231	0.4958
8	0.8703	0.7116	0.5325	0.5406	0.4934	0.4478	0.368	0.3658	0.4116	0.4026
9	0.6147	0.5867	0.4746	0.5121	0.3051	0.449	0.3726	0.4182	0.4621	0.346
10	0.8993	0.7792	0.7288	0.7019	0.4492	0.4858	0.5517	0.4558	0.495	0.4612
11	0.8381	0.7762	0.629	0.6251	0.5813	0.5748	0.4568	0.4971	0.5171	0.4785
12	0.7209	0.7236	0.8116	0.6394	0.4116	0.4732	0.566	0.3655	0.3686	0.4404
13	0.7654	0.8351	0.7262	0.681	0.784	0.6485	0.5443	0.5877	0.5922	0.5517
14	0.6275	0.7084	0.7591	0.6066	0.3856	0.3459	0.5882	0.3085	0.3127	0.3049
OF Value	10.5585	10.4152	9.6264	8.9947	7.5196	7.3155	6.9065	6.4385	6.6997	6.4092

APPENDIX D – Pseudo Code of WCMFO Algorithm

```
WCMFO Algorithm Pseudo Code
set the parameters of WCMFO such as Npop, Nsr, a, and maximum number of iterations
 for i=1:Npop
    Create a random stream
    Calculate the objective function value of the stream
end for
sort the streams from best to worst based on their objective function value
Sea ←the first stream
Rivers ←n_sr - 1
Stream←n_pop - n_sr
Determine the intensity of flow for rivers and sea
 i=0;
While     i < maximum number of iterations
i=i+1;
     for     streams
Update the position of stream using spiral movement
Stream_objective=objective function value of the new stream
               if     stream_objective < river_objective
                    River_position= the new stream
               if     stream_objective < sea_objective
               Sea_position= the new stream
               end if
              end if
              if river_objective < sea_objective
                          Sea_position =River_position
 end if
end for
for     rivers
Update the position of rivers using spiral movement
river_objective =objective function value of the new river
              if river_objective < sea_objective
               Sea_position =River_position
end if
 end for
     for    streams
           Update the position of the streams using Levy flight
  end for
     for    Rivers and streams
      d=calculate the distance between each river or stream and the sea
      if     d < d_max
                  raining process (for both rivers and streams)
 end if
end for
     Linearly decrease the parameter  d_max
    Linearly decrease the parameter a
 end while
```

