東海大学大学院平成２７年度博士論文

DISTRIBUTION SYSTEM RESTORATION PROBLEM WITH COMBINATORIAL OPTIMIZATION METHOD

（組合せ最適化手法を用いた配電系統事故復旧問題に関する研究）

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Nomenclatures

b_{ik} current capacity of k^{th} feeder i [A]

b_t current capacity of substation t [A]

f_0 fitness

I current [A]

I_{DG} load of DG [A]

I_{ij} load of the section j of feeder i [A]

I_j total sum of the current that flow out and pass through the section [A]

inn_m outage load of each section [A]

I_p current at the point P [A]

I_s current that pass through the section [A]

I_t current that flow out from the section [A]

J_1 objective function

L length of the whole section [m]

$loss_n$ distribution losses of each section [W]

P_{DG} size of DG [W]

r length of a section [m]

V voltage drop [V]

V_{il} voltage drop limits of last node l of feeder i [V]

W power [W]

w_1 weighting factor

X length from initial to point P [m]

x_{ij} function of switch opened and closed condition

z_{il} impedance of section l of feeder i [R]

Chapter 1

INTRODUCTION

1.1. Background

Electrical power is a vital resource for humankind in practicing and completing daily life. Blackout of this crucial source, specifically by the failure of electrical equipment or natural disasters such as flash floods, hurricanes, and earthquakes, can have catastrophic results [1-1], [1-2]. These failures cause many problems in administration, industrial and commercial production, public health, and citizens' households [1-3]. Therefore, electrical power companies have acted to enhance distribution systems in efficiency, organization, competence, and recovery times, in order to satisfy users and ensure development in the country [1-4]–[1-7].

Generally, power systems consist of three main sections for generation, transmission, transmission, and distribution, as illustrated in Figure 1-1. Distribution systems typically occupy the largest physical regions among the components of power systems [1-8]. Therefore, they are highly susceptible to environmental conditions, including bad weather, trees, and animals, as well as human errors and equipment failures, which are responsible for most outage phenomena.

Source: http://www.utilityproducts.com/content/dam/up/print-articles/volume-18/issue-6/HULL.jpg

Figure 1-2 shows an example of an interrupted distribution line caused by a fallen tree, while Figure 1-3 depicts an example of a car crashing into an electric pole used to support distribution lines.

A distribution system is typically serviced by several substations to which one or more primary feeders are radially connected. Each feeder is divided into multiple load sections with sectionalizing switches and is connected to other feeders via several open cut switches. Figure 1-4 illustrates the switch located on an electric pole. The main purpose of sectionalizing switches is to isolate or restore loads during a fault or maintenance. For example, when a fault occurs on a bus, all the load sections surrounded by cut switches, including the fault point, can be isolated from the system [1-9].

As demand for electricity has increased, distribution automation (DA) has gained importance. DA offers solutions to voltage and reactive power, network reconfiguration, state estimation, and service restoration, which is the main issue addressed in this work [1-10]. In recent years, progress in computers and communications technology has occurred rapidly. This situation enables the automation of several functions in distribution systems. Such automation can make delivery of electricity more efficient, enhance reliability, and lead to more effective utilization and extended lifetimes for the existing electricity distribution infrastructure. Moreover, the overall quality of service to customers can be increased, which can result in greater customer satisfaction. In addition to these operating benefits, DA can be realized by using new design concepts [1-11].

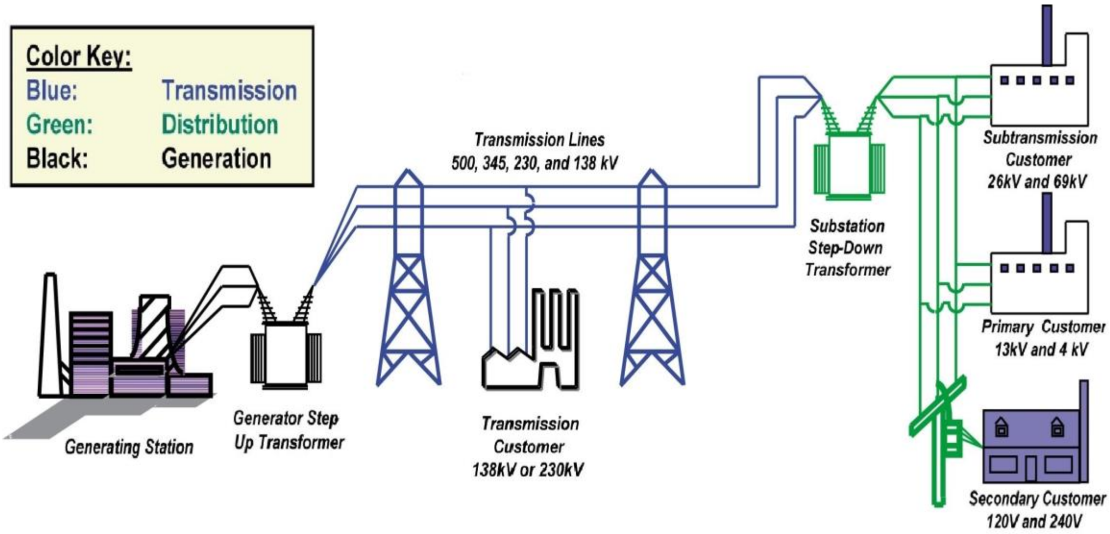

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Figure 1-1 Basic structure of power electric system

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Figure 1-2 Distribution line interrupted by fallen tree

Source: http://oakridgetoday.com/wp-content/uploads/2013/03/lafayette-drive-utility-pole-crash.jpg

Figure 1-3 Electric pole car crash

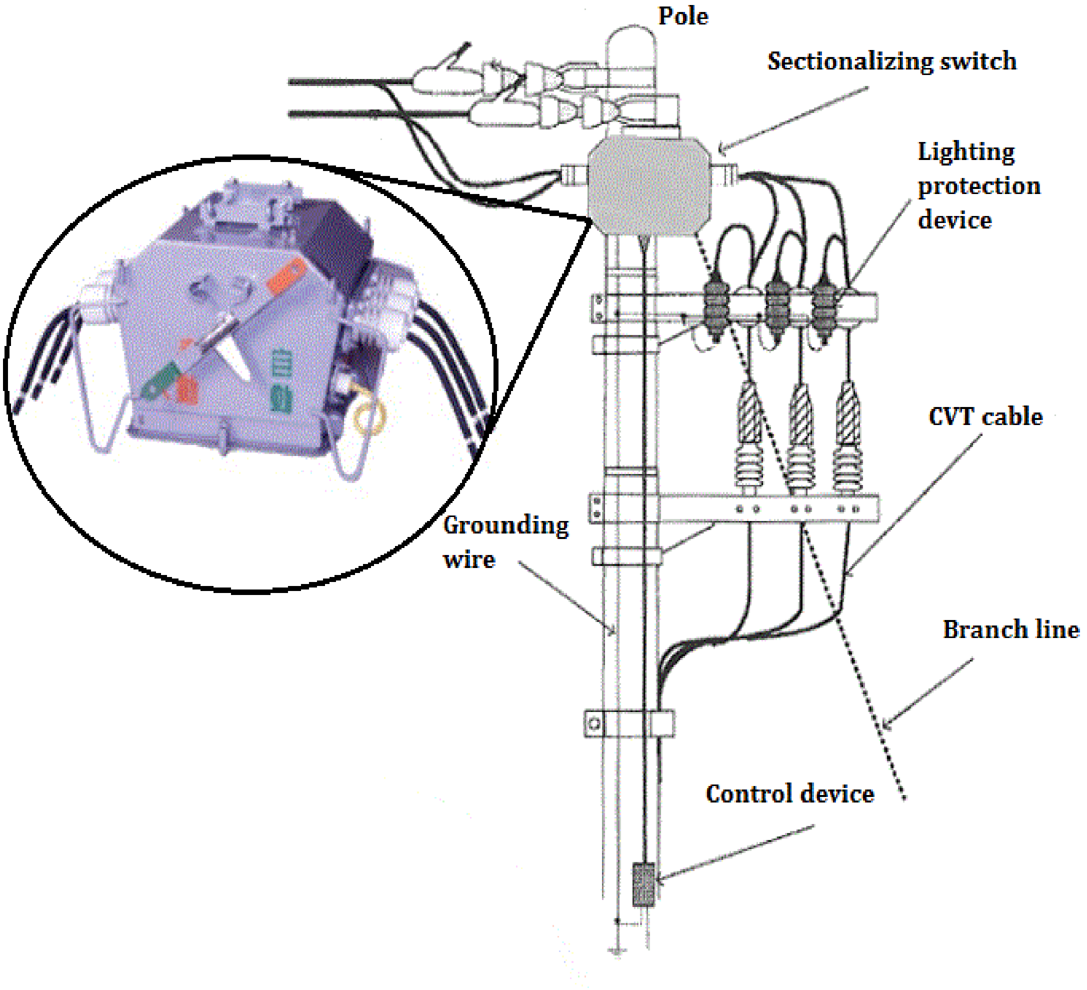

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Figure 1-4　Schematic of sectionalizing switch on electric pole

1.2. Problem Statement

The general distribution restoration problem is broadly defined, since it may involve the restoration of loads from the primary feeder of the distribution feeder, service restoration by system reconfigurations, or alternative distribution techniques. However, the reconfiguration problem is very complicated and time-consuming, since it is a combinatorial optimization problem [1-12]–[1-14]. For instance, an urban distribution system is usually large in scale with numerous sectionalizing switches to be operated. In a simple calculation, a system with N switches has 2^N candidate solution combinations to choose from. As shown in Figure 1-5, a system with 10 switches has 1024 solutions; one with 50 switches has 1.12×10^{15} possible solutions. For reconfiguration problems, it is necessary to develop the best possible algorithm to arrive at a solution.

Service restoration is also a multi-objective and multi-constrained problem. It is generally treated as an optimization problem aiming to minimize the area of an outage by wheeling power from other operational feeders. From an economic point of view, distribution loss after the completion of service restoration, as well as the number of switching operations, should be minimized [1-15]. For this purpose, conventional methods require weighting factors for the objective function; these factors are very complicated and difficult to optimize [1-16]. Moreover, the issue of service restoration involves many restrictions and conditions that require the judgment of operators, rendering the issue even more complex. For the safety and security of power system components, it is important for bus voltages and line currents to remain below the operational limits specified [1-17]. All these conditions must be considered simultaneously while service restoration is underway.

In order to accommodate the demand for electricity, one necessary action is the extension of the power system the increase of the load section. However, in restructuring the electric power industry, there will be a time when bulk power systems are operated at capacities approaching their design limits. This will make power systems more vulnerable to potential blackouts, and present new challenges for the prompt and effective restoration of power. With the increasing number of switches in a system, the number of possible solutions for system reconfiguration is also increased. This problem becomes even more complex when the consideration of multiple objectives and condition constraints is included [1-18]–[1-20].

The substation fault, or bank fault, is one of several possible cases during an outage. When this situation occurs, the substation itself is disconnected from the system, affecting large areas. The situation worsens when a system requiring two substations to supply power only has one substation available to cover the whole system. In a simple calculation, it is impossible to restore load to every section because of the limited power source [1-21], as illustrated in Figure 1-6. In the case of a line fault, as shown in Figure 1-7, all substations can still be operated, so the source load should be sufficient to cover the outage area [1-22].

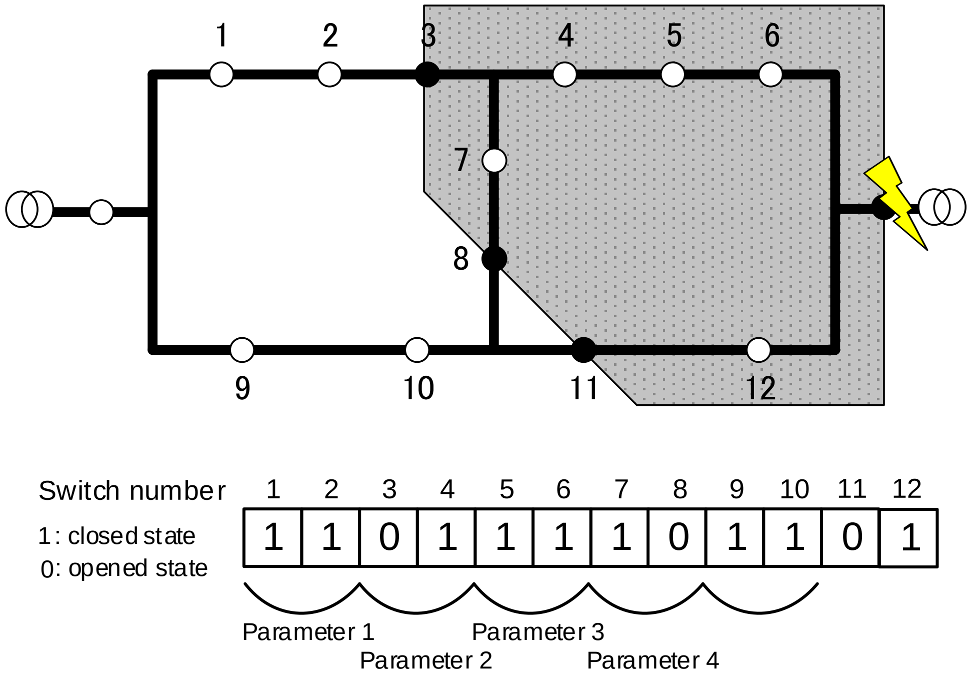
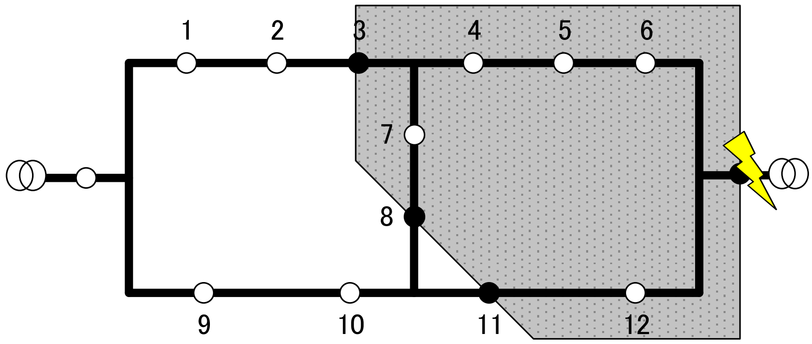
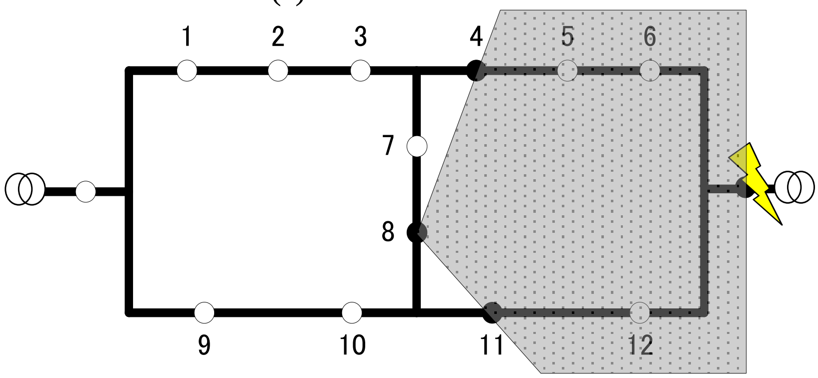


Figure 1-5 Example of distribution system and an individual distribution solution

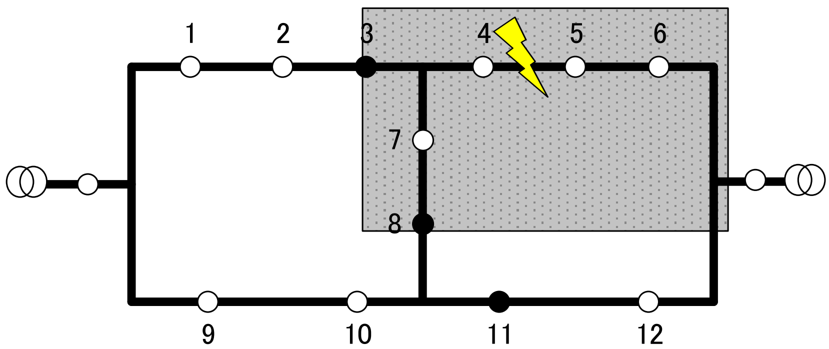


(a) Before restoration

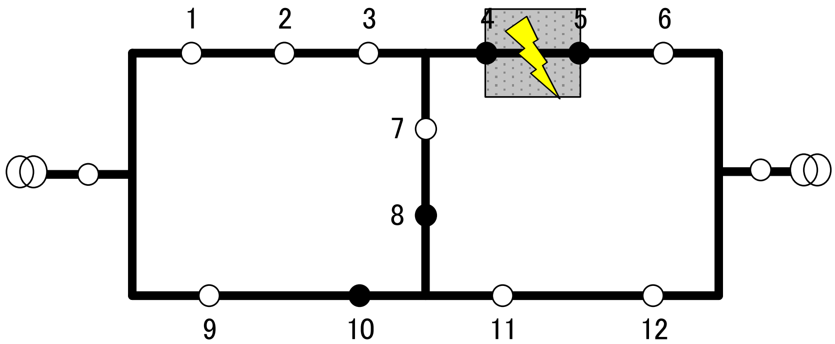


(b) After restoration

Figure 1-6 Substation fault study case



(a) Before restoration



(b) After restoration

Figure 1-7 Substation line fault study case

1.3. Literature Review

In recent years, many studies have been performed on optimizing the reliability of distribution system restoration, also known as service restoration. These studies can be divided into two scopes: distribution restoration models and distribution restoration techniques. The objective of these studies is to consider as many situations as possible that could occur in a distribution system both during and after restoration. Studies on distribution restoration models include cold load pickup, transformer thermal behavior, distributed generators, and the optimal energization order [1-23]–[1-34].

On the other hand, the purpose of studies on distribution restoration techniques is to find the best solution for restoration, even those involving trade-off problems, so the emphasis in any given technique has been a matter of choice [1-35]–[1-51]. These studies involve combinations of several heuristic methods [1-35]–[1-42], analytical [1-43]–[1-48], combinatorial, and knowledge-based systems [1-49]–[1-51]. In heuristic techniques, the most popular and optimal methods are fuzzy [1-52]–[1-55] and genetic algorithms (GA) [1-56]–[1-65]. Improved versions of GA are also presented in which service restoration can be optimized [1-66], [1-67].

The most important part of this study is to integrate distributed generation (DG) and apply multi-objective methods in the restoration of service. In the first stage of this study, the characteristics and benefits of DG systems and multi-objective methods are reviewed.

1.3.1. Distributed generator (DG) in distribution system review

In previous studies on power sources with low emissions of carbon dioxide (CO_2), environmental friendliness, and economic benefits, many reports have been made on the implementation of DG in distribution systems for several purposes and methods [1-68]–[1-70]. Carmen and Falcao (2006) proposed DG to optimize system reliability, reduce power losses, and improve voltage profiles [1-69].Y. Alinejad-Beromi et al. (2007) also proposed DG for the same objectives, but used GA as an analysis method to optimize the location of DG installation [1-70].

In 2012, Cuong P. Nguyen et al. suggested DG for a different approach as an energy storage support for smart grid systems [1-71]. Other reports focused on the reconfiguration of distribution systems with DG in different application approaches [1-72]–[1-74]. Olamaei et al. (2008) applied particle swarm optimization (PSO), Khodr et al. (2009) used the Benders' decomposition approach, and Wu et al. proposed a reconfiguration methodology based on the Ant Colony Algorithm (ACA).

Despite the positive impacts of installing DG in power systems, other studies have reported negative side effects and suggested solutions regarding these issues, especially when system faults have occurred [1-75], [1-76]. In 2006, H. Takano et al. reported on a service restoration method considering DGs simultaneously disconnected from the system [1-77]. Five years later, a new islanding method for DG and their application in service restoration was proposed by XuePin et al. [1-78]. Hadi et al. (2012) invented a novel neural network and backtracking-based protection coordination scheme for distribution systems to prevent fault current level changes by DG [1-79].

However, all studies addressed conditions in which DGs were present from the beginning of the system, as either main or cover power sources. There are no reports on the use of DG only for service restoration combined with switch reconfiguration. Based on the studies that have been conducted, DG is the most suitable method to maintain the continuity of electricity when power breakdowns occur.

1.3.2. Multi-objective optimization of restoration service review

Multi-objective formulations are realistic models for many complex engineering optimization problems, including service restoration problems and even distribution optimization [1-80]–[1-82]. As these situations are not limited to the goal of restoring power to the fault area, other condition constraints must be considered to ensure the reliability of the systems [83]. Regarding this matter, Augliaro et al. (2000) began to study multi-objective service restorations using an evolutionary approach and fuzzy sets [1-84]. A fuzzy cause-effect (FCE) network was proposed by Huang and Chou Ming three years later [1-85].

Garcia et al. designed a new multi-objective local search-based heuristic in 2008. The purpose was to minimize the number of consumers affected by the fault, while simultaneously respecting the operational conditions of radial network configuration, equipment, and voltage drop limits [1-86]. Three years later, a multi-objective service restoration using a fuzzy decision algorithm and node-depth encoding (NDE) was developed by Kaewmanee et al. [1-87]. More recently, Stepien et al. (2014) applied an evolutionary algorithm with memory at the population level to optimize service restoration.

GA-based multi-objective approaches have been used in service restoration. Kumar et al. (2008) applied the fast and elitist multi-objective GA, non-dominated genetic algorithm-II (NSGA-II) for restoration optimization with the constraint of considering priority customers [1-88], [1-89]. Five years later, a hybrid version of that method was developed by Danilo et al. (2014). It combined NDE with NSGA-II [1-90]. However, the case study used in all studies only addressed the line-fault situation; fortunately, much room remains to improve and enhance the method.

1.4. Research Objective

The objective of this study is to optimize service restoration by minimizing the impact of an outage caused by a substation fault in the distribution system. A novel combinatorial method integrating distributed generators (DG) and applying the non-dominated genetic algorithm (NSGA-II) was proposed to find the minimal outage area and distribution loss after load restoration. Both small-scale and large-scale model systems with substation faults were tested to prove the reliability and efficiency of the proposed method. Finally, the restoration of service was optimized.

1.5. Thesis Organization

This thesis is organized into five chapters. A brief outline is as follows:

Chapter 1 In this chapter, brief explanations on power service restoration are presented. In addition, the background of the study, problem statement, research objectives, previous works, and organization of the thesis are described.

Chapter 2 In this chapter, the basic idea of the application of GA in service restoration is introduced. First, the theory of power flow analysis is explained. Then, the problem formulation of service restoration is described. Next, a brief explanation of GA and how it is implemented in this study is elaborated. The formulation of the problem, including its objective function and condition constraints, is given. Lastly, a numerical analysis and results of recent work on two model systems of different scales are shown.

Chapter 3 This chapter discusses the simulation model of service restoration by using environmentally friendly and high-efficiency DG. In this simulation, DG is assumed to be installed in each fault section after network reconfiguration by GA. Then, the size of DG is increased gradually until the outage is fully restored. This method is tested in both small- and large-scale model systems. The assumptions for simulation conditions, calculation settings, and amount of DGs are also explained.

Chapter 4 This chapter proposes the multi-objective optimization of service restoration. First, based on the theory of non-dominated algorithm-II (NSGA-II), a novel algorithm for service restoration optimization during substation fault is created. Then, a numerical analysis of restoration optimization by using NSGA-II is performed to find the minimum outage area and distribution losses. The algorithm is also tested in both a small-scale model and a large-scale system. The assumptions for conditions during the simulation are also given.

Chapter 5 In the last chapter, the overall conclusions of the performed study are discussed. Recommendations for further study are also presented.

Chapter 2

APPLICATION OF GENETIC ALGORITHM IN SERVICE RESTORATION

2.1. Introduction

In this part, the numerical analysis of application recent improved genetic algorithm in restoration service is presented. First, the rough idea of service restoration is explained. Next, the theory of power flow calculation is describe. Mainly, the theory will be focused on current flow during load restoration. Then, how genetic algorithm is implement in restoration service will be defined. Lastly, the numerical analysis of previous work is presented.

2.2. Service Restoration

Generally, distribution system are getting power supply from several substations. It is configured as a loop for a better control, stability and reliability for the customers. To supply the power in each area, system are operated as open-loop radial distribution lines with some of sectionalizing switches open. However, the sections in the radial distribution lines are separated by the sectionalizing switches or protection equipment.

Figure 2-1 shows the radial model of distribution which have simplified for explanation of service restoration. The white and black circles represent ON and OFF states of sectionalizing switches respectively. All the sections are supplied by the two substations or power bank Tr.1 and Tr.2. They are protected by the safety switch which represent with a small white circle.

