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An efficient method for estimating energy losses in distribution's feeder

Nur Diana Izzani Masdzarif[1], Khairul Anwar Ibrahim[2], Chin Kim Gan[1], Mau Teng Au[3], Kyairul Azmi Baharin[1], Nurul A. Emran[4], Zaheera Zainal Abidin[4]
[1]Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, Malaysia
[2]Fakulti Teknologi Kejuruteraan Elektrikal and Elektronik, Universiti Teknikal Malaysia Melaka, Malaysia
[3]Electrical Power Engineering, Institute of Power Engineering, Universiti Tenaga Nasional, Kajang, Malaysia
[4] Fakulti Teknologi Maklumat dan Komunikasi, Universiti Teknikal Malaysia Melaka, Malaysia

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ABSTRACT

This paper explains a simple and efficient methodology for calculating monthly energy losses (EL) using the load loss factor technique and a representative composite load profile. One of the important benefits of the proposed work is a simpler, more efficient and less rigorous method to estimate the system-wide energy loss of an extensive distribution network with reasonable accuracy. The sum of all EL provided by each feeder section is used to calculate the total feeder EL. A base case feeder with a typical cable type and power factor is used to generate regression equations, a peak power loss function to estimate the EL. A case study is then used to show the models and techniques that have been established. The result indicates a high level of agreement with the time-series load flow simulations (smaller than 10% deviations). With this model, an approach to estimate the EL of all radial feeders of various configurations and characteristics could be extended and implemented. The spreadsheet approach is ideal for completing a quick energy audit of existing distribution feeder EL and determining the sensitivity of distribution network efficiency to changes in feeder sections and load characteristics.

Corresponding Author:

Khairul Anwar Ibrahim
Fakulti Teknologi Kejuruteraan Elektrik dan Elektronik, Kampus Teknologi
Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: khairulanwar@utem.edu.my

1. INTRODUCTION

Energy losses (EL) is a measurement of the power system's efficiency in delivering energy to its customers. These EL are causing a significant impact on utility economic, regulatory and environmental issues. This waste or loss of electrical energy increases system capacity while degrading network performance and economic efficiency, which leads to large sums of losses and increased investment costs [1]–[4]. Because these costs are not covered directly by the privately-owned distribution network operation (DNO), EL is transferred to customers as part of service costs by increasing tariff [5]. As a result, regulatory authorities put additional restrictions on DNOs to decrease network losses to a predetermined standard. In some countries, if the losses measured are more significant than the standard, the DNO is penalized or receives financial incentives if it does the reverse [6]. EL also contribute to excessive emissions of greenhouse gases (GHG), provided that they have been entirely generated from fossil fuels power plants [1], [7]–[9]. Thus, the economics of the distribution network is dependent on the assessment of technical losses [10]. This is due to the fact that lowering losses lowers CO_2 emissions [11]. A study has shown that peak demand-driven network design is costlier in the long run compared to the loss-inclusive network design [12]. A significant contribution of EL comes from the distribution network, primarily contributed by I^2R losses in distribution feeders and both I^2R and no-load losses from transformers [13]. Power companies and regulators all over the world are continuously finding solutions to accurately assess and mitigate EL in power systems as it is a crucial signal for an energy-efficient system [3], [14]–[16].

The straightforward way to analyze feeder EL is to install energy meters at key locations along feeders to track the amount of energy moving into and out of specific feeder sections or any network component, but this would be costly [17]. Numerous theoretical calculation methods to determine EL are found in the literature, such as in reference [4], [18]–[20] are well established. Numerical simulations of load flow over time intervals are commonly utilized to analyze EL precisely in distribution feeders [11], [14], [21]–[23]. Fuzzy logic [24], clustering algorithm [25], and machine learning [26] are examples of artificial intelligence techniques. However, these methods require a thorough understanding and detailed modeling of a load profile (LP) of the distribution system, making EL estimation complicated and impractical when dealing with extensive distribution networks. When the detail networks and energy metering data are unavailable, the loss factor approach is frequently used by utilities to estimate EL in the distribution network [11], [27]. Researchers in [4], [17], [28]–[30] use benchmark networks to calculate the EL of wide distribution networks based on their clusters. However, because it is very unlikely that two networks or feeders will display similar characteristics, this benchmarking approach to determine the EL of a large distribution network may not produce acceptable findings [31]. Thus, there is still an opportunity to establish a more effective method for estimating distribution feeder EL in the absence of precise and real-time energy metering data.

