INTRODUCTION

During recent years, distribution systems have received great attention mainly due to the restructuring and privatization processes of the power sectors that many countries are undergoing. This has changed the utilities management towards capital controlled business where owners are trying to maximize their profits with cost optimization. Thus the most challenging tasks for the utilities are to reduce costs and improve reliability at the same time. There are very few research papers focusing on the interruption cost and/or life-cycle cost of the distribution system [1-5]. Furthermore, none of them considered outage cost and life-cycle cost of a large size system and load curve of distribution system, where modern optimization techniques such as genetic algorithm should be applied. This paper presents an efficient method for improving reliability on electrical distribution system by considering annual load curve changing, and failure rate changing data to relocate feeder-switches and pole-mounted RTUs in the main feeder. The design of distribution system is optimized by minimizing outage cost of customers and utility providers as well as the feeder device life-cycle cost considering feeder device relocation with approximate actual load profile. Genetic Algorithm is applied to solve the optimization problem. The customer cost and utility cost can be minimized with limited number of feeder-switches and pole-mounted RTUs.

1. NOTATION

\( n \) Total number of sections in the main feeder, and the number of feeder-switches must not be greater than the amount of feeder which provided by the utility provider

\( m \) Number of pole-mounted RTUs

\( j \) Number of feeder-switches that are installed at the first time and later are relocated to new positions

\( q \) Number of pole-mounted RTUs that are installed at the first time and later are relocated to new positions

\( IC_i \) Customer outage cost due to outage in section \( i \) (Baht)

\( UC_i \) Utility outage cost due to outage in section \( i \) (Baht)

\( SSC \) Total cost of feeder switches (Baht); \( SSC = SC + SIC \)

\( RSC \) Total cost of pole-mounted RTUs (Baht); \( RSC = RIC + RSC \)

\( SC \) Average cost of a feeder-switch component including maintenance cost (Baht)

\( RRC \) Average cost of a pole-mounted RTU component including maintenance cost (Baht)

\( SIC \) Average cost of a feeder-switch that is installed at the first time and later are relocated to new positions (Baht)

\( RIC \) Average cost of a pole-mounted RTU that is installed at the first time and later are relocated to new positions (Baht)

\( LCC \) Life cycle cost (Baht)

\( Li \) Load of section \( i \) (kW)

\( C_{ij} \) Customer cost multiplier of section \( j \) due to a fault at section \( i \) (Baht/kW)

\( \lambda_i \) Outage rate of section \( i \) (Failure/year)

\( B_{ij} \) Utility cost multiplier of section \( j \) due to a fault at section \( i \) (Baht/kW)

\( x_i \) Position of feeder-switch \( i \) (kms.). If \( i = \) number of section, \( x_i \) is the position of a normally open switch.

\( PR_i \) Position of a right-side RTU of section \( i \)

\( PL_i \) Position of a left-side RTU of section \( i \)

\( A_k \) Average load at load area \( k \) (KW)

\( F_k \) Average failure rate at area \( k \) (times/year)

\( Res_j(\%) \) The load percentage of residence customers

\( Com_j(\%) \) The load percentage of commercial customers

\( Ind_j(\%) \) The load percentage of industrial customers

\( Impt_j(\%) \) The load percentage of very important places

\( fr(\%) \) The customer outage cost function of resident customers, its input is outage duration and its output is damaged cost per kW (Baht/kW)

\( fc(\%) \) The customer outage cost function of commercial customer, its input is outage duration and its output is damaged cost per kW (Baht/kW)

\( fl(\%) \) The customer outage cost function of industrial customer, its input is outage duration and its output is damaged cost per kW (Baht/kW)

\( fp(\%) \) The customer outage cost function of important places, its input is outage duration and its output is damaged cost per kW (Baht/kW)

\( Y_j \) Outage duration of section \( j \) due to a fault at section \( i \) (hours)

\( ELo_i \) Average electric sale price of large consumers per kWh at time \( t \) (Baht/kWh)

\( ES_i \) Average electric sale price of small consumers per kWh at time \( t \) (Baht/kWh)

\( T_f \) Amount of time for finding a faulty location and isolating it (hours)
Ts  Amount of time for switching to an alternate source without preparation (hours)
Te  Amount of time for a crew to reach to a faulty feeder from a crew center (hours)
V  Velocity of a crew vehicle for inspecting a faulty feeder (km/h)
Lk  Amount of load at section k.
Lt  Amount of load that can be transferred to other feeder
ceil()  A function for changing a decimal value to its nearest integer value by increasing, such as ceil(4.5) has its result equal to 5.
floor()  A function for changing a decimal value to its nearest integer value by decreasing, such as floor(4.5) has its result equal to 4.

