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THE IMPACT OF LOSSES ON THE SELECTION OF DISTRIBUTION CABLES AND TRANSFORMERS OF MALAYSIAN MEDIUM VOLTAGE REFERENCE NETWORKS

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ABSTRACT

The ordinary cable and transformer selection method is based on the safety guidelines and voltage level without concerning the power loss produced during the operation of the cables and transformers. Therefore, this paper aims to discuss the impact of losses on the selection of distribution cables and transformers. The methodology used in the optimization is based on minimum life-cycle cost methodology which proposed to balance investment cost and cost of losses throughout the technical lifespan of the cable and transformer. Apart from that, some other factors which contribute to the selection are also taken into account, such as power factor, interest rate, and energy price. In this paper, urban, sub-urban, and rural Malaysian medium voltage (MV) reference networks (RNs) have been considered. The DIgSILENT power factory software was used to perform time-series load flow simulation. The results obtained show that the total losses of the three RN_s reduced between 4.52% to 10.85% after changing the cables and transformers to the optimal selection.

1. INTRODUCTION

The electric power distribution network plays an important role in sustaining our daily power supplies. Therefore, the development of the distribution network is vital and significant for the future of human race. In addition to the dependency of human being on electricity is growing rapidly and unstoppably, the equipment used in distribution network is expensive and should give the best profit out of it. In terms of engineering, the profit gained can be expressed as the reduction in power losses. Thus, power losses should be determined critically in order to yield optimal power loss reduction. As a result, investment made in purchasing equipment should also consider the cost of losses in the long run [1].

In Malaysia, from 1999 to 2009, the electricity peak demand has increased 66%, from 9,690 MW to 16,132MW, and is projected to grow at 3.5% over the next 10 years [2,3]. One of the most cost-effective ways to meet increasing demand is through reduce energy waste or (reduce losses) to improve network energy and economic efficiency of existing power distribution network where the majority of these energy losses occur [4]. Distribution network losses refers to the natural and inherent energy loss resulting from resistance and current flow primarily in cables and transformer windings, and transformer core losses [5,6]. Studies have shown that the average energy losses in distribution network worldwide ranges between 5% and 10% of the total energy delivered [7-10]. Considering that the amount of energy delivered through a typical utility distribution network is substantial, a reduction of even a fraction of that percentage could translate into reducing tonnes of greenhouse gases (GHG) and financial savings of hundreds of millions of dollars annually. For example, in Malaysia, it is estimated that, a 1% reduction in distribution losses equals to approximately RM200 to RM300 millions of saving a year [9].

A majority of the electrical distribution cables and transformers currently utilized in the Malaysian distribution network is set up circa the 1980s [11], and the equipment's expiration time would have arrived and their substitution needed. The selection of cables and transformers in substitution should be upgraded and analyzed to achieve better performance. Losses play a prominent role in distribution network which may significantly increase the total cost of distribution network and decreasing the efficiency of the network [12-14]. At present, the strategies to design a network are mainly concerned with ensuring that the system satisfies certain safety and quality standards with minimum investment cost, without taking the role of losses into consideration. This may lead to the installation of inefficient plants for the next 25 years. In other words, it is important to consider the cost of losses when designing distribution networks and selection of distribution cables and transformers. To achieve this, the minimum life-cycle cost methodology is used as a basic for network design [13,14]. The minimum life-cycle cost methodology is a method that balances the capital cost against the cost of losses.

This paper discusses the impact of losses on the selection of distribution cables and transformers. A minimum life-cycle cost methodology is used as a basis for the cable and transformer selection, which balances the capital investment against the cost of the losses. A comprehensive analysis is performed to calculate the optimal utilization of distribution cables. The evaluation of the annual saving for replacing cables and transformers to optimal selection is performed in this paper. Furthermore, three types of Malaysian MV reference networks were considered.

II. METHODOLOGY

(a) Modelling of Reference Networks

Three types of Malaysian MV reference networks, namely urban, sub-urban, and rural networks with three voltage levels transformations of 132/33/11kV were modelled utilizing DIgSILENT power factory software. Fifteen-minute time interval of load flow simulations were performed on RNs models. The reference network for 132/33/11kV voltage transformation is indicated in the line diagram in Figure 1, which consists of two stages of voltage transformation that are 132/33kV and 33/11kV primary substations.