This paper focuses on developing a simple and efficient approach to estimating EL in distribution's feeder sections (hence the entire feeder) and transformers based on representative composite LPs, feeder's loss characteristics and peak power loss (PPL) functions. The estimated LP of the load points, PPL general features, and the load loss factor approach are used to compute monthly EL for each feeder section. The total feeder EL is then calculated by adding all EL contributed by the feeder and the transformer in each section.

2. METHOD

Higher levels of current or load in a distribution system result in higher levels of power losses. This uniformity of the load and loss profile can be explained by the load factor (LF) and the loss factor (LsF) [32]. The equation of LF commonly employed by utilities is written in (2). The value of energy, E and maximum demand, P_{max} can be obtained from direct readings at the substations. Rearranging (2) yields (3), where the energy consumed or PPL can be calculated. The power demand, P_{max} can be computed using either (4) or load flow results. LF represents the load factor, $P_{average}$ is the average power over period T, P_{Max} indicates the maximum power over period T in MW, E indicates the total energy or units served over period T in MWh, T indicates the period in hours, P_t indicates the instantaneous power value at time t, where $t = 0 \ldots T$, V represents the voltage in kV, I_{max} expresses the maximum current in kW and θ_{pf} indicates the power factor angle in degree.

$$LF = \frac{P_{average}}{P_{max}} = \frac{1}{P_{max}} \times \frac{\int_{t=0}^{T} P_t(t)dt}{T} \quad (1)$$

$$LF = \frac{E}{P_{Max} \times T} \quad (2)$$

$$E = P_{max} \times LF \times T \quad (3)$$

$$P_{max} = \sqrt{3} \times V \times I_{max} \times \cos\theta_{pf} \quad (4)$$

LsF is calculated based on "the ratio of the average loss in kilowatts occurring during a specified period to the peak or maximum loss occurring in that period," as shown in (5). Where (6) is obtained by rearranging (5). The fundamental loss factor formulation is illustrated in (7), where the EL are estimated. The PPL, $P_{loss,max}$ can be calculated from load flow results or (8). $P_{Loss,Average}$ represents the average power loss in MW, $P_{Loss,Max}$ indicates the peak MW loss in MW, $P_{Loss,t}$ is the instantaneous power losses value at time t, where $t = 0 \ldots T$, E_{Loss} represents the EL in MWh, T indicates the period in hours, I_{max} indicates the maximum current in kW, and R shows the resistance in kΩ. Nevertheless, the loss factor can also be calculated using analytical equations, as depicted in (9). EL results are based on empirical approximation of LsF based on LF and LsF coefficient, α.

$$LsF = \frac{P_{loss,ave}}{P_{loss,max}} = \frac{1}{P_{loss,max}} \times \frac{\int_{t=0}^{T} P_{loss,t}(t)dt}{T} \tag{5}$$

