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System wide MV distribution network technical losses estimation based on reference feeder and energy flow model

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A B S T R A C T

This paper presents an integrated analytical approach to estimate technical losses (TL) of medium voltage (MV) distribution network. The concept of energy flow in a radial MV distribution network is modelled using representative feeders (RF) characterized by feeder peak power demand, feeder length, load distribution, and load factor to develop the generic analytical TL equations. The TL estimation approach is applied to typical utility MV distribution network equipped with energy meters at transmission/distribution interface substation (TDIS) which register monthly inflow energy and peak power demand to the distribution networks. Additional input parameters for the TL estimation are from the feeder ammeters of the outgoing primary and secondary MV feeders. The developed models have been demonstrated through case study performed on a utility MV distribution network supplied from grid source through a TDIS with a registered total maximum demand of 44.9 MW, connected to four (4) 33 kV feeders, four (4) 33/11 kV 30 MVA transformers, and twelve (12) 11 kV feeders. The result shows close agreement with TL provided by the local power utility company. With RF, the approach could be extended and applied to estimate TL of any radial MV distribution network of different sizes and demography.

1. Introduction

Technical losses (TL) are an inevitable consequence of transferring energy across the electrical network components. According to World Bank, from 2003 to 2013, TL in transmission and distribution (T&D) system worldwide contributes between 7 and 10% of the total energy output [1], of which mostly coming from the distribution network [2,3]. The reduction of even a fraction of the 7–10% TL would translate into financial savings of billions of dollars annually [4]. In today's competitive environment, the increasing costs of energy, power equipment, drive to reduce greenhouse gases emissions, and pressures from energy regulator to improve network efficiency, are forcing utility companies to embark on loss mitigation initiatives [5,6].

In order to carry out successful distribution loss mitigation programs, it is necessary to accurately identify the causes, contributors and magnitude of TL in the system. The definitive method is to install energy meters at strategic locations of feeders and transformers to record the energy in and out of the individual component or network, of which would be a costly exercise [7]. Theoretical calculation methods to determine TL [8–11] and time-interval load flow simulations [3,12,13] were carried out to estimate TL in power system networks. However, the methods require in-depth knowledge and detail modelling of the distribution system, making the computation of TL difficult and inefficient when dealing with large distribution networks.

When the complete set of networks and loads data are not available, the prevailing method to estimate TL in the distribution network is to use loss factor (LsF) [14]. For example, in [15–18], LsF were applied to empirical peak power loss (PPL) equations to estimate TL of distribution feeders. TL estimation based on percentage loading of network components as reported in [19] is accurate but rigorous, as it requires numerous input parameters. A simple and efficient TL calculation method for radial distribution feeders using specific node voltages were obtained by load flow program under average loading conditions as reported in [20]. In [7,21,22],a benchmarking approach based on samples of typical feeders were used to infer TL of large distribution network according to their clusters. However, since it is unlikely that any two networks and/or feeders exhibit the same characteristics, the benchmarking approach to infer TL of large distribution network might not yield

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Nomenclature

Variables

E_S	total energy recorded at transmission/distribution interface substation (TDIS) for a 30-day period
$pf_{33}(i)$	power factor (PF) of the i^{th} 33 kV feeder
$pf_{11}(j)$	PF of the j^{th} 11 kV feeder
$\mathcal{F}_{33}(i)$	load factor (LF)of the i^{th} 33 kV feeder
$\mathcal{F}_{11}(j)$	LF of the j^{th} 11 kV feeder
$E^B_{33}(i)$	energy recorded by energy meter of 33 kV bulk customers connected at the i^{th} primary distribution substation (PDS)
$E^B_{11}(i)$	energy recorded by energy meter of 11 kV bulk customers connected at the i^{th} PDS
$I^{Max}_{33}(i)$	maximum current recorded by the i^{th} 33 kV feeder ammeter
$I^{Max}_{11}(j)$	maximum current recorded by the j^{th} 11 kV feeder ammeter
ρ_{33}	peak power demand (PPD) of 33 kV feeder
ρ_{11}	PPD of 11 kV feeder
l	feeder length