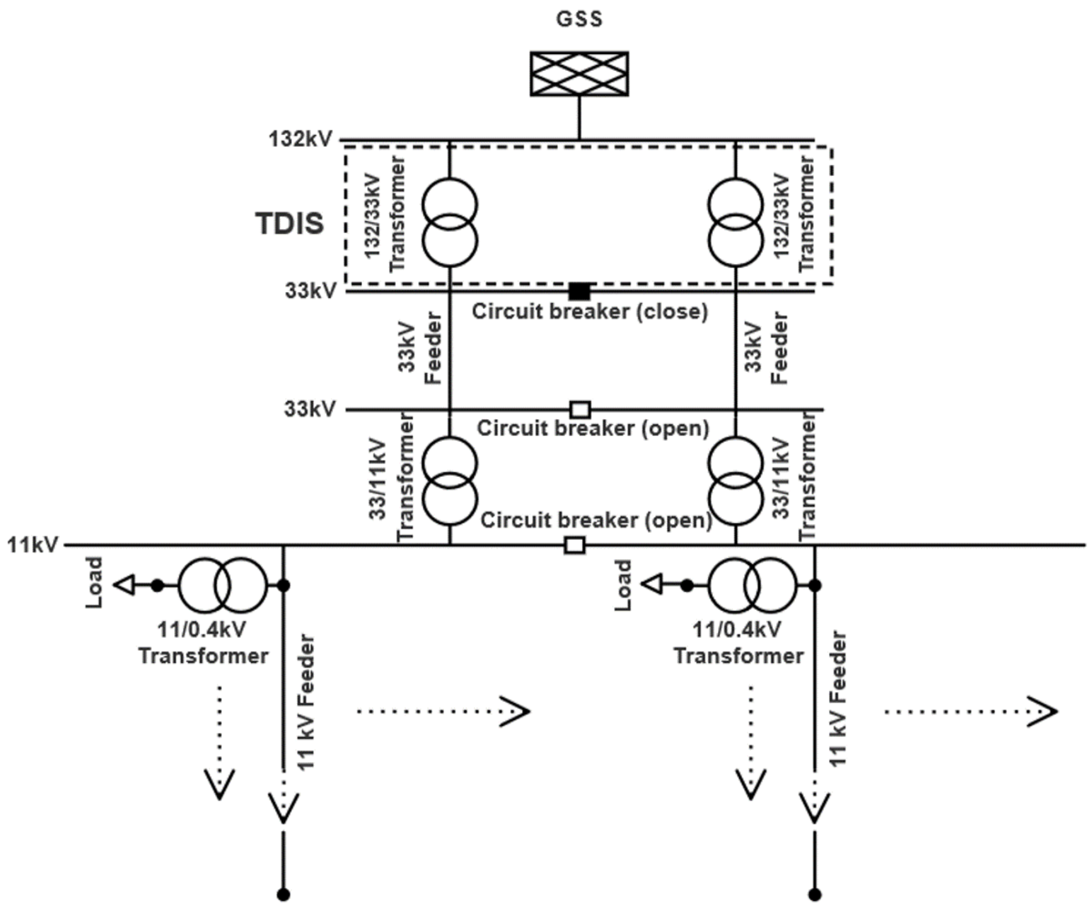

Figure 1: Single line diagram for medium voltage Reference Network (RN) with 33kV and 11kV feeders.

1) Urban RN with 33 and 11 kV feeders

The second column in Table 1 shows the parameters for urban reference network development. Four 11kV feeders were linked to each of the 33/11kV power transformers. Every individual 11kV feeder was linked to a number of 11/0.4 kV transformers ranged between 3 to 7 units. Additionally, two transformers of 11/0.4kV and 33/11kV capacities were configured to 1MVA and 30MVA, accordingly. The entire load for the 11/0.4kV transformer was ranged between 0.452 to 0.681 MW each, with an assumed power factor (p.f) equal to 0.90. The mean distance was ranged between 0.311 to 0.607 km between each 11/0.4kV distribution transformer; where each 11kV feeder possesses the average total length ranged between 0.935 to 4.25 km.

2) Sub-urban RN with 33 and 11 kV feeders

The parameters for the sub-urban network are indicated in the third column in Table 1. Each 33/11kV transformer was linked to four 11kV outgoing feeders. Additionally, a range of 8 to 10 units of 11/0.4 kV transformers were set up in each 11kV feeders. The distance of the 33kV line from 132/33kV transformer to the 33/11kV power transformer was 9 km long. The entire length of 11kV feeder was ranged between 6 to 16 km, while the length between each 11/0.4 kV transformers was ranged between 0.75 to 1.6 km individually. The 33/11kV transformer capacity was 30 MVA, while the 11/0.4 kV transformer capacity was ranged between 0.75 to 1 MVA. The low voltage (LV) transformer showed maximum energy needed ranged between 0.229 to 0.367 MW.

3) Rural RN with 33 and 11 kV feeders

Rural network parameters are illustrated in the fourth column in Table 1. The maximum demand was ranged between 0.153 to 0.217 MW for individual 11/0.4 kV transformer for Rural. The distance of the 33kV line from 30MVA rated 33/11kV power transformer was 21 km, which is a more extensive length in comparison to urban and sub-urban. A 11kV feeder length ranged between 23 to 30 km was connected with a number of 11/0.4kV transformers ranged between 12 to 16 units. The length between each 11/0.4 kV transformer was ranged between 1.53 to 2.5 km, while the 11/0.4 kV transformer capacity was ranged between 0.5 to 0.75 MVA.