$$LsF = \frac{E_{Loss}}{P_{loss,max} \times T} \tag{6}$$

$$E_{Loss} = P_{loss,max} \times LsF \times T \tag{7}$$

$$P_{loss,max} = I_{max}^2 \times R \tag{8}$$

$$LsF = \alpha \times LF + (1 - \alpha) \times LF^2 \tag{9}$$

2.1. Estimation of feeder section load profile

Distribution feeders usually are configured radially, with energy flowing uni-directionally from the grid supply substation (GSS) to the load. The current flows via numerous feeder sections to supply energy to all connected loads in a distribution feeder. As infeed energy flows from the power generation into each feeder, some energy flow in every feeder section is lost, primarily as I^2R losses and dissipates as heat. The amount of losses associated with each feeder section varies due to different lengths, loading profiles, topology, and cable sizes. Analytical calculations based on the cable length, peak power demand (PPD), PPL, LF, and LsF are formulated in [27], [33], [34]. During the period, T, the load for any number of feeder sections can be obtained by adding all the loads at each downstream load point. The coincident sum of all LPs at load points 1 to n can be used to compute the LP for the first feeder segment.

2.2. Feeder energy losses estimation

The 30-days EL (in MWh) can be estimated for each i^{th} feeder section based on its PPL, LsF and the period for 1 month [35], as shown in (10). In (11) calculates the LsF based on the feeder section's LF and LsF coefficient, α. The LF of the feeder section is calculated as the ratio of the average demand to the PPD.

$$EL_i = PPL_i \times LsF_i \times 30 \times 24, for\ all\ i = 0 \dots n \tag{10}$$

$$LsF_i = \alpha \cdot LF_i + (1 - \alpha) \times LF_i^2, for\ all\ i = 0 \dots n \tag{11}$$

In order to counter the problem of where detailed energy data are unavailable, a representative LP and LF are estimated at every point load. The representative LP is displayed in normalized form, as in Figure 1, using the data obtained by a load survey provided by the local power utility. It is then categorized by the different customer types and their percent composition. Table 1 shows the representative composite LP and the referring LF obtained from Figure 1. The normalized LP is then adjusted to the set peak demand to get various LP data for each load segment with different percent compositions. In this case, 100% load composition is used for each load segment. These new LPs now have the same LF with different peak demands. Table 2 shows the new LF from the adjusted LP.

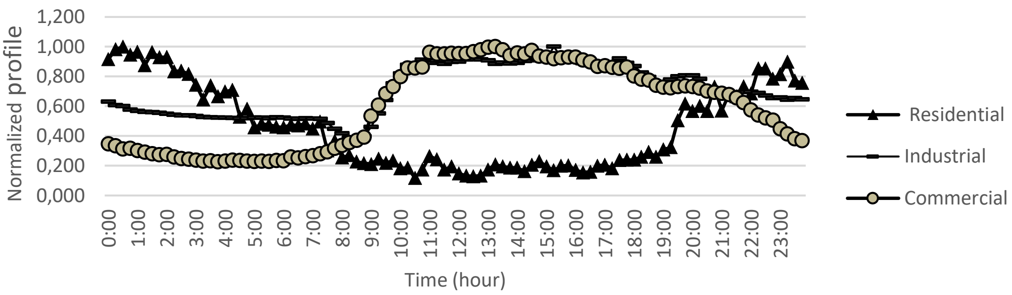


Figure 1. Representative composite LP in normalized form

Table 1. Load segment and their corresponding load factor

	Residential, R	Industrial, I	Commercial, C
Average load (normalized)	0.457	0.702	0.597
Peak load (normalized)	1.000	1.000	1.000
Load factor (normalized)	0.457	0.702	0.597

Table 2. New load factor

Load composition (%)			Load factor, LF
Residential, R	Industrial, I	Commercial, C	
100	0	0	0.445
0	100	0	0.704
0	0	100	0.601

Traditionally, running load flow simulations for every feeder section to determine the PPL for each power demand seems impractical because it requires a large amount of data and resources. This study aims to propose the easiest and more efficient way to estimate EL using a set of generic or representative feeders. This can be achieved by developing several general and generic equations that will allow users to estimate the PPL of the feeder section for any PPD value.

