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Power Distribution System Improvement Planning Considering Financial Losses Due to Faults in Power Systems

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Abstract: This research article presents a method for selecting an improvement approach for the power distribution system by analyzing financial losses caused by faults in the system. These losses can be in two parts: the first part arises from power outages, which lead to lost sales, estimated opportunities, and expenses for resolving the outages, while the second part results from voltage sags that affect sensitive electrical equipment. The method involves simulating faults at various points in the distribution system and assessing their impact on industrial, commercial, and large-scale electricity consumers. The results demonstrate that by combining the total financial losses from both parts and comparing these losses before and after implementing system improvements, effective and economically viable decision-making information can be obtained for enhancing the power distribution system.

Keywords: power distribution system; financial loss; voltage sag; interruption; faults

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1. Introduction

The power distribution system is a system that receives electrical power from substations and then transmits it to electricity users. The transmitted power has a medium–high voltage value, between 2 and 33 kV. The power distribution system consists of many types of electrical equipment, such as electrical wires, electrical insulators, electric poles, and electrical transformers. When this electrical equipment begins to deteriorate due to its age or being damaged, it will be the cause of electrical system failures [1,2].

The occurrence of faults in the power system is the occurrence of short circuits, which can be caused by many reasons, such as damaged electrical equipment, branches or animals touching the power lines, and lightning strikes [3]. It can affect both the distributor and the electricity user. A permanent fault will cause a power outage, resulting in the loss of opportunity in distributing electricity to the electricity user. A temporary fault will cause a voltage sag, resulting in damage to the electricity user from equipment that is sensitive to voltage changes being disrupted or malfunctioning. Therefore, when the damage values of both of these parts are combined, it will be possible to estimate the financial losses caused by faults in the power system [4]. To prevent or reduce this loss, it can be performed by improving the power distribution system. This will result in a reduction in the statistics of faults.

Improving the power distribution system involves installing additional electrical equipment or replacing old or damaged electrical equipment with new ones, such as changing the type of electrical wires and types of electrical insulators, etc., to reduce the number of times and the impact of faults, making the power distribution system more efficient in transmitting electricity. In improving the power distribution system in each form, there will be different costs and results of reducing financial losses. When comparing the financial losses before and after improving the power distribution system in each situation with the costs, the payback period will be known [5]. This can be used as information for planning and selecting a form of improving the distribution system to be economically worthwhile and efficient in distributing electricity to electricity users. The losses caused by faults in the distribution system, which result in damage, can be categorized into two parts [6,7].

1.1. Losses from Voltage Sags (LS)

This refers to the damage experienced by electricity consumers due to voltage sags. Such sags can cause voltage-sensitive equipment to malfunction or stop operating [8].

1.2. Losses from Power Outages (LO)

This refers to the loss of opportunity to distribute electricity to consumers during a power outage, leading to potential financial and operational impacts.

By combining the losses from these two categories, the total financial loss caused by faults in the power distribution system can be estimated. This is illustrated in the accompanying Figure 1.

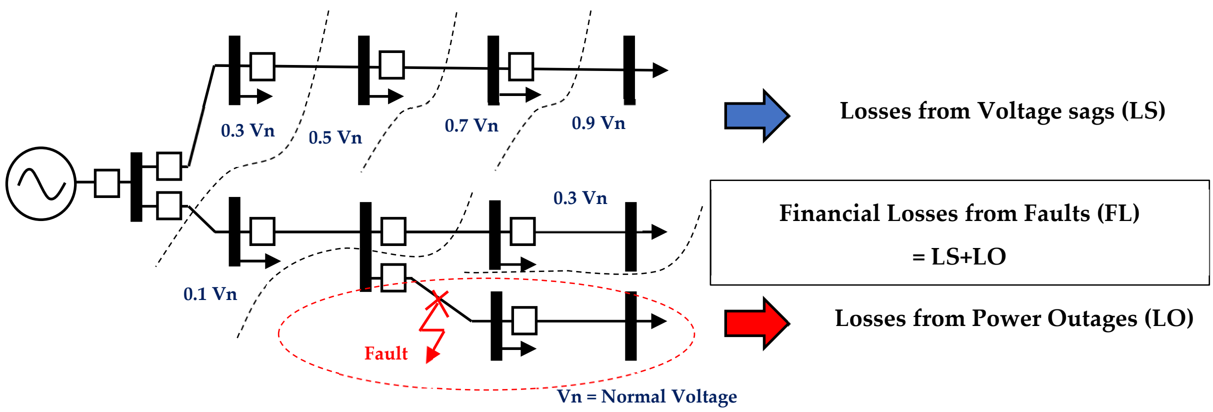

Figure 1. The financial losses resulting from faults in the power distribution system.