APPENDIX E- MATLAB Code for Cluster 4 Optimization

```
function FVAL=fun(x)

k(1)=0.14;
k(2)=0.02;

%min current from cluster 4  - 10,12,13 topologies
FVAL =     k(1)  *((x(1)*0.01/((13358/300/x(17))^k(2)-1))+...
               (x(2)*0.01/((3132/100/x(18))^k(2)-1))+...
               (x(3)*0.01/((3996/100/x(19))^k(2)-1))+...
               (x(4)*0.01/((8659/300/x(20))^k(2)-1))+...
               (x(5)*0.01/((3875/320/x(21))^k(2)-1))+...
               (x(6)*0.01/((8096/250/x(22))^k(2)-1))+...
               (x(7)*0.01/((4011/120/x(23))^k(2)-1))+...
               (x(8)*0.01/((2935/150/x(24))^k(2)-1))+...
               (x(9)*0.01/((11184/300/x(25))^k(2)-1))+...
               (x(10)*0.01/((10703/400/x(26))^k(2)-1))+...
               (x(11)*0.01/((2945/200/x(27))^k(2)-1))+...
               (x(12)*0.01/((7055/300/x(28))^k(2)-1))+...
               (x(13)*0.01/((4918/200/x(29))^k(2)-1))+...
               (x(14)*0.01/((3898/160/x(30))^k(2)-1))+...
               (x(15)*0.01/((12104/400/x(31))^k(2)-1))+...
               (x(16)*0.01/((9715/400/x(32))^k(2)-1)));

End

function c=Constraints(x)

k(1)=0.14;
k(2)=0.02;
cti=0.2;
%%---------Cluster 4 , 10,12,13 Constraints---------------%%

%3ph near end
c =[cti + k(1)*(x(1)*0.01/((17141/300/x(17))^k(2)-1) - x(5)*0.01/((1250/320/x(21))^k(2)-1)) ;...
   cti + k(1)*(x(1)*0.01/((17141/300/x(17))^k(2)-1) - x(14)*0.01/((2535/160/x(30))^k(2)-1)) ;...
   cti + k(1)*(x(1)*0.01/((13358/300/x(17))^k(2)-1) - x(5)*0.01/((5001/320/x(21))^k(2)-1)) ;...
   cti + k(1)*(x(1)*0.01/((13358/300/x(17))^k(2)-1) - x(14)*0.01/((2642/160/x(30))^k(2)-1)) ;...
   cti + k(1)*(x(1)*0.01/((15752/300/x(17))^k(2)-1) - x(5)*0.01/((4900/320/x(21))^k(2)-1)) ;...
   cti + k(1)*(x(1)*0.01/((15752/300/x(17))^k(2)-1) - x(14)*0.01/((2370/160/x(30))^k(2)-1)) ;...

   cti + k(1)*(x(2)*0.01/((3132/100/x(18))^k(2)-1) - x(4)*0.01/((3132/300/x(20))^k(2)-1)) ;...
   cti + k(1)*(x(2)*0.01/((4026/100/x(18))^k(2)-1) - x(4)*0.01/((4026/300/x(20))^k(2)-1)) ;...
   cti + k(1)*(x(2)*0.01/((4138/100/x(18))^k(2)-1) - x(4)*0.01/((4138/300/x(20))^k(2)-1)) ;...

   cti + k(1)*(x(3)*0.01/((4270/100/x(19))^k(2)-1) - x(1)*0.01/((4270/300/x(17))^k(2)-1)) ;...
   cti + k(1)*(x(3)*0.01/((3996/100/x(19))^k(2)-1) - x(1)*0.01/((3996/300/x(17))^k(2)-1)) ;...
   cti + k(1)*(x(3)*0.01/((4289/100/x(19))^k(2)-1) - x(1)*0.01/((4289/300/x(17))^k(2)-1)) ;...

   cti + k(1)*(x(4)*0.01/((8659/300/x(20))^k(2)-1) - x(16)*0.01/((6476/400/x(32))^k(2)-1)) ;...
   cti + k(1)*(x(4)*0.01/((8659/300/x(20))^k(2)-1) - x(7)*0.01/((2193/120/x(23))^k(2)-1)) ;...
   cti + k(1)*(x(4)*0.01/((14816/300/x(20))^k(2)-1) - x(16)*0.01/((4257/400/x(32))^k(2)-1)) ;...
   cti + k(1)*(x(4)*0.01/((14816/300/x(20))^k(2)-1) - x(7)*0.01/((2070/120/x(23))^k(2)-1)) ;...
   cti + k(1)*(x(4)*0.01/((15448/300/x(20))^k(2)-1) - x(16)*0.01/((5073/400/x(32))^k(2)-1)) ;...
   cti + k(1)*(x(4)*0.01/((15448/300/x(20))^k(2)-1) - x(7)*0.01/((1871/120/x(23))^k(2)-1)) ;...


   cti + k(1)*(x(5)*0.01/((3875/320/x(21))^k(2)-1) - x(3)*0.01/((1667/100/x(19))^k(2)-1)) ;...
   cti + k(1)*(x(5)*0.01/((3875/320/x(21))^k(2)-1) - x(7)*0.01/((2211/120/x(23))^k(2)-1)) ;...
   cti + k(1)*(x(5)*0.01/((11724/320/x(21))^k(2)-1) - x(3)*0.01/((1089/100/x(19))^k(2)-1)) ;...
   cti + k(1)*(x(5)*0.01/((11724/320/x(21))^k(2)-1) - x(7)*0.01/((2087/120/x(23))^k(2)-1)) ;...
   cti + k(1)*(x(5)*0.01/((11755/320/x(21))^k(2)-1) - x(3)*0.01/((1302/100/x(19))^k(2)-1)) ;...
   cti + k(1)*(x(5)*0.01/((11755/320/x(21))^k(2)-1) - x(7)*0.01/((1888/120/x(23))^k(2)-1)) ;...


   cti + k(1)*(x(6)*0.01/((8096/250/x(22))^k(2)-1) - x(16)*0.01/((6462/400/x(32))^k(2)-1)) ;...
   cti + k(1)*(x(6)*0.01/((8096/250/x(22))^k(2)-1) - x(3)*0.01/((1654/100/x(19))^k(2)-1)) ;...
   cti + k(1)*(x(6)*0.01/((13773/250/x(22))^k(2)-1) - x(16)*0.01/((4253/400/x(32))^k(2)-1)) ;...
   cti + k(1)*(x(6)*0.01/((13773/250/x(22))^k(2)-1) - x(3)*0.01/((1089/100/x(19))^k(2)-1)) ;...
   cti + k(1)*(x(6)*0.01/((14750/250/x(22))^k(2)-1) - x(16)*0.01/((5053/400/x(32))^k(2)-1)) ;...
   cti + k(1)*(x(6)*0.01/((14750/250/x(22))^k(2)-1) - x(3)*0.01/((1293/100/x(19))^k(2)-1)) ;...

   cti + k(1)*(x(7)*0.01/((4709/120/x(23))^k(2)-1) - x(9)*0.01/((4709/300/x(25))^k(2)-1)) ;...
   cti + k(1)*(x(7)*0.01/((4705/120/x(23))^k(2)-1) - x(9)*0.01/((4705/300/x(25))^k(2)-1)) ;...
   cti + k(1)*(x(7)*0.01/((4011/120/x(23))^k(2)-1) - x(9)*0.01/((4011/300/x(25))^k(2)-1)) ;...


   cti + k(1)*(x(8)*0.01/((2935/150/x(24))^k(2)-1) - x(6)*0.01/((2935/250/x(22))^k(2)-1)) ;...
   cti + k(1)*(x(8)*0.01/((3539/150/x(24))^k(2)-1) - x(6)*0.01/((3539/250/x(22))^k(2)-1)) ;...
   cti + k(1)*(x(8)*0.01/((3619/150/x(24))^k(2)-1) - x(6)*0.01/((3619/250/x(22))^k(2)-1)) ;...
```

```
cti + k(1)*(x(9)*0.01/((19165/300/x(25))^k(2)-1) - x(11)*0.01/((2312/200/x(27))^k(2)-1));...
cti + k(1)*(x(9)*0.01/((18933/300/x(25))^k(2)-1) - x(11)*0.01/((2162/200/x(27))^k(2)-1));...
cti + k(1)*(x(9)*0.01/((11184/300/x(25))^k(2)-1) - x(11)*0.01/((2661/200/x(27))^k(2)-1));...


cti + k(1)*(x(10)*0.01/((18730/400/x(26))^k(2)-1) - x(8)*0.01/((1530/150/x(24))^k(2)-1));...
cti + k(1)*(x(10)*0.01/((18965/400/x(26))^k(2)-1) - x(8)*0.01/((1857/150/x(24))^k(2)-1));...
cti + k(1)*(x(10)*0.01/((10703/400/x(26))^k(2)-1) - x(8)*0.01/((2082/150/x(24))^k(2)-1));...


cti + k(1)*(x(11)*0.01/((3145/200/x(27))^k(2)-1) - x(13)*0.01/((3145/200/x(29))^k(2)-1)) ;...
cti + k(1)*(x(11)*0.01/((2945/200/x(27))^k(2)-1) - x(13)*0.01/((2945/200/x(29))^k(2)-1)) ;...
cti + k(1)*(x(11)*0.01/((3272/200/x(27))^k(2)-1) - x(13)*0.01/((3272/200/x(29))^k(2)-1)) ;...


cti + k(1)*(x(12)*0.01/((9808/300/x(28))^k(2)-1) - x(10)*0.01/((9808/400/x(26))^k(2)-1)) ;...