For instance, when one of the substation which Tr.1 is assumed to be fault and lead to some part of the system became outage as shown at Figure 2-2. During restoration service is conducted as shown in Figure 2-3, switches number 2 and 7 are operated to allow the health substation Tr.2 supply the power to the outage area. Then, the outage area are minimized after service restoration when intact sections are cut off by operating.

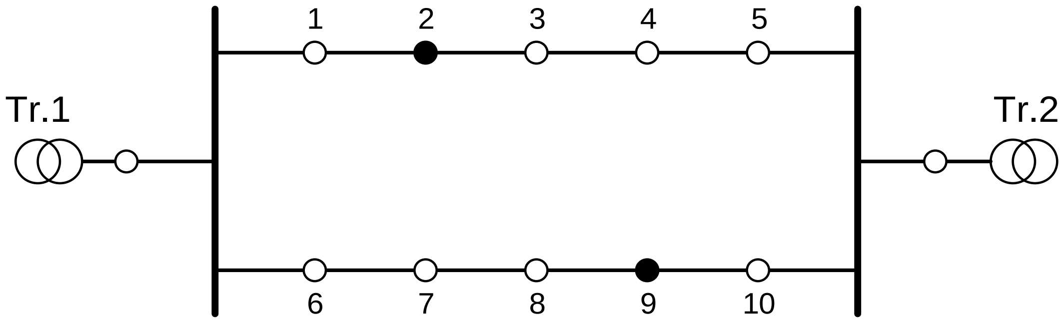


Figure 2-1 An example radial model distribution system

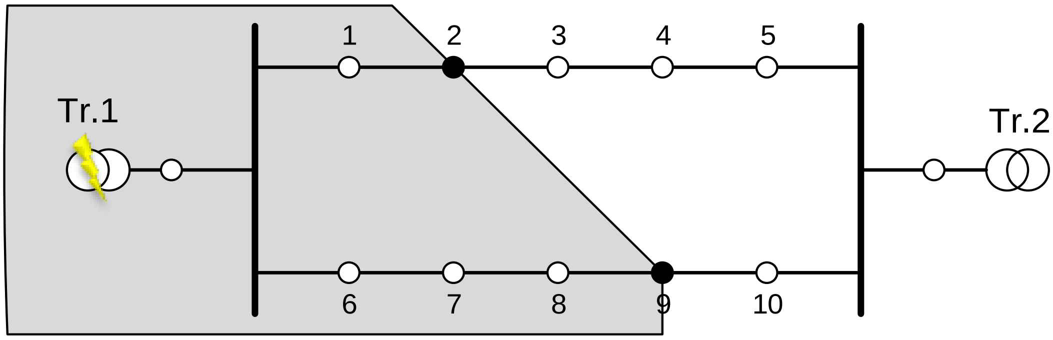


Figure 2-2 Tr.1 is assumed to be fault

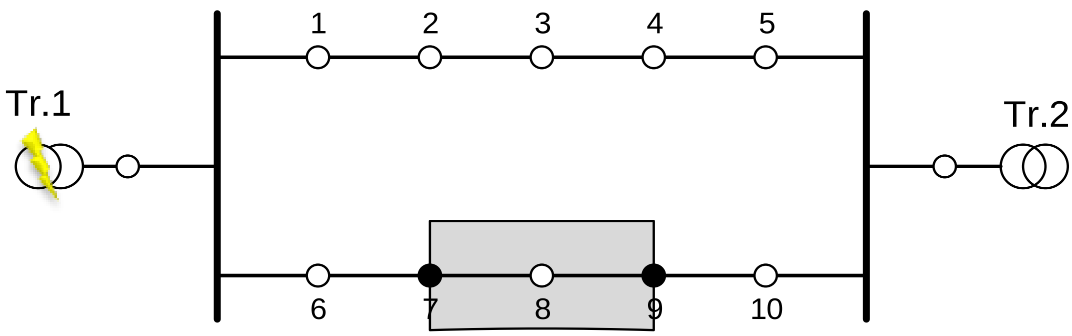


Figure 2-3 System after restoration

2.3. Theory

2.3.1. Power flow calculation

Power flow analysis is the most fundamental study to be performed in a power system both during the operation and future expand planning. Moreover, it is an important tool involving numerical analysis applied to a power system. For simplify the each circuit and notation elements analysis in the power system, we usually use simplified method such as a one-line diagram and per unit system. On the other hand, we have to determine the various value form of alternating current (AC) power (apparent, real and reactive power) and magnitude and phase angle of voltage at each bus. This study is concerned with the normal steady state operation of power system and involves the determination of bus voltages and power flows for a power system configuration and loading condition. The results of power flow analysis can get some concept:

- Online monitoring on the present status of the power system
- Determine the best operation of existing power system
- Protection and compensation equipment on the power system
- Power system planning for future expansion to meet increasing demand

In power system operation, the first to be undertaken is calculation for each demand point hereinafter for supplying active and reactive power required by the prescribed voltage as follows:-

- Determine the output and node voltage for each power plant
- Operation method of voltage adjuster equipment of each substation
- Either the line current flowing in the transmission line is within the proper value

Then, the strengthening of the interconnection between the change and other system power demand, whether the expansion of power plants and transmission lines gives effect to power flow through the node voltage value and the transmission line of each power plant.

2.3.2. Load distribution equality

In distribution system, load is treated as centralized load and equality distribution load. As described in the previous section, the system that used power flow calculation is affiliated as centralized load because it is treated as load that flow out from respective node. In other words, the substation in transmission system and the transformer pole in distribution system are considered as a direct load and present at both ends of the section. Meanwhile, in this study, the same degree of load is distributed equally for one section. Therefore, the location where the power is taken as the load which not exists in both ends of the section. It is the section that consists of some ends beside the load point and the load is distributed equally.

As for example, the section construction can be considered as sectionalizing switch. In distribution system, as the correspondence for such as power outage, radial system consists the open state of sectionalizing switch that installed in certain section of the loop-type network. Then, the sectionalizing switch in distribution system exists numbered but less than the load of pole transformer. So that, it is possible to treat more than one load in 1 section. Therefore it's treated as an equal distribution load.

Figure 2-4 shows the image of equal distribution load that happen in current flow through the sections. Vertical axis is represent the current, while horizontal axis represent the section length. In other words, if the resistant of 1 km distribution line is r Ω/km, the length of horizontal axis is represented as the distribution line resistant. Then, I_t is the load current that taken out from the section, while I_s is the current that pass through the section and I_j is the current that flow into the section. Additionally, as shown in Figure 2-4 the current distribution in through the section become 0 at the end of the line because it has gradually taken out and continuously distributed from upper side of the system toward end point. Thus, if L is the distance of the whole section, the current I_p of the initial point P which have range X from starting point of the section defined as bellow [2-1]–[2-3]:

$$I_p = I_s + \left(1 - \frac{X}{L}\right) I_t \tag{2-1}$$

2.3.3. Distribution loss

Distribution loss *dw* occurred in a section *dX* is calculated as follows:

$$dw = I_p^{\,2} \cdot r \cdot dX \tag{2-2}$$

Then, (2-1) is substituted into (2-2) and integrated with *dX*: *0 ~ L*, the distribution losses, *W* of the whole section as follows:

$$W = \left(I_s^2 + I_s \cdot I_t + \frac{1}{3} I_t^2 \right) \cdot r \cdot L \tag{2-3}$$

From the (2-3), $r \cdot L$ is represented the resistance of the whole section.

2.3.4. Voltage drop

The voltage drop of a section is defined as *dv* and the equation as follows:

$$dv = I_p \cdot r \cdot dX \tag{2-4}$$

Then, when (2-4) is integrated the voltage drop of the whole sections can be defined as follow:

$$V = \left(I_s + \frac{1}{2} I_2 \right) \cdot r \cdot L \tag{2-5}$$

2.3.5. Transformer current

Transformer current is the current of load that supplied by a transformer. The total of I_j of the feeder connected to a transformer purchases I_j of the system peak is the total of the current that transformer supply to a load. For example, as shown at transformer Tr2 on Figure 2-12, the current Tr2 is supplied to a load is the total I_j of section (53) and (54).

2.3.6. Line current

The line current is the maximum value of current that flow into each section. In other words, the total current I_j is sum of the current I_s flow through into the section and the current I_t that taken out from the section.

$$I_j = I_s + I_t \tag{2-6}$$

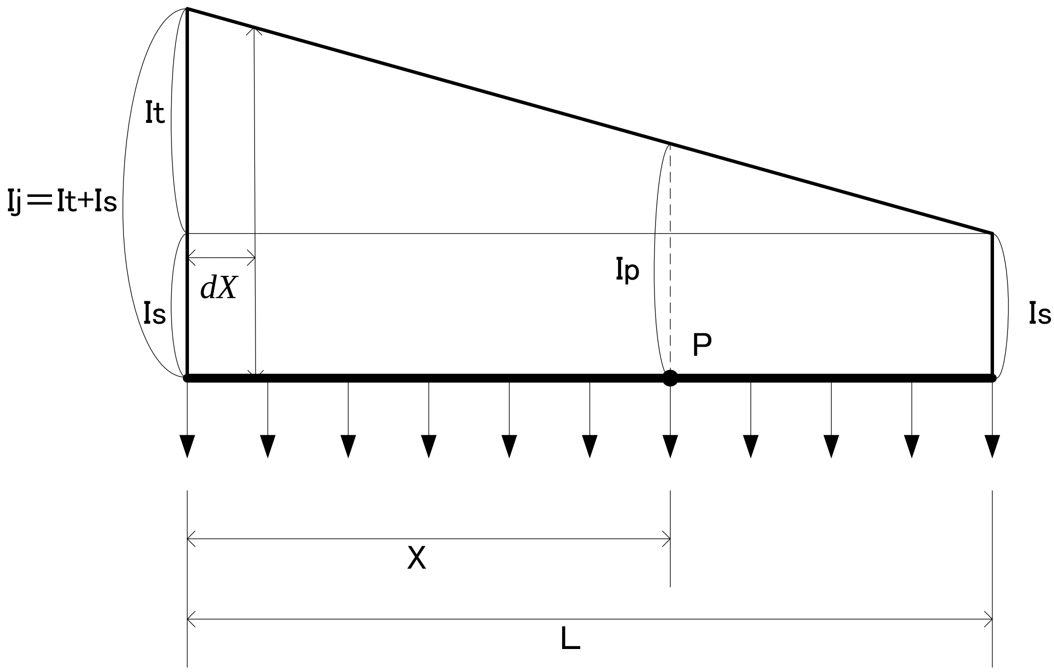


Figure 2-4 Equal distribution load

2.4. Problem Formulation

2.4.1. Objective Function

During service restoration, the number of outage area is the main thing for the operator to consider. The distribution loss is also the necessary economic status for the supplier. Therefore, the objective function is defined as in the purpose of minimizing outage loads, power losses and number of active switches. On the other hand, fitness function must not only correlate closely with operation's goal, but also it has to find out and justify the best result in the specific section that we should consider to apply the service restoration. According to operators design but comes up with the final result by computer simulation, the fitness function will either coverage on an appropriate solution, or it will be as a catalyst to simplify the service restoration section in the network.

$$J_i = w_1 \sum_{m=1}^{L} inn_m + w_2 \sum_{n=1}^{L} loss_n \quad (2\text{-}7)$$

$$f_i = \frac{1}{J_1} \quad (2\text{-}8)$$

Where

- W_1, W_2: weighting factors
- inn_m: outage loads in section *m*
- $Loss_n$: the electrical distribution loss in section *n*
- *L*: the number of load sections
- *sw*: the number of switches
- f_i: the fitness function
- J_i: objective function
- *i*: the number of an individual generated by GA

Weighting factors are established values indicating the relative importance or impact of each item or value in a group as compared to the other items or value in the group. The process of weighting factor involves emphasizing some aspects of a phenomenon or of a set of data which are giving them more weight in the final effect or result. Thus, the purpose of assigning or finding weighting factors is straightforward which it helps or simplifies us establishes work priorities or some equivalent result as we prefer. In the appropriate assessment on the effective result or performance appraisal, they are part of the calculation and some preferable value used to determine an accurate overall performance rating and result.

On the other hand, the appropriate use of priority weighting factors for relevant kind of data input is an important data relation between the preferable output or result and input data to reach the priority or balancing result on the work priorities for the whole work. The weighting factors are probably based on some different parameters such as the amount of time spent on a particular accountability and some appropriate cases, accountability of critical process, the importance of work and result, the impact and scope of the expected outputs, affected of accountability and work and some consequences affected if the work does not happen. In this study, the weighting factor of $W_1$and W_2 are 1 and 0.000333 respectively.

2.4.2. Condition Constrains

During the service restoration, the power distribution network need to reconfigure some sectionalizing switches and re-check the availability of the section capacity in order to allow the flowing of electrical power in the network. As we know, the flowing of electrical power always changes every step while service restoration is being applied in the network. That’s why; some condition constraints have to be satisfied in the network such as:

I. **Radial Constraint**: power distribution system has to keep as a radial shape from the substation or power bank for supplying to the customers.

II. **Feeder Loading Limits**: total of the current load is not necessary to exceed the current capacity or which substation it is supplied.

$$\sum_{j \in J_{ik}} I_{ij} \cdot x_{ij} \leq b_{ik} \tag{2-9}$$

III. **Current Flow Capacity Limits:** current flow amount is not necessary to exceed the line current capacity of which section it is flowed.

$$\sum_{j \in J_t} I_{ij} \cdot x_{ij} \leq b_t \tag{2-10}$$

IV. **Voltage Drop Limits:** voltage drop from initial to end point must be within the permissible amount.

$$\sum_{l \in T_l} \left(\sum_{q \in J_{il}} I_{iq} \cdot x_{ij} \right) \cdot z_{il} \leq V_{il} \tag{2-11}$$

V. **Health Section Constraint:** during service restoration, health section is no necessary to become an outage area.

Where

- I_{ij}: the load of the section *j* of feeder *i*
- x_{ij}: the function of switch opened and closed condition
- b_{ik}: the current capacity of k^{th} feeder *i*
- b_t: the current capacity of substation *t*
- z_{il}: the impedance of section *l* of feeder *i*
- V_{il}: the voltage drop limits of last node *l* of feeder *i*

All condition constraints are necessary to keep in the permissible value during the service restoration in the power distribution network. Moreover, the qualified and experienced operator could be considered as the catalyst of service restoration. Also, the time management is a factor to get the better result in service restoration. In addition, the actively accuracy protection equipment and sectionalizing switches are the important parameter in the power distribution network when the designer decides to use.

2.5. Genetic Algorithm

Genetic Algorithm (GA) are adaptive heuristic search algorithm based on the evolution ideas of natural selection and genetics [2-4]–[2-7]. As such they represent an intelligent exploitation of a random search used to solve optimization problems. Although randomized, GAs are by no means random, instead they exploit historical information to direct the search into the region of better performance within the search space. The basic techniques of the GAs are designed to simulate processes in natural systems necessary for evolution and search. GA simulate the survival of the fittest among individuals over consecutive generation for solving a problem. Each generation consists of a population of character string that is analogous to the chromosome. Each individual represents a point in a search space and a possible solution.

The individuals in the population are then made to go through a process of evolution. Then, Genetic Algorithms are based on an analogy with the genetic structure and behavior of chromosomes within a population of individuals. A population of individual is maintained within search space for a GA, each representing a possible solution to a given problem. Each individual is coded as a finite length vector of components or variables representing as the binary {0, 1}. To continue the genetic analogy these individuals are linked to chromosomes and the variables are analogous to genes. So, a chromosome is sought. The Genetic Algorithm aims to use selective breeding of the solutions to produce the new offspring better than the parents by combining or sorting information from the chromosomes. Also, the Genetic Algorithm maintains a population of chromosomes with associated fitness values. On the basic of their fitness, parents are selected to mate producing offspring via a reproductive plan. Consequently highly fit chromosomes are also given more opportunities to reproduce, so that the offspring inherit characteristics from each parent. On the other hand, new generations of the chromosomes are produced containing more good genes than a typical solution in a previous generation on average.

In addition, GA are also applied in many fields in order to solve and optimize the problem [2-8]–[2-11]. Those applications such as making parameter and system identification, control methodologies, robotics, pattern recognition, speech recognition, engineering designs, planning and scheduling and classifier system. The sections of power distribution network are separated by the protection equipment or sectionalizing switch. Thus, those sectionalizing switches play an important role to protect the electrical equipment and isolate some sections during the network has the problem. That's why, each sectionalizing switches in the power distribution network are determined as "1" when it is in closed state and "0" when it is in opened state. The mechanism and procedure of GA is shown Figure 2-5 and the explanations are as follows [2-1].

2.5.1. Design of Individual

Figure 2-6 shows the gene strings are expressed as an individual. The gene length use as a parameter is adjusted to the state of the sectionalizing switches for instance N switch. Then, the sectionalizing switch numbers are related to gene number which with "1" and "0" representing the closed and opened switch state respectively in the network. Moreover, a 2-bit parameter setting is employed for efficient restoration.

2.5.2. Initial Population

The first procedure of initial population is that the "m" individuals are generated from the faulty individual which is obtained from the procedure of design of individual by selecting those parameters at random, after that it is changed the state. The individuals start to be generated and searched for the faulty section in the network, and then selection of that sectionalizing switch at that section to change the status of sectionalizing switch from "1" to "0" and from "0" to "1". However, only individuals with radial shape of the power distribution radial system are evaluated. If non-radial individuals occur, they are re-generated without any evaluation. Furthermore, in case that an evaluated individual violates with any of the constraints, such an individual is rejected because of the constraint condition need to keep its conditions in the power distribution network. Then, the procedure is being continued until “m” valid individuals are obtained.

2.5.3. Selection

Selection is the process of choosing two different parents from the Initial Population for crossing. After deciding on an encoding, and the next step is to decide how to perform the process of selection especially how to choose individuals in the design of individual that will create the new offspring for the next generation and how many offspring each will create. Then, the purpose of selection is to emphasize fitter individual in the hope that the new offspring have a higher fitness. On the other hand, selection is a method that randomly picks chromosomes out of the design of individual according to their evaluation function. Anyway, the higher the fitness function, the more chance an individual has to be selected. Also, the selection pressure is defined as the degree of which the better individuals are in favor of selection. The higher the selection pressured, the more the better individuals are favored. Thus, this selection pressure drives the application of genetic algorithm to improve the better next generations. There are many kind of selection in genetic algorithm such roulette wheel selection, random selection, rank selection, tournament selection and Boltzmann selection. Generally, during the process of selection, about 40% of the individuals in the worst fitness which are discarded at every generation change.

2.5.4. Crossover

Crossover is the process of taking two parent solutions and producing from them a child. After the selection (reproduction) process, the population is enriched with better individuals. The reproduction make clones of good strings but does not create new ones. In addition, crossover is a recombination operator that proceeds in three steps as follow:

I. The reproduction operator selects at random a pair of two individual strings for the mating.
II. A cross site is selected at random along the string length.
III. Finally, the position values are swapped between the two strings following the cross site.

There are much kind of crossover in genetic algorithm such as single point crossover, two point crossover, multi-point crossover, uniform crossover, three parent crossovers, shuffle crossover and ordered crossover. To continue processing of the crossover after the selection in genetic algorithm, many new individuals are generated after some amounts were discarded. The sectionalizing switches are searched by the genetic algorithm process. Then, the finally target restoration system ideally includes only sections blacked out by fault. The blackout sections are concentrated around the fault location. Moreover, the final blackout sections are located within the initial faulty sections. Thus, the conventional genetic algorithm focuses the blackout sections assumed to remain in the network, and crossover is applied only to the parameters within the blackout sections. Thus, the search is concentrated inside the blackout section, increasing the number on inner combinations as well as the probability of good solutions. Usually, it replaces by individuals which newly generated based on the new individual chosen by roulette method form among *60%* high rank. As can be seen in Figure 2-7, the 2 design of individuals which *Parent A* and *Parent B* are picked up during the fault. Then, the opened-closed conditions of the failure section which are randomly picked up are switched. Then, the new offspring s, *Child A* and *Child B* are created.

2.5.5. Mutation

After the crossover, the next process is subjected to mutation. Mutation is performed in a somewhat uncommon way: the mutation rate is defined as the probability of selection of individuals for mutation. Therefore, the mutation probability in the genetic algorithm is set rather high. In such selected individuals, genes with arbitrary bits are chosen by using uniform random number. Then, these genes and its neighbors are change from “0” to “1” and from “1” to “0”. Usually, only gene selections are changed in the process of mutation. However, violation of the radial shape constraint is highly probable, and the involvement of neighbor genes contributes to the generation of individuals meeting the constraint condition. As shown in the Figure 2-8, the sectionalizing switches *“5” and “6”* are changed the switch status during the process of mutation. After this process, the process of minimization and optimization of outage is made in the power distribution network during the fault.

Fortunately, I. Michibata and H. Aoki (2008) have developed the improve version of mutation [2-12]. This approach making the all locations adjacent to sectionalizing switches at the branch points in the network are memorized in the program, so the sectionalizing switches can be updated not only in the mutation sites, but also at all neighbor locations in the network as well as around the outage sections. For instance, Figure 2-9 shows that about half of the system is becoming the outage area because of the Tr.2 is fault. In this context, the branch point control of the conventional genetic algorithm, the sectionalizing switch no.4 is operated from closed-state to opened-state when the sectionalizing switch no.3 is selected by mutation process as shown in Figure 2-8. Then, there is also a possibility of producing individuals with many blackout sections in one control step in the network. In case that the sectionalizing switch no.3 is selected in this propose method, so the sectionalizing switches no.2 and 7 can be operated by searching to get the availability of better result with that branch point in the network. In addition, after searching the availability of better result by switching the sectionalizing switch no.4 from opened-state to closed-state. As a result, the sectionalizing switch no.7 is selected in the improved method which decreased the number of blackout sections in the network as shown in Figure 2-11.