Table 1: Parameters for the development of urban, sub-urban, and rural reference networks

Parameters	Urban RN with 33 & 11kV feeders	Sub-Urban RN with 33 & 11kV feeders	Rural RN with 33 & 11kV feeders
132/33 kV transformer capacity (MVA)	45	45	45
No. of 11kV feeders per 33/11 kV Transformer	4	4	3
33/11 kV transformer capacity (MVA)	30	30	30
33 kV feeder length per feeder (km/feeder)	4.431	9	21
11 kV feeder length (km)	F1= 4.25 F2= 2.876 F3= 1.699 F4= 0.935	F1= 16 F2= 11 F3= 8 F4= 6	F1= 30 F2= 27 F3= 23
No. of 11/0.4 kV transformers	F1= 7 F2= 6 F3= 5 F4= 3	F1= 10 F2= 10 F3= 8 F4= 8	F1= 12 F2= 16 F3= 15
Distance between 11/0.4 kV transformers (km/each)	F1= 0.607 F2= 0.479 F3= 0.339 F4= 0.311	F1= 1.6 F2= 1.1 F3= 1 F4= 0.75	F1= 2.5 F2= 1.68 F3= 1.53
11/0.4 kV transformer loading (MW)	F1= 0.52 F2= 0.452 F3= 0.498 F4= 0.681	F1= 0.258 F2= 0.229 F3= 0.367 F4= 0.297	F1= 0.217 F2= 0.153 F3= 0.18

11/0.4 kV transformer capacity (MVA)	F1= 1 F2= 1 F3= 1 F4= 1	F1= 0.75 F2= 0.75 F3= 1 F4= 1	F1= 0.75 F2= 0.5 F3= 0.5

(b) Modelling of Demand

Demand profile with different types of the load is a vital parameter for assessing the losses in the reference network [15]. These three reference networks were developed based on typical residential, commercial, and industrial demand profiles obtained from power utility [16-20]. In order to perform time-series load flow simulation in DIgSILENT, a set of composite load profiles was used in this study. Samples of load composition for residential, commercial, and industrial load profiles are shown in Figure 2. In addition, all the loads modeled in DIgSILENT has power load with power factor equal to 0.90. The minimum and maximum load change according to each reference network because of different user mix in the network. Load factor (LF) serves as a measure of uniformity or variance in electricity usage pattern and can be calculated using Equation (1). Tables from 2 to 4 show the load composition and load factor for urban, sub-urban, and rural reference networks.

$$\mathrm{LF} = \frac{P_{average}}{P_{max}} \quad (1)$$

Where, $P_{average}$: Average power over period T, P_{max}: Maximum power over period T, T: The period in hours, i.e. 24 (daily hours), 720 (monthly hours) or 8760 (yearly hours).

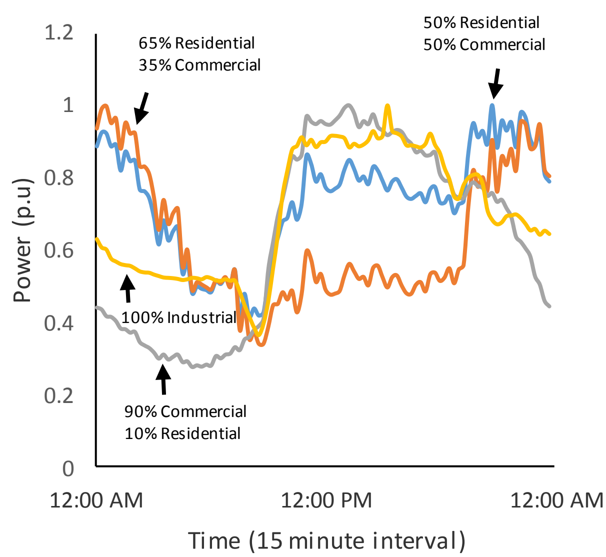

Figure 2: Samples of load composition utilized in time-series simulation for different load types

Table 2: Load composition and load factor for urban RN with 33 & 11 kV feeders

Load composition (%)			Load Factor (LF)	11kV feeder number
Residential	Commercial	Industrial		
50	50	0	0.739	F1
65	35	0	0.665	F2
55	45	0	0.728	F3
10	90	0	0.632	F4

Table 3: Load composition and load factor for sub-urban RN with 33 & 11 kV feeders

Load composition (%)			Load Factor (LF)	11kV feeder number
Residential	Commercial	Industrial		
60	40	0	0.704	F1
55	45	0	0.728	F2
65	35	0	0.665	F3
0	0	100	0.755	F4

Table 4: Load composition and load factor for rural RN with 33 & 11 kV feeders

Load composition (%)			Load Factor (LF)	11kV feeder number
Residential	Commercial	Industrial		
45	55	0	0.751	F1
65	35	0	0.665	F2
60	40	0	0.704	F3