2. Estimation of Losses from Voltage Sags (LS)

According to the IEEE 1159-1995 standard [9] voltage sag is reducing the magnitude of the voltage down to between 0.1 and 0.9 percent of normal voltage. Within a time of 0.5 cycles to 1 min. The method that can be used to evaluate the voltage sags is the fault position method [10,11], which simulates the occurrence of faults at different locations, both symmetrical and asymmetrical, in the electrical system using recorded statistical data. This method can evaluate the magnitude, duration, and number of voltage sags as follows:

2.1. Magnitude of Voltage Sag

The fault in the power distribution system, specifically the magnitude of voltage sag at the point of common coupling (PCC), can be calculated using Equation (1) [12].

$$V_{SAG} = \frac{Z_F}{Z_F + Z_S} \times E_S \tag{1}$$

The fault in the electrical system is shown in Figure 2.

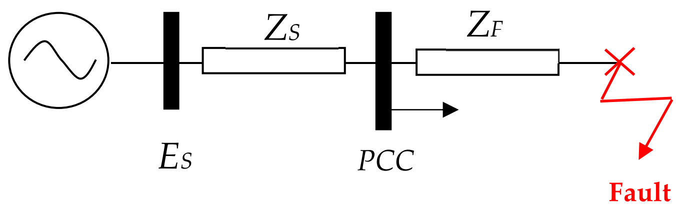

Figure 2. The fault in the power distribution system.

2.2. Duration of Voltage Sag

The duration of a fault can be estimated from the fault clearance time of the protection devices in the power distribution system, where the calculated time varies with the fault current flowing through it and follows the current–time curve.

2.3. Frequency of Voltage Sag

The frequency will use the voltage resistance line according to the SEMI F47 standard [13] to represent the electrical equipment installed on the buses in the electrical distribution system. Counting the number of times the devices in the trip zone stop, derived from the duration and the remaining voltage level at the time of the transient voltage sag, considering the operation of the primary protection device against all types of faults, proportional to the probability of occurrence of each type [14]. The frequency comes from the number of trips (*NT*) at each bus that can be calculated using Equation (2).

$$NT = \sum_{i=1}^{m} F_i \cdot P_i \cdot \rho_i \tag{2}$$

2.4. Loss from Voltage Sags (LS)

The total losses incurred in the power distribution system are obtained by summing the damage values of the buses with electrical equipment sensitive to voltage sags installed [15,16]. It can be calculated according to Equation (3).

$$LS = \sum_{j=1}^{k} CODT_j \cdot NT_j \tag{3}$$

The cost of downtime (*CODT*) incurred comes from a number of factors, including lost product, lost labor, and hidden costs, which can be derived by collecting data and interviewing employees who work on the downed electrical equipment and employees who are required to perform restart operations [11,17].

3. Estimation of Loss from Power Outages (LO)

The outage is the loss of the ability of a component to deliver power [18]. Estimation of losses in case of a power outage will be caused by a permanent failure in the distribution system. The losses are caused by two parts: the first is the loss of opportunities to sell electricity; the second is the costs required to restore the electricity distribution system to normal, such as employee wages, electrical equipment parts, and vehicle fuel. It can be calculated using Equation (4).

$$LO = \sum_{\mathrm{p}=1}^{q} F_p \cdot L_p \cdot (U_p \cdot TR \cdot EC + RC) \tag{4}$$

4. Economic Analysis

In decision-making for selecting the most cost-effective approach to improving the electrical distribution system, the following methods can be used for evaluation [19]:

(1) Payback period (PB);
(2) Net present value (NPV);
(3) Discounted payback period (DPB).

4.1. Payback Period (PB)

The selection criteria will focus on choosing the configuration with the shortest payback period, which can be calculated using Equation (5).

$$PB = \frac{Improve\ cost}{Save\ cost} \tag{5}$$

4.2. Net Present Value (NPV)

It is a method for evaluating the value of future cash flows by discounting them to their present value, considering the time value of money using a specified discount rate. If the NPV is positive, it indicates that the project or investment under consideration is worthwhile. Conversely, if the NPV is negative, it suggests that the investment may not be advisable [20]. The *NPV* can be calculated using Equation (6).

$$NPV = \sum_{t=1}^{n} \left(\frac{C_t}{(1+r)^t} \right) - C_0 \tag{6}$$

The selection will be based on choosing the configuration with the highest positive *NPV*.