A PPL characteristic equation for the base case is constructed, as illustrated in Figure 2. The PPL of each feeder section is proportional to its PPD, measured in MW, which changes with time. This base case feeder section is simulated in DigSILENT Powerfactory™. The model of this base case feeder is set at 11 kV, 240 mm^2, three-core Cu XLPE cable type. Using power factor of 0.95, the static load flow simulations are performed at various percent (%) of loading. Then, with the PPL plotted at each PPD, the regression analysis of load flow results based on the base case feeder is constructed. Table 3 and Figure 3 depict a result obtained using base case, an 11 kV feeder. The PPL of the feeder sections is then estimated using this equation for any PPD with the condition that the feeder has the same length and size as the base case feeder.

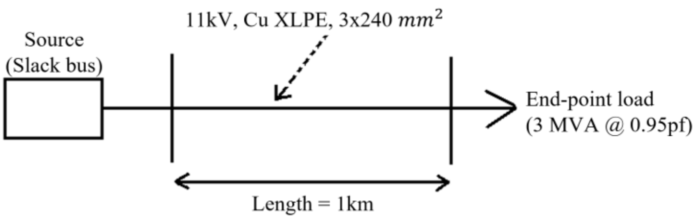


Figure 2. Model of the base case feeder section in a single line

Table 3. PPD and PPL for various percent (%) of load

Loading (%)	S (MVA)	P (MW)	Losses (MW)
10	0.3	0.285	5.49E-05
30	0.9	0.855	0.000501
50	1.5	1.425	0.001399
70	2.1	1.995	0.002749
90	2.7	2.565	0.004552
100	3.0	2.850	0.005623

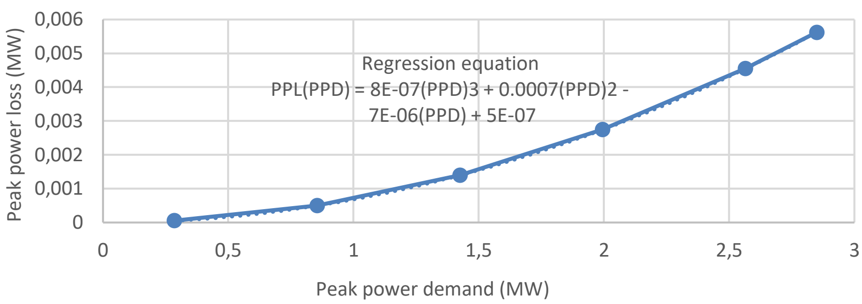


Figure 3. PPL regression equation for an 11 kV feeder section

The PPL regression equation must be modified to account for different feeder lengths to increase the accuracy of calculating PPL based on PPD. Research by Ibrahim *et al.* [35], the feeder PPL equation is proven to be linearly related to cable length. As a result, length correction factors are simply calculated by multiplying the PPL equation by the ratio of the length of the interest feeder (l_i) to the base case feeder length (l_b), as shown in (12). The coefficients a, b, c and d are the PPL coefficients for the base case feeder section. The 30-day EL for each feeder section with varying PPD and lengths are then calculated using this equation. Finally, as indicated in (13), the total feeder EL, EL_f may be determined by adding the EL of each feeder section, EL_i.

$$PPL_b = \frac{l_i}{l_b} \times \{a\rho_i^3 + b\rho_i^2 - c\rho_i - d\} \tag{12}$$

$$EL_f = \sum_{i=1}^{n} EL_i \tag{13}$$

2.3. Transformer energy losses estimation

The transformer losses consist of the NLL and FLL. The NLL and FLL in MW are fixed at 1 kW and 4 kW, respectively. These values are obtained from [36]. After that, both values in MW are converted into energy form in MWh as in (14) and (15). The total ELs (MWh) is the summation of the NLL and FLL in the energy unit is shown in (16).

$$NLL(MWh) = NLL(MW) \times 30 \times 24 \tag{14}$$

$$FLL(MWh) = TCF^2 \times FLL(MW) \times LsF \times 30 \times 24 \tag{15}$$

$$TL\ (MWh) = NLL(MWh) + FLL(MWh) \tag{16}$$

Then, based on the adjusted energy inflow in the feeders, the TL and percentage TL of the complete network is calculated. Finally, the whole process is repeated for the following network under study. It is important to note that the proposed approach is robust, meaning that it can be extended and used to estimate the TL of any radial MV distribution network of various sizes and demography. The following section will cover a case study utilizing the suggested method to estimate feeder losses in the Malaysian power utilities distribution network.