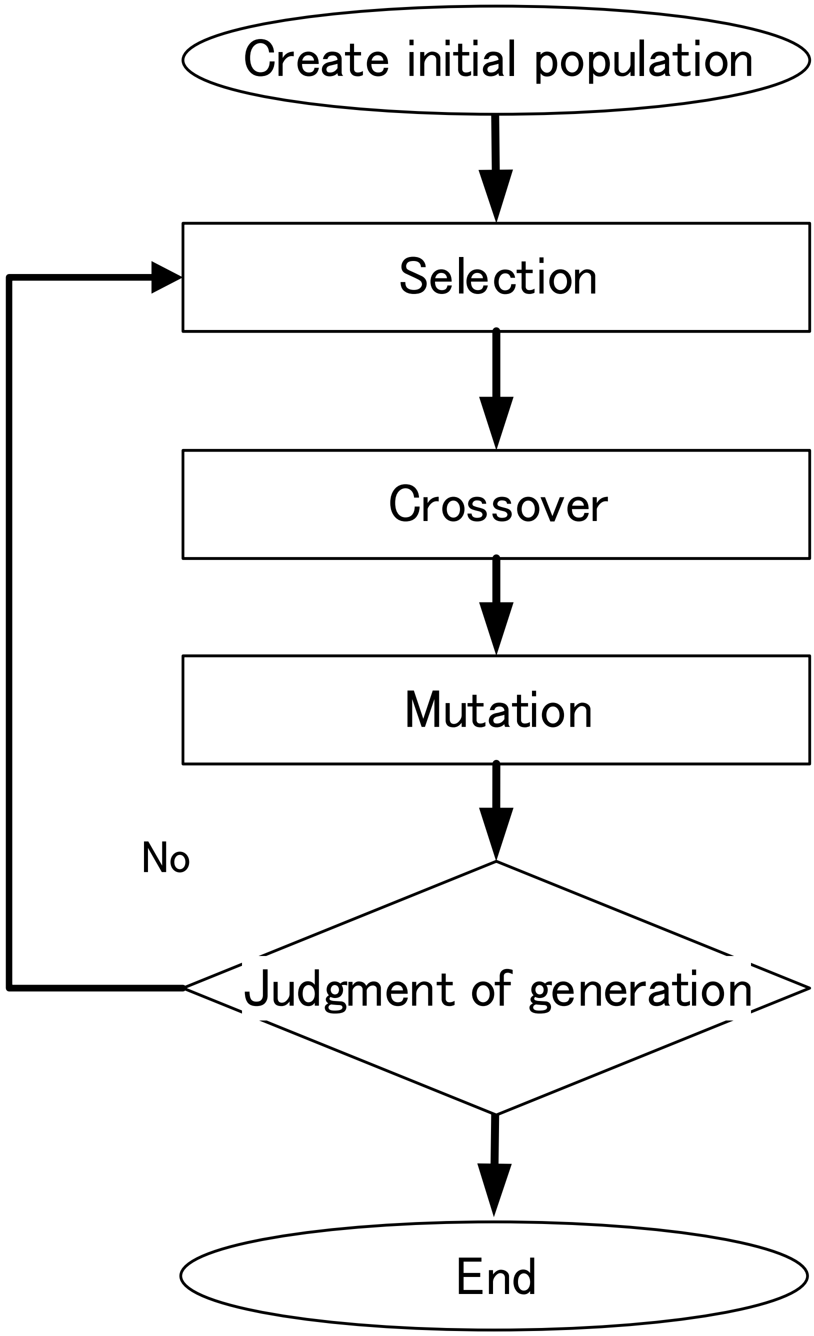


Figure 2-5 Flow chart of GA

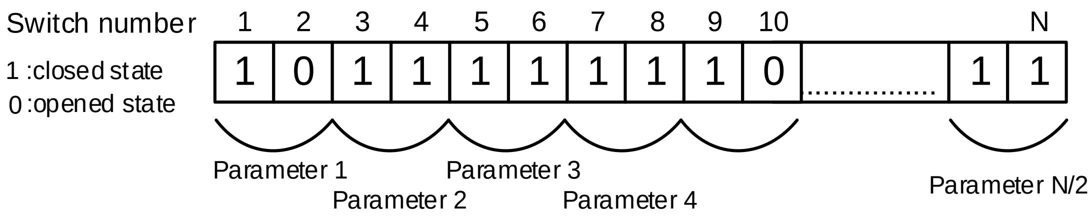


Figure 2-6 Expression of an individual

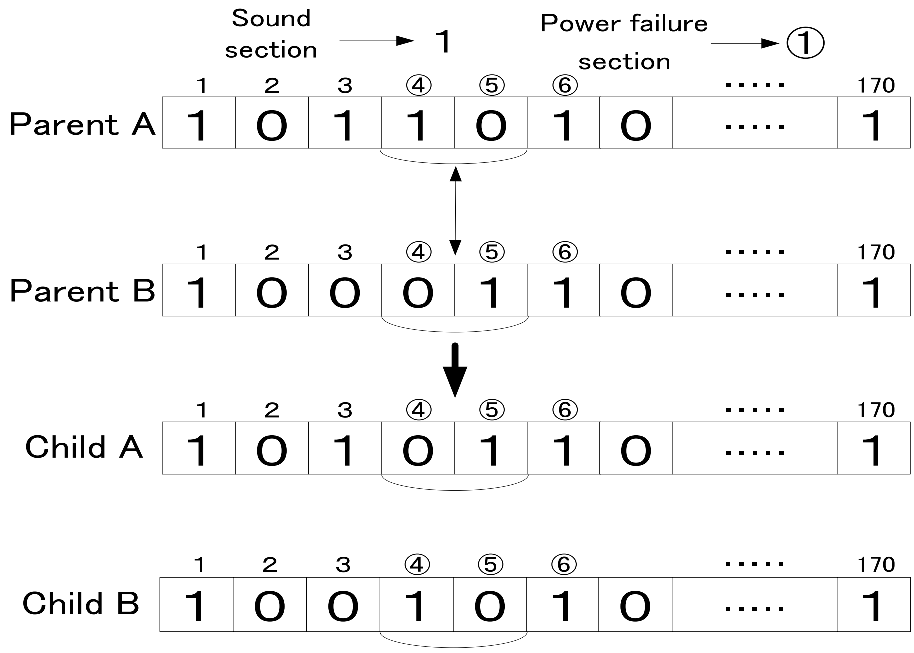


Figure 2-7 Selection and crossover

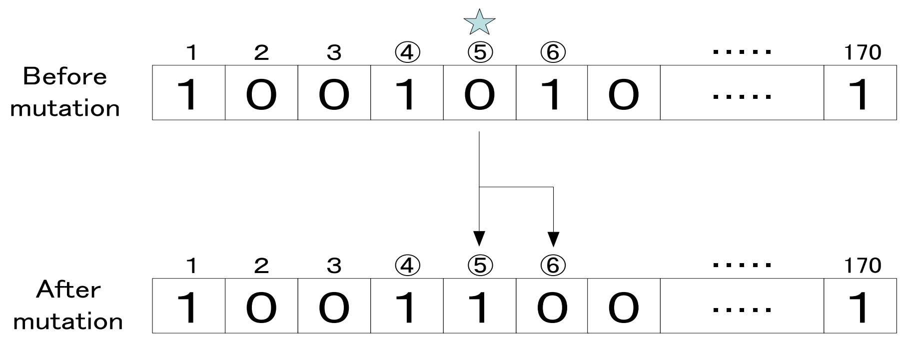


Figure 2-8 Mutation

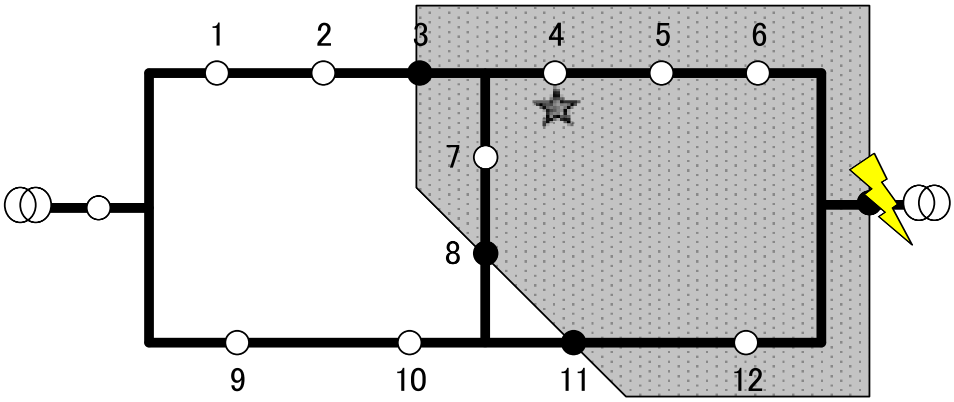


Figure 2-9 Initial faulty state system

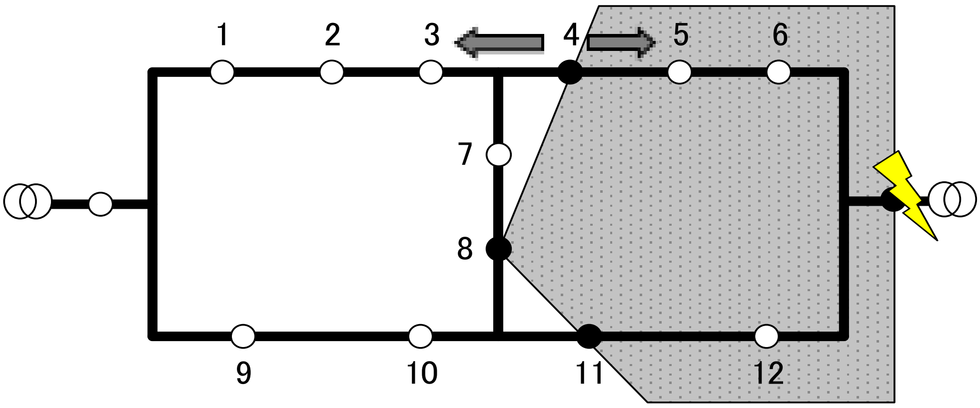


Figure 2-10 Conventional mutation

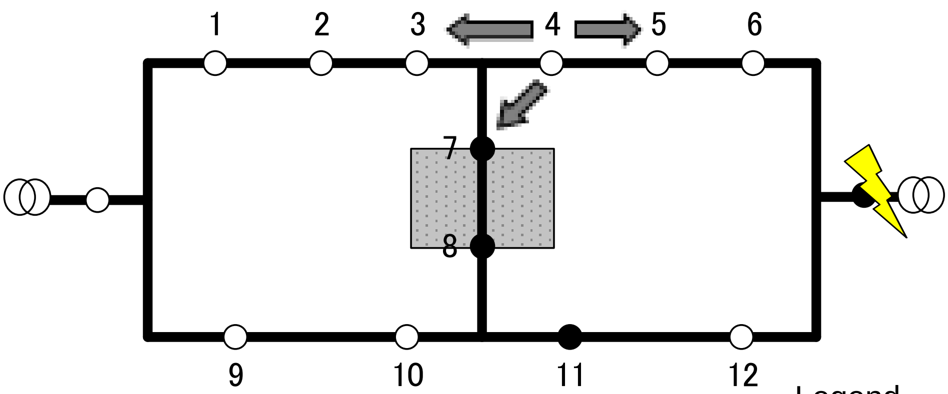
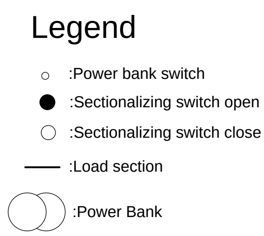


Figure 2-11 Improved mutation



2.6. Model System

There are 2 type of model systems are applied for numerical analysis which are small-scale system and large-scale system. The details specification of them are described below.

2.6.1. Small-scale system

This model system includes 4 substations as shown in Figure 2-12 which are Tr1, Tr2, Tr3, Tr4 which have 700 A, 400 A, 400 A and 900 A respectively [2-1], [2-12]–[2-14]. It is connected with 53 sectionalizing switches, and 78 load sections; the delivery voltage is 6600 V. The loads are distributed uniformly in every section, and the load power factor is 1.0. The allowed voltage drop from the top level to the bottom level is 660 V. In addition, the thick and thin lines in the diagram represent main and branch lines, with current capacities of 455 and 125 A, respectively. The impedance and load for each section are mentioned in Table 2-1. For research purpose, power bank of Tr4 is assumed to fail and as a result, blackout sections occur as shown by the grey area in Fig. 10 which total outage load is 488 A. In this fault condition, the total current capacity of the sound banks is 1500 A, which is lower than the total load capacity of 1632 which mean the smallest outage load could be decreased is 132 A.

Table 2-1 Small-scale model system data

section No	Impedance[Ω]	Load [A]	section No	Impedance [Ω]	Load [A]
(1)	0.0205	25	(40)	0.01	12
(2)	0.0315	51	(41)	0.0551	20
(3)	0.104	36	(42)	0.0949	2
(4)	0.0473	35	(43)	0.0037	4
(5)	0.0362	43	(44)	0.1029	5
(6)	0.0153	71	(45)	0.0278	8
(7)	0.0947	34	(46)	0.0211	10
(8)	0.0079	23	(47)	0.0476	20
(9)	0.0142	37	(48)	0.0499	25
(10)	0.0239	51	(49)	0.0072	23
(11)	0.056	48	(50)	0.0061	32
(12)	0.0843	30	(51)	0.0723	48
(13)	0.001	40	(52)	0.0619	18
(14)	0.0205	21	(53)	0.0723	15
(15)	0.0384	2	(54)	0.0174	13
(16)	0.0925	23	(55)	0.0423	8
(17)	0.0529	29	(56)	0.1329	25
(18)	0.0382	4	(57)	0.1654	14
(19)	0.0621	3	(58)	0.1792	22
(20)	0.0823	1	(59)	0.1218	30
(21)	0.0127	52	(60)	0.1111	22
(22)	0.0327	27	(61)	0.0721	13
(23)	0.0113	11	(62)	0.0651	16
(24)	0.0012	2	(63)	0.0325	9
(25)	0.2001	8	(64)	0.0693	14
(26)	0.0012	2	(65)	0.0721	25
(27)	0.0078	1	(66)	0.0125	41
(28)	0.0109	6	(67)	0.0117	67
(29)	0.0109	21	(68)	0.0432	21
(30)	0.0247	14	(69)	0.0739	42
(31)	0.0625	12	(70)	0.0202	20
(32)	0.0055	1	(71)	0.0315	31
(33)	0.0139	3	(72)	0.0018	8
(34)	0.0725	10	(73)	0.0128	15
(35)	0.0839	18	(74)	0.0256	29
(36)	0.0127	10	(75)	0.0119	4
(37)	0.0666	3	(76)	0.0076	12
(38)	0.0266	10	(77)	0.0529	59
(39)	0.0125	10	(78)	0.01	2

2.6.2. Large-scale system

Meanwhile, the large scale have been developed by I. Michibata and H. Aoki (2009) based on small-scale model. As shown in Figure 2-13, this model have 10 substations which Figure 2-13 Tr1 and Tr10 supply 455 A and Tr2 to Tr9 supply 910 A to the system. It is connected with 170 sectionalizing switches, and 322 load sections. Alike as in the small-scale model, the delivery voltage is 6600 V, and the current capacity is 455 and 125 A, respectively. The load power factor is set to 0.8, allowing for reactance. The impedance and load for each section are mentioned in Table 2-2 until Table 2-5. In reference [2-12], two cases are tested which assumed single-bank fault and double-bank fault. However, because of single-bank fault is reported successfully restored, only double-bank fault is tested in this thesis. Specifically, double-bank fault is refer to power bank Tr3 and Tr4 is assumed to fail simultaneously and caused the total 1028 A of outage load area. Here, because of the total capacity of sound banks which is 6370 A exceeds the total load capacity 5110 A, in this case all outage sections could be fully restored theoretically.

Table 2-2 Large-scale model system data (1)

section No	resistance [Ω]	reactance [Ω]	Impedance [Ω]	Load [A]	section No	resistance [Ω]	reactance [Ω]	Impedance [Ω]	Load [A]
(1)	0.0526	0.0395	0.0658	25	(51)	0.0329	0.0247	0.0412	12
(2)	0.0099	0.0074	0.0124	51	(52)	0.0128	0.0096	0.0160	20
(3)	0.0625	0.0469	0.0781	36	(53)	0.0447	0.0335	0.0558	2
(4)	0.0372	0.0279	0.0466	35	(54)	0.0366	0.0275	0.0458	4
(5)	0.0097	0.0073	0.0122	43	(55)	0.0180	0.0135	0.0225	5
(6)	0.0434	0.0326	0.0543	71	(56)	0.0595	0.0446	0.0744	8
(7)	0.0242	0.0181	0.0302	34	(57)	0.0349	0.0262	0.0437	10
(8)	0.0311	0.0234	0.0389	23	(58)	0.0363	0.0272	0.0454	20
(9)	0.0368	0.0276	0.0460	37	(59)	0.0310	0.0233	0.0388	25
(10)	0.0199	0.0149	0.0249	51	(60)	0.0132	0.0099	0.0165	23
(11)	0.0302	0.0226	0.0377	48	(61)	0.0209	0.0156	0.0261	32
(12)	0.0604	0.0453	0.0755	30	(62)	0.0625	0.0469	0.0782	48
(13)	0.0883	0.0663	0.1104	40	(63)	0.0600	0.0450	0.0750	18
(14)	0.1000	0.0750	0.1250	21	(64)	0.0279	0.0209	0.0348	15
(15)	0.0384	0.0288	0.0479	2	(65)	0.0715	0.0537	0.0894	13
(16)	0.0146	0.0110	0.0183	23	(66)	0.0243	0.0182	0.0304	8
(17)	0.0448	0.0336	0.0560	29	(67)	0.0363	0.0272	0.0453	25
(18)	0.0861	0.0646	0.1076	4	(68)	0.0363	0.0272	0.0454	14
(19)	0.0719	0.0539	0.0899	3	(69)	0.0177	0.0133	0.0222	22
(20)	0.0751	0.0564	0.0939	1	(70)	0.0248	0.0186	0.0310	30
(21)	0.0496	0.0372	0.0620	52	(71)	0.0664	0.0498	0.0830	22
(22)	0.0583	0.0437	0.0729	27	(72)	0.0623	0.0467	0.0779	13
(23)	0.0187	0.0140	0.0234	11	(73)	0.0340	0.0255	0.0424	16
(24)	0.0303	0.0227	0.0378	2	(74)	0.0453	0.0340	0.0566	9
(25)	0.0149	0.0112	0.0186	8	(75)	0.0530	0.0397	0.0662	14
(26)	0.0356	0.0267	0.0445	2	(76)	0.0397	0.0298	0.0497	25
(27)	0.0517	0.0388	0.0647	1	(77)	0.0261	0.0196	0.0327	41
(28)	0.0092	0.0069	0.0115	6	(78)	0.0344	0.0258	0.0429	67
(29)	0.0209	0.0156	0.0261	21	(79)	0.0431	0.0323	0.0539	21
(30)	0.0220	0.0165	0.0275	14	(80)	0.0105	0.0079	0.0132	42
(31)	0.0499	0.0374	0.0624	12	(81)	0.0751	0.0563	0.0939	20
(32)	0.0707	0.0530	0.0884	1	(82)	0.0518	0.0389	0.0648	31
(33)	0.0350	0.0262	0.0437	3	(83)	0.0777	0.0583	0.0972	8
(34)	0.0409	0.0307	0.0511	10	(84)	0.0305	0.0229	0.0381	15
(35)	0.0166	0.0124	0.0207	18	(85)	0.0268	0.0201	0.0336	29
(36)	0.0232	0.0174	0.0289	10	(86)	0.0353	0.0265	0.0441	4
(37)	0.0527	0.0396	0.0659	3	(87)	0.0457	0.0343	0.0571	12
(38)	0.0717	0.0538	0.0896	10	(88)	0.0125	0.0093	0.0156	59
(39)	0.0072	0.0054	0.0090	10	(89)	0.0615	0.0461	0.0769	2
(40)	0.0588	0.0441	0.0735	15	(90)	0.0355	0.0266	0.0444	20
(41)	0.0267	0.0200	0.0333	35	(91)	0.0399	0.0299	0.0499	14
(42)	0.0129	0.0096	0.0161	5	(92)	0.0645	0.0484	0.0807	41
(43)	0.0409	0.0307	0.0511	51	(93)	0.0126	0.0095	0.0158	5
(44)	0.0144	0.0108	0.0180	21	(94)	0.0256	0.0192	0.0320	23
(45)	0.0414	0.0311	0.0518	13	(95)	0.0954	0.0716	0.1193	42
(46)	0.0177	0.0133	0.0221	12	(96)	0.0762	0.0571	0.0952	4
(47)	0.0818	0.0614	0.1023	7	(97)	0.0714	0.0536	0.0893	18
(48)	0.0715	0.0537	0.0894	41	(98)	0.0493	0.0370	0.0616	22
(49)	0.0219	0.0164	0.0273	23	(99)	0.0379	0.0284	0.0474	38
(50)	0.0376	0.0282	0.0470	6	(100)	0.0051	0.0038	0.0064	10

Table 2-3 Large-scale model system data (2)

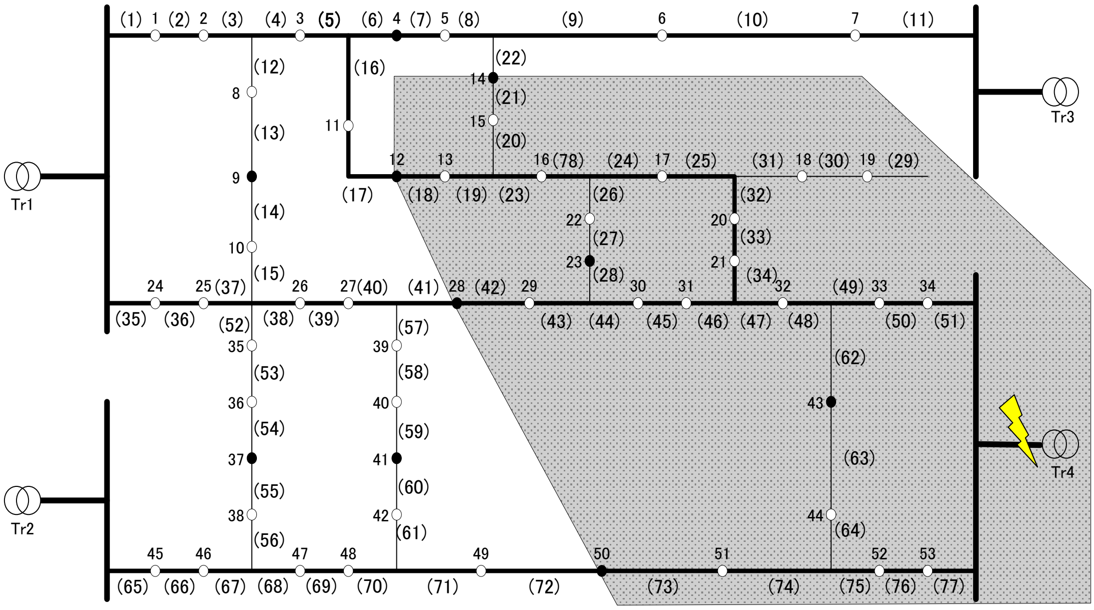
section No	resistance [Ω]	reactance [Ω]	Impedance[Ω]	Load [A]	section No	resistance [Ω]	reactance [Ω]	Impedance [Ω]	Load [A]
(101)	0.0324	0.0243	0.0405	20	(151)	0.0304	0.0228	0.0379	13
(102)	0.0196	0.0147	0.0245	11	(152)	0.0282	0.0211	0.0352	45
(103)	0.0599	0.0449	0.0749	2	(153)	0.0215	0.0161	0.0269	35
(104)	0.0746	0.0560	0.0933	35	(154)	0.0729	0.0547	0.0911	2
(105)	0.0204	0.0153	0.0255	10	(155)	0.0251	0.0188	0.0314	8
(106)	0.0818	0.0614	0.1023	12	(156)	0.0697	0.0523	0.0871	13
(107)	0.0403	0.0303	0.0504	6	(157)	0.0550	0.0413	0.0688	10
(108)	0.0148	0.0111	0.0186	54	(158)	0.0513	0.0385	0.0642	53
(109)	0.0568	0.0426	0.0710	40	(159)	0.0254	0.0190	0.0317	22
(110)	0.0234	0.0175	0.0292	20	(160)	0.1068	0.0801	0.1335	30
(111)	0.0870	0.0652	0.1087	14	(161)	0.0206	0.0154	0.0257	18
(112)	0.0459	0.0344	0.0573	6	(162)	0.0041	0.0031	0.0051	6
(113)	0.0483	0.0362	0.0604	4	(163)	0.0190	0.0143	0.0238	1
(114)	0.0353	0.0264	0.0441	10	(164)	0.0537	0.0403	0.0672	25
(115)	0.0320	0.0240	0.0400	32	(165)	0.0636	0.0477	0.0795	38
(116)	0.0363	0.0272	0.0454	23	(166)	0.0367	0.0275	0.0459	40
(117)	0.0459	0.0344	0.0574	16	(167)	0.0273	0.0205	0.0341	12
(118)	0.0379	0.0284	0.0474	2	(168)	0.0590	0.0442	0.0737	8
(119)	0.0517	0.0388	0.0647	1	(169)	0.0233	0.0175	0.0291	1
(120)	0.0488	0.0366	0.0610	33	(170)	0.0540	0.0405	0.0675	2
(121)	0.0403	0.0302	0.0504	15	(171)	0.0461	0.0346	0.0576	36
(122)	0.0103	0.0077	0.0128	36	(172)	0.0483	0.0363	0.0604	42
(123)	0.0379	0.0284	0.0473	45	(173)	0.0191	0.0144	0.0239	18
(124)	0.0294	0.0220	0.0367	24	(174)	0.0660	0.0495	0.0825	36
(125)	0.0754	0.0566	0.0943	8	(175)	0.0482	0.0362	0.0603	10
(126)	0.1086	0.0815	0.1358	55	(176)	0.0714	0.0535	0.0892	27
(127)	0.0235	0.0176	0.0294	26	(177)	0.0342	0.0257	0.0428	13
(128)	0.0740	0.0555	0.0925	17	(178)	0.0265	0.0198	0.0331	7
(129)	0.0346	0.0259	0.0432	11	(179)	0.0163	0.0122	0.0204	3
(130)	0.0211	0.0158	0.0264	2	(180)	0.0264	0.0198	0.0330	21
(131)	0.0342	0.0256	0.0427	4	(181)	0.0611	0.0458	0.0764	25
(132)	0.0203	0.0152	0.0254	34	(182)	0.0370	0.0278	0.0463	16
(133)	0.0169	0.0127	0.0212	28	(183)	0.0354	0.0265	0.0442	52
(134)	0.0679	0.0509	0.0849	21	(184)	0.0204	0.0153	0.0256	23
(135)	0.0390	0.0292	0.0487	16	(185)	0.0460	0.0345	0.0575	13
(136)	0.0409	0.0306	0.0511	5	(186)	0.0814	0.0610	0.1017	47
(137)	0.0321	0.0240	0.0401	32	(187)	0.0259	0.0194	0.0324	12
(138)	0.0217	0.0163	0.0272	19	(188)	0.0582	0.0436	0.0727	15
(139)	0.0139	0.0104	0.0173	54	(189)	0.0337	0.0253	0.0422	6
(140)	0.0167	0.0125	0.0208	23	(190)	0.0721	0.0541	0.0902	20
(141)	0.0394	0.0296	0.0493	11	(191)	0.0198	0.0148	0.0247	1
(142)	0.0721	0.0541	0.0902	8	(192)	0.0566	0.0425	0.0708	8
(143)	0.0352	0.0264	0.0440	1	(193)	0.0198	0.0149	0.0248	35
(144)	0.0116	0.0087	0.0145	33	(194)	0.0217	0.0163	0.0271	24
(145)	0.0407	0.0305	0.0509	22	(195)	0.0330	0.0247	0.0412	15
(146)	0.0771	0.0578	0.0964	40	(196)	0.0210	0.0158	0.0263	11
(147)	0.0171	0.0129	0.0214	18	(197)	0.0942	0.0706	0.1177	44
(148)	0.0108	0.0081	0.0135	28	(198)	0.0432	0.0324	0.0540	28
(149)	0.0390	0.0292	0.0487	10	(199)	0.0387	0.0290	0.0484	15
(150)	0.0665	0.0499	0.0831	3	(200)	0.0099	0.0074	0.0123	9