(c) Optimal Selection of Distribution Cables and Distribution Transformers

1) Optimal Selection of Distribution Cables

This section presents the impact of losses on the selection of distribution cables. The minimum life-cycle cost methodology is utilized as a basis for the selection of distribution cable, that balances the capital investment cost against the cost of losses. The cable capital investment cost entails the price of buying the cable. Nevertheless, there is a high possibility that the cable is bought through borrowing in the form of a loan. Hence, the interest rate analysis must be taken into account in analyzing the cable investment cost. The greater is the value of the cable interest rate, the higher is the investment cost that was utilized to buy the cable. The losses in the electrical power are the result of the instant current and the cable resistance. The electrical power loses varies as the result of the load along the feeder. The current research takes into account , the investment cost as the annuitized capital cost of the cable (C_c) and computed through the utilization of Equation (2), meanwhile the annual cost of energy losses caused by the cable (C_L) is computed in Equation (3).

$$C_C = \frac{\frac{i}{100} \times (1 + \frac{i}{100})^n}{(1 + \frac{i}{100})^n - 1} \times S_o \qquad (2)$$

Where, C_C: Annuitized capital cost of cable (RM/km, year), S_o: Total capital expense (RM/km), i: Interest rate (%), n: Number of years.

$$C_L = 3 \times \mathrm{R} \times \sum_{t=1}^{8760} I^2(t) \times ep\,(t) \qquad (3)$$

Where, C_L: Total annual cost of losses in the cable (RM/km, year), R: Resistance of the cable (Ω/km), I(t): Current in (A) in the cable in time period t, ep(t): Energy price in time period t (RM/kWh).

The optimal size of distribution cables is determined by trading-off the annual cost of losses (C_L) and the annuitized capital cost (C_C). In order to determine the optimal capacity of the cable (I_{cap}), the sum of the annual cost of losses and the annuitized capital cost therefore has to be minimised. The objective function in this case is formally expressed in Equation (4). The optimal cable current-carrying capacity (I_{cap}^{opt}) can be found in Equation (5).

$$\underset{I_{cap}}{Minimise}\ \emptyset = (C_C + C_L) \qquad (4)$$

$$I_{cap}^{opt} = \sqrt[\left(\frac{1}{\beta}+\mathrm{b}\right)]{\frac{3 \times \rho \times \sum_{t=1}^{8760} I^2(t) \times \mathrm{ep}\,(t)}{\mathrm{a} \times \mathrm{b} \times \beta \times \left(\frac{1}{\alpha}\right)^{\frac{1}{\beta}}}} \qquad (5)$$

Where, ρ: Resistivity of the cable ($\Omega.mm^2$/km), α: Coefficient for current rating/cable size correlation for a given circuit topology (p.u.), β: Exponent for current rating/cable size correlation for a given circuit topology (p.u.), a: Correlation coefficient for annuitized capital cost/current rating correlation for a given circuit topology ($\frac{RM}{km.A^b}$), b: Exponent for annuitized capital cost/current rating correlation for a given circuit topology (p.u.). Equation (5) gives the current capacity minimizing the life cycle cost of the cable. This expression should be used for determining the optimal size of distribution cables required for the given circuit loading. It reflects the essence of the cable selection problem which is about balancing the annuitized cable capital cost and annual cost of losses. Clearly, the larger the cost of losses the larger the optimal cable size, and the larger the capital cost the smaller the optimal size, as expected. However, it is important to emphasize that the relationship between these quantities and the optimal cable size is strongly non-linear. Finally, the optimal utilization of distribution cables is given in Equation (6).

$$U^{opt} = \frac{I_{max}}{I_{cap}^{opt}} \times 100\% \qquad (6)$$

Where, U^{opt}: Optimal utilization of cable (%), I_{max}: Maximum current (A).

In this section, interest rate of 7%, voltage level of 11kV, energy price of RM 0.3853/kWh, cable technical lifespan 25 years, power factor of 0.9, and AL XLPE cable with resistivity of 28.8 Ω.mm^2/km is utilized to study the optimal cable selection. Figure 3 shows the flowchart of optimal cable selection operation. Table 5 shows the Aluminium (Al) cross-linked polyethylene (XLPE) insulated polyvinyl chloride (PVC) power sheathed underground cable data obtained from local vendor.