3. CASE STUDY

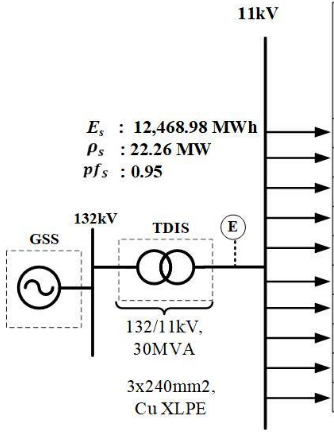
A case study based on a representative LP and base case feeders is used to demonstrate the proposed methodology. The feeders are generic and typical feeders based on different types of geographical areas. Based on the typical installation of the local power utility, base case feeders are set at 11 kV, 240 mm^2, three-core, Cu XLPE cable type. These characteristics are based on a statistical study performed on the data provided by Tenaga Nasional Berhad (TNB). Since the length of the feeder varies depending on the location of the area served, (12) can be used to adjust the regression equation. PPL can be obtained through the proposed method. For simplification, loads are assumed to be balanced, with a power factor of 0.95 and constant voltage along the feeder. The 30-day EL obtained in the result is just an assumption where the estimated loading profile does not significantly change during the whole loss calculation period. Table 4 summarises the features of the studied MV distribution network at Bandar Segamat. The estimation of EL is then verified and validated using load flow simulation with a 15-minute time interval. Further addition and change of the parameter values, such as the PPL regression equation, is required for feeders of a different type.

Table 4. Real data of feeder network and its respective generic characteristics in Bandar Segamat

Description	Parameter
Ratio (kV)	132/11
Energy (MWh)	12468.9797
Feeder MD (MW)	22.26061
11 kV UG feeder number	10
11 kV UG feeder length (km)	103.75
No. of distribution transformer 11 kV	154
Distribution transformer capacity 11 kV	80.34
LV underground (UG) feeder number	53
LV Overhead (OH) feeder number	335

4. RESULTS AND DISCUSSION

The case study's findings are divided into the estimation of total feeder EL and validation using a time-series load flow simulation. Figure 4 shows the system used as a case study. TCF represents the transformer capacity factor. The results of the 30-day EL estimation for feeder EL and transformer EL are shown in Tables 5 and 6. The EL calculated using the suggested method are consistent with only some changes in the feeder section's characteristics. Since the feeder length is the manipulated variable, in this case, the PPL regression equation is adjusted as in (12) for the length correction factors. As a response, it provides valuable data to help network planners or utilities prioritize EL mitigation plans.



11kV feeder no.	Infeed Energy (MWh/month)	Load section @ No. of 0.5MVA, 11/0.4kV distribution transformer	Length (km)	Recorded maximum current (A)	LF	TCF
F11-01	1786.265	21	14.863	200	0.703	5.608
F11-02	1575.686	19	13.111	205	0.605	4.364
F11-03	1130.708	14	9.408	200	0.445	3.210
F11-04	1268.235	16	10.553	165	0.605	3.596
F11-05	848.031	11	7.056	150	0.445	2.372
F11-06	1431.045	18	11.907	160	0.704	4.016
F11-07	1259.850	16	10.483	165	0.601	3.520
F11-08	1388.294	17	11.552	155	0.705	5.224
F11-09	904.567	11	7.527	160	0.445	2.892
F11-10	876.299	11	7.291	155	0.445	2.810