Table 2-4 Large-scale model system data (3)

section No	resistance [Ω]	reactance [Ω]	Impedance[Ω]	Load [A]	section No	resistance [Ω]	reactance [Ω]	Impedance [Ω]	Load [A]
(201)	0.0390	0.0293	0.0488	15	(251)	0.0459	0.0344	0.0573	35
(202)	0.0480	0.0360	0.0600	23	(252)	0.0815	0.0611	0.1018	10
(203)	0.0309	0.0232	0.0386	11	(253)	0.0331	0.0249	0.0414	25
(204)	0.0136	0.0102	0.0170	45	(254)	0.0487	0.0365	0.0609	11
(205)	0.0444	0.0333	0.0555	55	(255)	0.0210	0.0157	0.0262	16
(206)	0.0331	0.0248	0.0413	16	(256)	0.0444	0.0333	0.0555	5
(207)	0.0252	0.0189	0.0315	5	(257)	0.0627	0.0470	0.0784	2
(208)	0.0394	0.0295	0.0492	2	(258)	0.0229	0.0172	0.0286	23
(209)	0.0201	0.0151	0.0252	22	(259)	0.0210	0.0157	0.0262	12
(210)	0.0518	0.0388	0.0647	35	(260)	0.0418	0.0314	0.0523	48
(211)	0.0990	0.0743	0.1238	41	(261)	0.0234	0.0176	0.0293	22
(212)	0.0224	0.0168	0.0280	10	(262)	0.0782	0.0586	0.0977	52
(213)	0.0559	0.0419	0.0699	15	(263)	0.0657	0.0493	0.0821	19
(214)	0.0156	0.0117	0.0194	19	(264)	0.0940	0.0705	0.1175	40
(215)	0.0356	0.0267	0.0445	24	(265)	0.0286	0.0214	0.0357	20
(216)	0.0327	0.0245	0.0409	36	(266)	0.0355	0.0266	0.0444	16
(217)	0.0594	0.0446	0.0743	48	(267)	0.0226	0.0170	0.0283	8
(218)	0.0203	0.0153	0.0254	8	(268)	0.0170	0.0127	0.0212	1
(219)	0.0167	0.0126	0.0209	4	(269)	0.0306	0.0230	0.0383	15
(220)	0.0360	0.0270	0.0450	24	(270)	0.0644	0.0483	0.0805	21
(221)	0.0282	0.0212	0.0353	35	(271)	0.0639	0.0479	0.0798	17
(222)	0.0757	0.0568	0.0947	33	(272)	0.0211	0.0158	0.0263	38
(223)	0.0779	0.0584	0.0974	20	(273)	0.0663	0.0497	0.0828	20
(224)	0.0337	0.0253	0.0422	10	(274)	0.0293	0.0219	0.0366	9
(225)	0.0358	0.0269	0.0448	14	(275)	0.000000008	0.000000006	1E-08	0
(226)	0.0477	0.0358	0.0596	7	(276)	0.000000008	0.000000006	1E-08	0
(227)	0.0595	0.0446	0.0744	46	(277)	0.000000008	0.000000006	1E-08	0
(228)	0.0671	0.0504	0.0839	52	(278)	0.000000008	0.000000006	1E-08	0
(229)	0.0226	0.0169	0.0282	12	(279)	0.000000008	0.000000006	1E-08	0
(230)	0.0360	0.0270	0.0450	15	(280)	0.000000008	0.000000006	1E-08	0
(231)	0.0329	0.0247	0.0412	27	(281)	0.000000008	0.000000006	1E-08	0
(232)	0.0314	0.0235	0.0392	33	(282)	0.000000008	0.000000006	1E-08	0
(233)	0.0812	0.0609	0.1015	13	(283)	0.000000008	0.000000006	1E-08	0
(234)	0.0142	0.0107	0.0178	10	(284)	0.000000008	0.000000006	1E-08	0
(235)	0.0244	0.0183	0.0305	20	(285)	0.000000008	0.000000006	1E-08	0
(236)	0.0398	0.0299	0.0498	19	(286)	0.000000008	0.000000006	1E-08	0
(237)	0.0464	0.0348	0.0580	37	(287)	0.000000008	0.000000006	1E-08	0
(238)	0.0669	0.0502	0.0836	4	(288)	0.000000008	0.000000006	1E-08	0
(239)	0.0469	0.0352	0.0587	1	(289)	0.000000008	0.000000006	1E-08	0
(240)	0.0537	0.0403	0.0671	11	(290)	0.000000008	0.000000006	1E-08	0
(241)	0.0670	0.0502	0.0837	26	(291)	0.000000008	0.000000006	1E-08	0
(242)	0.0344	0.0258	0.0430	13	(292)	0.000000008	0.000000006	1E-08	0
(243)	0.0454	0.0341	0.0568	8	(293)	0.000000008	0.000000006	1E-08	0
(244)	0.0637	0.0478	0.0796	3	(294)	0.000000008	0.000000006	1E-08	0
(245)	0.0229	0.0172	0.0287	31	(295)	0.000000008	0.000000006	1E-08	0
(246)	0.0094	0.0070	0.0117	27	(296)	0.000000008	0.000000006	1E-08	0
(247)	0.0073	0.0055	0.0092	16	(297)	0.000000008	0.000000006	1E-08	0
(248)	0.0873	0.0655	0.1092	17	(298)	0.000000008	0.000000006	1E-08	0
(249)	0.0305	0.0229	0.0381	10	(299)	0.000000008	0.000000006	1E-08	0
(250)	0.0167	0.0125	0.0209	5	(300)	0.000000008	0.000000006	1E-08	0

Table 2-5 Large-scale model system data (4)

section No	resistance [Ω]	reactance [Ω]	Impedance [Ω]	Load [A]
(301)	0.000000008	0.000000006	1E-08	0
(302)	0.000000008	0.000000006	1E-08	0
(303)	0.000000008	0.000000006	1E-08	0
(304)	0.000000008	0.000000006	1E-08	0
(305)	0.000000008	0.000000006	1E-08	0
(306)	0.000000008	0.000000006	1E-08	0
(307)	0.000000008	0.000000006	1E-08	0
(308)	0.000000008	0.000000006	1E-08	0
(309)	0.000000008	0.000000006	1E-08	0
(310)	0.000000008	0.000000006	1E-08	0
(311)	0.000000008	0.000000006	1E-08	0
(312)	0.000000008	0.000000006	1E-08	0
(313)	0.000000008	0.000000006	1E-08	0
(314)	0.000000008	0.000000006	1E-08	0
(315)	0.000000008	0.000000006	1E-08	0
(316)	0.000000008	0.000000006	1E-08	0
(317)	0.000000008	0.000000006	1E-08	0
(318)	0.000000008	0.000000006	1E-08	0
(319)	0.000000008	0.000000006	1E-08	0
(320)	0.000000008	0.000000006	1E-08	0
(321)	0.000000008	0.000000006	1E-08	0
(322)	0.000000008	0.000000006	1E-08	0
(323)	0.000000008	0.000000006	1E-08	0
(324)	0.000000008	0.000000006	1E-08	0
(325)	0.000000008	0.000000006	1E-08	0
(326)	0.000000008	0.000000006	1E-08	0
(327)	0.000000008	0.000000006	1E-08	0
(328)	0.000000008	0.000000006	1E-08	0
(329)	0.000000008	0.000000006	1E-08	0
(330)	0.000000008	0.000000006	1E-08	0
(331)	0.000000008	0.000000006	1E-08	0
(332)	0.000000008	0.000000006	1E-08	0
(333)	0.000000008	0.000000006	1E-08	0
(334)	0.000000008	0.000000006	1E-08	0
(335)	0.000000008	0.000000006	1E-08	0
(336)	0.000000008	0.000000006	1E-08	0
(337)	0.000000008	0.000000006	1E-08	0
(338)	0.000000008	0.000000006	1E-08	0
(339)	0.000000008	0.000000006	1E-08	0
(340)	0.000000008	0.000000006	1E-08	0
(341)	0.000000008	0.000000006	1E-08	0
(342)	0.000000008	0.000000006	1E-08	0
(343)	0.000000008	0.000000006	1E-08	0
(344)	0.000000008	0.000000006	1E-08	0
(345)	0.000000008	0.000000006	1E-08	0
(346)	0.000000008	0.000000006	1E-08	0
(347)	0.000000008	0.000000006	1E-08	0
(348)	0.000000008	0.000000006	1E-08	0



Total outage load: 488 A

Figure 2-12 Small-scale model system

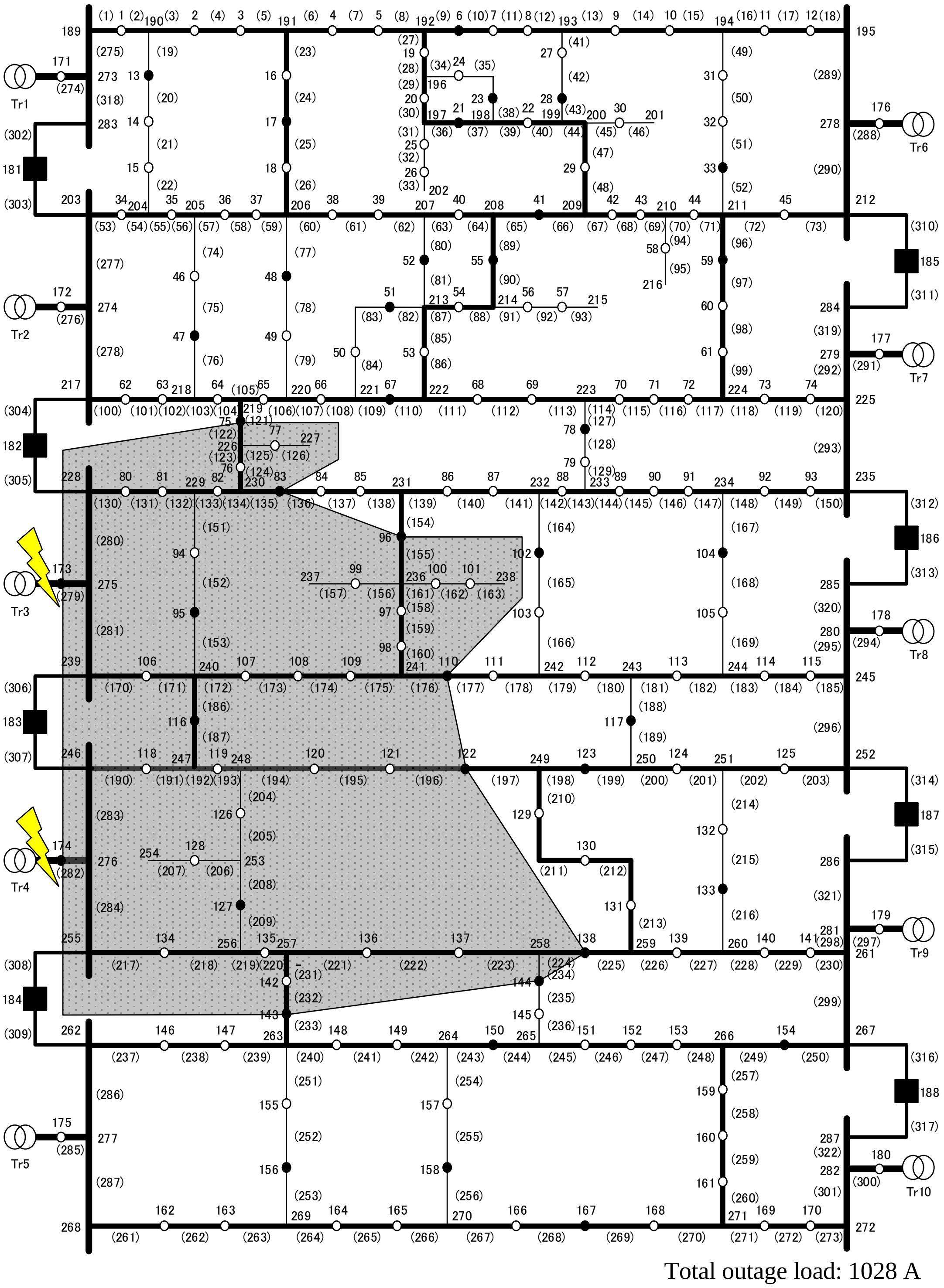


Figure 2-13 Large-scale model system

2.7. Results and Discussion

2.7.1. Small-scale result

The best restoration results obtained by K. Iwasaki and H. Aoki (2007) are shown in Figure 2-14. As can be seen from the diagram, four blackout sections remain, and the total of outage loads is 160 A. Meanwhile, the best results obtained by I. Michibata and H. Aoki (2008) are shown in

Figure 2-15. Here, the outage loads are reduced to 154 A but five blackout sections remain, and the distribution loss increases somewhat. In any case, the purpose of improvement, namely, the minimization of outage loads, has been achieved. Furthermore, the comparison of the previous result by the existing methods are given in Table 2-6. As can be seen from the table, the method developed by Michibata. I (2008) performs best in terms of outage loads, which confirms its effectiveness.

Table 2-6 Comparison of previous result

Bibliography	Outage load [A]	Loss [kW]	Fitness
K. Aoki et al. (1990)	238	192.2	3.311E-03
J. Nakajima et al. (2002)	161	288.6	3.889E-03
K. Iwasaki et al. (2007)	160	266.7	3.986E-03
I. Michibata et al. (2008)	154	280.8	4.041E-03

2.7.2. Large-scale result

Then, I. Michibata and H. Aoki (2008) also implement into more severe conditions which double-faulty of large-scale system as shown in Figure 2-13. Here the outage loads are 1028 A. When the conventional GA is applied to this case, outage loads of 604 A remain in 29 blackout sections, as shown in Figure 2-16. On the other hand, as shown in Figure 2-17 the fault of Tr4 is recovered completely, and outage loads of 118 A remain for the fault of Tr3. Thus, in these severe conditions, the method was more effective in elimination of blackout sections as well as minimization of outage loads than the conventional GA. Here, too, the neighborhood search around branch points proved effective, thus improving the restoration results.

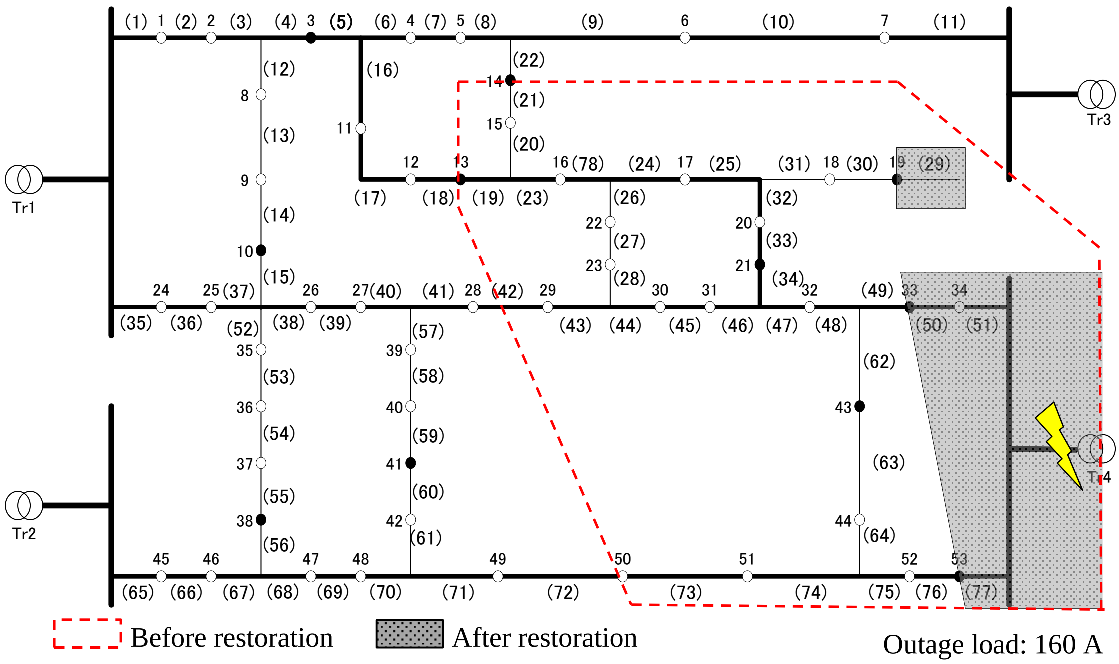


Figure 2-14 Small-scale system after restoration with conventional GA [1]

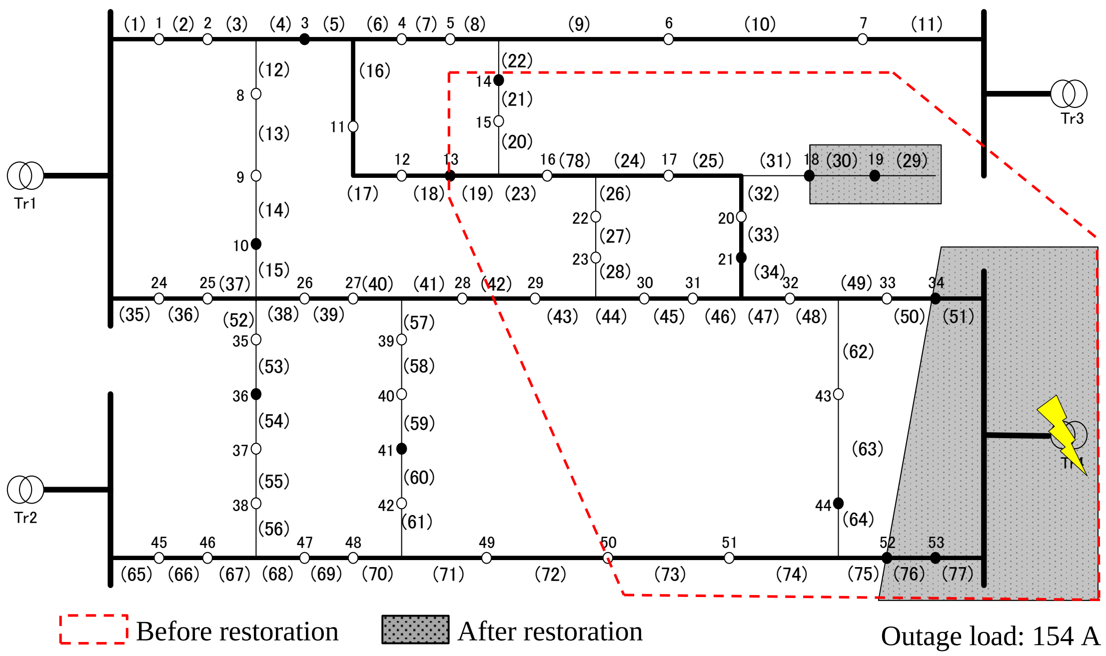


Figure 2-15 Small-scale system after restoration with conventional GA [12]

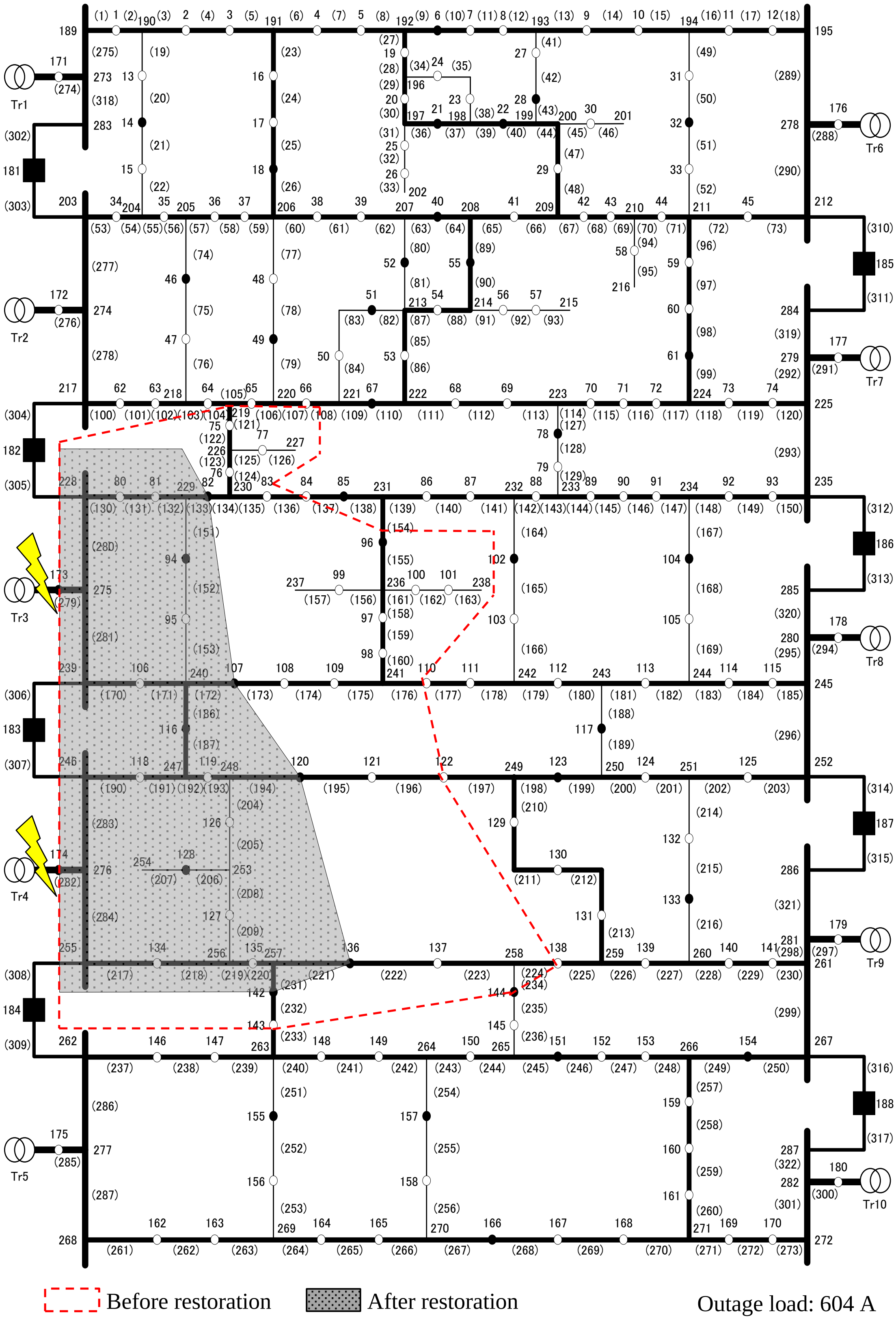


Figure 2-16 Large scale system after restoration with conventional GA

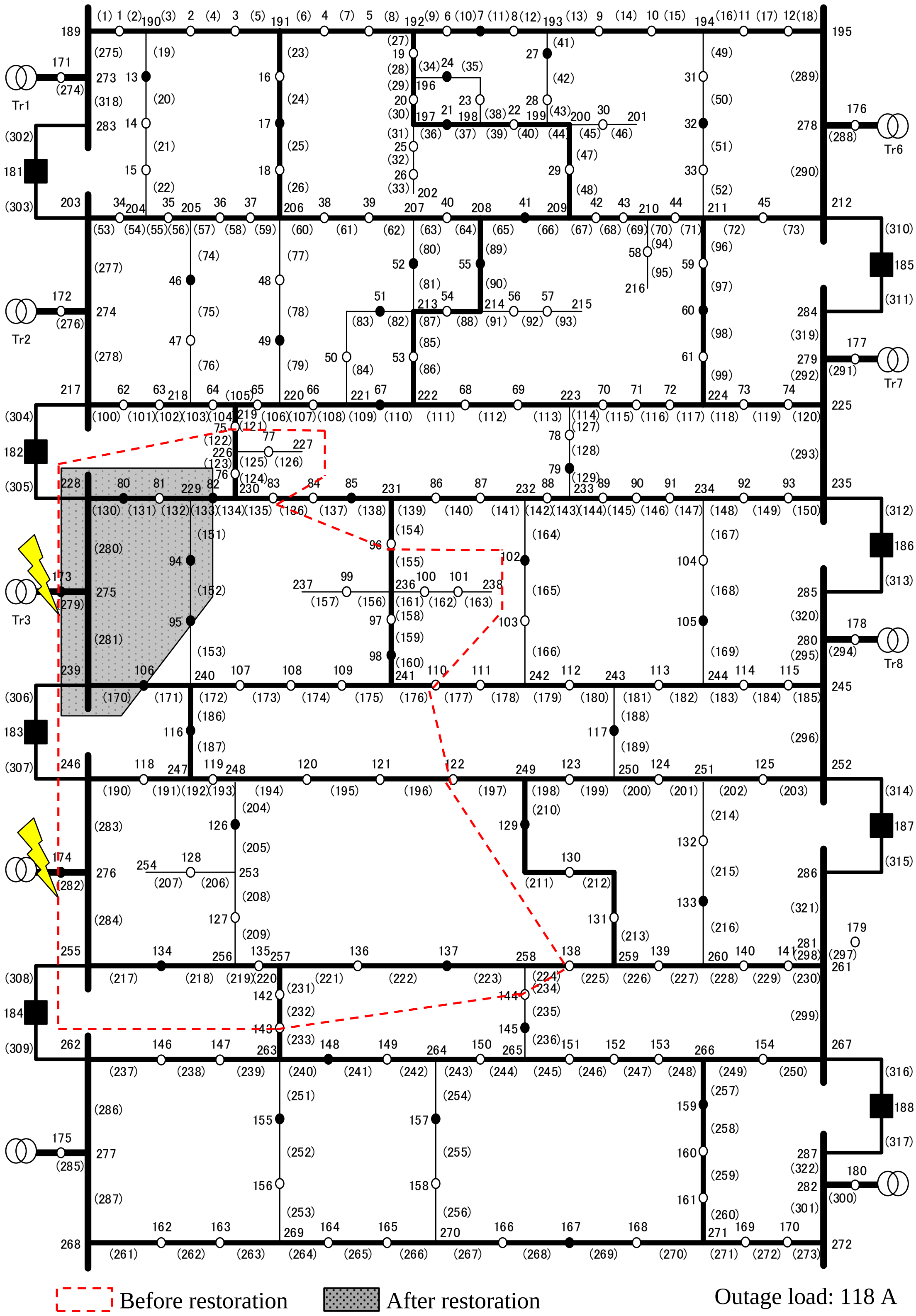


Figure 2-17 Large-scale system after restoration with conventional GA

2.8. Summary

In this chapter, the recent improvement of genetic algorithm and the application in service restoration have been introduced. The improvement was for minimization of outage area during service restoration. It was approved by testing it at small-scale system and the extended version large-scale system. From the previous numerical results, it can be concluded as below:

1. The GA that developed by Michibata. I (2008) had gave better result of outage load compare to all the previous methods.
2. It is also proven with outage area and distribution losses are minimized in both small and large-scale system.
3. However, there are still outage areas remain even after restoration have been done and in theory it supposedly could get better result.
4. Due to the problem of service restoration involves with several constrains and factors, weighting factor made it more complicated and difficult to find the optimal value and best result.
5. Moreover, the method has already improved several times and come to the limit, it is necessary to apply other method such as considering multi-objective optimization method.