4.3. Discounted Payback Period (DPB)

The calculation of the number of years required for the total profit from an investment to equal the investment cost, considering the time value of money, is performed using the discounted payback period. The DPB can be calculated using Equation (7).

$$C_0 = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \tag{7}$$

This method differs from the standard Payback Period calculation, which does not account for the depreciation of money over time. The discounted payback period considers the present value of future cash flows, applying a discount rate to determine how long it will take for the investment to break even in today's value.

Investments related to infrastructure and public utilities, such as the development of electricity networks, often use the yield on long-term government bonds, such as 10-year bonds, which are usually around 2–4%, as a basis for calculating the discount rate.

5. Power Distribution System Improvement

Power distribution system improvement refers to the process of enhancing the efficiency and reliability of the electrical network used to transmit electricity from power substations to consumers. This process focuses on improving the reliability, safety, and efficiency of electricity transmission to meet evolving demands. This study emphasizes improving the electrical distribution system to ensure stability, security, and the ability to support increasing energy demands while reducing losses caused by voltage sags and power outages. The primary approach involves upgrading or replacing outdated electrical equipment with modern technology, which enhances the reliability and efficiency of the network while ensuring safer operation [21,22]. Examples of equipment upgrades in the electrical distribution system improvement include the following:

5.1. Electrical Conductors Replacement

Electrical wires play a crucial role in transmitting power from substations to consumers. Replacing old or undersized conductors with modern ones reduces energy losses and minimizes risks such as short circuits or damage to electrical equipment. This upgrade supports the increasing load demand and enhances overall system performance.

5.2. Insulators Replacement

Electrical insulators prevent the flow of electricity in unintended areas, such as along electrical poles or between conductors. Replacing worn or damaged insulators with modern, weather-resistant, and high-voltage-resistant alternatives reduces the risk of short circuits and enhances system stability. By implementing these improvements, the electrical distribution system can effectively adapt to growing energy demands while maintaining safety and reliability.

6. Test System

The data of test system is 22 kV power distribution system of the Saraburi 1 Substation (2005) of the Provincial Electricity Authority, consisting of 2 feeder lines, 45 buses, total length 36.74 km, single-line circuit diagram, as shown in Figure 3 [23].

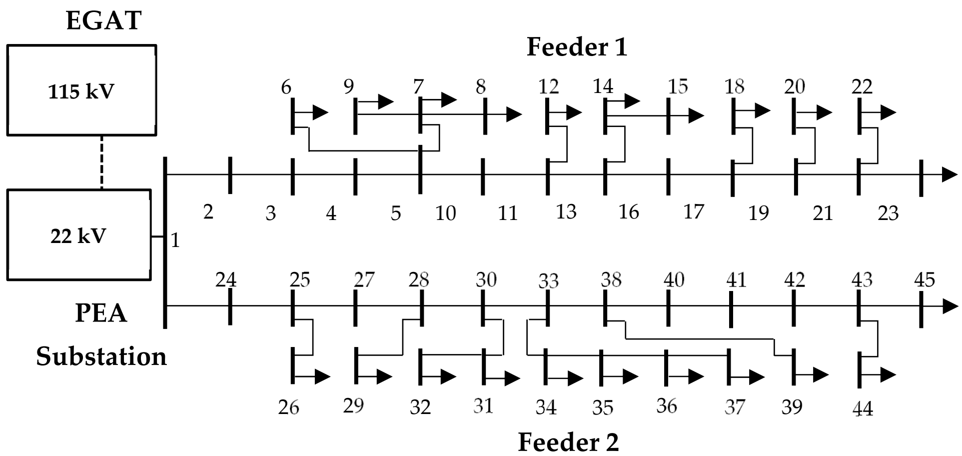

Figure 3. Saraburi 1 Substation, Provincial Electricity Authority.

The data of the resistance and reactance values of the conductors and conductor information and types of protection devices of the feeder lines are shown in Tables 1 and 2.

Table 1. Resistance and reactance values of the conductor.