2. RADIAL FEEDER CONFIGURATION

In this research, we focus on radial feeder configuration because it is the most common feeder architecture in Thailand. A radial feeder configuration is presented in Figure 1, where all main feeders start from a substation. The first protective device is a breaker with an over-current/earth fault (OC/EF) relay. Fuses are installed at every branch and coordinately work with the OC/EF relay. The main feeder can be partitioned into sections by feeder-switches such as disconnecting switches that can be installed with a remote terminal unit (RTU) for controlling and monitoring from an operation center for fast operating. Some feeders, that are very long and pass through violent area, prefer reclosor installations. The reclosor can automatically reclose when the corresponding fault disappears.

Figure 1. Radial Feeder Configuration

2.1 Service Restoration Operation

If a permanent fault exists in a main feeder, generally an OC/EF relay detects a fault and trips circuit breaker to isolate fault from the distribution system. Figure 2 presents a configuration of feeder-switches and pole-mounted RTUs. A main feeder, that installs feeder-switches to segment areas into sections, has service-restore procedure to recover load, as follows:
1) Find the faulty location and isolate the fault by opening two adjacent switches that cover the faulty location. If switches are installed with a RTU, fault finding is easier and switching operation can be done remotely.
2) Restore the services from substation to customers that are not in the faulty area by closing circuit breaker.
3) Perform load transfer from other feeders by closing a normally-open (NO) switch if the other feeders have load remain with load profile consideration.
4) Repair the faulty equipment and restore service to normal state.

Figure 2. Configuration of Feeder-Switches and Pole-Mounted RTUs

3. RESEARCH METHODOLOGY

We consider feeder-switches and pole-mounted RTU relocation to minimize customer interruption cost and utility interruption. The design of the distribution system is optimized by considering minimizing outage cost (i.e., customer interruption cost and utility interruption cost) as well as any cost of feeder-device constraints. Essentially, load profile in each customer area is considered to make the design more realistic. The number of feeder-switches and pole-mounted RTUs are minimized for the feeder. Also the locations of the protective devices in the system are analyzed for the best positions. Genetic algorithm is a selected technique to make an optimization approach.

3.1. Basic Assumption

We consider a radial distribution system, which is divided into sections where each section has a number of load points. Each of the load points has information that is used to calculate average of load in each section/area such as the first 0.5 km is 650 kW and the next 0.5 km is 600 kW in a main feeder, as shown in Figure 3. The proposed protective devices are switches which partition the main feeder into sections. The following basic assumptions are used in formulation of our objective function.

- A main feeder has various types of customers. There is only one type of customers in a load point because types of customers in each feeder are designed in a substation configuration. There are four types of customers: residential, commercial, industrial customers and important-place customers such as king palace.
- The known information of each load point are the number and type of customers, permanent failure rate ($\lambda$), mean repair time ($r$), number of customers, and number of connected KVA.
- Only permanent faults are considered because they affect on electrical crew operation.
- Multiple faults are not considered at a given time and all failures are repaired before the next fault occurs.
- One load area covers 0.5 kilometer of a main feeder, as shown in Figure 3.
- Position of section is a multiple of 40 meters from the substation because an interval of distribution pole is 40 meters.
- Maximum length of a main feeder is 10 kilometers.
• The time interval of sampling load curve data is 15 minutes. Thus the load profile is represented by 96 load values throughout the day.

3.2 Model Formulation

3.2.1 Objective function. The research aims to minimize the total cost of a main feeder configuration by rearranging positions of feeder-switches and pole-mounted RTUs. The total cost of main feeder is the summation of customer and electrical power utilities outage cost in each section including life cycle cost of feeder-switches and pole-mounted RTUs that are installed at the feeder. Normally, the LCCs (e.g. SC, RC, SIC, RIC) are not varied by the outage duration, but by the number of sections.

\[ \text{min Total Cost} = \sum_{i=1}^{N} (IC_i + UC_j) + (n-1) \times SC + m \times RC + j \times SIC + q \times RIC \] (1)

3.2.2 Customer outage cost due to a fault at section \( i \). The cost is the summation of customer outage cost in every section that is outaged by a fault at section \( i \). Each section has its outage cost depending on its amount of load, proportion of load types, and the corresponding outage durations.

\[ IC_j = \lambda_j \left( C_1 \cdot L_1 + C_2 \cdot L_2 + C_3 \cdot L_3 + \ldots + C_n \cdot L_n \right) \] (2)