Chapter 3

INTEGRATING DISTRIBUTED GENERATORS IN SERVICE RESTORATION

3.1. Introduction

In this chapter, to minimize the outage load and increase the liability, DG in installed to the system during restoration after switch configuration is done by GA. First, the function and type of DG is described. Then, the simulation model of installation DG during restoration process is developed. After that, for approve the effectiveness of installation DG, the small-scale and large-scale system are tested. Then, the numerical results are presented and discussed. Finally, the finding from the results are explained in the summary.

3.2. Distributed Generator

Distributed Generation (DG) is an alternative to the traditional electricity sources such as oil, gas, coal, water and can also be used to enhance the current electrical system as shown in Figure 3-1. A study by the Electric Power Research Institute (EPRI) indicates that by 2010, 25% of the new generation will be distributed, a study by the Natural Gas Foundation concluded that this figure could be as high as 30%. The European Renewable Energy Study (TERES), commissioned by the European Union (EU) to examine the feasibility of EU CO_2 reduction goals and the EU renewable energy targets, found that around 60% of the renewable energy potential that can be utilized until 2010 can be categorized as decentralized power sources.

However, there are large variations in definitions of DG used in the literature such as purpose, location, rating, technology, environmental impact etc. [3-1]–[3-3]. For example, technologies for DG are based on reciprocating engines, photovoltaic, fuel cells, combustion gas turbines, micro turbines and wind turbines. Therefore, this thesis applied the most significant scope that can define DG is the location which is connected directly to the distribution network or on the customer site of the meter. In addition, for the size rating of DG the following distinction is referred [3-1].

Table 3-1 Size rating of DG

CATEGORIES	SIZE RATING
Micro	1 Watt < 5kW
Small	5 kW < 5 MW
Medium	5 MW < 50 MW
Large	50 MW < 300 MW

Source: http://www.11thhourproject.org/grantees/clean-coalition

Figure 3-1 Examples of DGs use in power system

3.3. Simulation Setup

After restoration process is done by switch reconfiguration using the genetic algorithm method, due to limitation of power bank source there are some outage load left at certain areas. Therefore to solve this problem, the idea is to immediately install distributed generations between the blackout sections in the distribution system after the restoration system is occurred. By using this method, the continuity of electricity in the distribution system could be maintained long enough before the necessary process of repairing at the damaged substation is taken.

As stated in introduction above, because there are still have problem in getting the optimum restoration due to involving the heuristic that is becoming complex, this paper proposes the integrating DG to solve that problem by following steps[3-4].

1. **Determine the non-restored load**: The non-restored load of each outage section is determined to know how much amount of DGs is necessary needed.
2. **Integrate DG(s)**: According to that amount, DG(s) is integrated.
3. **Calculate the total DG sizes**: Then, total integrated DG(s) sizes in the system are calculated.
4. **Calculate power flow**: Lastly, the new power flow after integrate DG is calculated to determine either all outage sections are restored or not.

Before the size of DG is determined in unit of watt, due to the load of each sections are calculated as ampere unit, then the I_{DG} are as blow:

$$I_{DG} \geq inn_m \tag{3-1}$$

Where inn_m is the load of outage section. Then the size of DG can be defined as:

$$P_{DG} = V \cdot I_{DG} \tag{3-2}$$

Where, V is the feeder voltage.

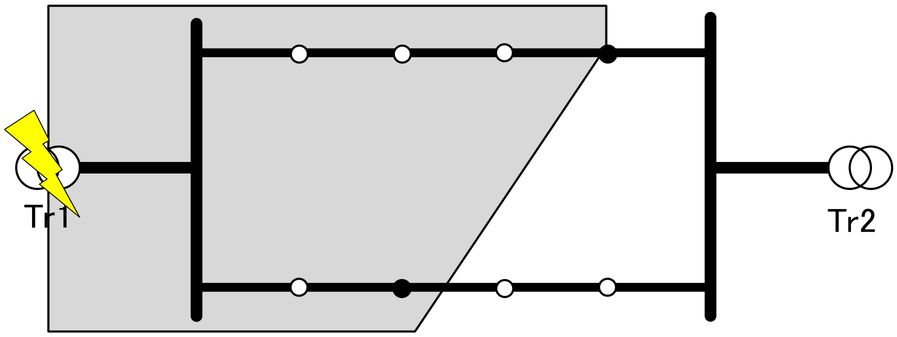


Figure 3-2 System during fault

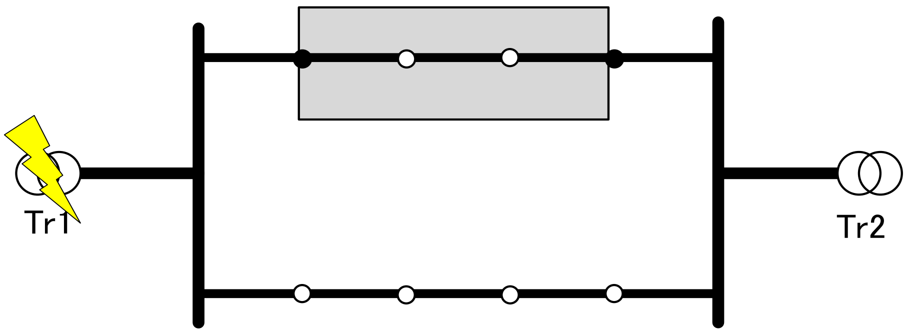


Figure 3-3 System after switch reconfiguration during restoration

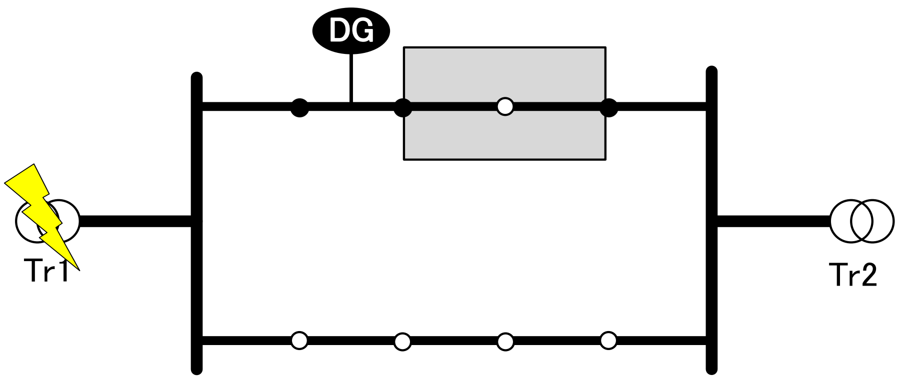


Figure 3-4 System after installation DG

3.4. Results and Discussion

3.4.1. Small-scale system

Figure 3-5 shows the result after restoration by switch reconfiguration without DG and with DG when substation Tr4 is assumed to be fault. The vertical axis represent the initial value of 1 to 100. The amount of DG which install in the first stage is 20 A equivalent to 132 kW. As can been seen from the graph, in all initial 1 – to 100, when DG is installed, the outage load is decreased compare to before the installation of DG. The smallest outage load is 68 A and the system before and after restoration is illustrated in Figure 3-6 and Figure 3-7 respectively.

Then, further investigation have been done regarding the relationship between the increasing size of DG and the outage load. The results of 1~100 initial are shown in Figure 3-8 which size of DG is increased 30 A, 40 A, 50 A and 60 A. Then, the average outage load from 100 data is recorded in Figure 3-9. From the figure, it can been seen that, when 50 A of DG installed, the outage load become 0 A which means system are fully restored. However, for avoid the reverse flow phenomenon when to DG size is bigger than load section, it necessary to calculate the only needed amount of DG in each case of initial 1 to 100. The result is shown in Figure 3-10. The left-hand side horizontal axis represent the outage load after restoration, while the right-hand side shows the amount of DG is needed. From this figure, at least 1.76 MW is needed to fully restored and maximum size of DG is 3.81 MW

3.4.2. Large-scale system

Moreover, for research purpose it is also have been tested in large-scale model which shown in エラー! 参照元が見つかりません。. Figure 3-11 shows the result after restoration by switch reconfiguration without DG and with DG when substation Tr3 and Tr4 are assumed to be fault simultaneously. The vertical axis represent the initial value of 1 to 100. The amount of DG which install in the first stage is 20 A equivalent to 132 kW. As can been seen from the graph, in all initial 1 to 100, when DG is installed, the outage load is decreased compare to before the installation of DG. The smallest outage load is 27 A and the system before and after restoration is illustrated in

Figure 3-12 and

Figure 3-13 respectively.

Then, further investigation have been done regarding the relationship between the increasing size of DG and the outage load. The result is shown in Figure 3-14 which size of DG is increased 30 A, 40 A and 50 A. Then, the average outage load from 100 data is recorded in Figure 3-15. From the figure, it can been seen that, when 50 A of DG installed, the outage load become 0 A which means system are fully restored. However, for avoid the reverse flow phenomenon when to DG size is bigger than load section, it necessary to calculate the only needed amount of DG in each case of initial 1 to 100. The result is shown in Figure 3-16. The left-hand side horizontal axis represent the outage load after restoration, while the right-hand side shows the amount of DG is needed. From this figure, at least 1.07 MW is needed to fully restored and maximum size of DG is 3.75 MW