Conductor Type	R_1 (ohm/km)	X_1 (ohm/km)	R_0 (ohm/km)	X_0 (ohm/km)
Z th *	0.0606	0.29896	0.0000103	0.46514
185 SAC	0.1805	0.2455	0.3285	1.7549
185 PIC	0.21435	0.33976	0.39186	1.5538
120 PIC	0.26643	0.34869	0.41443	1.57551
120 AAC	0.26643	0.36382	0.56243	2.70319

* Thevenin equivalent impedance of Saraburi 1 Substation (22 kV).

Table 2. Conductor information and types of protection devices.

Bus to Bus	Distance (km)	Conductor Type	Protection Type	Bus to Bus	Distance (km)	Conductor Type	Protection Type
1–2	0.12	185 PIC	Relay	1–24	0.15	185 SAC	Relay
2–3	0.12	185 PIC	Relay	24–25	0.15	185 SAC	Relay
3–4	2.0	185 SAC	Relay	25–26	0.3	185 PIC	Relay
4–5	5.0	185 PIC	Relay	25–27	1.5	185 PIC	Relay
5–6	2.6	185 PIC	Relay	27–28	0.1	185 PIC	Relay
5–7	0.5	185 SAC	Relay	28–29	0.2	185 SAC	Relay
5–10	0.1	185 SAC	Relay	28–30	0.65	185 SAC	Relay
7–8	4.15	185 SAC	Relay	30–31	0.75	185 SAC	Relay
7–9	0.9	120 PIC	Relay	30–33	1.15	185 SAC	Relay
10–11	0.1	185 SAC	Relay	31–32	1.5	185 PIC	Relay
11–12	0.5	120 AAC	Relay	33–34	0.5	185 PIC	Relay
11–13	1.2	185 SAC	Relay	33–38	0.5	185 PIC	Relay
13–14	0.7	185 SAC	Relay	34–35	0.2	120 AAC	Relay
13–16	0.2	120 AAC	Relay	35–36	0.8	120 AAC	Relay
14–15	0.5	120 PIC	Fuse	36–37	0.1	120 AAC	Relay
16–17	0.3	120 AAC	Fuse	38–39	0.2	185 PIC	Relay
17–18	0.1	120 AAC	Fuse	38–40	0.5	185 PIC	Relay
17–19	0.2	120 AAC	Fuse	40–41	0.1	185 PIC	Relay
19–20	1.1	120 AAC	Fuse	41–42	0.2	185 PIC	Relay
19–21	0.3	120 AAC	Fuse	42–43	1	185 PIC	Fuse
21–22	1.0	120 AAC	Fuse	43–44	0.5	120 AAC	Fuse
21–23	1.5	120 AAC	Fuse	43–45	2.5	120 AAC	Fuse

The probability of occurrence of each type of fault is as follows: Single Line to Ground (SLG) 70%, 3 Phase (3PH) 15%, Double Line to Ground (DLG) 10%, and Line to Line (LL) 5%, respectively.

The data for each power outage are as follows: average time to reset (*TR*) 1.5 hr. The electricity cost (*EC*) 5.0 THB/unit. Average reset cost/times (*RC*) 50,000 THB/times.

Information of power consumer is shown in Table 3.

Table 3. Information of power consumer.

Power Consumer Type	Feeder 1 at Bus	Feeder 2 at Bus	CODT (Million Baht)	Load (kW)
Large user	8,20	32,39	0.500	3500
Industrial	6,7,9,12	26,29,31,34	0.025	500
Commercial	14,15,18,22,23	35,36,37,44,45	0.005	100

7. Methodology

The data analysis involves comparing the financial losses resulting from faults in the electrical distribution system for each case of system improvement with the investment costs for each scenario. This comparison is performed using the proposed decision-making method to identify the most economically viable approach. The goal is to provide information to guide investment decisions for improving the electrical distribution system, ensuring alignment with budget constraints while maximizing cost-effectiveness and enhancing distribution efficiency. The analysis process is divided into 6 steps as follows:

Step 1: Input the distribution system data to be studied.
Step 2: Bus impedance formation.
Step 3: Specify the bus positions of interest in the program.
Step 4: Simulate four types of faults at various positions in the line of the distribution system until all positions are covered. For each position, evaluate the following:
4.1 The magnitude of the voltage sag at the bus.
4.2 The duration of the voltage sag from the database of protections.
4.3 Compare the results with the voltage tolerance curve according to the SEMI F47 standard [12] to count the frequency of voltage sag.
Step 5: Calculate the financial losses caused by faults at the bus of interest, categorized by type of electricity consumer, as follows:
5.1 Losses due to voltage sags.
5.2 Losses from missed opportunities to supply electrical energy to customers.
Step 6: Repeat Steps 3–5 for all buses in the distribution system.