3.2.3 Customer cost multiplier of load at section \( j \) due to a fault at section \( i \). Customer cost multiplier is the cost per kilowatt (Baht/kW) that depends on amount of outage duration and price of electric at time \( t \).

\[ B_{ij} = Y_j \left( ES_i \cdot \text{Res}_i(\%) + \text{Imp}_j(\%) \right) + EL_i \cdot \text{Ind}_i(\%) + \text{Com}_j(\%) \] (5)

3.2.4 Utility outage cost due to a fault at section \( i \). The cost is the summation of utility outage cost of every section that is outaged by a fault at section \( i \).

\[ UC_j = \lambda_j \left( B_1 \cdot L_1 + B_2 \cdot L_2 + B_3 \cdot L_3 + \ldots + B_n \cdot L_n \right) \] (4)

3.2.6 The duration of service interruption of section \( j \) due to a fault at section \( i \). The service duration of each section depends on amount of load in its section, number of sections, and position of sections. Note that the position can be classified into three positions: near an original source, near an alternate source, or neither and amount of load that can be transferred.

\[ T_f + T_r, \quad i = j \]

\[ T_f + T_r, \quad i > j, \quad \sum_{k=j}^{n} L_k > L_T \]

\[ T_f + T_s, \quad i > j, \quad \sum_{k=j}^{n} L_k \leq L_T \]

\[ T_f, \quad i < j \]

(6)

3.2.7 Load in section \( i \). The following formula is used to calculate amount of load between two adjacent switches. Summation of load in the area that the two switches (i.e., switches \( i-1 \) and \( i \)) cover is called load of section \( i \).

\[ L_i = \left(1 - \text{ceil}(\text{ceil}(x_{i-0.5}) - \text{ceil}(x_{i-0.5});/30) \right) \times \text{floor}([n - (n - i)];/n) \]

\[ + [\text{ceil}(\text{ceil}(x_{i-0.5}) - \text{ceil}(x_{i-0.5});/30);] \times \sum_{k=\text{ceil}(x_{i-0.5})+1}^{\text{ceil}(x_{i-0.5})} A_k \]

\[ + [\text{ceil}(x_{i-0.5}) \times 0.5 - x_{i-0.5})/A_{\text{ceil}(x_{i-0.5})}] \times \text{ceil}(x_{i-0.5}) \]

(7)

3.2.8 Failure rate in section \( i \). The formula (9) is used to calculate amount of failure rate between two adjacent switches. Summation of failure rate in the area that two switches (i.e., switches \( i-1 \) and \( i \)) cover is called failure rate of section \( i \).

\[ \lambda_i = \left(1 - \text{ceil}(\text{ceil}(x_{i-0.5}) - \text{ceil}(x_{i-0.5});/30) \right) \times \text{floor}([n - (n - i)];/n) \]

\[ + [\text{ceil}(\text{ceil}(x_{i-0.5}) - \text{ceil}(x_{i-0.5});/30);] \times \sum_{k=\text{ceil}(x_{i-0.5})+1}^{\text{ceil}(x_{i-0.5})} F_k \]

\[ + [\text{ceil}(x_{i-0.5}) \times 0.5 - x_{i-0.5})/F_{\text{ceil}(x_{i-0.5})}] \times \text{ceil}(x_{i-0.5}) \]

(9)
3.3 Genetic Algorithm (GA) Parameters [7]. GA is a stochastic optimization technique that uses the biological paradigm of evolution to resolve a very large problem. It has a concept where good chromosome has a better potential of being carried to the next generation than the bad chromosome. It uses mathematical principle to indicate which chromosome is better or worse than the others. The ability of GA in finding good solutions often depends on properly customizing the encoding, breeding operators and fitness measures. In this research GA is applied to optimize the location of feeder-switches and pole-mounted RTUs on a main feeder. The GA parameters are discussed as follows:

3.3.1 Encoding. The position of a pole that is installed with a feeder-switch acts as a gene. Each gene has an attribution that specifies RTU installation whether or not. The pole position can be referred to a distance of a feeder-switch from a substation. For example in a five-section feeder configuration, its chromosome can be represented with string $P_1$-$R_1$|$P_2$-$R_2$|$P_3$-$R_3$|$P_4$-$R_4$; where $P_i$ is a pole number selected to install feeder-switch $i$, $R_i$ is a status to indicate that feeder-switch $i$ has a pole-mounted RTU whether or not.