cti + k(1)*(x(12)*0.01/((9869/300/x(28))^k(2)-1) - x(10)*0.01/((9869/400/x(26))^k(2)-1)) ;...
cti + k(1)*(x(12)*0.01/((7055/300/x(28))^k(2)-1) - x(10)*0.01/((7055/400/x(26))^k(2)-1)) ;...

cti + k(1)*(x(13)*0.01/((5401/200/x(29))^k(2)-1) - x(15)*0.01/((5401/400/x(31))^k(2)-1)) ;...
cti + k(1)*(x(13)*0.01/((4918/200/x(29))^k(2)-1) - x(15)*0.01/((4918/400/x(31))^k(2)-1)) ;...
cti + k(1)*(x(13)*0.01/((5403/200/x(29))^k(2)-1) - x(15)*0.01/((5403/400/x(31))^k(2)-1)) ;...


cti + k(1)*(x(14)*0.01/((4572/160/x(30))^k(2)-1) - x(12)*0.01/((4572/300/x(28))^k(2)-1)) ;...
cti + k(1)*(x(14)*0.01/((4593/160/x(30))^k(2)-1) - x(12)*0.01/((4593/300/x(28))^k(2)-1)) ;...
cti + k(1)*(x(14)*0.01/((3898/160/x(30))^k(2)-1) - x(12)*0.01/((3898/300/x(28))^k(2)-1)) ;...


cti+ k(1)*(x(15)*0.01/((15147/400/x(31))^k(2)-1) - x(5)*0.01/((1314/320/x(21))^k(2)-1)) ;...
cti+ k(1)*(x(15)*0.01/((15147/400/x(31))^k(2)-1) - x(2)*0.01/((336/100/x(18))^k(2)-1)) ;...
cti+ k(1)*(x(15)*0.01/((12104/400/x(31))^k(2)-1) - x(5)*0.01/((5061/320/x(21))^k(2)-1)) ;...
cti+ k(1)*(x(15)*0.01/((12104/400/x(31))^k(2)-1) - x(2)*0.01/((1295/100/x(18))^k(2)-1)) ;...
cti+ k(1)*(x(15)*0.01/((14751/400/x(31))^k(2)-1) - x(5)*0.01/((4964/320/x(21))^k(2)-1)) ;...
cti+ k(1)*(x(15)*0.01/((14751/400/x(31))^k(2)-1) - x(2)*0.01/((1271/100/x(18))^k(2)-1)) ;...

cti+ k(1)*(x(16)*0.01/((16403/400/x(32))^k(2)-1) - x(14)*0.01/((2565/160/x(30))^k(2)-1)) ;...
cti + k(1)*(x(16)*0.01/((16403/400/x(32))^k(2)-1) - x(2)*0.01/((309/100/x(18))^k(2)-1));...
cti+ k(1)*(x(16)*0.01/((9715/400/x(32))^k(2)-1) - x(14)*0.01/((2672/160/x(30))^k(2)-1)) ;...
cti + k(1)*(x(16)*0.01/((9715/400/x(32))^k(2)-1) - x(2)*0.01/((1286/100/x(18))^k(2)-1));...
cti+ k(1)*(x(16)*0.01/((12231/400/x(32))^k(2)-1) - x(14)*0.01/((2400/160/x(30))^k(2)-1)) ;...
cti + k(1)*(x(16)*0.01/((12231/400/x(32))^k(2)-1) - x(2)*0.01/((1260/100/x(18))^k(2)-1));...

%farend 3ph fault coordination

cti + k(1)*(x(1)*0.01/((4341/300/x(17))^k(2)-1) - x(5)*0.01/((1999/320/x(21))^k(2)-1)) ;...
cti + k(1)*(x(1)*0.01/((4341/300/x(17))^k(2)-1) - x(14)*0.01/((937/160/x(30))^k(2)-1)) ;...
%cti + k(1)*(x(1)*0.01/((4059/300/x(17))^k(2)-1) - x(5)*0.01/((-626/320/x(21))^k(2)-1)) ;...
cti + k(1)*(x(1)*0.01/((4059/300/x(17))^k(2)-1) - x(14)*0.01/((1106/160/x(30))^k(2)-1)) ;...
%cti + k(1)*(x(1)*0.01/((4358/300/x(17))^k(2)-1) - x(5)*0.01/((-488/320/x(21))^k(2)-1)) ;...
cti + k(1)*(x(1)*0.01/((4358/300/x(17))^k(2)-1) - x(14)*0.01/((850/160/x(30))^k(2)-1)) ;...

cti + k(1)*(x(2)*0.01/((406/100/x(18))^k(2)-1) - x(4)*0.01/((406/300/x(20))^k(2)-1)) ;...
cti + k(1)*(x(2)*0.01/((1353/100/x(18))^k(2)-1) - x(4)*0.01/((1353/300/x(20))^k(2)-1)) ;...
cti + k(1)*(x(2)*0.01/((1339/100/x(18))^k(2)-1) - x(4)*0.01/((1339/300/x(20))^k(2)-1)) ;...

cti + k(1)*(x(3)*0.01/((1709/100/x(19))^k(2)-1) - x(1)*0.01/((1709/300/x(17))^k(2)-1)) ;...
cti + k(1)*(x(3)*0.01/((1166/100/x(19))^k(2)-1) - x(1)*0.01/((1166/300/x(17))^k(2)-1)) ;...
cti + k(1)*(x(3)*0.01/((1379/100/x(19))^k(2)-1) - x(1)*0.01/((1379/300/x(17))^k(2)-1)) ;...

cti + k(1)*(x(4)*0.01/((3183/300/x(20))^k(2)-1) - x(16)*0.01/((2045/400/x(32))^k(2)-1)) ;...
cti + k(1)*(x(4)*0.01/((3183/300/x(20))^k(2)-1) - x(7)*0.01/((1139/120/x(23))^k(2)-1)) ;...
cti + k(1)*(x(4)*0.01/((4096/300/x(20))^k(2)-1) - x(16)*0.01/((598/400/x(32))^k(2)-1)) ;...
cti + k(1)*(x(4)*0.01/((4096/300/x(20))^k(2)-1) - x(7)*0.01/((787/120/x(23))^k(2)-1)) ;...
cti + k(1)*(x(4)*0.01/((4210/300/x(20))^k(2)-1) - x(16)*0.01/((489/400/x(32))^k(2)-1)) ;...
cti + k(1)*(x(4)*0.01/((4210/300/x(20))^k(2)-1) - x(7)*0.01/((661/120/x(23))^k(2)-1)) ;...

%cti + k(1)*(x(5)*0.01/((1380/320/x(21))^k(2)-1) - x(3)*0.01/((-309/100/x(19))^k(2)-1)) ;...
cti + k(1)*(x(5)*0.01/((1380/320/x(21))^k(2)-1) - x(7)*0.01/((1684/120/x(23))^k(2)-1)) ;...
%cti + k(1)*(x(5)*0.01/((5173/320/x(21))^k(2)-1) - x(3)*0.01/((-1286/100/x(19))^k(2)-1)) ;...
cti + k(1)*(x(5)*0.01/((5173/320/x(21))^k(2)-1) - x(7)*0.01/((984/120/x(23))^k(2)-1)) ;...
%cti + k(1)*(x(5)*0.01/((5096/320/x(21))^k(2)-1) - x(3)*0.01/((-1260/100/x(19))^k(2)-1)) ;...
cti + k(1)*(x(5)*0.01/((5096/320/x(21))^k(2)-1) - x(7)*0.01/((785/120/x(23))^k(2)-1)) ;...


cti + k(1)*(x(6)*0.01/((2972/250/x(22))^k(2)-1) - x(16)*0.01/((2372/400/x(32))^k(2)-1)) ;...
cti + k(1)*(x(6)*0.01/((2972/250/x(22))^k(2)-1) - x(3)*0.01/((607/100/x(19))^k(2)-1)) ;...
cti + k(1)*(x(6)*0.01/((3589/250/x(22))^k(2)-1) - x(16)*0.01/((791/400/x(32))^k(2)-1)) ;...
cti + k(1)*(x(6)*0.01/((3589/250/x(22))^k(2)-1) - x(3)*0.01/((202/100/x(19))^k(2)-1)) ;...
cti + k(1)*(x(6)*0.01/((3671/250/x(22))^k(2)-1) - x(16)*0.01/((969/400/x(32))^k(2)-1)) ;...
cti + k(1)*(x(6)*0.01/((3671/250/x(22))^k(2)-1) - x(3)*0.01/((248/100/x(19))^k(2)-1)) ;...
```

```
    cti + k(1)*(x(7)*0.01/((2235/120/x(23))^k(2)-1) - x(9)*0.01/((2235/300/x(25))^k(2)-1)) ;...
    cti + k(1)*(x(7)*0.01/((2130/120/x(23))^k(2)-1) - x(9)*0.01/((2130/300/x(25))^k(2)-1)) ;...
    cti + k(1)*(x(7)*0.01/((1929/120/x(23))^k(2)-1) - x(9)*0.01/((1929/300/x(25))^k(2)-1)) ;...


    cti + k(1)*(x(8)*0.01/((1570/150/x(24))^k(2)-1) - x(6)*0.01/((1570/250/x(22))^k(2)-1)) ;...
    cti + k(1)*(x(8)*0.01/((1899/150/x(24))^k(2)-1) - x(6)*0.01/((1899/250/x(22))^k(2)-1)) ;...
    cti + k(1)*(x(8)*0.01/((2107/150/x(24))^k(2)-1) - x(6)*0.01/((2107/250/x(22))^k(2)-1)) ;...


    cti + k(1)*(x(9)*0.01/((4795/300/x(25))^k(2)-1) - x(11)*0.01/((138/200/x(27))^k(2)-1));...
    cti + k(1)*(x(9)*0.01/((4790/300/x(25))^k(2)-1) - x(11)*0.01/((150/200/x(27))^k(2)-1));...
    cti + k(1)*(x(9)*0.01/((4073/300/x(25))^k(2)-1) - x(11)*0.01/((677/200/x(27))^k(2)-1));...