A diagram for estimating the financial losses caused by faults in the power distribution system is presented in Figure 4.

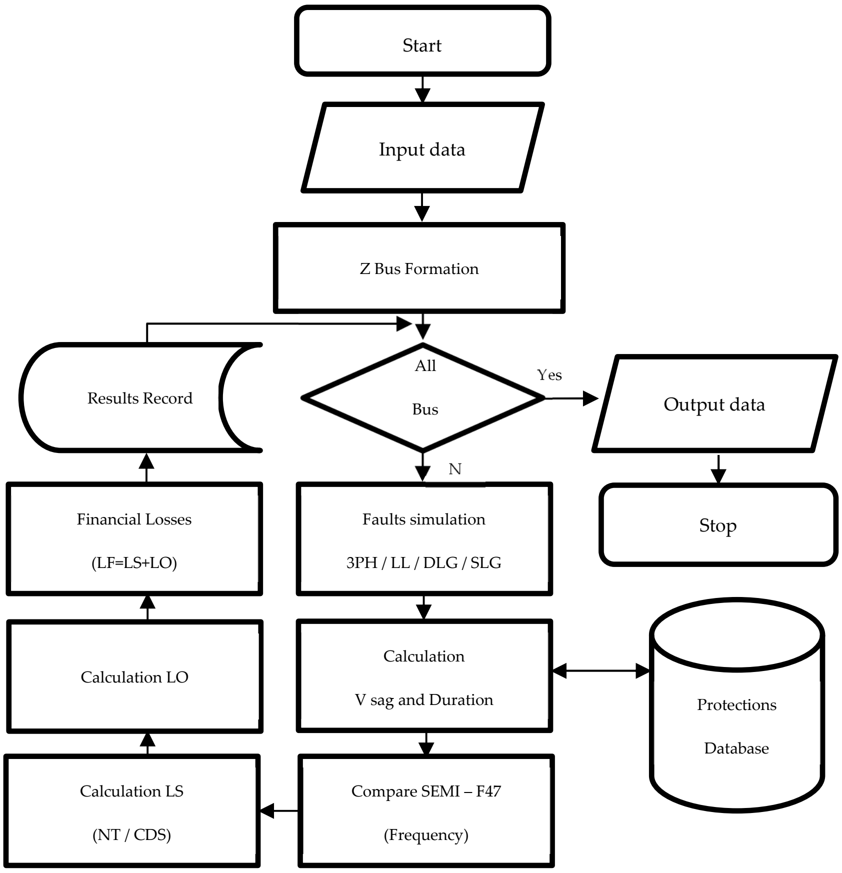

Figure 4. A diagram for estimating the financial losses caused by faults in the distribution system.

8. Case Study

In this study, the process of improving the power distribution system is divided into three approaches:

A. Changing the type of insulator from Pin type to Line post type for insulators installed on circuits using All Aluminum Conductor (AAC).

B. Replacing the electrical conductors from All Aluminum Conductor (AAC) to Partial Insulated Conductor (PIC).
C. Replacing the electrical conductors from Partial Insulated Conductor (PIC) to Space Aerial Cable (SAC).

The simulation of events to improve the distribution system for various approaches in each feeder circuit will include a total of 14 scenarios. The cost of improving the power distribution system in this study includes expenses for replacing the type of insulator in circuits with all-aluminum conductors and changing the type of electrical wires. This encompasses removal costs, installation costs, and operational costs. The objective is to mitigate the impact of voltage sag caused by faults in the power distribution system. The data and costs related to system improvements are presented in Table 4.

Table 4. Information and costs for improving the power distribution system.

Improvement Pattern	Fault Occurrence Rate (times/km/year)		Cost of Improvement (Million Baht)/km
	Before Improvement	After Improvement	
A	0.250	0.225	0.20
B	0.250	0.200	1.00
C	0.200	0.150	1.50

Table 4 shows that improving pattern A can reduce the fault occurrence rate by 0.025 times/km./year. Pattern B can reduce fault occurrence rate 0.050 times/km./year. Pattern C can reduce the fault occurrence rate by 0.050 times/km./year. Although patterns A and C are discounted equally, pattern C is 1.3 million THB/km more expensive than pattern A.

Case studies of improving the power distribution system are presented in Table 5.

Table 5. Case study of improving the power distribution system.