3.3.2 Initial Population. The size of the initial population is varied by the size of the feeder system. The longer the length of a main feeder is, the larger the size of its sample space. In this mathematical analysis, A set of chromosomes is randomly generated as initial population.

3.3.3 Selection. The chromosomes or population are sorted by their fitness values. The top-twenty percent have high fitness values. The top-ten fitness ranking chromosomes or 10% chromosomes are selected to reproduce the next generation possibility for crossover process. Therefore 70% pair-chromosomes can reproduce one new chromosome. The chromosome can be any chromosome. One couple chromosome interchanges their genes. Their offspring can be referred to the next generation (Offspring). The top-ten fitness ranking chromosomes or 10% of population size are considered as long-live chromosomes; they will survive to the next-generation.

3.3.4 Crossover. A father chromosome is selected from roulette wheel method. Thus a chromosome with high fitness value has potential to be a father chromosome and a mother chromosome can be any chromosome. One couple chromosome can reproduce one new chromosome. The couple chromosome interchanges their genes. Their offspring will have 20-50% of its father genes and 50%-80% of its mother genes.

3.3.5 Mutation. All new generations except the top ranking chromosomes have 30% possibility to mutate. If they are in mutation process, 50%-60% of their genes can be altered. Mutation process may produce better or worse chromosomes with equaled probability.

3.3.6 Alien Migration. 10% of populations in the new generation are aliens. Their genes are randomly generated. This process could help the GA to escape from a local optimum trap. This process has similar purpose as the mutation process, but it is free from the existing chromosomes completely.

4. EXAMPLE CASE STUDY

In this research a 2.5-kilometer feeder is analyzed as a case study. Utility provider can provide up to 14 feeder-switches and 4 pole-mounted RTUs. Failure rate in each area is represented as $F[3, 0, 4, 5, 1]$ where each column presents failure rate in each load area. Historical load data in each area is the load curve shown in Figure 6. Small consumers electric sale price are 4.3093 Baht/kWh on peak and 1.2246 Baht/kWh off peak. Large consumers electric sale price are 2.848 Baht/kWh on peak and 4.3093 Baht/kWh off peak. Extra condition for large consumer is additional charge that is 210 Baht/kW. Alternate source capacity is 10,090.68 kW. The alternate source’s load curve is shown in Figure 7 to compute alternate source’s load remain in each time period. We assume percentages of residential, commercial, industrial and important places are set to 27, 23, 46 and 4, respectively. Their IC functions are: $f_r(Y_r) = 2*Y_r$, $f_c(Y_c) = 30*Y_c * Y_r$, $f_f(Y_f) = 200*Y_f * Y_r$ and $f_p(Y_p) = 250*Y_p * Y_r$. This analytical case defines SC=350,000 baht per set, RIC=180,000 baht per set, SIC=50,000 baht per set, RIC=20,000 baht per set, $T_r = 0.3$ hours, $T_c = 2.5$ hours, $T_f = 0.3$ hours and $V = 10$ km/h.

Table 1 shows optimization results of the analytical case that expresses system costs and positions of feeder-switches and pole-mounted RTUs. Using GA approach, suitable relocations of feeder-switches and pole-mounted RTUs on this main feeder can be obtained. With reasonable number of simulation runs, we obtain optimization results consisting of total cost, interruption cost, utility cost and life-cycle cost, as shown in Table 1.
In table 1, with a few number of switches, we verified that the location switches and RTUs results are optimal or else near optimal positions. Figures 8 and 9 graphically present the costs with varying number of feeder-switches. As a result in Figure 8, with very few numbers of switches, the total system cost is very high due to the customer interruption cost, which is very high. Adding extra protective devices or switches, during this time, can tremendously safe the total cost, even though the price of the switches have to be compensated, shown as the increasing of the SSC and the RSC in Figure 9. The total cost is minimal with eight feeder-switches and four pole-mounted RTUs, adding an extra switch, at this time, would increase the total cost. This is because the cost of the extra switch is higher than its returned benefit.

5. CONCLUSION

Business-oriented management of distribution process has been greatly enhanced. Reliability based network analysis is essentially required for asset management. This paper proposed a technique to optimize the total costs in distribution system, which consist of outage costs and life-cycle cost of the switches and the RTUs considering load profile of electrical power usage and duration in all customer areas. This is performed by relocating limited number of protective devices, which are feeder-switches and pole-mounted RTUs on the corresponding distribution feeder. The results achieved with reliability based network analysis can be used to optimize total life cycle costs of the feeder components and gives guidance to take into account the effects of environmental and component based aspects in network management such as in the control of the planning process.

REFERENCE