Figure 4. Distribution system of a case study

Table 5. EL estimation for feeder line

Feeder no.	Length (km)	Estimated peak demand (MW)	Load segment	LF	Corrected infeed energy (MWh/month)	Length correction factor (exclude LV)	PPL (MW)	New PPL	LsF	Line losses in 30-days (MWh)
F11-01	14.863	3.620	I	0.703	1786.265	5.899	0.009	0.054	0.546	21.319
F11-02	13.111	3.710	C	0.605	1575.686	5.204	0.010	0.050	0.426	15.398
F11-03	9.408	3.620	R	0.445	1130.708	3.734	0.009	0.034	0.260	6.416
F11-04	10.553	2.986	C	0.605	1268.235	4.188	0.006	0.026	0.426	8.017
F11-05	7.056	2.715	R	0.445	848.031	2.801	0.005	0.014	0.260	2.701
F11-06	11.907	2.896	I	0.704	1431.045	4.726	0.006	0.028	0.548	10.941
F11-07	10.483	2.986	C	0.601	1259.850	4.161	0.006	0.026	0.421	7.878
F11-08	11.552	2.805	I	0.705	1388.294	4.585	0.006	0.025	0.549	9.983
F11-09	7.527	2.896	R	0.445	904.567	2.987	0.006	0.018	0.260	3.280
F11-10	7.291	2.805	R	0.445	876.299	2.894	0.006	0.016	0.260	2.981
Total	103.75	31.04			12468.98	41.18				88.915

Table 6. EL estimation for transformer

Feeder No.	MVA capacity	LF	LsF	Net infeed energy (MWh)	No. of tx.	Power (MW)	TCF	NLL (MWh)	FLL (MWh)	Transformer losses (MWh)
F11-01	0.5	0.703	0.546	1764.95	21	2.804	5.608	15.120	2.459	17.579
F11-02	0.5	0.605	0.426	1560.29	19	2.182	4.364	13.680	1.341	15.021
F11-03	0.5	0.445	0.260	1124.29	14	1.605	3.210	10.080	0.585	10.665
F11-04	0.5	0.605	0.426	1260.22	16	1.798	3.596	11.520	1.048	12.568
F11-05	0.5	0.445	0.260	845.33	11	1.186	2.372	7.920	0.386	8.306
F11-06	0.5	0.704	0.548	1420.10	18	2.008	4.016	12.960	1.473	14.433
F11-07	0.5	0.601	0.421	1251.97	16	1.760	3.520	11.520	0.964	12.484
F11-08	0.5	0.705	0.549	1378.31	17	2.612	5.224	12.240	2.606	14.846
F11-09	0.5	0.445	0.260	901.29	11	1.446	2.892	7.920	0.575	8.495
F11-10	0.5	0.445	0.260	873.32	11	1.405	2.810	7.920	0.540	8.460
Total		5.703	3.955	12380.065		18.806	37.612	110.880	11.977	122.857

Table 5 shows feeder section 1 has the highest PPD for the industrial segment, resulting in the highest losses, although the average feeder length is short. From Table 6, the PPD of the LP does not deviate too much from other feeder sections. However, the losses at feeder section 1 and section 2 are higher than the others. The significant losses of these two feeder sections are primarily due to the high PPD and longer feeder length. Furthermore, feeder section 5 has the lowest losses due to the low PPD and LF. Table 6 shows that feeder section 1 has the highest number of transformers of all the sections in the same feeder. Hence the EL is also the highest because of the high PPD. Table 7 shows that when total feeder EL are compared to time-series load flow simulations, the total differences are less than 10%. It is suggested that the proposed method produces reasonably accurate findings.

The data from Tables 5-7 are presented in a chart form, as shown in Figures 5 and 6. From Figure 5, the estimated EL for 30 days in MWh contributed from each feeder section shows a decreasing trend as the feeder moves away from the source. For this particular generic feeder, as we move downstream towards the end of the feeder, the total current accumulated for each feeder section increases, hence, the EL also decreases. However, in some cases, like feeder sections 3-5, the losses can be smaller, which may be caused by shorter length feeder sections and different types of load segments which variates the PPD. Another example is that the EL for feeder section 6 is more than feeder section 5 because feeder section 6 has a bigger LF since the load segment is for an industrial area.