Case Study	Feeder 1	Feeder 2
1	Base case or before improvement.	
2	Pattern C	Pattern C
3	Pattern A and C	-
4	-	Pattern A and C
5	Pattern A and C	Pattern A and C
6	Pattern C	Pattern A and C
7	Pattern A and C	Pattern C
8	Pattern B and C	-
9	-	Pattern B and C
10	Pattern C	Pattern B and C
11	Pattern B and C	Pattern C
12	Pattern B and C	Pattern B and C
13	Pattern A and C	Pattern B and C
14	Pattern B and C	Pattern A and C

9. Results

In this study, losses are divided into two parts, viz. loss from voltage sags (LS) and loss from power outages (LO). When these two damage values are combined, it is possible to estimate the financial losses caused by power system failures. Therefore, the results of the study are divided into three parts as follows:

(1) The analysis of loss from voltage sag.
(2) The analysis of loss from interruption.
(3) The analysis of financial losses.

9.1. The Analysis of Losses from Voltage Sags

The result of the analysis of losses from voltage sags is show in Table 6.

Table 6. The result of the analysis of losses from voltage sags.

Case Study	Damage Costs by Type of Electricity User (Million Baht)			(A + B + C) Damage Cost/Year (Million Baht)	(1) Damage Reduction/Year (Million Baht)
	A Large Load	B Industrial Load	C Commercial Load		
1	9.42	0.94	0.24	10.59	-
2	8.18	0.82	0.20	9.20	1.39
3	8.73	0.87	0.22	9.81	0.78
4	8.85	0.88	0.22	9.96	0.64
5	8.17	0.82	0.20	9.19	1.40
6	8.13	0.81	0.20	9.15	1.45
7	8.21	0.82	0.21	9.23	1.36
8	8.44	0.84	0.21	9.49	1.10
9	8.84	0.88	0.22	9.94	0.65
10	8.11	0.81	0.20	9.13	1.47
11	7.92	0.79	0.20	8.91	1.69
12	7.86	0.79	0.20	8.84	1.76
13	8.05	0.80	0.20	9.06	1.53
14	7.87	0.79	0.20	8.85	1.74

Table 6 shows that the top 5 most damage reduction/year are cases 12, 14, 11, 13, and 10, respectively.

9.2. The Analysis of Losses from Power Outages

The result of the analysis of losses from power outages is shown in Table 7.

Table 7. The result of the analysis of losses from power outages.

Case Study	D Opportunity Cost of Selling Electricity (Million Baht)	E Cost of Fixing Power Outages (Million Baht)	(D + E) Damage Cost/Year (Million Baht)	(2) Damage Reduction/Year (Million Baht)
1	0.192	0.361	0.553	-
2	0.164	0.322	0.486	0.0669
3	0.171	0.331	0.502	0.0503
4	0.183	0.340	0.523	0.0296
5	0.162	0.310	0.473	0.0799
6	0.164	0.317	0.481	0.0721
7	0.162	0.316	0.478	0.0747
8	0.170	0.325	0.495	0.0581
9	0.183	0.335	0.518	0.0349
10	0.164	0.312	0.475	0.0773
11	0.161	0.309	0.470	0.0825
12	0.161	0.299	0.460	0.0929
13	0.162	0.305	0.468	0.0851
14	0.161	0.304	0.465	0.0877

Table 7 shows that the top 5 most damage reduction/year are cases 12, 14, 13, 11, and 5, respectively.

9.3. The Analysis of Financial Losses

The result of financial losses is shown in Table 8.

Table 8. The result of financial losses.

Case Study	Cost of Improving the Distribution System (Million Baht)	(1) + (2) Total Damage Reduction/Year (Million Baht)	Payback Period (Year)	Discounted Payback Period (Years) (r = 3.5%)	Net Present Value (Million Baht) (t = 30 Years and r = 3.5%)
1	-	-	-	-	-
2	23.46	1.4579	**16.09**	**24.1**	**3.39**
3	14.9	0.8293	17.97	28.5	0.37
4	10.42	0.6673	**15.61**	**22.8**	1.902
5	25.32	1.4797	17.11	26.5	1.900
6	24.28	1.5172	**16.00**	**23.6**	**3.676**
7	24.50	1.4373	17.05	26.5	1.985
8	19.06	1.1606	16.42	24.8	**2.274**
9	13.7	0.6877	19.92	34.8	−1.00
10	27.56	1.5463	17.82	28.6	0.947
11	28.66	1.7686	**16.21**	**24.6**	**3.893**
12	32.76	1.8483	17.72	28.1	1.265
13	28.6	1.6193	17.66	28.0	1.195
14	29.48	1.8278	**16.13**	**24.2**	**4.177**

The top five shortest of payback period, and discounted payback period were bold/color. For the column of net present value are the top five highest positive value.