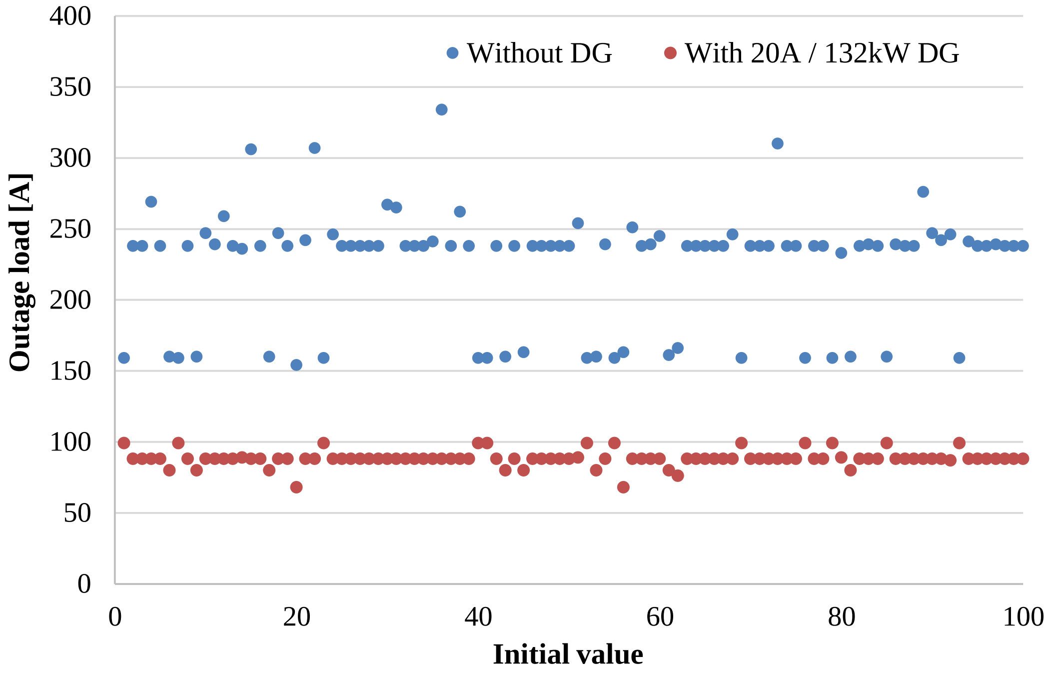


Figure 3-5 Outage load after restoration with and without 20 A of DG

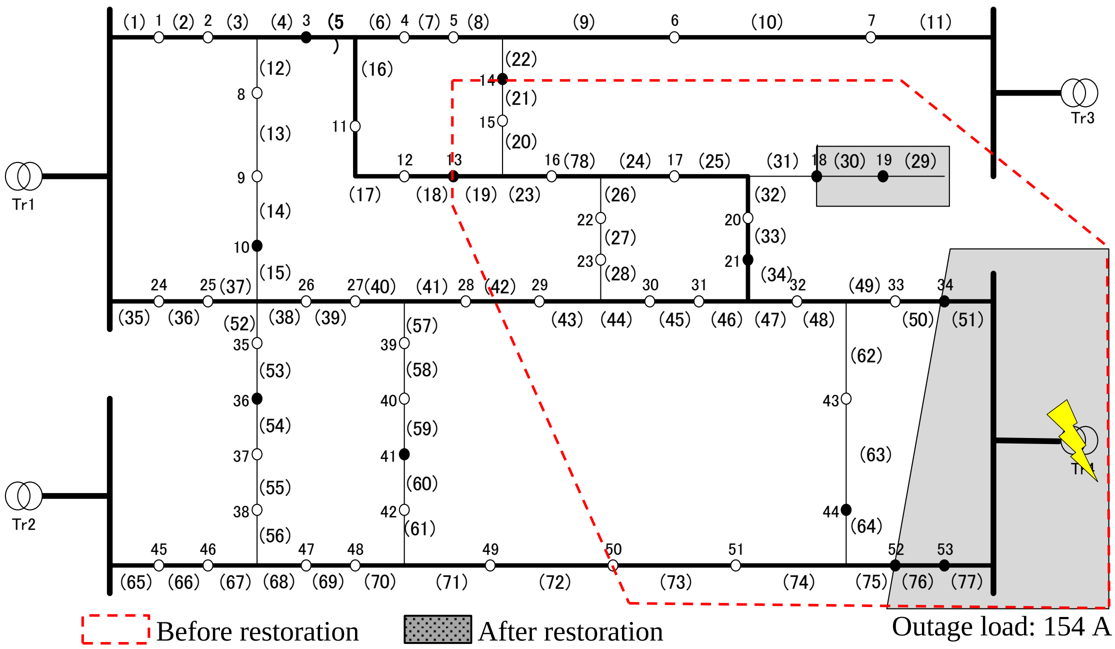


Figure 3-6 System before DG installation

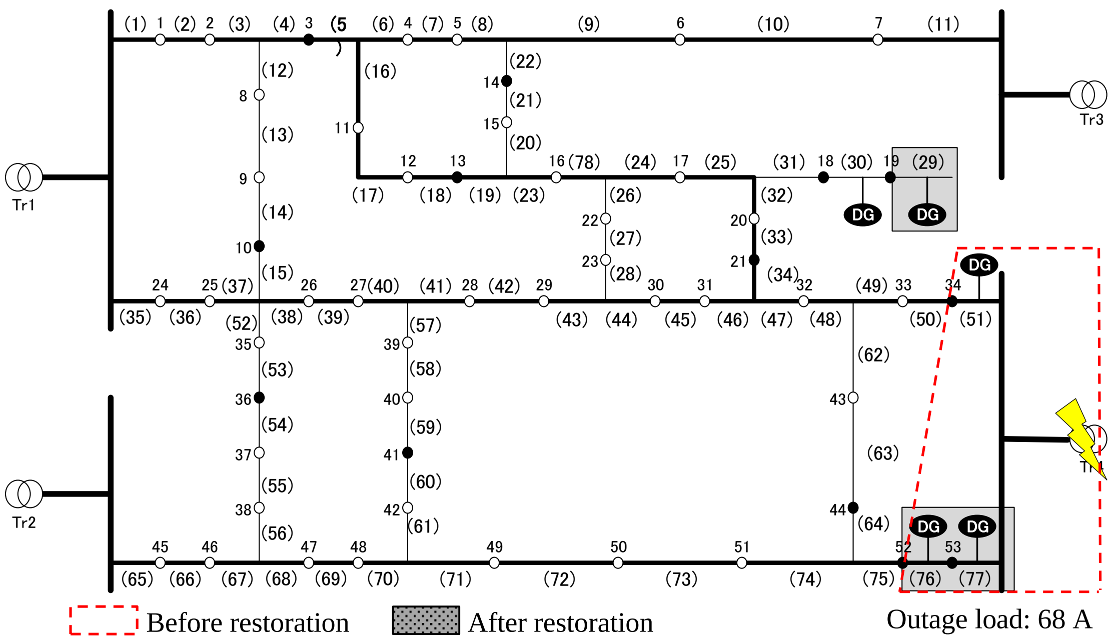


Figure 3-7 System after 20 A of DG is installed

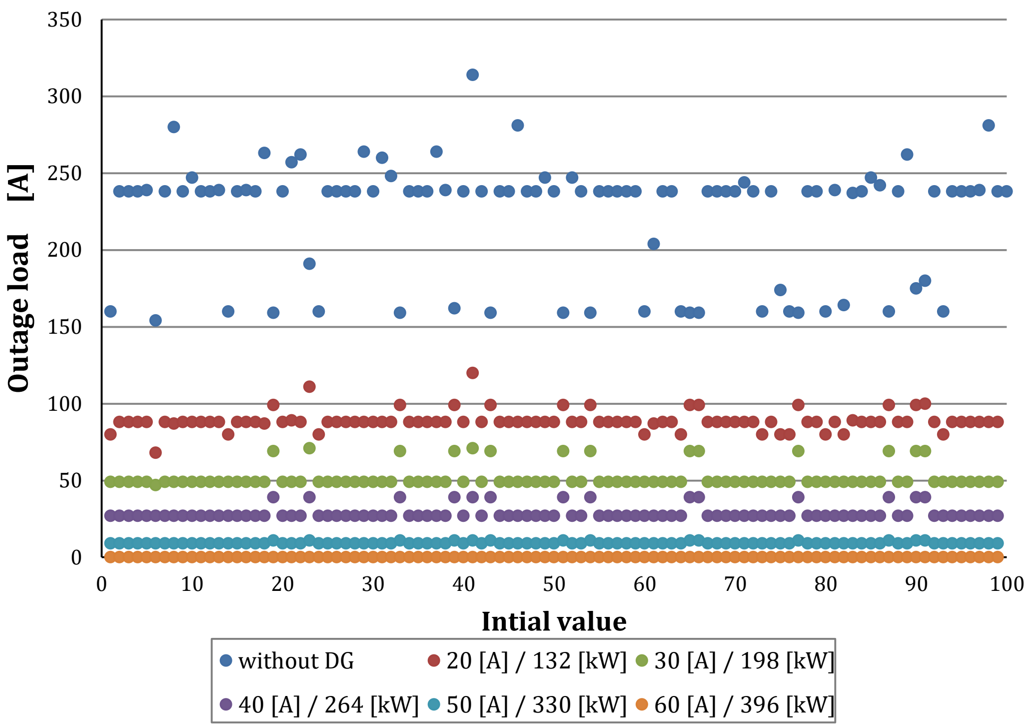


Figure 3-8 Further result after increasing the amount of DG

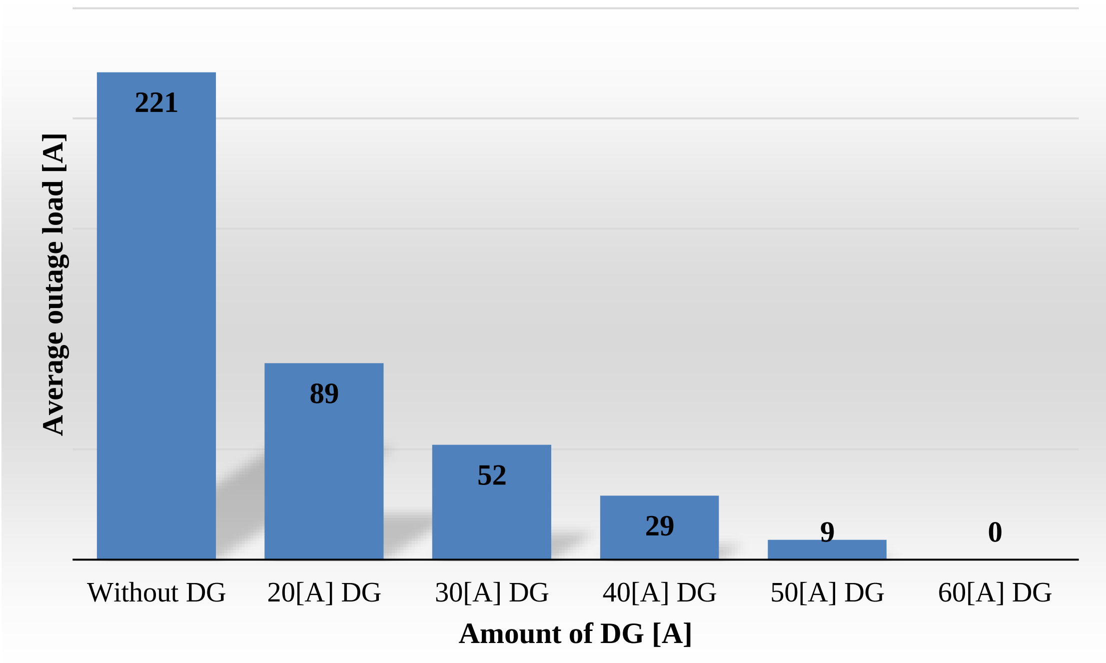


Figure 3-9 Average outage load after increasing the size of DG

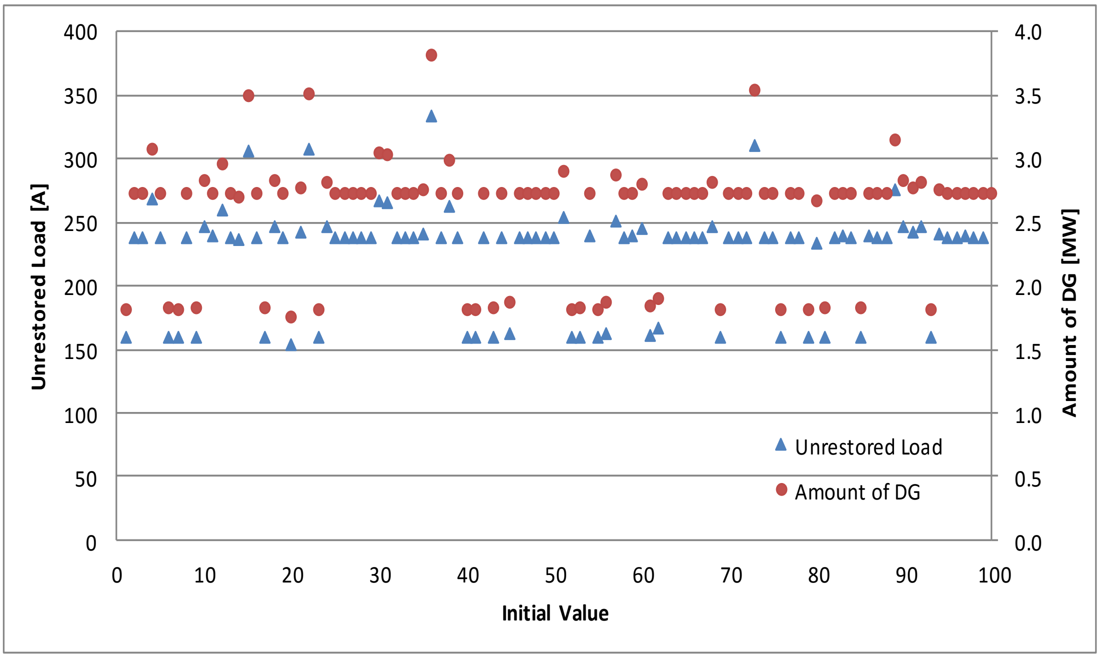


Figure 3-10 Necessary amount of DG needed for full restoration

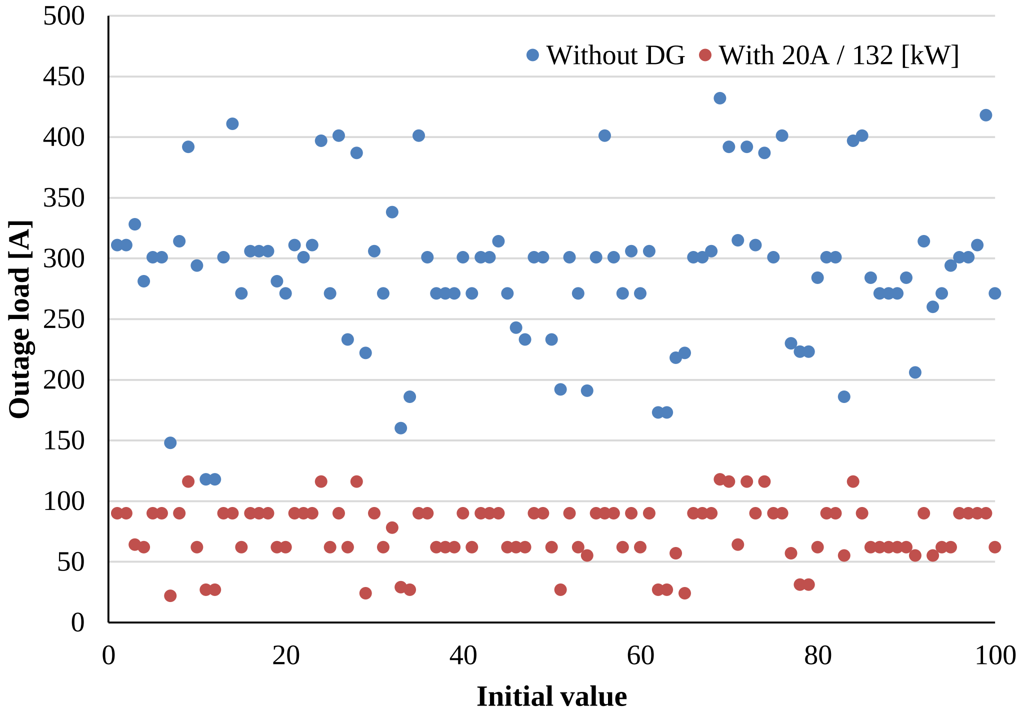


Figure 3-11 Outage load after restoration with and without DG

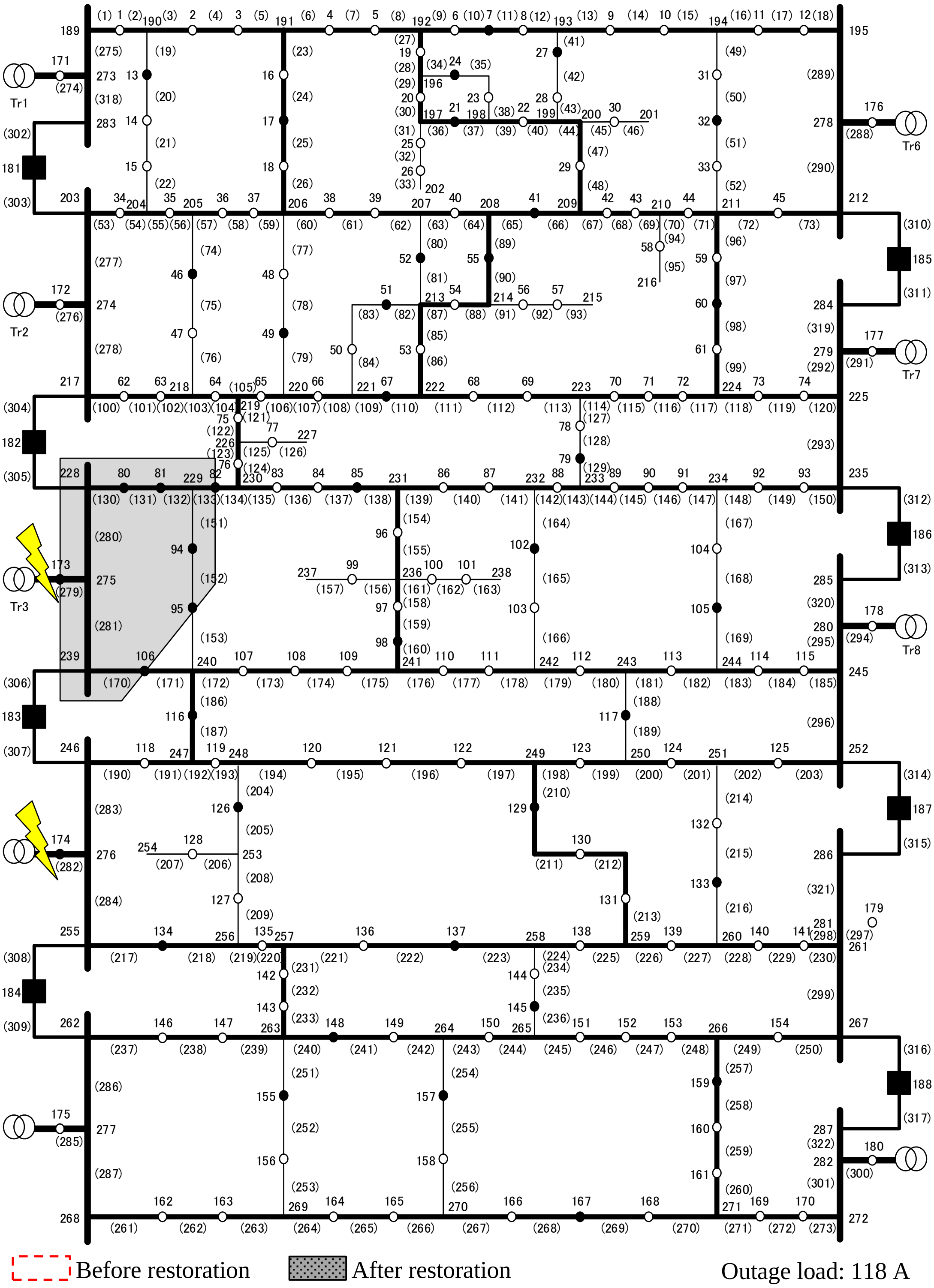


Figure 3-12 Large-scale system before DG installation

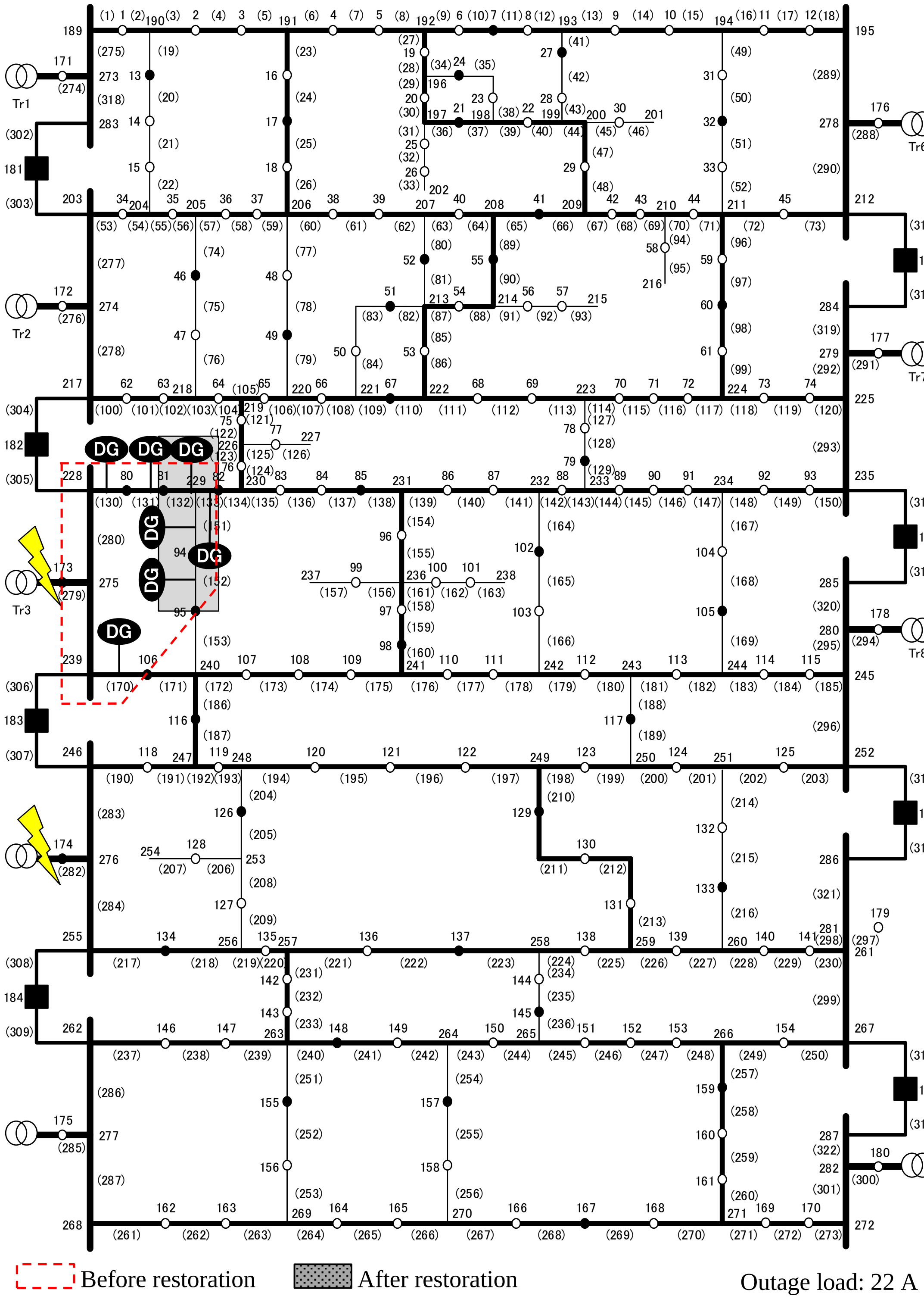


Figure 3-13 Large-scale system after restoration with DGs

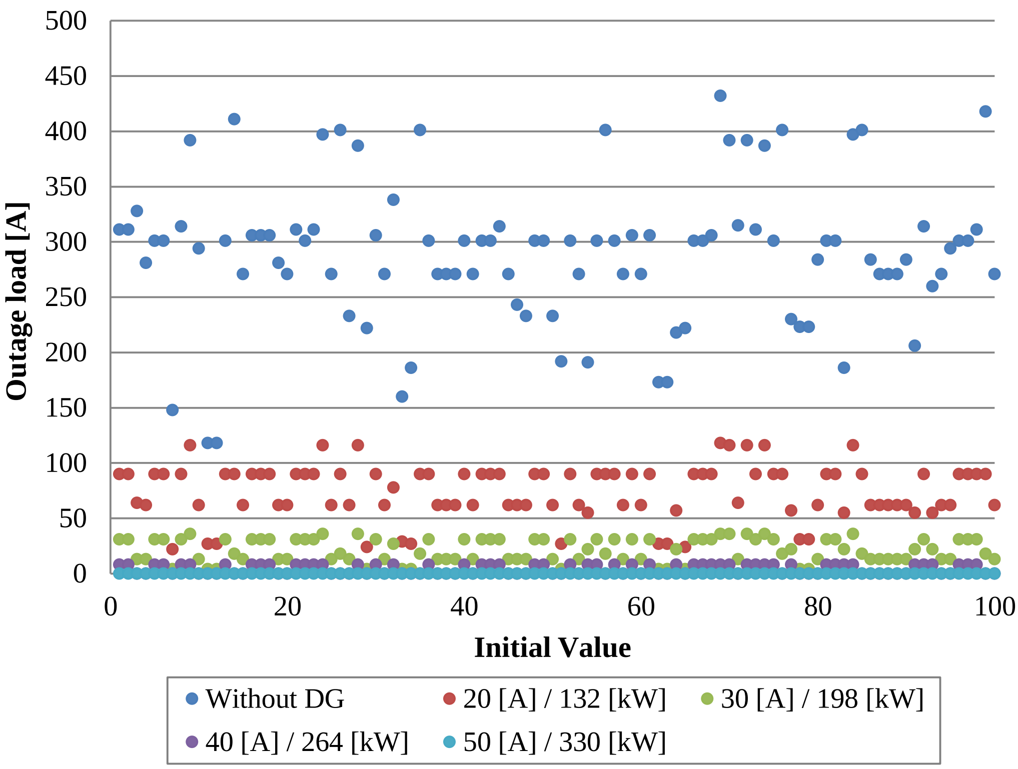


Figure 3-14 Further result after increase the amount of DG

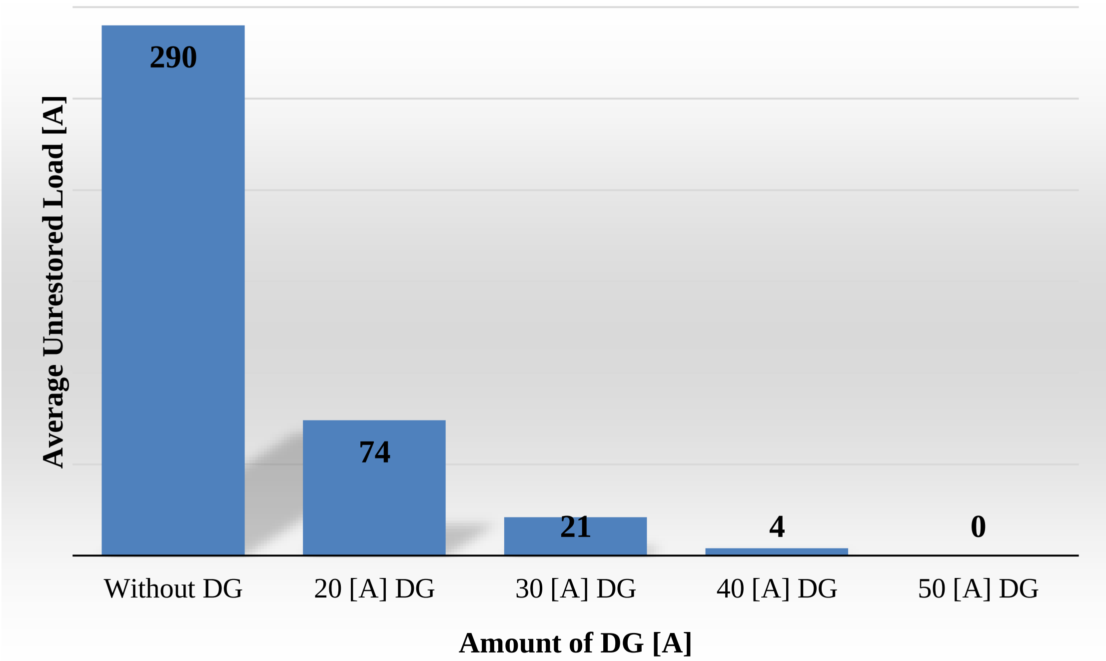


Figure 3-15 Average outage load after installed DG

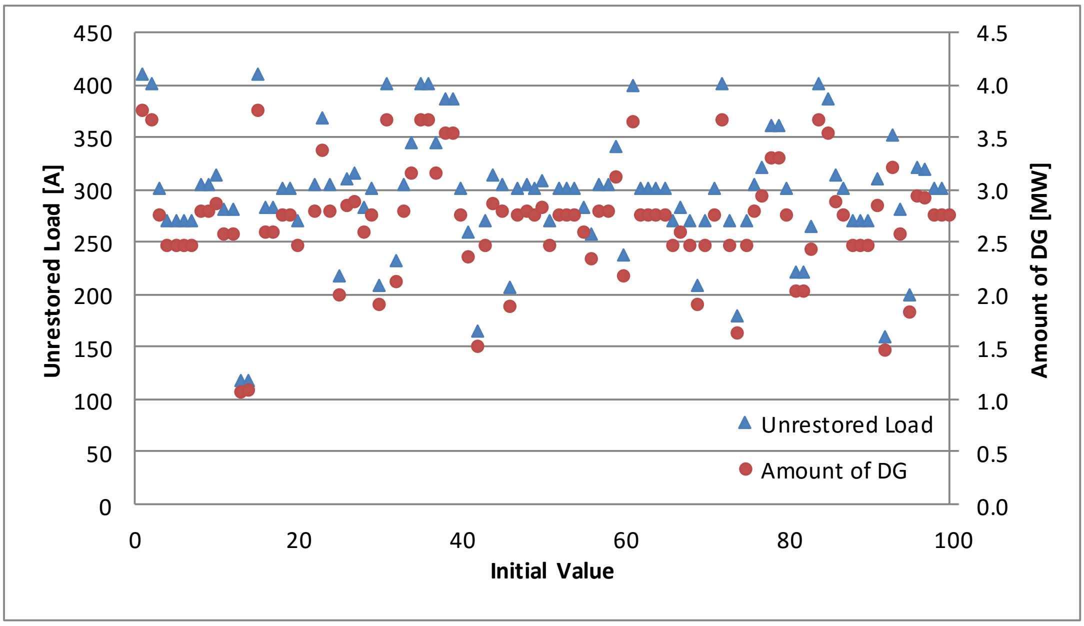


Figure 3-16 Amount of DG which necessary for fully restored the system

3.5. Summary

In this chapter, the simulation model of integrating DG for service restoration optimization was developed. It is also have been tested in both small and large-scale model system with bank-fault condition. The findings from the results are as follows:

1. By installing DG in the outage section after switch reconfiguration during service, the outage areas were reduced in size compared to those resulting without DG.
2. By increasing the size of DG to a certain amount, the system could be fully restored.
3. This new approach has successfully been applied in both small- and large-scale model systems.
4. To avoid the reverse flow phenomenon, accurate calculations of the amount of DGs necessary to fully restore the system have been performed.
5. In conclusion, the use of DG after switch reconfiguration can be considered as a new approach for service restoration.

Chapter 4

MULTI-OBJECTIVE SERVICE RESTORATION

4.1. Introduction

In this section, the combination of previously recent improved genetic algorithm which had reduced the outage load recently and multi-objective optimization called non-dominating sorting genetic algorithm-II (NSGA-II) is develop. Firstly, the theory and procedure of the NSGA-II is explained. Then, the simulation of restoration service by using proposed NSGA-II is set up at small-scale and large-scale model system. Next, the simulation results are presented and discussed. Lastly, the finding from the simulation results are described in the summary.

4.2. Multi-objective Optimization

The objective of multi-objective (MO) optimization is to find the set of acceptable solutions and present them to the decision maker which will then choose among of them. Additional constraints or criteria specified either before or after the search by the decision maker can help guide, refine or narrow the search but will look at the generic case where there is no a priori information from the decision maker [4-1].

4.2.1. Pareto optimality concepts

To compare candidate solutions to the MO problems, the concepts of Pareto dominance and Pareto optimality are commonly used. These concepts were originally introduced by Francis Ysidro, and then generalized by Vilfredo Pareto [4-2]. A solution belongs to the Pareto set if there is no other solution that can improve at least one of the objectives without degradation any other objective.

Formally, a decision vector $\vec{u} = [u_1, u_2 \ldots, u_P]^T$ is said to Pareto-dominate the decision vector $\vec{v} = [v_1, v_2 \ldots, v_P]^T$, in a minimization context, if and only if:

$$\forall i \in \{1, \ldots, N\}, f_i(\vec{u}) \leq f_i(\vec{v}), \text{ and } \exists j \in \{1, \ldots, N\}: f_j(\vec{u}) < f_j(\vec{v}) \qquad (4\text{-}1)$$

In the context of MO optimization, Pareto dominance is used to compare and rank decision vectors: $\vec{u}$ dominates $\vec{v}$ in the Pareto sense means that $\vec{F}(\vec{u})$ is better than $\vec{F}(\vec{v})$ for all objectives, and there is at least one objective function for which $\vec{F}(\vec{u})$ is strictly better than $\vec{F}(\vec{v})$.

A solution $\vec{a}$ is said to be Pareto optimal if and only if there does not exist another solution that dominates it. In other words, solution $\vec{a}$ cannot be improved in one of the objectives without adversely affecting at least one other objective. The corresponding objective vector $\vec{F}(\vec{a})$is called a Pareto dominant vector, or non-inferior or non-dominated vector. The set of all Pareto optimal solutions is called the Pareto optimal set. The corresponding objective vectors are said to be on the Pareto front. It is generally impossible to come up with an analytical expression of the Pareto front.

Figure 4-1 illustrates a Pareto set for two-objective minimization problem. Potential solutions that optimize f_1 and f_2 are shown on the graphs.

4.2.2. Multi-objective genetic algorithm

Being a population-based approach, GA are well suited to solve multi-objective optimization problems. A generic single-objective GA can be modified to find a set of multiple non-dominated solutions in a single run. The ability of GA to simultaneously search different regions of a solution space makes it possible to find a diverse set of solutions for difficult problems with non-convex, discontinuous, and multi-modal solutions spaces. The crossover operator of GA may exploit structures of good solutions with respect to different objectives to create new non- dominated solutions in unexplored parts of the Pareto front. In addition, most multi-objective GA do not require the user to prioritize, scale, or weigh objectives. Therefore, GA have been the most popular heuristic approach to multi-objective design and optimization problems. Jones et al. reported that 90% of the approaches to multi- objective optimization aimed to approximate the true Pareto front for the underlying problem. A majority of these used a meta-heuristic technique, and 70% of all meta- heuristics approaches were based on evolutionary approaches.

As can be seen from Figure 4-2, the first multi-objective GA, called vector evaluated GA (VEGA), was proposed by Schaffer [4-3]. Afterwards, several multi-objective evolutionary algorithms were developed including Multi-objective Genetic Algorithm (MOGA) , Niched Pareto Genetic Algorithm (NPGA) [4-4], Non-dominated Sorting Genetic Algorithm (NSGA) [4-5], Strength Pareto Evolutionary Algorithm (SPEA) [4-6], improved SPEA (SPEA2) [4-7], Pareto-Archived Evolution Strategy (PAES) [4-8], and Fast Non- dominated Sorting Genetic Algorithm (NSGA-II) [4-9]. Note that although there are many variations of multi-objective GA in the literature, these cited GA are well-known and credible algorithms that have been used in many applications and their performances were tested in several comparative studies.