    cti + k(1)*(x(10)*0.01/((9965/400/x(26))^k(2)-1) - x(8)*0.01/((580/150/x(24))^k(2)-1));...
    cti + k(1)*(x(10)*0.01/((10028/400/x(26))^k(2)-1) - x(8)*0.01/((803/150/x(24))^k(2)-1));...
    cti + k(1)*(x(10)*0.01/((7135/400/x(26))^k(2)-1) - x(8)*0.01/((1263/150/x(24))^k(2)-1));...


    cti + k(1)*(x(11)*0.01/((2402/200/x(27))^k(2)-1) - x(13)*0.01/((2402/200/x(29))^k(2)-1)) ;...
    cti + k(1)*(x(11)*0.01/((2244/200/x(27))^k(2)-1) - x(13)*0.01/((2244/200/x(29))^k(2)-1)) ;...
    cti + k(1)*(x(11)*0.01/((2717/200/x(27))^k(2)-1) - x(13)*0.01/((2717/200/x(29))^k(2)-1)) ;...


    cti + k(1)*(x(12)*0.01/((4626/300/x(28))^k(2)-1) - x(10)*0.01/((4626/400/x(26))^k(2)-1)) ;...
    cti + k(1)*(x(12)*0.01/((4646/300/x(28))^k(2)-1) - x(10)*0.01/((4646/400/x(26))^k(2)-1)) ;...
    cti + k(1)*(x(12)*0.01/((3935/300/x(28))^k(2)-1) - x(10)*0.01/((3935/400/x(26))^k(2)-1)) ;...

    cti + k(1)*(x(13)*0.01/((3168/200/x(29))^k(2)-1) - x(15)*0.01/((3168/400/x(31))^k(2)-1)) ;...
    cti + k(1)*(x(13)*0.01/((2967/200/x(29))^k(2)-1) - x(15)*0.01/((2967/400/x(31))^k(2)-1)) ;...
    cti + k(1)*(x(13)*0.01/((3293/200/x(29))^k(2)-1) - x(15)*0.01/((3293/400/x(31))^k(2)-1)) ;...


    cti + k(1)*(x(14)*0.01/((2618/160/x(30))^k(2)-1) - x(12)*0.01/((2618/300/x(28))^k(2)-1)) ;...
    cti + k(1)*(x(14)*0.01/((2710/160/x(30))^k(2)-1) - x(12)*0.01/((2710/300/x(28))^k(2)-1)) ;...
    cti + k(1)*(x(14)*0.01/((2440/160/x(30))^k(2)-1) - x(12)*0.01/((2440/300/x(28))^k(2)-1)) ;...


    cti+ k(1)*(x(15)*0.01/((5473/400/x(31))^k(2)-1) - x(5)*0.01/((191/320/x(21))^k(2)-1)) ;...
    cti+ k(1)*(x(15)*0.01/((5473/400/x(31))^k(2)-1) - x(2)*0.01/((49/100/x(18))^k(2)-1)) ;...
    cti+ k(1)*(x(15)*0.01/((4978/400/x(31))^k(2)-1) - x(5)*0.01/((2079/320/x(21))^k(2)-1)) ;...
    cti+ k(1)*(x(15)*0.01/((4978/400/x(31))^k(2)-1) - x(2)*0.01/((532/100/x(18))^k(2)-1)) ;...
    cti+ k(1)*(x(15)*0.01/((5473/400/x(31))^k(2)-1) - x(5)*0.01/((1636/320/x(21))^k(2)-1)) ;...
    cti+ k(1)*(x(15)*0.01/((5473/400/x(31))^k(2)-1) - x(2)*0.01/((419/100/x(18))^k(2)-1)) ;...

    cti+ k(1)*(x(16)*0.01/((6616/400/x(32))^k(2)-1) - x(14)*0.01/((1130/160/x(30))^k(2)-1)) ;...
    %cti + k(1)*(x(16)*0.01/((6616/400/x(32))^k(2)-1) - x(2)*0.01/((-1667/100/x(18))^k(2)-1));...
    cti+ k(1)*(x(16)*0.01/((4417/400/x(32))^k(2)-1) - x(14)*0.01/((1590/160/x(30))^k(2)-1)) ;...
    %cti + k(1)*(x(16)*0.01/((4417/400/x(32))^k(2)-1) - x(2)*0.01/((-1089/100/x(18))^k(2)-1));...
    cti+ k(1)*(x(16)*0.01/((5255/400/x(32))^k(2)-1) - x(14)*0.01/((1086/160/x(30))^k(2)-1)) ;...
    %cti + k(1)*(x(16)*0.01/((5255/400/x(32))^k(2)-1) - x(2)*0.01/((-1302/100/x(18))^k(2)-1));...




%%optime limits minimum 0.05s for near end 3p


% %min far end current for 10,12,13 less than 1s
            (k(1)*x(1)*0.01/((4059/300/x(17))^k(2)-1))-1.0 ;...
            (k(1)*x(2)*0.01/((406/100/x(18))^k(2)-1))-1.0 ;...
            (k(1)*x(3)*0.01/((1166/100/x(19))^k(2)-1))-1.0 ;...
            (k(1)*x(4)*0.01/((3183/300/x(20))^k(2)-1))-1.0 ;...
            (k(1)*x(5)*0.01/((1380/320/x(21))^k(2)-1))-1.0 ;...
            (k(1)*x(6)*0.01/((2972/250/x(22))^k(2)-1))-1.0 ;...
            (k(1)*x(7)*0.01/((1929/120/x(23))^k(2)-1))-1.0 ;...
            (k(1)*x(8)*0.01/((1570/150/x(24))^k(2)-1))-1.0 ;...
            (k(1)*x(9)*0.01/((4073/300/x(25))^k(2)-1))-1.0 ;...
            (k(1)*x(10)*0.01/((7135/400/x(26))^k(2)-1))-1.0 ;...
            (k(1)*x(11)*0.01/((2244/200/x(27))^k(2)-1))-1.0 ;...
            (k(1)*x(12)*0.01/((3935/300/x(28))^k(2)-1))-1.0 ;...
            (k(1)*x(13)*0.01/((2967/200/x(29))^k(2)-1))-1.0 ;...
            (k(1)*x(14)*0.01/((2440/160/x(30))^k(2)-1))-1.0 ;...
            (k(1)*x(15)*0.01/((4978/400/x(31))^k(2)-1))-1.0 ;...
            (k(1)*x(16)*0.01/((4417/400/x(32))^k(2)-1))-1.0 ;...
```

```
% %max current for 10,12,13 greater than 0.05s

            0.05-(k(1)*(x(1)*0.01/((17141/300/x(17))^k(2)-1)));...
            0.05-(k(1)*(x(2)*0.01/((4138/100/x(18))^k(2)-1)));...
            0.05-(k(1)*(x(3)*0.01/((4289/100/x(19))^k(2)-1)));...
            0.05-(k(1)*(x(4)*0.01/((15448/300/x(20))^k(2)-1)));...
            0.05-(k(1)*(x(5)*0.01/((11755/320/x(21))^k(2)-1)));...
            0.05-(k(1)*(x(6)*0.01/((14750/250/x(22))^k(2)-1)));...
            0.05-(k(1)*(x(7)*0.01/((4709/120/x(23))^k(2)-1)));...
            0.05-(k(1)*(x(8)*0.01/((3619/150/x(24))^k(2)-1)));...
            0.05-(k(1)*(x(9)*0.01/((19165/300/x(25))^k(2)-1)));...
            0.05-(k(1)*(x(10)*0.01/((18965/400/x(26))^k(2)-1)));...
            0.05-(k(1)*(x(11)*0.01/((3272/200/x(27))^k(2)-1)));...
            0.05-(k(1)*(x(12)*0.01/((9869/300/x(28))^k(2)-1)));...
            0.05-(k(1)*(x(13)*0.01/((5403/200/x(29))^k(2)-1)));...
            0.05-(k(1)*(x(14)*0.01/((4593/160/x(30))^k(2)-1)));...
            0.05-(k(1)*(x(15)*0.01/((15147/400/x(31))^k(2)-1)));...
            0.05-(k(1)*(x(16)*0.01/((16403/400/x(32))^k(2)-1)))];

%-----------------------------------------------------------------------------


clear;
close all;
clc;



objective_function=@fun;
constraints=@Constraints;
%%Cluster 4 Topology 10,12,13 bounds
LB = [5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 1 1 1.095 1 1 2.022 1 1.79 1 1 2.8425 1 3.3 1 1.815
1.5225];
UB = [110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 9.02 2.7067 7.7733 7.0733
2.875 7.9253 10 6.978 9.051 10 7.48 8.74 9.89 10 8.2967 7.3617];

nvars=32;
Npop=1e5;
Nsr=100;
dmax=1e-5;
max_it=200;
flag=0;

% Run WCMFO
[Xmin,Fmin,av_obj,FF,SUM_Constraints,NFEs,Elapsed_Time]…
=WCMFO(objective_function,constraints,LB,UB,nvars,Npop,Nsr,dmax,max_it,flag);

% plot the results
plotdata(Xmin,Fmin,av_obj,FF,SUM_Constraints,NFEs,Elapsed_Time);
```