10. Discussion

10.1. Comparison of Results from Economic Methods

When considering the results from the table, it was found that the top 5 of each method are the payback period method, the discounted payback period method, and the net present value method, which can be shown in Figure 5.

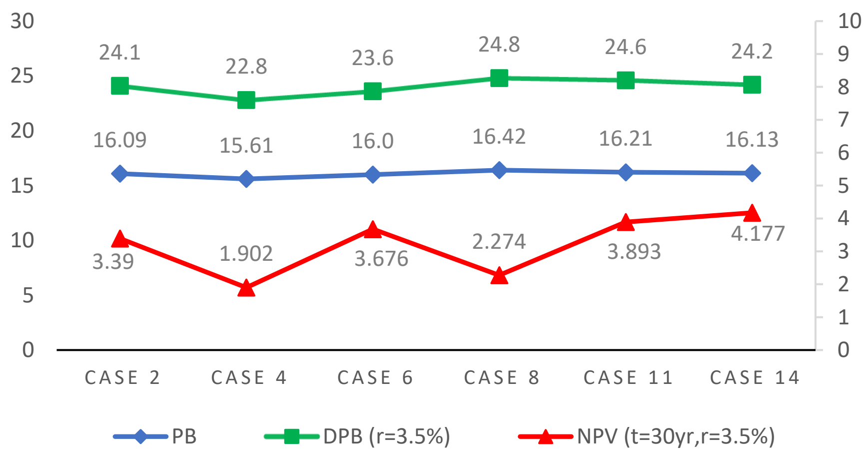

Figure 5. Comparison of the payback period method, the discounted payback period method, and the net present value method.

Figure 5 shows the top five configurations with the following:

(1) Payback period (PB) method: case studies 4, 6, 2, 14, and 11, respectively;
(2) Discounted payback period (DPB) method: case studies 4, 6, 2, 14, and 11, respectively;
(3) Net present value (NPV) method: case studies 14, 11, 6, 2, and 8, respectively.

When considering the top five case studies of each method and comparing the cost of improving the power distribution system, the reduced damage, and the ratio of reduced damage to the cost of improvement, it can be shown in Figure 6.

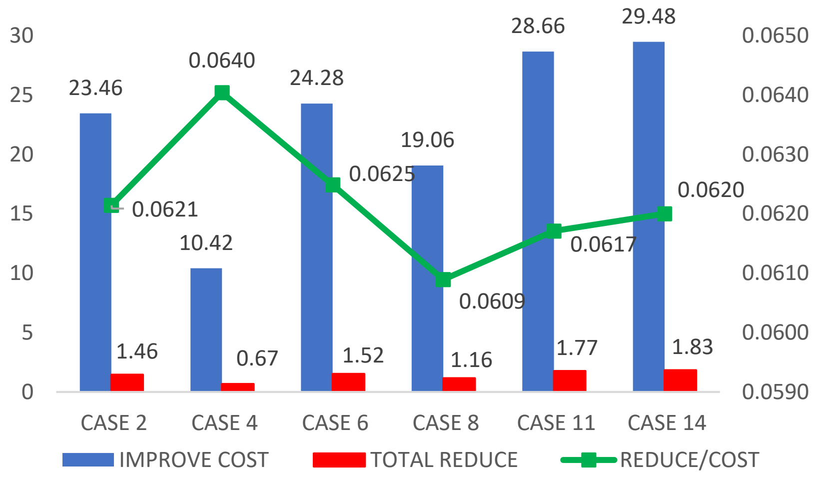

Figure 6. Comparison of the cost of improving the power distribution system, the reduced damage, and the ratio of reduced damage per the cost of improving from the top 5 case studies of each method.

Figure 6 shows the top five configurations with the shortest discounted payback periods (less than 25 years), which are configurations 4, 6, 2, 14, and 11, respectively (r = 3.5%). When considering the ratio of reduced damage to the cost of improving, the order can be as follows: case studies 4, 6, 2, 14, 11, and 8, respectively.

10.2. Route Map of the Power Distribution System Improvement Model

When the results of the study are considered together with the cost of improving the power distribution system in each case study, a route map can be drawn to use in making investment decisions as shown in Figure 7.