4.2.3. Non-dominated sorting genetic algorithm-II (NSGA-II)

In recent years, studies of multipurpose optimization method based on GA are in great numbers. This method is able to obtain multiple Pareto optimum solution by using GA's multi-point search feature, thus making it possible for an efficient search. NSGA-II includes parent population *Pt*, offspring population *Qt* and genetic operations such as crossover and mutation. However, as proposed approach in this thesis, the improved part of mutation in [4-10] is being implement in this NSGA-II to make it improved NSGA-II. In addition, other step is same as illustrated in Figure 4-3. Elite population is saved to the parent population *Pt*. Then, offspring population Qt is used as child population where the new population is saved. Next, *Qt* is updated through the genetic operations [4-11].

Step 1: A combined population *Rt* (*Pt+Qt*) is formed. This allows parent solutions to be compared with the child population, thereby ensuring elitism. The population *Rt* is of size *2N*.

Step 2: The population *Rt* is sorted according to non-domination and different non-dominated fronts *F1*, *F2*, and so on are found. The new parent population *Pt+1* is formed by adding solutions from the first front *F1* and continuing to other fronts successively till the size exceeds *N*.

Step 3: Individual of each front are used to calculate the crowding distance-the distance between the neighboring solutions. Thereafter, the solutions is important, the crowded comparison criterion uses a relation.

Step 4: *Qt+1* is made using crowded comparison tournament selection, crossover and mutation based on *Pt+1*.

Multi-objective optimization problem is a comprehensive assessment while clarifying the trade-off relation between two or more objective functions. It is also reasonable to seek a Pareto optimum solution that is assured to be better than other solutions. Fast non-dominated sort is an operation that ranks each individual based on the valuation basis according to the dominance relationship of Pareto optimum solution. Rank 1 is considered as the best, as the numbers go higher, the value drops. First, for each individual, dominant and dominated individuals are counted at the same time. Next, the individual that is not dominated at all is considered as rank 1. Only individuals of rank 1 are saved to the next search. To find the next Pareto front, the rank 1 individuals are excluded, while the remaining individual number is subtracted by 1. The processes up till now is then repeated. The whole repeated process above is the ranking operation. Fast non-dominated sorting diagrammatic illustration is shown in Figure 4-4.

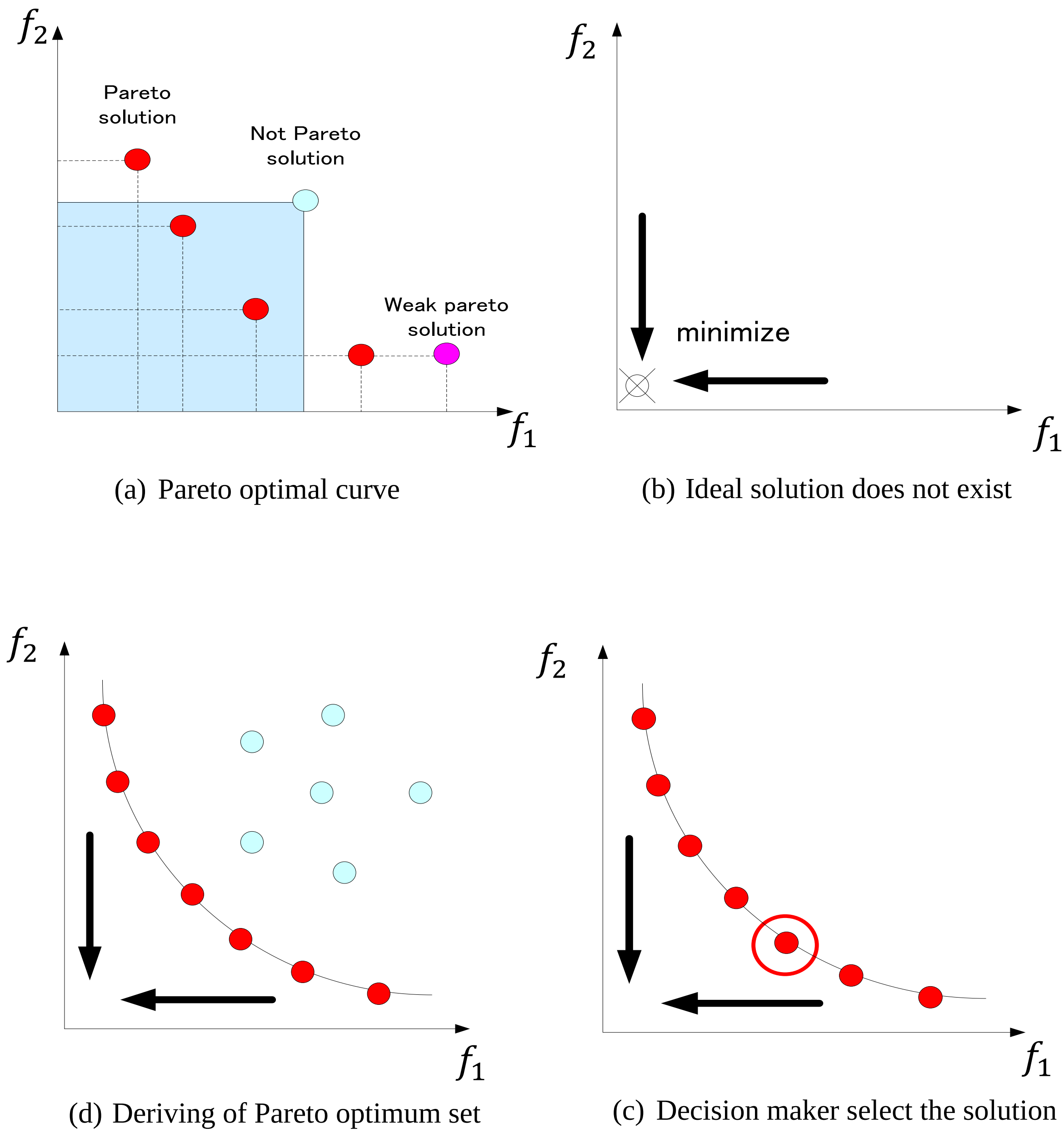


Figure 4-1 Illustration of Pareto front for optimization problem

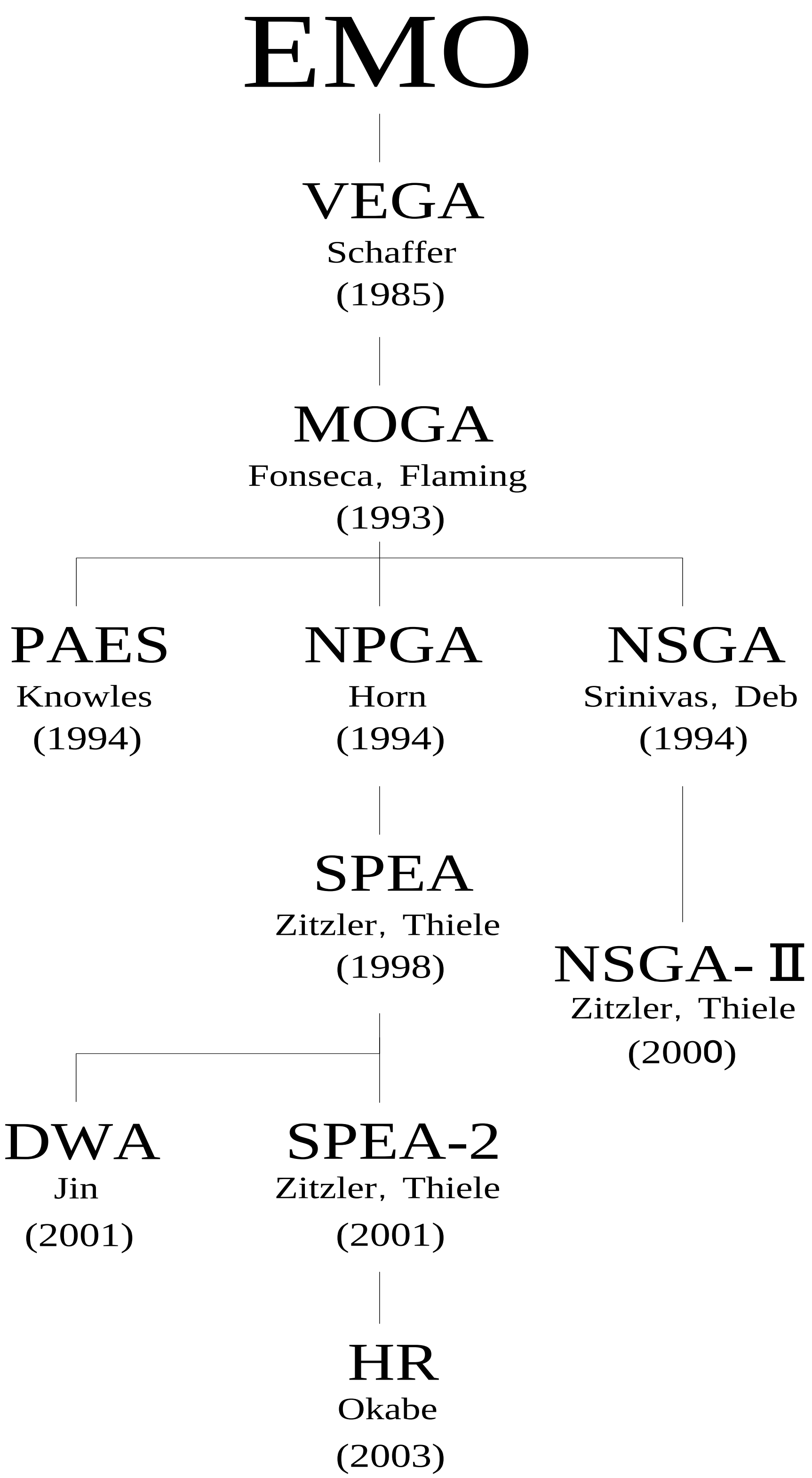


Figure 4-2 History of evolutionary multi-objective (EMO)

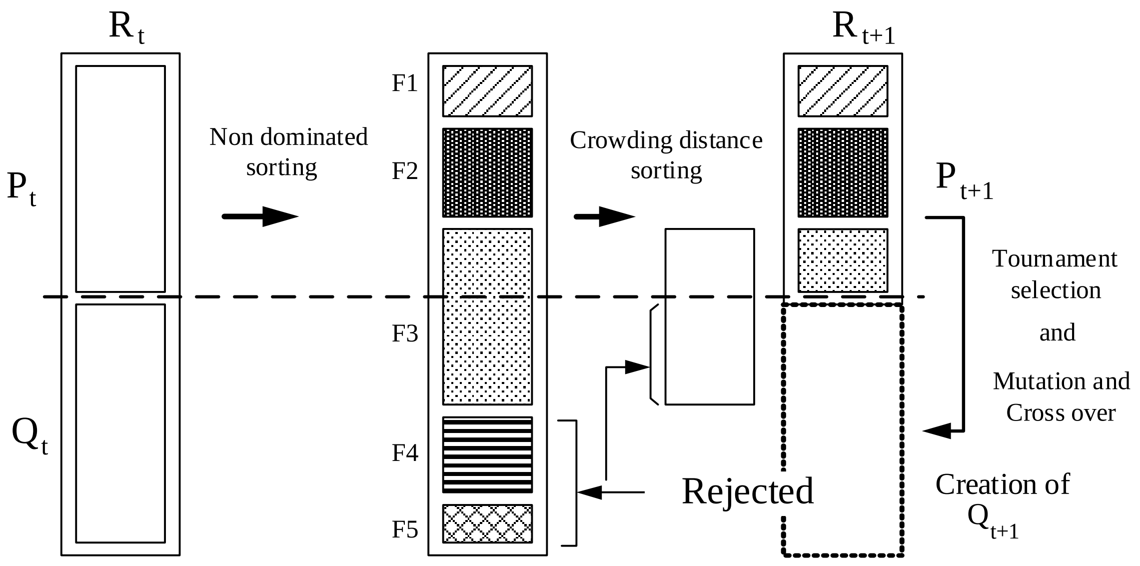


Figure 4-3 Illustration of NSGA-II

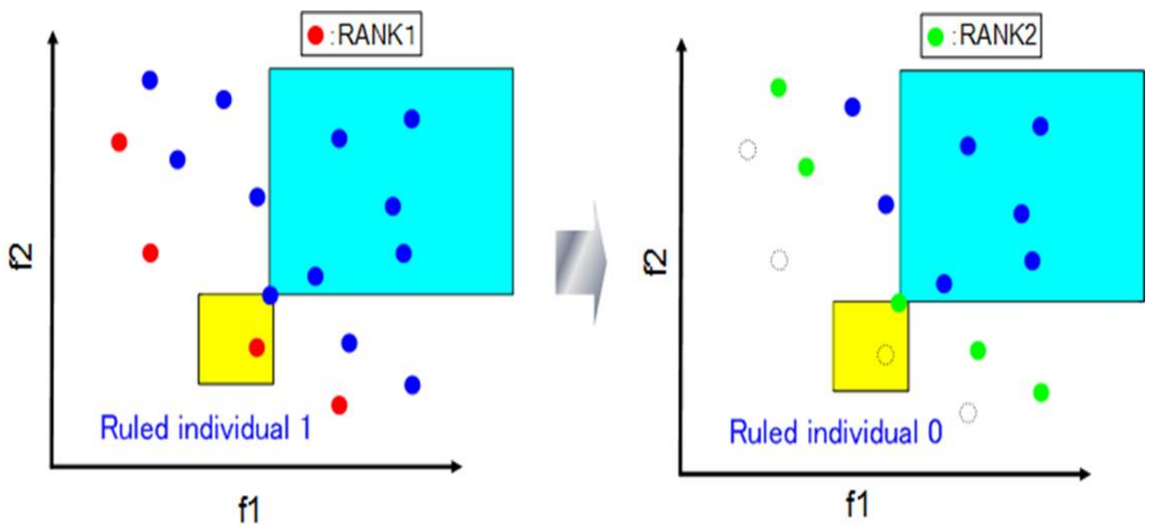


Figure 4-4 Non-dominated sorting

4.3. Problem Formulation

4.3.1. Objective Function

Differ to conventional GA, for multi-objective NSGA-II required separated objective function as below with f_1 and f_2 are targeted to be minimized:

Min $$f_1 = \sum_{m=1}^{L} (inn_m) \tag{4-2}$$

Min $$f_2 = \sum_{n=1}^{L} (loss_n) \tag{4-3}$$

Where, L is number of load section, inn_m is outage load of section-m, and $loss_n$ is distribution loss of section-n.

4.4. Result and Discussion

4.4.1. Small-scale system

Figure 4-5 shows the result outage load for small-scale of proposed NSGA-II in random of initial value 1 to 100. From the graph, it can be realized that the proposed NSGA-II recorded smallest outage load which is 151 A and the biggest is 246 A while the average is 159 A. The Pareto optimal graph of initial 40 is shown in Figure 4-6. Because of this is trade-off problem, minimum value of outage load which is 151 A is chosen even the distribution loss is slightly bigger than previous method which is 311.1 kW. Table 4-1 and Figure 4-8 show the full comparison with other previous researches. It can be seen that the outage loads were decreasing through the references. On top of that, NSGA-II give the best result which is reduced 69% from the 488 A outage load during fault condition, where approximately less 2% compared to previous method 154 A. However, there are slightly increased of distribution loss but it still considerable number. For details of the system after restoration for best of NSGA-II is illustrated in Figure 4-10.

Table 4-1 Comparison with previous work

References	**K. Aoki (1990)**	**K. Iwasaki (2007)**	**I. Michibata (2008)**	**NSGA-II**	
				Solution 1	**Solution 2**
Outage load [A]	238	160	154	151	152
Distribution loss [kW]	192.2	266.7	280.8	311.1	281.1

4.4.2. Large-scale system

For the purpose to approve the effectiveness of this proposed NSGA-II, it also tested in much strict condition which larger network with a lot of power banks, switches and load added with double-bank fault as simulation condition. The result of outage load by using proposed NSGA-II in random of initial value 1 to 100 is shown in Figure 4-11. From the graph, the least value of outage load is 107 A and the largest is 415 A while the average is 162 A. Additionally, the Pareto optimal graph of smallest outage load which is initial 65 is shown at Figure 4-12. Then, Table 4-2 and Figure 4-13 show the full comparison with other previous researches, which it can be seen that the outage loads are decreasing through the references with NSGA-II give the best result. Furthermore, it can be realized that proposed NSGA-II recorded smaller outage load than conventional GA which it reduced 90% from the 1028 A outage load during fault condition, where approximately less 11% compared to previous method. Whereas, distribution loss of NSGA-II also decreased compared to conventional GA. For details of the system after restoration for best of NSGA-II is illustrated in Figure 4-15.

Table 4-2 Comparison with previous work

References	***K. Iwasaki (2007)***	***I. Michibata (2008)***	***NSGA-II***
Outage load [A]	604	118	107
Distribution loss [kW]	914	1089	1080