APPENDIX F- Modified 14 bus System Optimization Results

Topology 1 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5										
1	14										
2	4										
3	1	0	0	0	0	-	-	-	-	-	-
4	16	17707	7116	4999	2009	0.2314	0.4910	0.2595	0.4474	0.9582	0.5109
4	7	17707	2200	4999	621	0.2314	0.5378	0.3064	0.4474	1.8698	1.4224
5	3	10811	0	5864	0	0.3338	-	-	0.4371	-	-
5	7	10811	2228	5864	873	0.3338	0.5340	0.2002	0.4371	1.1259	0.6888
6	16	15415	7051	3752	1479	0.2926	0.4927	0.2001	0.5472	1.2395	0.6923
6	3	15415	0	3752	0	0.2926	-	-	0.5472	-	-
7	9	4805	4805	2268	2268	0.3711	0.5713	0.2001	0.5286	0.8298	0.3012
8	6	3699	3699	2123	2123	0.3471	0.5519	0.2049	0.5132	0.8337	0.3206
9	11	19591	2655	4891	411	0.3579	0.5748	0.2169	0.5671	2.7443	2.1773
10	8	19378	2085	10219	983	0.2859	0.5213	0.2353	0.4804	1.4874	1.0070
11	13	3442	3442	2749	2749	0.5168	0.7448	0.2280	0.5663	1.1234	0.5571
12	10	10057	10057	4753	4753	0.2819	0.4886	0.2068	0.6645	2.4279	1.7634
13	15	5923	5923	3466	3466	0.4092	0.6484	0.2392	0.7371	316.7247	315.9876
14	12	4699	4699	2764	2764	0.4780	0.6784	0.2004	0.5700	21.6069	21.0369
15	5	19177	5706	6006	1660	0.2010	0.4432	0.2422	0.6319	1.1705	0.5385
15	2	19177	0	6006	0	0.2010	-	-	0.6319	-	-
16	14	16311	2710	7319	965	0.3701	0.5741	0.2041	0.4856	0.9135	0.4279
16	2	16311	0	7319	0	0.3701	-	-	0.4856	-	-

Topology 2 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	21601	5656	5285	1384	0.2449	0.4452	0.2003	0.5375	1.5366	0.9992
1	14	21601	2662	5285	651	0.2449	0.5779	0.3330	0.5375	1.1744	0.6369
2	4	0	0	0	0	-	-	-	-	-	-
3	1										
4	16										
4	7										
5	3	10811	0	5864	0	0.3338	-	-	0.4371	-	-
5	7	10811	2228	5864	873	0.3338	0.5340	0.2002	0.4371	1.1259	0.6888
6	16	15415	7051	3752	1479	0.2926	0.4927	0.2001	0.5472	1.2395	0.6923
6	3	15415	0	3752	0	0.2926	-	-	0.5472	-	-
7	9	4805	4805	2268	2268	0.3711	0.5713	0.2001	0.5286	0.8298	0.3012
8	6	3699	3699	2123	2123	0.3471	0.5519	0.2049	0.5132	0.8337	0.3206
9	11	19591	2655	4891	411	0.3579	0.5748	0.2169	0.5671	2.7443	2.1773
10	8	19378	2085	10219	983	0.2859	0.5213	0.2353	0.4804	1.4874	1.0070
11	13	3442	3442	2749	2749	0.5168	0.7448	0.2280	0.5663	1.1234	0.5571
12	10	10057	10057	4753	4753	0.2819	0.4886	0.2068	0.6645	2.4279	1.7634
13	15	5923	5923	3466	3466	0.4092	0.6484	0.2392	0.7371	316.7247	315.9876
14	12	4699	4699	2764	2764	0.4780	0.6784	0.2004	0.5700	21.6069	21.0369
15	5	19177	5706	6006	1660	0.2010	0.4432	0.2422	0.6319	1.1705	0.5385
15	2	19177	0	6006	0	0.2010	-	-	0.6319	-	-
16	14	16311	2710	7319	965	0.3701	0.5741	0.2041	0.4856	0.9135	0.4279
16	2	16311	0	7319	0	0.3701	-	-	0.4856	-	-

Topology 3 with Cluster 3 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	16286	0	4884	0	0.2754	-	-	0.5274	-	-
1	14	16286	2804	4884	749	0.2754	0.5030	0.2276	0.5274	1.9526	1.4253
2	4	4255	4255	2541	2541	0.5155	0.7233	0.2078	0.6188	1.1801	0.5613
3	1	4816	4816	2793	2793	0.3321	0.5330	0.2009	0.4114	0.9047	0.4933
4	16	10892	0	4311	0	0.4215	-	-	0.7162	-	-
4	7	10892	2369	4311	834	0.4215	0.6220	0.2005	0.7162	1.7006	0.9843
5	3										
5	7										
6	16	11022	0	3465	0	0.2136	-	-	0.6264	-	-
6	3	11022	2717	3465	730	0.2136	0.4164	0.2027	0.6264	0.9721	0.3457
7	9	4854	4854	2416	2416	0.4309	0.6342	0.2033	0.6146	0.9736	0.3590
8	6	3421	3421	2140	2140	0.3912	0.6399	0.2487	0.6258	3.0054	2.3796
9	11	19571	2641	4940	549	0.3706	0.6423	0.2717	0.6286	1.8342	1.2055
10	8	19399	2108	10250	1069	0.3085	0.6381	0.3296	0.4901	5.1059	4.6157
11	13	3354	3354	2729	2729	0.5835	0.7840	0.2005	0.6335	0.8480	0.2144
12	10	10088	10088	4787	4787	0.2957	0.4974	0.2017	0.5834	1.5966	1.0132
13	15	5596	5596	3375	3375	0.6595	0.9057	0.2462	0.7822	3.1231	2.3409
14	12	4734	4734	2887	2887	0.3869	0.5919	0.2050	0.4948	1.6757	1.1809
15	5	15922	0	5670	0	0.3636	-	-	0.8892	-	-
15	2	15922	2482	5670	819	0.3636	0.6245	0.2609	0.8892	1.0913	0.2021
16	14										
16	2										