Figure 6 indicates the comparison graph between the estimated total energy feeder and simulated total energy feeder for the transformer and feeder line at 11 kV feeder section. It clearly shows that the differences between estimated and simulated are close for each representative feeder type, as recorded in Table 7, which is less than 10%. With this information, we can rank the feeders based on the amount of EL, enabling power utility companies to have a more strategic approach for planning mitigation action.

Table 7. Validation of estimated EL using time-series load flow simulations

Representative feeder type	Estimated total feeder EL (MWh)	Simulated feeder EL (time series) (MWh)	% Difference (MWh)
Transformer	122.857	142.525	14.822
Feeder line	88.915	84.086	5.583
Total	211.772	226.611	6.770

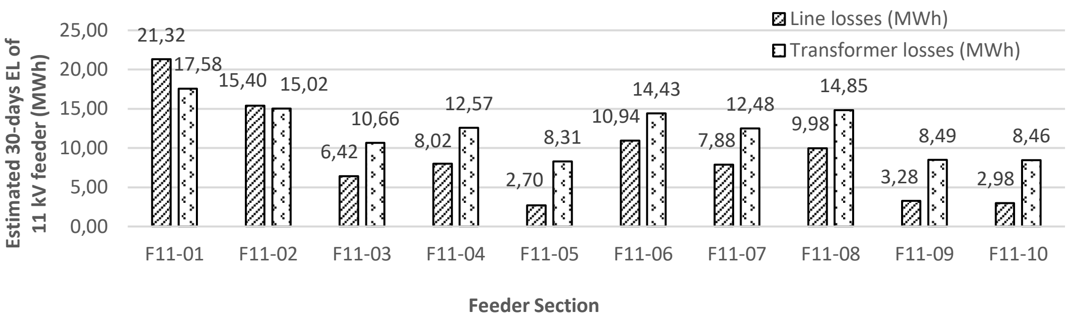


Figure 5. Estimated 30-days EL versus feeder section for each feeder type

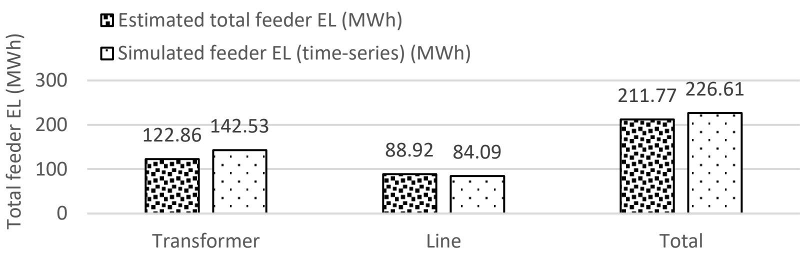


Figure 6. Comparison between estimated and simulated feeder EL

5. CONCLUSION

The objective of this study was to determine the EL in a power distribution network using the load loss factor technique and energy flow model. A simplified approach employing analytical methods based on equations developed from simulations and energy distribution is used to estimate EL of any characteristics of the utility distribution feeder. The technique helps assess the performance of a distribution feeder by comparing its EL to those of other feeders. It is demonstrated that the findings acquired using the proposed method are reasonably accurate. According to a spreadsheet developed using the analytical process, changes in feeder peak demand, normal off-point, power factor, and other factors could all affect EL. For further research, estimations on the loss of power by feeder with bidirectional power flow due to the penetration of distributed generation, harmonic effects and unbalanced circumstances could be extended. This methodology is helpful for power utilities where Smart Meters are not yet a reality and resources are limited, allowing for efficient system-wide estimation with reasonably accurate findings.