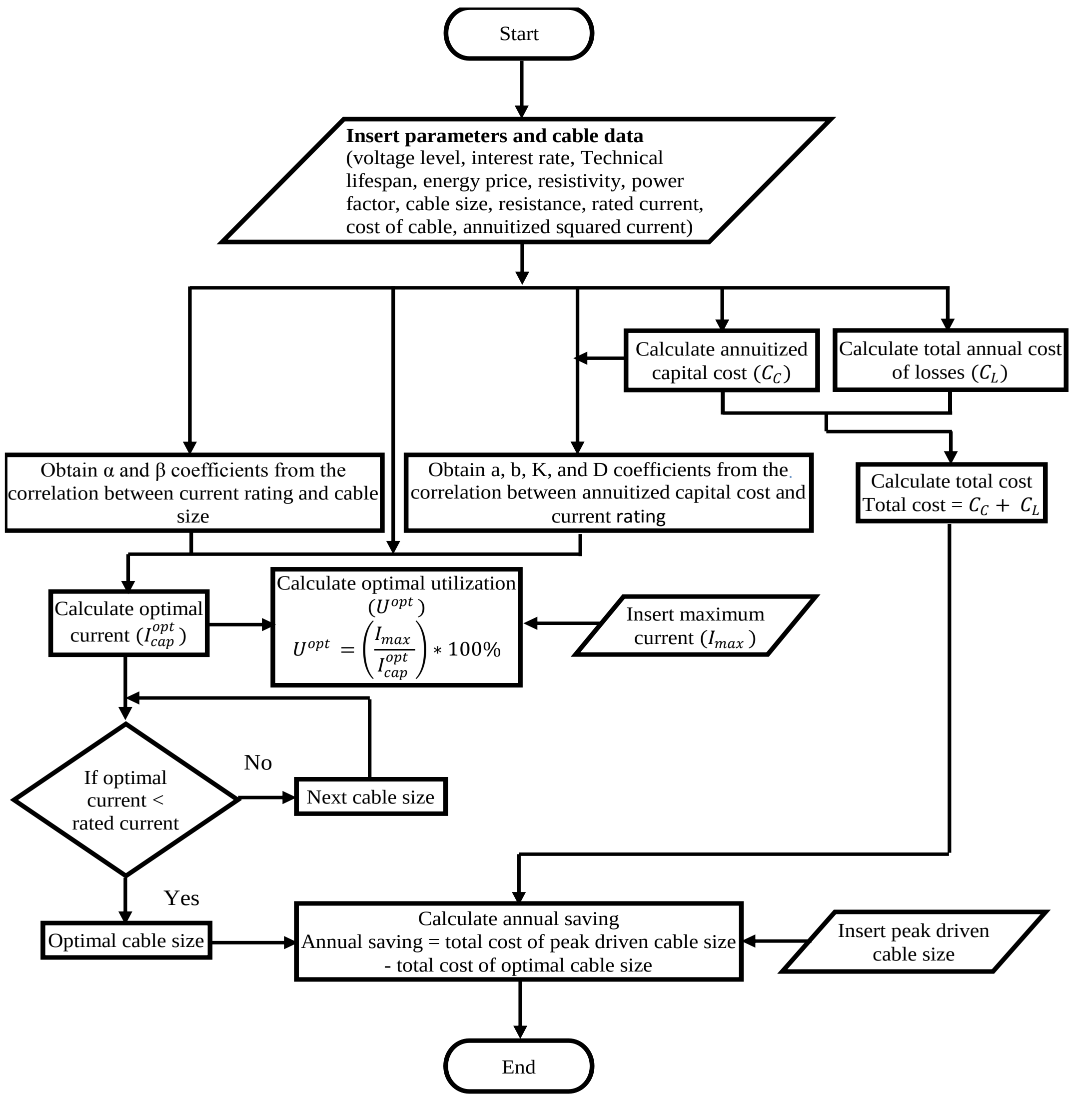

Figure 3: Flowchart of optimal cable selection operation

Table 5: Standard 11kV (Al/XLPE/PVC) cable data from local vendor

Cable size (mm^2)	Resistance (Ω/km)	Reactance (Ω/km)	Capacitance (µF/km)	Current rating (A)	Cost (RM/km)
50	0.822	0.111	0.28	160	69870
70	0.568	0.106	0.32	195	83060
95	0.41	0.100	0.36	230	99220
120	0.325	0.097	0.39	265	114460
150	0.265	0.094	0.42	300	127760
185	0.211	0.092	0.46	335	148650
240	0.161	0.089	0.51	380	178400
300	0.13	0.086	0.56	435	207630
400	0.102	0.083	0.62	490	260720
2×300	0.065	0.043	1.12	835	415260
3×300	0.043	0.028	1.68	1252	622890
4×300	0.032	0.021	2.24	1670	830520

2) Optimal Selection of Distribution Transformers

The same kind of approach using minimum life-cycle cost can be used for selecting the optimal capacity of a transformer. However, for a transformer operating at constant voltage and frequency, the losses can be divided into two components, usually described as no-load losses and load losses.

No-load losses result from energising the iron-core 24 hours a day, 365 days a year when a voltage is applied to the transformer regardless of the loading on the transformer. These are incurred whenever the transformer is coupled to the network, even if no power is being drawn. They result from the hysteresis and eddy-current losses in the iron core, which depend on the type of steel used to fabricate the core laminations. It can be assumed that these losses are independent of the load current passing through the transformer, but increase with increasing the voltage.

Load losses, sometimes called copper or winding losses, vary according to the loading of the transformer. They consist of the joule losses in the conductors caused by the load current in the primary and secondary windings. The total annual losses in kW is given in Equation (7).

$$P_{total} = LL \times \sum_{t=1}^{8760} \left(\frac{P_t}{P_{rated} \times cos\emptyset}\right)^2 \quad (7)$$

Where, P_{total}: Total annual losses (kW), LL: Load losses at rated power (kW), P_{rated}: Transformer capacity (kVA), Cos$\emptyset$: Load power factor, P_t: Active power in the transformer in time period t (kW).