Topology 4 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	20654	4479	4790	-942	0.2492	0.5053	0.2561	0.5856	-	-
1	14	20654	2792	4790	938	0.2492	0.5680	0.3187	0.5856	0.9284	0.3428
2	4	4192	4192	1255	1255	0.3024	0.5131	0.2106	0.6014	64.4068	63.8054
3	1	4712	4712	1768	1768	0.3926	0.5945	0.2019	0.5330	5.7440	5.2110
4	16	15091	6600	4263	984	0.2466	0.5058	0.2592	0.5060	2.0244	1.5184
4	7	15091	0	4263	0	0.2466	-	-	0.5060	-	-
5	3	10264	1699	4714	-1150	0.3407	0.5407	0.2001	0.4908	-	-
5	7	10264	0	4714	0	0.3407	-	-	0.4908	-	-
6	16										
6	3										
7	9										
8	6	0	0	0	0	-	-	-	-	-	-
9	11	19834	2860	4990	719	0.3568	0.5569	0.2002	0.5624	1.2965	0.7341
10	8	17481	0	9740	0	0.3060	-	-	0.5060	-	-
11	13	3552	3552	2951	2951	0.5105	0.7112	0.2007	0.5497	0.9684	0.4187
12	10	9595	9595	4701	4701	0.2925	0.5146	0.2221	0.6779	2.5768	1.8990
13	15	6004	6004	3574	3574	0.4047	0.6323	0.2277	0.7049	11.0076	10.3027
14	12	4650	4650	2889	2889	0.4795	0.6917	0.2122	0.5611	6.0714	5.5103
15	5	19289	4572	6088	1506	0.2003	0.4994	0.2991	0.6167	1.3418	0.7251
15	2	19289	1170	6088	386	0.2003	0.6376	0.4373	0.6167	10.6690	10.0524
16	14	17572	2839	6810	1464	0.3620	0.5646	0.2026	0.4995	0.7384	0.2389
16	2	17572	1150	6810	-1699	0.3620	0.6471	0.2851	0.4995	-	-

Topology 5 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	20654	4479	4790	-942	0.2492	0.5053	0.2561	0.5856	-	-
1	14	20654	2792	4790	938	0.2492	0.5680	0.3187	0.5856	0.9284	0.3428
2	4	4192	4192	1255	1255	0.3024	0.5131	0.2106	0.6014	64.4068	63.8054
3	1	4712	4712	1768	1768	0.3926	0.5945	0.2019	0.5330	5.7440	5.2110
4	16	15091	6600	4263	984	0.2466	0.5058	0.2592	0.5060	2.0244	1.5184
4	7	15091	0	4263	0	0.2466	-	-	0.5060	-	-
5	3	10264	1699	4714	-1150	0.3407	0.5407	0.2001	0.4908	-	-
5	7	10264	0	4714	0	0.3407	-	-	0.4908	-	-
6	16	16520	6542	3902	1545	0.2860	0.5076	0.2216	0.5344	1.1898	0.6554
6	3	16520	1674	3902	396	0.2860	0.5437	0.2577	0.5344	1.1400	0.6055
7	9	0	0	0	0	-	-	-	-	-	-
8	6										
9	11										
10	8	17481	0	9740	0	0.3060	-	-	0.5060	-	-
11	13	3552	3552	2951	2951	0.5105	0.7112	0.2007	0.5497	0.9684	0.4187
12	10	9595	9595	4701	4701	0.2925	0.5146	0.2221	0.6779	2.5768	1.8990
13	15	6004	6004	3574	3574	0.4047	0.6323	0.2277	0.7049	11.0076	10.3027
14	12	4650	4650	2889	2889	0.4795	0.6917	0.2122	0.5611	6.0714	5.5103
15	5	19289	4572	6088	1506	0.2003	0.4994	0.2991	0.6167	1.3418	0.7251
15	2	19289	1170	6088	386	0.2003	0.6376	0.4373	0.6167	10.6690	10.0524
16	14	17572	2839	6810	1464	0.3620	0.5646	0.2026	0.4995	0.7384	0.2389
16	2	17572	1150	6810	-1699	0.3620	0.6471	0.2851	0.4995	-	-

Topology 6 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	18703	5111	4674	-466	0.2595	0.4695	0.2100	0.5990	-	-
1	14	18703	0	4674	0	0.2595	-	-	0.5990	-	-
2	4	4307	4307	1407	1407	0.2990	0.5017	0.2027	0.5504	5.0807	4.5304
3	1	4599	4599	1622	1622	0.3952	0.6081	0.2130	0.5501	23.3021	22.7520
4	16	16728	5994	4381	494	0.2366	0.5261	0.2895	0.4949	-34.2233	-34.7182
4	7	16728	2299	4381	855	0.2366	0.5246	0.2880	0.4949	1.1540	0.6592
5	3	12369	1542	5343	-1316	0.3172	0.5606	0.2435	0.4585	-	-
5	7	12369	2325	5343	1337	0.3172	0.5214	0.2042	0.4585	0.7497	0.2912
6	16	15866	5970	3832	1372	0.2898	0.5270	0.2372	0.5402	1.3352	0.7950
6	3	15866	1528	3832	351	0.2898	0.5626	0.2728	0.5402	1.2532	0.7130
7	9	4714	4714	2362	2362	0.3740	0.5759	0.2019	0.5168	0.8101	0.2933
8	6	3780	3780	2315	2315	0.3427	0.5447	0.2020	0.4777	0.7725	0.2948
9	11	17273	0	4796	0	0.3705	-	-	0.5717	-	-
10	8										
11	13										
12	10	0	0	0	0	-	-	-	-	-	-
13	15	6155	6155	3721	3721	0.3965	0.6049	0.2083	0.6667	4.8516	4.1850
14	12	0	0	0	0	-	-	-	-	-	-
15	5	20092	5180	6240	1609	0.1956	0.4661	0.2705	0.5907	1.2204	0.6297
15	2	20092	1326	6240	412	0.1956	0.5757	0.3801	0.5907	5.5705	4.9798
16	14	15109	0	6210	0	0.3788	-	-	0.5185	-	-
16	2	15109	1316	6210	-1542	0.3788	0.5791	0.2004	0.5185	-	-

Topology 7 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	18703	5111	4674	-466	0.2595	0.4695	0.2100	0.5990	-	-
1	14	18703	0	4674	0	0.2595	-	-	0.5990	-	-
2	4	4307	4307	1407	1407	0.2990	0.5017	0.2027	0.5504	5.0807	4.5304
3	1	4599	4599	1622	1622	0.3952	0.6081	0.2130	0.5501	23.3021	22.7520
4	16	16728	5994	4381	494	0.2366	0.5261	0.2895	0.4949	-34.2233	-34.7182
4	7	16728	2299	4381	855	0.2366	0.5246	0.2880	0.4949	1.1540	0.6592
5	3	12369	1542	5343	-1316	0.3172	0.5606	0.2435	0.4585	-	-
5	7	12369	2325	5343	1337	0.3172	0.5214	0.2042	0.4585	0.7497	0.2912
6	16	15866	5970	3832	1372	0.2898	0.5270	0.2372	0.5402	1.3352	0.7950
6	3	15866	1528	3832	351	0.2898	0.5626	0.2728	0.5402	1.2532	0.7130
7	9	4714	4714	2362	2362	0.3740	0.5759	0.2019	0.5168	0.8101	0.2933
8	6	3780	3780	2315	2315	0.3427	0.5447	0.2020	0.4777	0.7725	0.2948
9	11	17273	0	4796	0	0.3705	-	-	0.5717	-	-
10	8	19709	2283	10436	1209	0.2829	0.4831	0.2002	0.4699	0.9868	0.5168
11	13	0	0	0	0	-	-	-	-	-	-
12	10										
13	15										
14	12	0	0	0	0	-	-	-	-	-	-
15	5	20092	5180	6240	1609	0.1956	0.4661	0.2705	0.5907	1.2204	0.6297
15	2	20092	1326	6240	412	0.1956	0.5757	0.3801	0.5907	5.5705	4.9798
16	14	15109	0	6210	0	0.3788	-	-	0.5185	-	-
16	2	15109	1316	6210	-1542	0.3788	0.5791	0.2004	0.5185	-	-