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BIOGRAPHIES OF AUTHORS

Nur Diana Izzani Masdzarif received the Bachelor of Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM), Malaysia in 2021. She is a Graduate Engineer, registered under Board of Engineers Malaysia (BEM). Currently, she is a Graduate Research Assistant (GRA) at Universiti Teknikal Malaysia Melaka. Her research interests include power distribution network and energy losses. She can be contacted at email: dianaizzani98@gmail.com.

Khairul Anwar Ibrahim finished his Bachelor's and Master's degree in Electrical Power Engineering from Rensselaer Polytechnic Institute (RPI), New York, USA in 2000 and 2002 respectively. From 2002-2009, he worked at the Tuanku Ja'afar Power Station and TNB Research Sdn. Bhd. Since 2010, he works as a senior lecturer at University Teknikal Malaysia Melaka (UTeM). In 2018, he finished his Ph.D in Electrical Engineering from Universiti Tenaga Nasional (UNITEN). His research interests include energy efficiency, energy losses and power distribution network. He can be contacted at email: khairulanwar@utem.edu.my.

Chin Kim Gan is an Associate Professor at the Department of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. He received his B.Eng and M.Eng degree both in electrical engineering from Universiti Teknologi Malaysia (UTM) and Ph.D degree from the Imperial College London, UK. He is currently an Associate Professor at Universiti Teknikal Malaysia Melaka (UTeM), Malaysia and also a registered Professional Engineer with the Board of Engineers Malaysia (BEM). His research interests are distribution network design integration of renewable energy and smart grid. He can be contacted at email: ckgan@utem.edu.my.

Mau Teng Au received the B.S.E.E. degree in Electrical Engineering from the University of Toledo, Toledo, Ohio, in 1986 and the M.Sc. degree in the same field from Purdue University, West Lafayette, IN, USA, in 1996 and Ph.D degree in electrical engineering from the University of Manchester in 2006. He was a Professor in the Institute of Power Engineering, UNITEN, Kajang. He is Professional Engineer registered with Board of Engineers Malaysia. He has been in numerous posts in Tenaga Nasional Berhad in TNB Distribution since 1980-1998 and a lecturer from 1998 to 2015. He was also a director of Power Engineering Center from 2008-2016. His research interest includes power distribution design and planning, power stability and power quality. He can be contacted at email: Mtau@uniten.edu.my.

Kyairul Azmi Baharin is a senior lecturer at the Department of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. He completed his bachelor's degree in UTeM, master's in University of New South Wales, Australia and Ph.D in Universiti Teknologi Malaysia, all in the field of electrical engineering. His research interests focus in the area of solar photovoltaic with emphasis on forecasting, system performance and grid integration challenges. He can be contacted at email: kyairulazmi@utem.edu.my.

Nurul A. Emran is an Associate Professor at the Universiti Teknikal Malaysia Melaka (UTeM). She received a bachelor's degree in Management Information System (MIS) from the International Islamic University Malaysia in 2001, an MSc in Internet and Database Systems from London South Bank University in 2003, and a Ph.D. degree in computer science from the University of Manchester, the UK in 2011. Her research interests include data quality (data completeness), database systems and security, storage space optimization, mobile analytics, and green computing. She can be contacted at email: nurulakmar@utem.edu.my.

Zaheera Zainal Abidin is a senior lecturer and researcher at Universiti Teknikal Malaysia Melaka. She received Bachelor of Information Technology from University of Canberra, Australia in 2002.She completed her MSc. in Quantitative Sciences (2004), MSc. in Computer Networking (2008) and PhD in I.T. and Quantitative Sciences (2016) from Faculty of Computer and Mathematical Sciences, Universiti Teknologi MARA, Shah Alam, Selangor. She served as a lecturer at Universiti Kuala Lumpur (2005-2009) and senior lecturer & researcher in Universiti Teknikal Malaysia Melaka (2009–present). She is the head of OptiMAS research group in FTMK. Research interest in internet of things and network security. She can be contacted at email: zaheera@utem.edu.my.