Similarly to Equation (4) for distribution cables, the objective function applied to derive the optimal capacity of transformers is presented in Equation (8). Cost of losses in a transformer consists of two components: cost of no load losses and cost of load losses, as is given by Equation (9).

$$Minimise\,(C_c + C_L) \qquad (8)$$

Where, C_L: Total annual cost of losses in the transformer (RM/year), C_c: Annuitized capital cost of transformer (RM/year).

$$C_L = NLL \times \sum_{t=1}^{8760} ep(t) + \mathrm{LL} \times \sum_{t=1}^{8760} \left(\frac{P_t}{P_{rated} \times \cos\emptyset}\right)^2 \times ep(t) \qquad (9)$$

Where, NLL: No load losses at rated power (kW)

Table 6 shows the technical data of distribution transformers obtained from local vendor. In this section, the parameters used to choose the optimal transformer capacity such as interest rate, technical lifespan, energy price, and power factor are the same parameters used to find the optimal cable size. Figure 4 shows the flowchart of optimal transformer selection operation.

Table 6: Technical data of distribution transformers

Rated capacity (kVA)	Rated voltage (kV)	Losses (kW)		Impedance (%)	Cost (RM)	Vector group
		Load	No load			
100	11/0.4	1.36	0.25	4.75	17540.12	Dyn11
300	11/0.4	2.8	0.6	4.75	31784.58	Dyn11
500	11/0.4	4.1	1	4.75	42769.60	Dyn11
750	11/0.4	5.6	1.2	4.75	57927.83	Dyn11
1000	11/0.4	7	1.4	4.75	67400.50	Dyn11
1500	11/0.4	17	2.2	6	89015.77	Dyn11
2000	11/0.4	25	2.2	6	113008.53	Dyn11

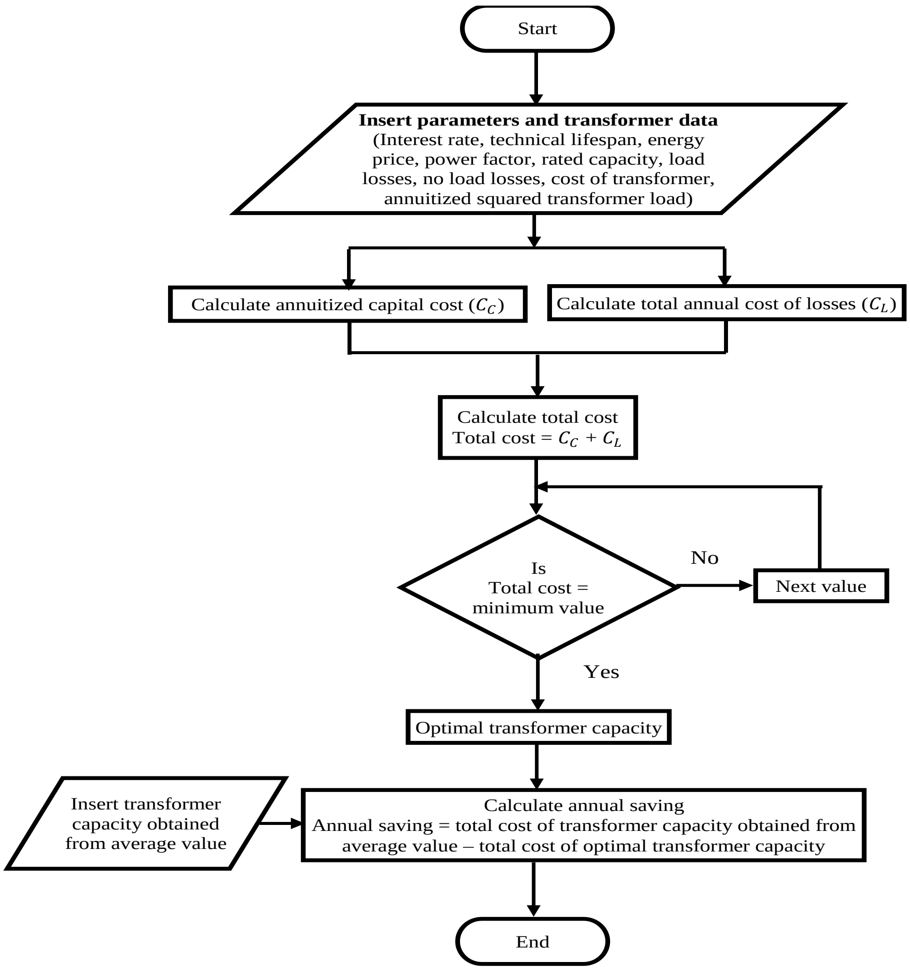

Figure 4: Flowchart of optimal transformer selection operation

III. RESULTS AND DISCUSSIONS

(a) Optimal Cable Selection

Figures from 5 to 7 show the peak driven and optimal cable size for urban, sub-urban, and rural reference networks. These figures also show that the cable size being selected by peak driven selection and optimal selection shows a huge gap. This suggests that due to the small cable size of the peak driven selection, the power loss is high and in turns this translated into high financial cost.