Topology 8 with Cluster 2 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	18703	5111	4674	-466	0.2595	0.4695	0.2100	0.5990	-	-
1	14	18703	0	4674	0	0.2595	-	-	0.5990	-	-
2	4	4307	4307	1407	1407	0.2990	0.5017	0.2027	0.5504	5.0807	4.5304
3	1	4599	4599	1622	1622	0.3952	0.6081	0.2130	0.5501	23.3021	22.7520
4	16	16728	5994	4381	494	0.2366	0.5261	0.2895	0.4949	-34.2233	-34.7182
4	7	16728	2299	4381	855	0.2366	0.5246	0.2880	0.4949	1.1540	0.6592
5	3	12369	1542	5343	-1316	0.3172	0.5606	0.2435	0.4585	-	-
5	7	12369	2325	5343	1337	0.3172	0.5214	0.2042	0.4585	0.7497	0.2912
6	16	15866	5970	3832	1372	0.2898	0.5270	0.2372	0.5402	1.3352	0.7950
6	3	15866	1528	3832	351	0.2898	0.5626	0.2728	0.5402	1.2532	0.7130
7	9	4714	4714	2362	2362	0.3740	0.5759	0.2019	0.5168	0.8101	0.2933
8	6	3780	3780	2315	2315	0.3427	0.5447	0.2020	0.4777	0.7725	0.2948
9	11	17273	0	4796	0	0.3705	-	-	0.5717	-	-
10	8	19709	2283	10436	1209	0.2829	0.4831	0.2002	0.4699	0.9868	0.5168
11	13	0	0	0	0	-	-	-	-	-	-
12	10	10272	10272	4930	4930	0.2773	0.4778	0.2005	0.6235	2.0364	1.4129
13	15	0	0	0	0	-	-	-	-	-	-
14	12										
15	5										
15	2	0	0	0	0	-	-	-	-	-	-
16	14	15109	0	6210	0	0.3788	-	-	0.5185	-	-
16	2	15109	1316	6210	-1542	0.3788	0.5791	0.2004	0.5185	-	-

Topology 9 with Cluster 1 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	20906	4941	4826	-660	0.2214	0.4245	0.2032	0.5423	-	-
1	14	20906	2643	4826	806	0.2214	0.5434	0.3220	0.5423	1.0869	0.5446
2	4	4350	4350	1375	1375	0.3076	0.5095	0.2019	0.5162	23.9936	23.4774
3	1	4747	4747	1726	1726	0.3495	0.5512	0.2017	0.4984	66.9691	66.4707
4	16	17001	6397	4425	696	0.2329	0.4640	0.2312	0.5021	2.4187	1.9166
4	7	17001	2171	4425	733	0.2329	0.5130	0.2801	0.5021	2.2162	1.7141
5	3	12348	1648	5195	-1272	0.3074	0.5082	0.2007	0.4159	-	-
5	7	12348	2196	5195	1005	0.3074	0.5088	0.2014	0.4159	1.1321	0.7161
6	16	16308	6357	3794	1276	0.2649	0.4651	0.2002	0.5212	1.1342	0.6131
6	3	16308	1627	3794	327	0.2649	0.5109	0.2461	0.5212	1.5675	1.0464
7	9	4798	4798	2240	2240	0.3263	0.5273	0.2009	0.5017	2.8713	2.3696
8	6	3740	3740	2121	2121	0.3253	0.5261	0.2008	0.4772	0.8379	0.3607
9	11	19594	2657	4884	390	0.2075	0.4081	0.2006	0.5173	2.0660	1.5487
10	8	19375	2081	10215	970	0.2845	0.4848	0.2003	0.4646	1.3105	0.8459
11	13	3455	3455	2752	2752	0.3669	0.5694	0.2025	0.4021	0.9094	0.5072
12	10	10052	10052	4748	4748	0.2716	0.4721	0.2005	0.6252	1.8349	1.2098
13	15	5971	5971	3479	3479	0.2988	0.5033	0.2045	0.5630	2.3226	1.7596
14	12	4694	4694	2744	2744	0.4360	0.6377	0.2017	0.5348	10.3479	9.8131
15	5	19750	5028	6056	1433	0.1820	0.4215	0.2395	0.4931	0.8553	0.3622
15	2	19750	1287	6056	367	0.1820	0.5368	0.3548	0.4931	2.1400	1.6469
16	14	17487	2689	6627	1130	0.3367	0.5394	0.2027	0.4580	0.8477	0.3897
16	2	17487	1272	6627	-1648	0.3367	0.5407	0.2040	0.4580	-	-

Topology 10 with Cluster 4 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	17141	1250	4341	1999	0.3629	1.1306	0.7676	0.7501	0.8369	0.0867
1	14	17141	2535	4341	937	0.3629	0.7777	0.4148	0.7501	2.1139	1.3638
2	4	3132	3132	406	406	0.3514	0.5933	0.2419	1.0151	31.8483	30.8333
3	1	4270	4270	1709	1709	0.5579	0.7597	0.2019	0.8014	2.5659	1.7646
4	16	8659	6476	3183	2045	0.3946	0.5945	0.1999	0.5887	809.1573	808.5687
4	7	8659	2193	3183	1139	0.3946	0.8159	0.4214	0.5887	1.2785	0.6899
5	3	3875	1667	1380	-309	0.6107	0.8109	0.2002	1.0530	-	-
5	7	3875	2211	1380	1684	0.6107	0.8123	0.2016	1.0530	0.9559	-0.0971
6	16	8096	6462	2972	2372	0.4221	0.5957	0.1735	1.0002	4.6435	3.6433
6	3	8096	1654	2972	607	0.4221	0.8139	0.3918	1.0002	1.5527	0.5525
7	9	4709	4709	2235	2235	0.5714	0.7710	0.1997	0.8074	4.7056	3.8981
8	6	2935	2935	1570	1570	0.6526	1.0174	0.3649	0.9382	7.0369	6.0986
9	11	19165	2312	4795	138	0.2955	0.6537	0.3581	0.7556	-0.5232	-1.2788
10	8	18730	1530	9965	580	0.4191	0.9554	0.5362	0.6172	2.9841	2.3669
11	13	3145	3145	2402	2402	0.5215	0.7569	0.2353	0.6338	1.8121	1.1783
12	10	9808	9808	4626	4626	0.4227	0.6246	0.2020	0.7612	1.4249	0.6637
13	15	5401	5401	3168	3168	0.3475	0.5465	0.1990	0.7451	2.0469	1.3018
14	12	4572	4572	2618	2618	0.5633	0.7708	0.2074	0.7620	1.8971	1.1351
15	5	15147	1314	5473	191	0.2241	1.0900	0.8660	0.5367	-3.0415	-3.5782
15	2	15147	336	5473	49	0.2241	1.2245	1.0004	0.5367	-1.1602	-1.6969
16	14	16403	2565	6616	1130	0.3262	0.7719	0.4457	0.5836	1.6006	1.0170
16	2	16403	309	6616	-1667	0.3262	1.3472	1.0210	0.5836	-	-