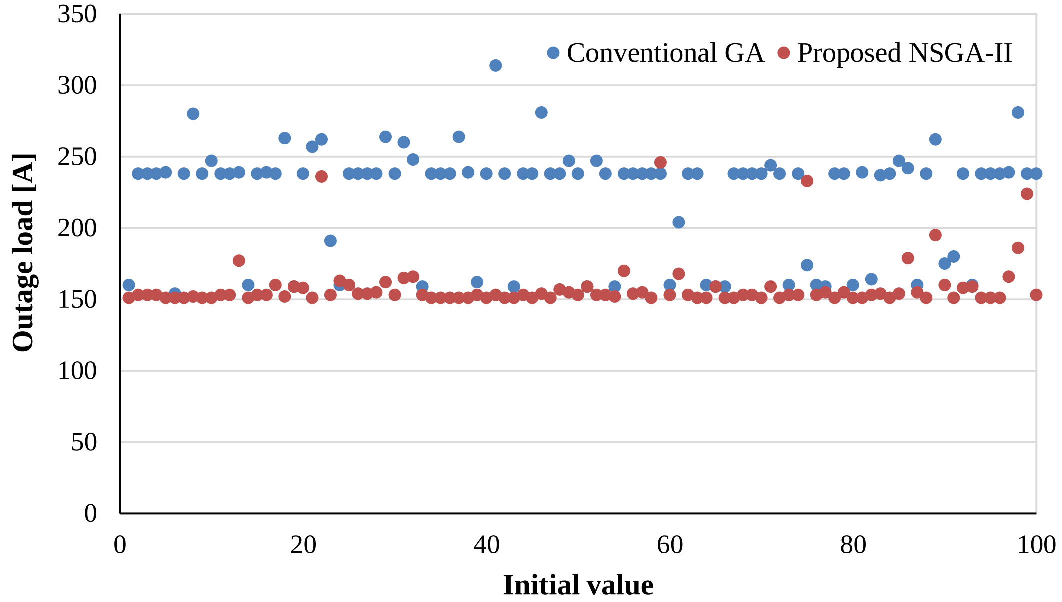


Figure 4-5 Result of outage load for small-scale

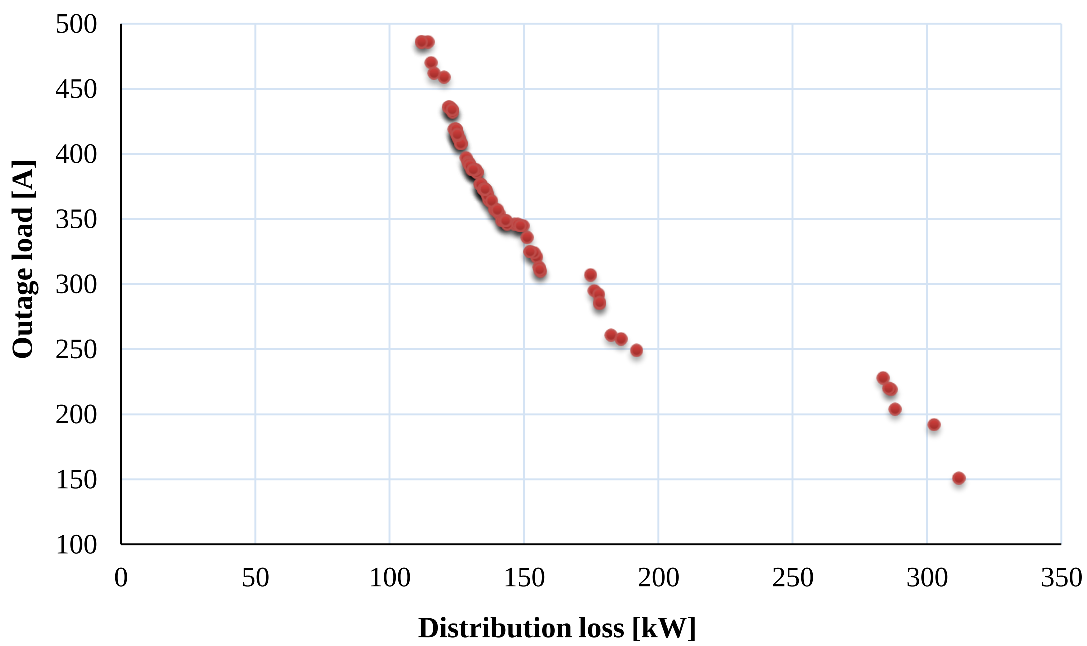


Figure 4-6 Pareto optimal of initial 40th

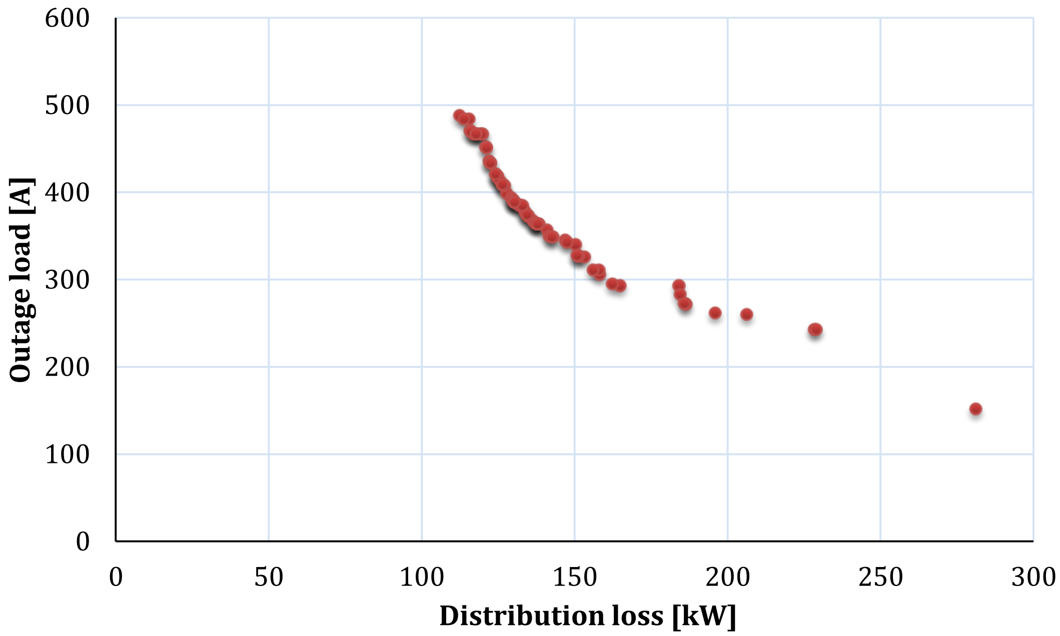


Figure 4-7 Pareto optimal of initial 54th

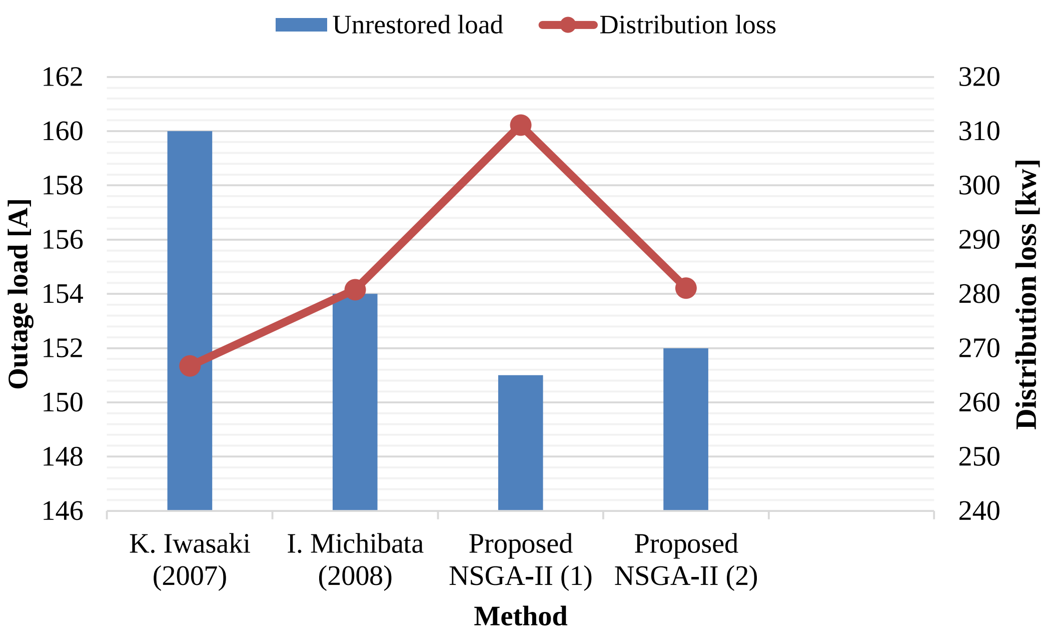


Figure 4-8 Result comparison of previous work

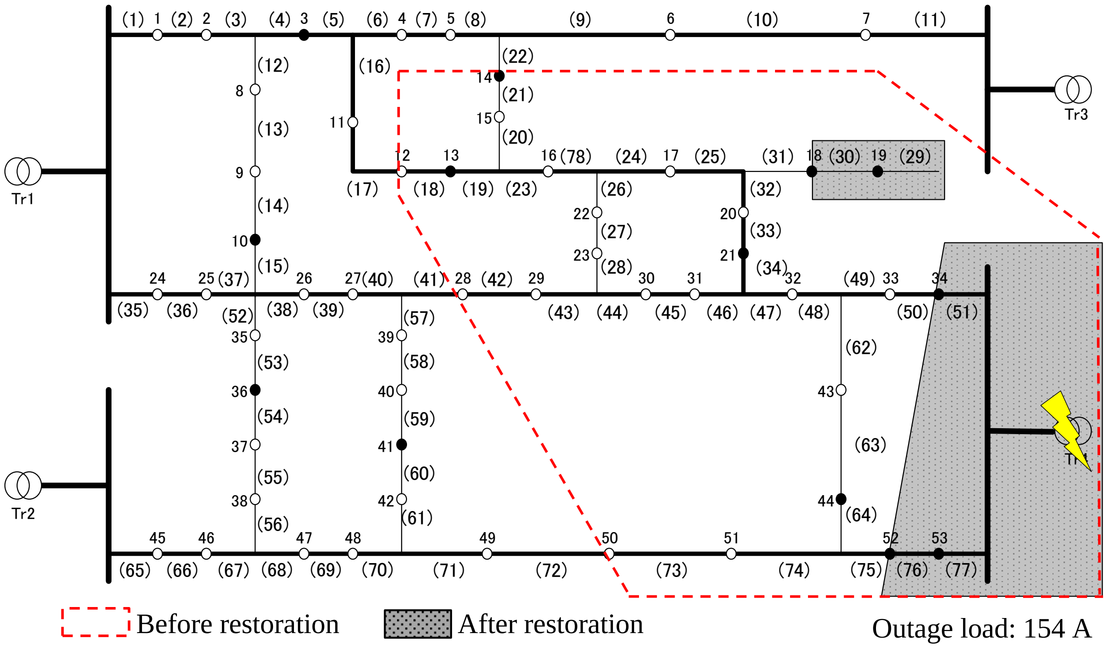


Figure 4-9 Small-scale system after restoration with conventional GA

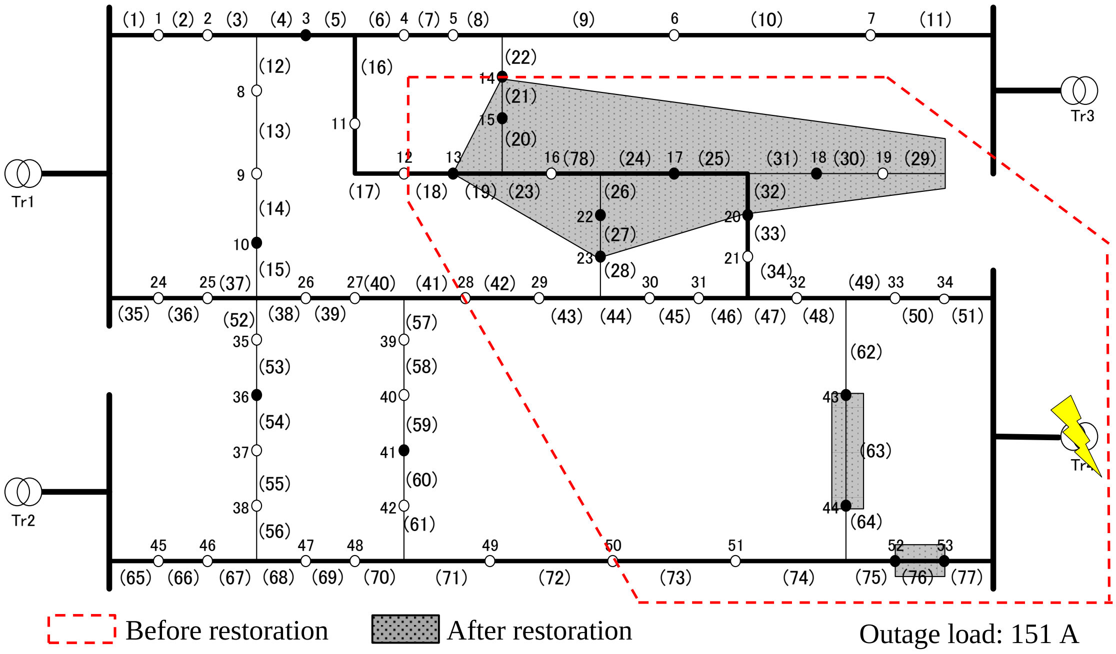


Figure 4-10 Small-scale system after restoration with NSGA-II

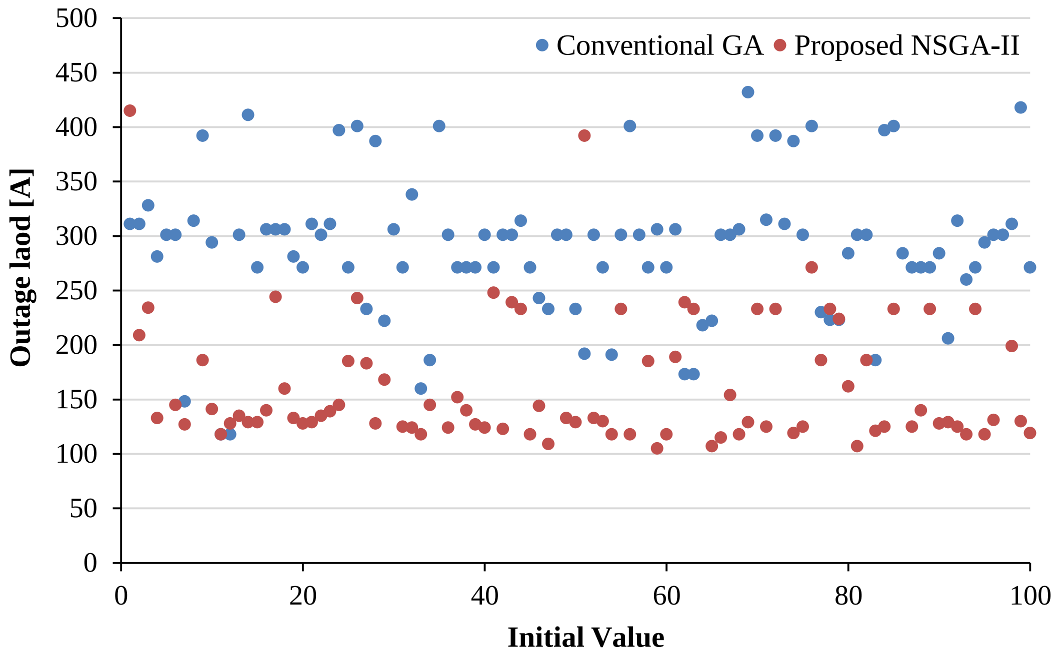


Figure 4-11 Result of outage load for large-scale

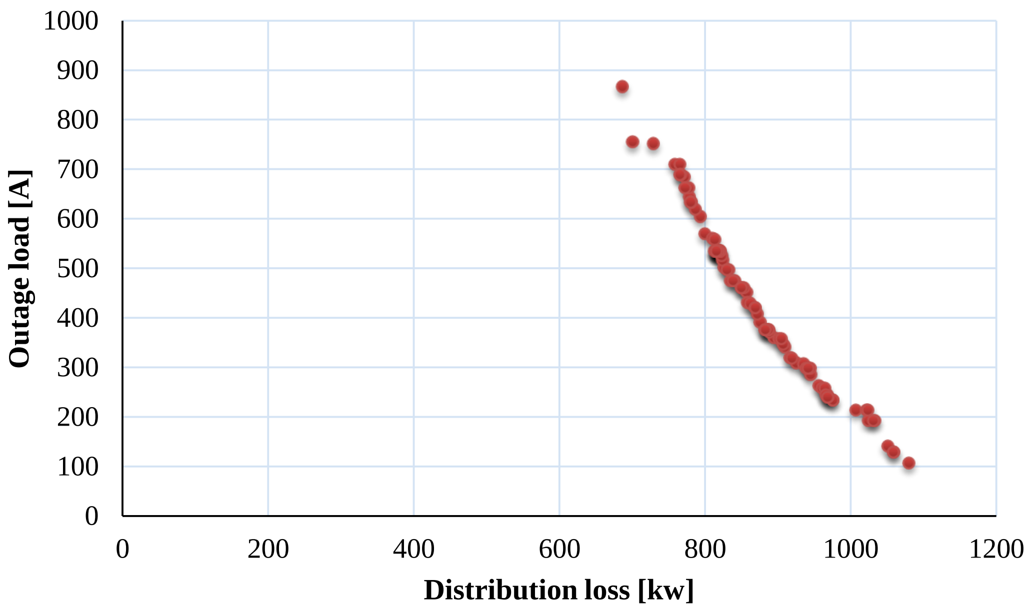


Figure 4-12 Pareto optimal of initial 65th

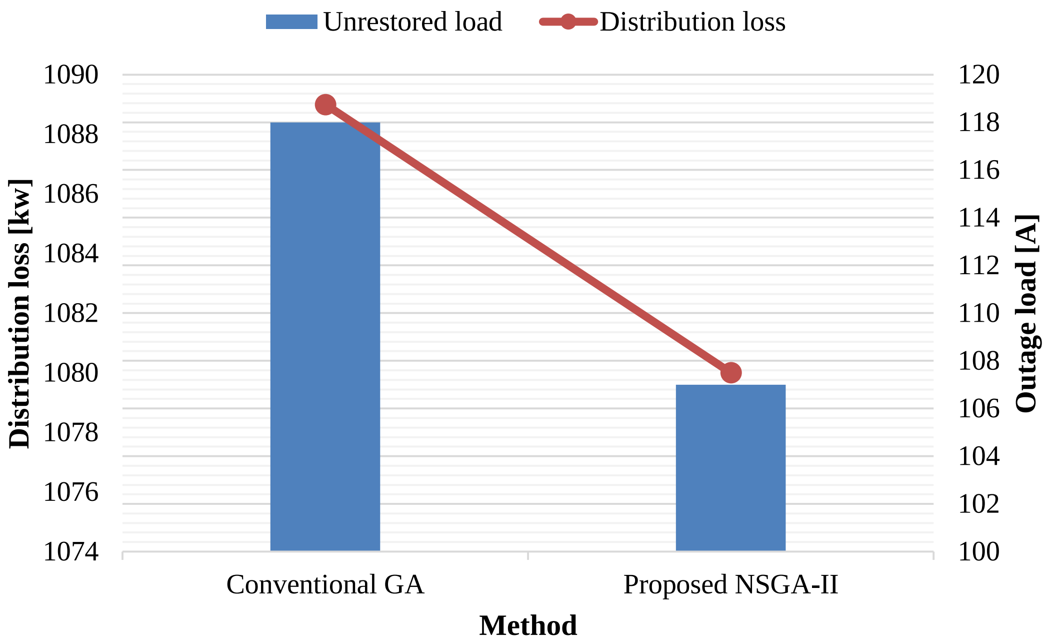


Figure 4-13 Result comparison with previous work

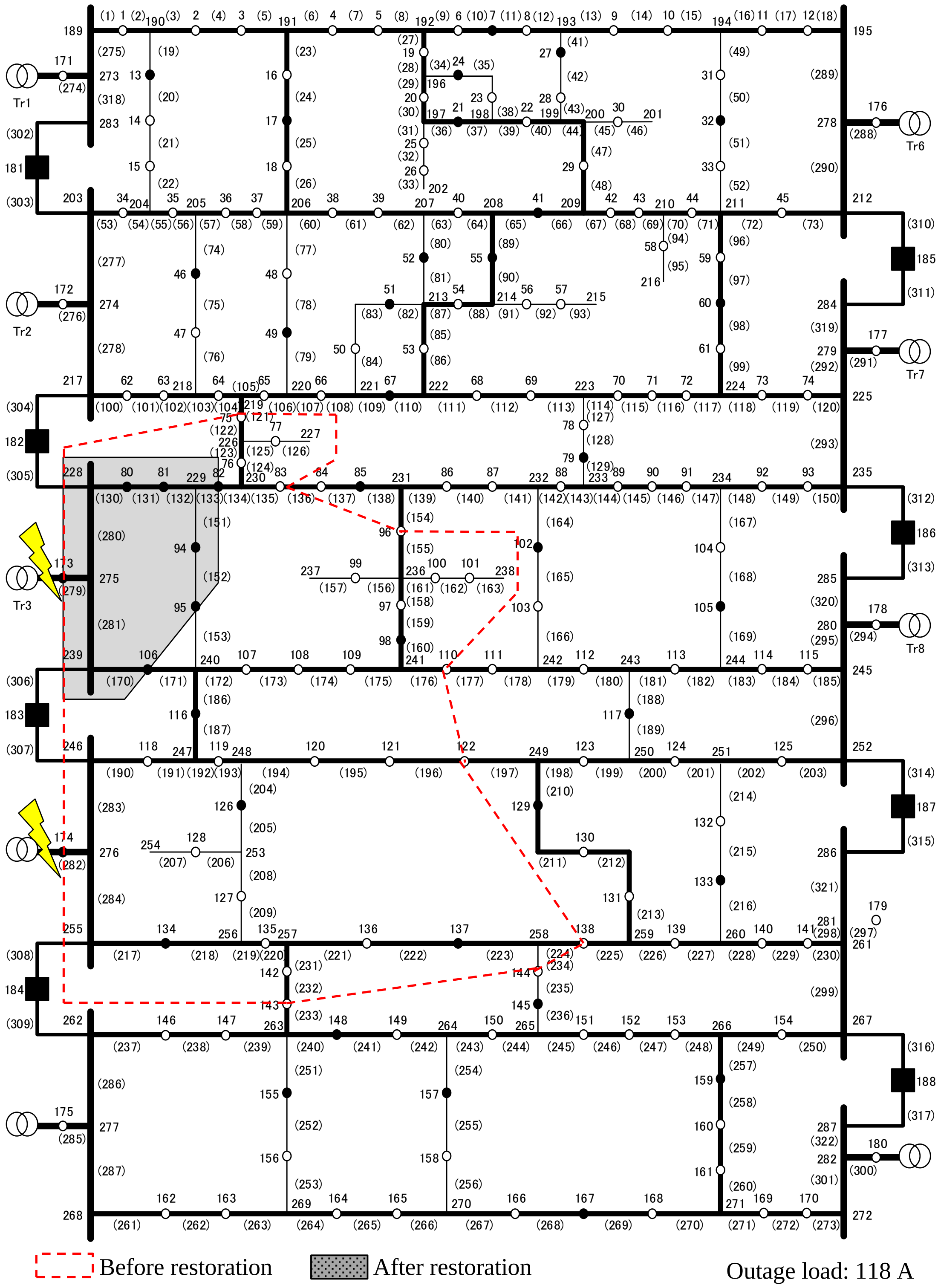


Figure 4-14 Large-scale system after restoration with conventional GA

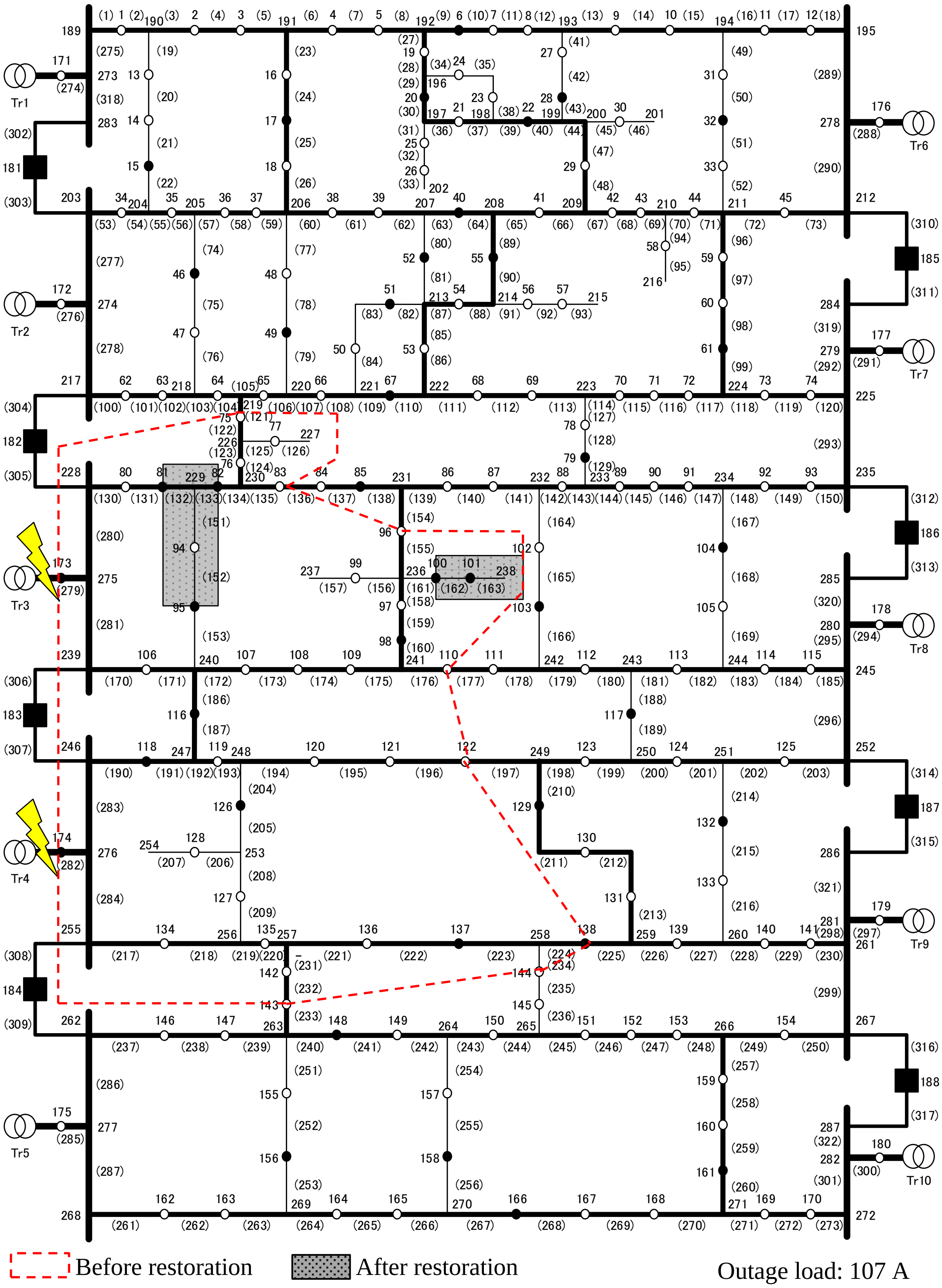


Figure 4-15 Large-scale system after restoration with NSGA-II

4.5. Summary

In this chapter, the multi-objective optimization of service restoration was proposed. Based on the theory of non-dominated algorithm-II (NSGA-II), a novel algorithm for service restoration optimization during substation fault was invented. In addition, the method was tested in a small-scale system with a single-bank fault, as well as the more strict conditions of a large-scale system with a double-bank fault. The findings from the simulation are as follows:

1. For both conditions, the proposed method reduced the outage areas to 151 A and 107 A for the small- and large-scale systems, respectively.
2. However, the distribution loss was slightly increased for the small-scale system, which remained in a considerable range value.
3. Fortunately, the large-scale model demonstrated that NSGA-II is better than conventional GA, in which both the outage area and distribution losses were decreased by using the NSGA-II method.
4. This proposed method also provides many options to choose with the Pareto optimal solution, which has not been done before.
5. To conclude, compared to the previous methods, the proposed NSGA-II could optimize the restoration of service.

Chapter 5

CONCLUSIONS

In this study, to optimize service restoration by minimizing the impact of the outage after a system fault, a novel combinatorial method of integrating distributed generators and applying non-dominated genetic algorithm (NSGA-II) is proposed. The outcome of each chapter is described below.

Chapter 1 Introduction

Since electricity is a vital source in our daily lives, service restoration after a fault has become more important, especially as distribution systems become automated to improve service quality. The problem of service restoration consists of choosing a procedure for the resumption of power transmission to system sections that were blacked out by a feeder fault or construction work.

Therefore, it is a difficult, complex, delicate, and time-consuming task, as losses to customers and the industry mount rapidly until service is restored. Moreover, as the number of switches in the system increases, the solution options to choose from are increased, and switch reconfiguration becomes increasingly complicated. To fulfill increasing demands for electricity, the extension of distribution systems is necessary, although this increases the potential and risk of faults. Furthermore, service restoration problems involve multi-objective and multi-constraint problems, further complicating the algorithms. Substation faults add complexity to the problem of service restoration.

In recent years, numerous heuristic methods have been applied and improved in service restoration. Unfortunately, the improvement of GA has reached the limit, necessitating the application of other approaches. Based on the need to improve the reliability and effectiveness of service restoration, the application of distributed generators (DG) in distribution system and multi-objective optimization methods has been reviewed. From a literature review, DG is used in distribution systems, but not for service restoration. On the other hand, the non-dominated genetic algorithm-II (NSGA-II) is the best solution for a multi-objective problem.

Chapter 2 Application Genetic Algorithm in Service Restoration

The recent improvement of genetic algorithm and its application in service restoration were introduced. The improvement allowed the minimization of the outage area during service restoration. It was approved by testing the method in a small-scale system and in a large-scale system. From the previous numerical results, the following can be concluded:

1. The GA that developed by I. Michibata et al. (2008) had gave better result of outage load in comparison to that achieved by previous methods.
2. Both outage areas and distribution losses are minimized in both small- and large-scale systems.
3. However, outage areas remain, even after restoration has been completed. In theory, better results could be achieved.
4. Because the problem of service restoration involves several constraints and factors, the weighting factor complicates the identification of an optimal value and the best result.
5. Moreover, the method has already been improved several times and reached a developmental limit; it is necessary to apply other methods, such as multi-objective optimization methods.

Chapter 3 Integrating Distributed Generators in Service Restoration

To optimize service restoration, the simulation model integrating DG has been developed. It is has also been tested in both small- and large-scale model systems with bank-fault conditions. The findings are as follows:

1. By installing DG in the outage section after switch reconfiguration during service, the outage areas were reduced in size compared to those resulting without DG.
2. By increasing the size of DG to a certain amount, the system could be fully restored.

3. This new approach has successfully been applied in both small- and large-scale model systems.
4. To avoid the reverse flow phenomenon, accurate calculations of the amount of DGs necessary to fully restore the system have been performed.
5. In conclusion, the use of DG after switch reconfiguration can be considered as a new approach for service restoration.

Chapter 4 Multi-objective Service Restoration

In this chapter, the multi-objective optimization of service restoration was proposed. Based on the theory of non-dominated algorithm-II (NSGA-II), a novel algorithm for service restoration optimization during substation fault was invented. In addition, the method was tested in a small-scale system with a single-bank fault, as well as the more strict conditions of a large-scale system with a double-bank fault. The findings from the simulation are as follows:

1. For both conditions, the proposed method reduced the outage areas to 151 A and 107 A for the small- and large-scale systems, respectively.
2. However, the distribution loss was slightly increased for the small-scale system, which remained in a considerable range value.
3. Fortunately, the large-scale model demonstrated that NSGA-II is better than conventional GA, in which both the outage area and distribution losses were decreased by using the NSGA-II method.
4. This proposed method also provides many options to choose with the Pareto optimal solution, which has not been done before.
5. To conclude, compared to the previous methods, the proposed NSGA-II could optimize the restoration of service.

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