As shown in Figure 5 and Figure 6, the gap of both types of selections ranges from 135 mm² to 305 mm² for urban reference network, while the gap of both types of selections for sub-urban reference network ranges from 190 mm² to 250 mm². For rural reference network as shown in Figure 7, the gap of both types of selections ranges from 190 mm² to 250 mm². Furthermore, the gap of cable capacity utilization ranges from 39.05% to 62.53% for urban reference network. The gap of cable capacity utilization for sub-urban reference network ranges from 44.85% to 58.46%, while the gap of cable capacity utilization for rural reference network ranges from 50.68% to 61.49%. This difference in utilization percentage suggests that a power loss reduction of at least 39.05% to 62.53%, 44.85% to 58.46%, and 50.68% to 61.49% will occur if optimal selection is used for urban, sub-urban, and rural reference networks, respectively. Apart from that, the annual savings for replacing cables to optimal selection from peak driven selection ranges from RM 24533.440 to RM 59884.103, from RM 41215.073 to RM 53847.904, and from RM 40779.077 to RM 59081.776 per annum for urban, sub-urban, and rural reference networks, respectively as shown in Tables from 7 to 9.

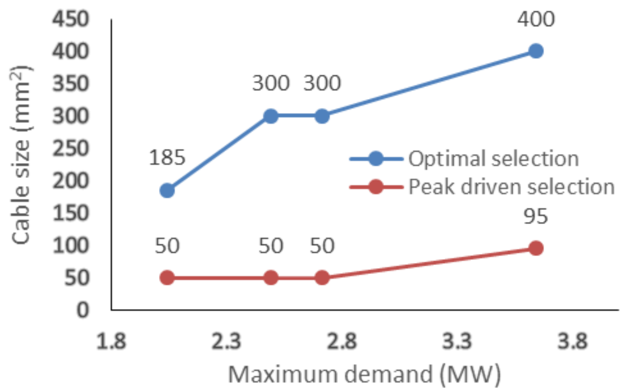

Figure 5: Peak driven and optimal cable size for urban RN with 33 & 11 kV feeders

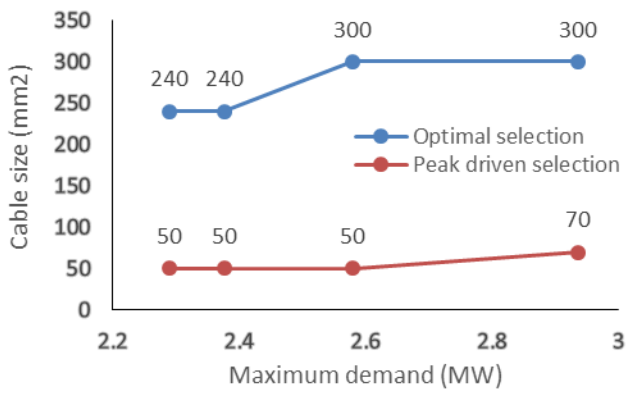

Figure 6: Peak driven and optimal cable size for sub-urban RN with 33 & 11 kV feeders

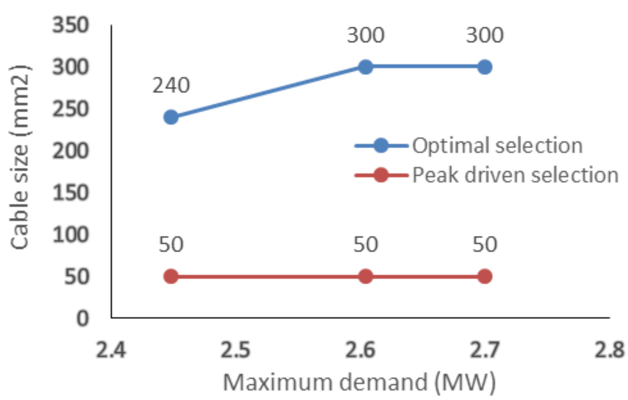

Figure 7: Peak driven and optimal cable size for rural RN with 33 & 11 kV feeders

Table 7: Cable utilization and annual saving for urban RN with 33 & 11 kV feeders

Difference in utilization (%)	Annual saving (RM/year)	Optimal selection cable utilization (%)	Peak driven selection cable utilization (%)	11kV feeder number
45.45	52406.134	40.20	85.66	F1
62.53	59884.103	36.38	98.92	F2
55.57	56881.751	32.33	87.90	F3
39.05	24533.440	35.70	74.76	F4

Table 8: Cable utilization and annual saving for sub-urban RN with 33 & 11 kV feeders