Topology 11 with Cluster 3 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	20047	4771	4757	-646	0.2542	0.5333	0.2791	0.5380	-	-
1	14	20047	2117	4757	626	0.2542	0.5986	0.3444	0.5380	3.1791	2.6411
2	4	4295	4295	1327	1327	0.5140	0.7182	0.2043	0.8247	5.5301	4.7054
3	1	4679	4679	1667	1667	0.3355	0.5449	0.2094	0.5299	2.6120	2.0821
4	16	16495	6176	4368	681	0.3552	0.5565	0.2013	0.7093	5.4587	4.7494
4	7	16495	1849	4368	591	0.3552	0.7332	0.3781	0.7093	3.9023	3.1930
5	3	11997	1590	5012	-1227	0.3273	0.5442	0.2169	0.5160	-	-
5	7	11997	1868	5012	634	0.3273	0.7279	0.4006	0.5160	3.0890	2.5729
6	16	16046	6132	3733	1131	0.1755	0.5581	0.3826	0.5578	1.8240	1.2662
6	3	16046	1569	3733	290	0.1755	0.5483	0.3728	0.5578	11.6865	11.1287
7	9	4086	4086	1913	1913	0.4654	0.6943	0.2289	0.7157	1.1835	0.4678
8	6	3679	3679	2108	2108	0.3696	0.5700	0.2004	0.6381	3.4081	2.7700
9	11	11849	2672	4151	727	0.4365	0.6391	0.2027	0.6883	1.3817	0.6934
10	8	11381	2081	7390	1270	0.4472	0.6489	0.2018	0.6993	1.8448	1.1455
11	13	3374	3374	2731	2731	0.5822	0.7823	0.2001	0.6334	0.8477	0.2144
12	10	7303	7303	3947	3947	0.3765	0.7102	0.3337	0.7774	3.6843	2.9070
13	15	5856	5856	3398	3398	0.6503	0.8512	0.2008	0.7803	3.0242	2.2439
14	12	3906	3906	2203	2203	0.4229	0.7916	0.3687	0.5830	254.6227	254.0397
15	5	19326	4849	5940	1343	0.3269	0.5275	0.2006	0.8354	3.4768	2.6415
15	2	19326	1241	5940	344	0.3269	0.8538	0.5269	0.8354	2.5580	1.7226
16	14	16729	2150	6394	748	0.3921	0.5924	0.2003	0.5485	1.9583	1.4098
16	2	16729	1227	6394	-1590	0.3921	0.8589	0.4668	0.5485	-	-

Topology 12 with Cluster 4 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	13358	5001	4059	-626	0.4009	0.5526	0.1517	0.7908	-	-
1	14	13358	2642	4059	1106	0.4009	0.7576	0.3567	0.7908	1.6465	0.8557
2	4	4026	4026	1353	1353	0.3247	0.5281	0.2034	0.4826	1.0023	0.5197
3	1	3996	3996	1166	1166	0.5705	0.8009	0.2304	0.9771	127.1157	126.1385
4	16	14816	4257	4096	598	0.3345	0.9383	0.6038	0.5242	-0.5716	-1.0958
4	7	14816	2070	4096	787	0.3345	0.8430	0.5085	0.5242	1.8709	1.3467
5	3	11724	1089	5173	-1286	0.4182	1.0168	0.5986	0.5457	-	-
5	7	11724	2087	5173	984	0.4182	0.8390	0.4208	0.5457	1.4621	0.9164
6	16	13773	4253	3589	791	0.3219	0.9395	0.6176	0.7965	-0.7381	-1.5346
6	3	13773	1089	3589	202	0.3219	1.0168	0.6949	0.7965	63.4407	62.6441
7	9	4705	4705	2130	2130	0.5716	0.7718	0.2002	0.8294	6.9908	6.1614
8	6	3539	3539	1899	1899	0.5977	0.8088	0.2111	0.8284	2.5210	1.6926
9	11	18933	2162	4790	150	0.2971	0.6917	0.3946	0.7564	-0.5518	-1.3083
10	8	18965	1857	10028	803	0.4165	0.8400	0.4235	0.6144	1.7475	1.1332
11	13	2945	2945	2244	2244	0.5451	0.8824	0.3373	0.6701	2.7912	2.1211
12	10	9869	9869	4646	4646	0.4211	0.6217	0.2006	0.7577	1.4145	0.6568
13	15	4918	4918	2967	2967	0.3836	0.6277	0.2440	0.8661	3.0795	2.2134
14	12	4593	4593	2710	2710	0.5621	0.7670	0.2049	0.7458	1.7404	0.9946
15	5	12104	5061	4978	2079	0.2573	0.5501	0.2928	0.6158	0.8190	0.2031
15	2	12104	1295	4978	532	0.2573	0.4921	0.2348	0.6158	0.8150	0.1992
16	14	9715	2672	4417	1590	0.4381	0.7523	0.3142	0.8931	1.1076	0.2145
16	2	9715	1286	4417	-1089	0.4381	0.4937	0.0556	0.8931	-	-

Topology 13 with Cluster 4 Settings

R_{pri}	R_{sec}	p/b 3ph near max		p/b 3ph far min		tmax pr	tmax bk	CTI max	tmin pr	tmin bk	CTI min
1	5	15752	4900	4358	-488	0.3750	0.5568	0.1818	0.7479	-	-
1	14	15752	2370	4358	850	0.3750	0.8128	0.4378	0.7479	2.5358	1.7879
2	4	4138	4138	1339	1339	0.3220	0.5219	0.1998	0.4848	1.0108	0.5260
3	1	4289	4289	1379	1379	0.5570	0.7571	0.2001	0.8915	5.7117	4.8202
4	16	15448	5073	4210	489	0.3306	0.7560	0.4255	0.5180	-0.4922	-1.0102
4	7	15448	1871	4210	661	0.3306	0.8948	0.5643	0.5180	2.3909	1.8729
5	3	11755	1302	5096	-1260	0.4179	0.9191	0.5012	0.5487	-	-
5	7	11755	1888	5096	785	0.4179	0.8899	0.4720	0.5487	1.8769	1.3281
6	16	14750	5053	3671	969	0.3123	0.7593	0.4470	0.7775	-0.9370	-1.7145
6	3	14750	1293	3671	248	0.3123	0.9226	0.6102	0.7775	7.5833	6.8057
7	9	4011	4011	1929	1929	0.6100	0.9415	0.3315	0.8785	6321.5251	6320.6465
8	6	3619	3619	2107	2107	0.5917	0.7894	0.1977	0.7785	1.8651	1.0866
9	11	11184	2661	4073	677	0.3882	0.5860	0.1978	0.9220	153.1618	152.2398
10	8	10703	2082	7135	1263	0.5861	0.7839	0.1979	0.8206	1.1051	0.2845
11	13	3272	3272	2717	2717	0.5083	0.6971	0.1888	0.5771	1.1073	0.5302
12	10	7055	7055	3935	3935	0.5256	0.8298	0.3042	0.9180	1.9607	1.0426
13	15	5403	5403	3293	3293	0.3474	0.5462	0.1988	0.6883	1.7084	1.0201
14	12	3898	3898	2440	2440	0.6089	0.9292	0.3203	0.7972	2.3231	1.5259
15	5	14751	4964	5473	1636	0.2275	0.5541	0.3266	0.5367	0.9415	0.4048
15	2	14751	1271	5473	419	0.2275	0.4963	0.2687	0.5367	0.9869	0.4502
16	14	12231	2400	5255	1086	0.3808	0.8060	0.4252	0.7276	1.6876	0.9601
16	2	12231	1260	5255	-1302	0.3808	0.4982	0.1174	0.7276	-	-