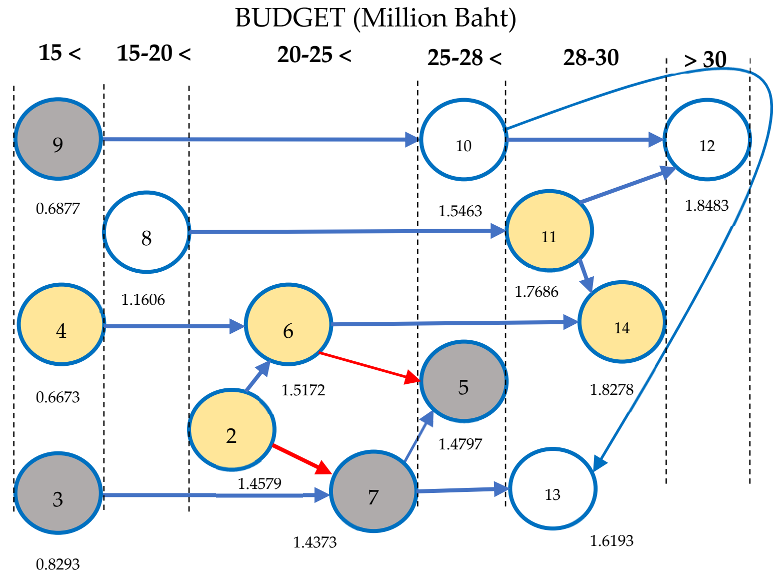

Figure 7. Route diagram of the power distribution system improvement model.

Each power distribution system improvement model will have different improvement costs. When considering the estimated financial loss data, investment decisions can be made to select a model that is consistent with the available budget and is economically worthwhile, as follows:

(1) In the case of a budget not exceeding THB 15 million, it is Model 4.
(2) In the case of a budget not exceeding THB 25 million, it is Model 6.
(3) In the case of a budget not exceeding THB 30 million, it is Model 14.

11. Conclusions

This paper considers improving the power distribution system of the Provincial Electricity Authority. The location is in Saraburi 1 Substation, Provincial Electricity Authority. The voltage base is 22 kV. The analysis is divided into three sections, viz. analysis loss from voltage sag, analysis loss from interruption, and analysis financial loss. This study is divided into three approaches, viz. changing the type of insulator from pin type to line post type, replacing the electrical wires from All Aluminum Conductor to Partial Insulated Conductor, and replacing the electrical wires from Partial Insulated Conductor to Space Aerial Cable. The economic index analyzed in this study includes the payback period, discounted payback period, and net present value.

The results found that configurations with the shortest payback periods (less than 17 years), which are configurations 4, 6, 2, 14, and 11, respectively. The configurations with the shortest discounted payback periods (less than 25 years), which are configurations 4, 6, 2, 14, and 11, respectively. The configurations with the highest positive net present value (exceeding THB 2 million), which are configurations 14, 11, 6, 2, and 8, respectively. The configurations that deliver the best economic value as the budget increases are configurations 4, 6, and 14, respectively.

The proposed method serves as a decision-making framework for selecting investment options to improve the power distribution system. During development, additional factors such as load growth and opportunities for electricity sales can be considered to enhance the accuracy of the decision-making process.

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Nomenclature

Parameter

E_S	Voltage of source.
V_{SAG}	Voltage sag at *PCC* (point of common coupling).
Z_S	Point of common coupling impedance of the source.
Z_F	Impedance between *PCC* and fault.
F_i	Annual fault rate of line i.
P_i	Probability of a fault occurring in line i.
ρ_i	Ratio of equipment malfunction to fault of line i.
m	Total line.
LS	Total loss from voltage sags.
$CODT_j$	Cost of downtime of the equipment at bus j.
NT_j	Number of trips at bus j.
k	Total number of damaged buses.

LO	Total loss from power outages.
Up	Number of customers' power outage when fault at line j (kW/times).
F_p	Annual fault rate of line j (times/km/year).
Lp	Distance of line j (km).
TR	Average time to reset (hr).
EC	Electricity cost (Baht/unit).
RC	Average reset cost (Baht/times).
q	Total number of lines.
Improve cost	Cost of improving the distribution system (Baht).
Save cost	Damage reduction potential (Baht/year).
r	Discount rate.
n	Total number of years (years).
Ct	Damage reduction value over time t (Baht/year).
C_0	Cost of improving the distribution system (Baht).

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