Difference in utilization (%)	Annual saving (RM/year)	Optimal selection cable utilization (%)	Peak driven selection cable utilization (%)	11kV feeder number
58.46	53847.904	34.01	92.48	F1
45.90	42630.433	33.38	79.29	F2
48.41	41215.073	39.34	87.76	F3
44.85	43809.102	32.62	77.48	F4

Table 9: Cable utilization and annual saving for rural RN with 33 & 11 kV feeders

Difference in utilization (%)	Annual saving (RM/year)	Optimal selection cable utilization (%)	Peak driven selection cable utilization (%)	11kV feeder number
52.58	58016.201	30.59	83.18	F1
50.68	40779.077	36.85	87.53	F2
61.49	59081.776	35.77	97.27	F3

b) Optimal Transformer Selection

The financial cost of the transformer based on average value is higher than optimal selection. This is due to the huge capacity of the transformer based on average value as compared to optimal transformer capacity selection. As shown in Table 10 and Table 11, the gap between average value and optimal selection for urban reference network is zero, while the gap between average value and optimal selection for sub-urban reference network ranges from 250 kVA to 500 kVA. For rural reference network as shown in Table 12, the gap between average value and optimal selection ranges from 200 kVA to 250 kVA. The annual savings for replacing transformers to optimal selection from average value ranges from RM 29.088 to RM 521.335 and from RM 264.695 to RM 555.192 per annum for sub-urban and rural reference networks, respectively.

Table 10: Average value and optimal transformer capacity selection for urban RN with 33 & 11 kV feeders

Annual saving (RM/year)	Optimal selection (kVA)	Average value from utility dataset (kVA)	Maximum transformer loading (MW)	11kV feeder number
0	1000	1000	0.52	F1
0	1000	1000	0.452	F2
0	1000	1000	0.498	F3
0	1000	1000	0.681	F4

Table 11: Average value and optimal transformer capacity selection for sub-urban RN with 33 & 11 kV feeders

Annual saving (RM/year)	Optimal selection (kVA)	Average value from utility dataset (kVA)	Maximum transformer loading (MW)	11kV feeder number
368.292	500	750	0.258	F1
521.335	500	750	0.229	F2
29.088	750	1000	0.367	F3
308.376	500	1000	0.297	F4

Table 12: Average value and optimal transformer capacity selection for rural RN with 33 & 11 kV feeders

Annual saving (RM/year)	Optimal selection (kVA)	Average value from utility dataset (kVA)	Maximum transformer loading (MW)	11kV feeder number
555.192	500	750	0.217	F1
264.695	300	500	0.153	F2
0	500	500	0.18	F3

Figure 8 shows the loss reduction for the three reference networks after selecting optimal cable size and transformer capacity based on minimum life-cycle cost methodology. In this section, the time-series load flow is performed with time interval 15-minutes. As shown in Figure 8, the total loss reduction in rural network is higher than urban and sub-urban networks. This is due to the fact that rural network has the highest feeder length and highest number of transformers in compare to urban and sub-urban networks. Changing the cable and transformer to the optimal one can contribute to reduce high percentage of losses.

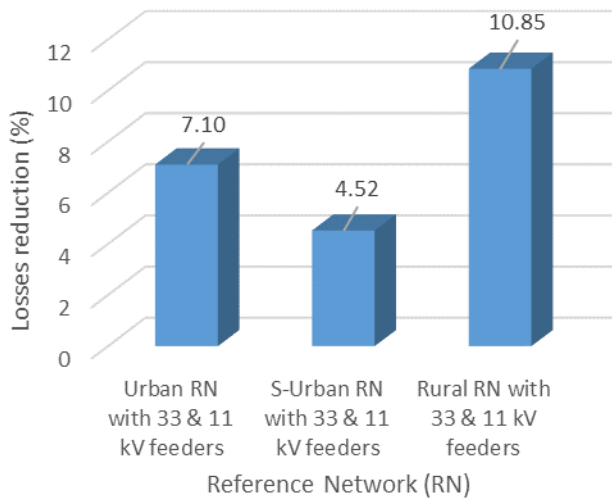

Figure 8: Loss reduction for the three reference networks after network optimization

IV. CONCLUSION

In conclusion, the strategy of cable and transformer selection should be changed from just fulfilling the safety and standard to optimal selection. The optimal cable and transformer selection for distribution network based on minimum life-cycle cost methodology can clearly indicate the need of optimal selection to reduce cost of loss and produce more revenue for a long-term lifespan. Three types of reference networks, namely urban, sub-urban, and rural networks with 33 kV and 11 kV feeders were modelled utilizing DIgSILENT power factory software. Different load compositions for typical residential, commercial, and industrial load profiles are considered to perform time-series load flow simulation. The output shows that the annual savings for replacing cables to optimal selection from peak driven selection ranges from RM 24533.440 to RM 59884.103 per annum, while the annual savings for replacing transformers to optimal selection from average value ranges from RM 29.088 to RM 555.192 per annum for the three RNs. Finally, the results show that the total loss reduction in rural network is higher than urban and sub-urban networks.

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