Functions

$\wp_{33}$	peak power loss (PPL) equation of 33 kV feeder
$\wp_{11}$	PPL equation of 11 kV feeder
$\Im_{33}(i)$	Technical Loss (TL) of the i^{th} 33 kV feeder
$\Im_{11}(j)$	TL of the j^{th} 11 kV feeder
$\Im_{TX}(i)$	TL of the i^{th} 33/11 kV transformer
$\Im_{TX}(i)$	TL of the i^{th} 33/11 kV transformer
$\varepsilon_{33}(i)$	percentage of TL for the i^{th} 33 kV feeder
$\varepsilon_{11}(j)$	TL of the j^{th} 11 kV feeder as a percentage of its inflow energy
$\varepsilon_{TX}(i)$	TL of the i^{th} 33/11 kV transformer as a percentage of its inflow energy
ε_{SYS}	TL of the whole MV distribution network as a percentage of its inflow energy
$E^I_{33}(i)$	energy inflow to the i^{th}33 kV feeder
$E^I_{33}(i)'$	adjusted energy inflow to the i^{th} 33 kV feeder
$E^O_{33}(i)$	energy outflow from the i^{th} 33 kV feeder
$E^I_{TX}(i)$	energy inflow to the i^{th} 33/11 kV transformer
$E^O_{TX}(i)$	energy outflow from 33/11 kV transformer
$E^I_{11}(j)$	energy inflow to the j^{th} 11 kV feeder
$E^I_{11}(j)'$	adjusted energy inflow to the j^{th} 11 kV feeder
μ_{33}	adjustment factor to adjust estimated inflow energy to 33 kV feeders
$\mu_{11}(i)$	adjustment factor to adjust estimated inflow energy to 11 kV feeders of the i^{th} PDS
$\wp_B$	PPL equation of base case feeder
$\wp_F$	PPL equation of MV feeder of interest
$\mathcal{L}_{33}(i)$	loss factor (LsF) of the i^{th} 33 kV feeder
$\mathcal{L}_{TX}(j)$	LsF of the i^{th} 33/11 kV transformer
$\mathcal{L}_{11}(j)$	LsF of the j^{th} 11 kV feeder

Parameters

i	index of PDS, 33 kV feeders and 33/11 kV transformers
m	total number of PDS, 33 kV feeders and 33/11 kV transformers
j	index of 11 kV feeders
$n(i)$	total number of 11 kV feeders of the i^{th} PDS
a_B, b_B, c_B, d_B	polynomial coefficients of base case PPL equation
$a_{33}, b_{33}, c_{33}, d_{33}$	polynomial coefficients of PPL equation for 33 kV feeder
$a_{11}, b_{11}, c_{11}, d_{11}$	polynomial coefficients of PPL equation for 11 kV feeder
σ_L	correction factor associated with feeder length
σ_T	correction factor associated with feeder topology
σ_{LD}	correction factor associated with feeder load distribution (LD)
α	LsF coefficient
δ	33/11 kV transformer capacity factor
P^{NL}_{TX}	33/11 kV transformer no-load loss
P^{FL}_{TX}	33/11 kV transformer full-load loss
$\mathcal{F}$	load factor
$\mathcal{L}$	loss factor

acceptable results [23]. Adoption of reference network (RN) approach has the potential to ensure that the analysis of benchmarked TL are representative of the actual TL of the system [24,25]. In [26], the average values of current with an improved loss coefficient were used to enhance the accuracy of calculating TL. In [27,28], a heuristic-based power loss model where large network information/data were trained and applied to estimate TL of large distribution network.

In recent years, many studies developed a generic distribution network models as benchmark network, known as reference network (RN). The application of RN has been reported to be mainly in the areas of distribution network planning [25,29], costs assessment under the incentive based regulation [30–32], and more recently, the assessment on the impact of integrating Smart Grid technologies [24] and distributed energy resources in distribution networks [33,34]. So far, however, research works in applying RN to determine TL for different applications are limited to using load flow simulations results [24,25,35]. One major difficulty is, load flow simulations need to be repeated each time any of the feeder parameters changes, making it a time consuming and rigorous task, especially for large network types and configuration.

To address the above-mentioned issues in TL estimation, this paper proposed on the idea of establishing a reference feeder (RF) on a MV distribution network characterized by feeder peak power demand (PPD), length, load distribution (LD) and loss factor (LsF) to develop the generic analytical TL equations. System wide estimation of TL is then estimated based on the energy flow model (EFM) that was developed for traditional radial MV network (i.e. with unidirectial power flow) with energy recorded at TDIS and customer bulk supply points, and feeder ammeter current.

The remaining part of this paper is arranged as follows: Section 2 presents the concept of modelling energy flow in a radial distribution network. Section 3 describes the characteristics of MV representative reference feeder (RF). Section 4 presents the methodology to estimate TL based on the EFM, RF, LF and LsF. Section 5 provides a case study based on a real utility MV network. The results and discussions of the case study are in Section 6. Finally, the conclusions of this work are drawn in Section 7.

2. Energy flow model in radial distribution network

Traditional distribution networks (without distribution generation) are normally equipped with energy meters at the transmission/distribution interface point to register the amount of active and reactive energy which flow unidirectially from the grid to the distribution network. The same energy meters would also register the PPD at the interface point. Typically, due to economic reasons, MV feeders are not equipped with energy meters, but are installed with ammeters that have maximum current indicator. Bulk customers connected at the MV level are installed with energy

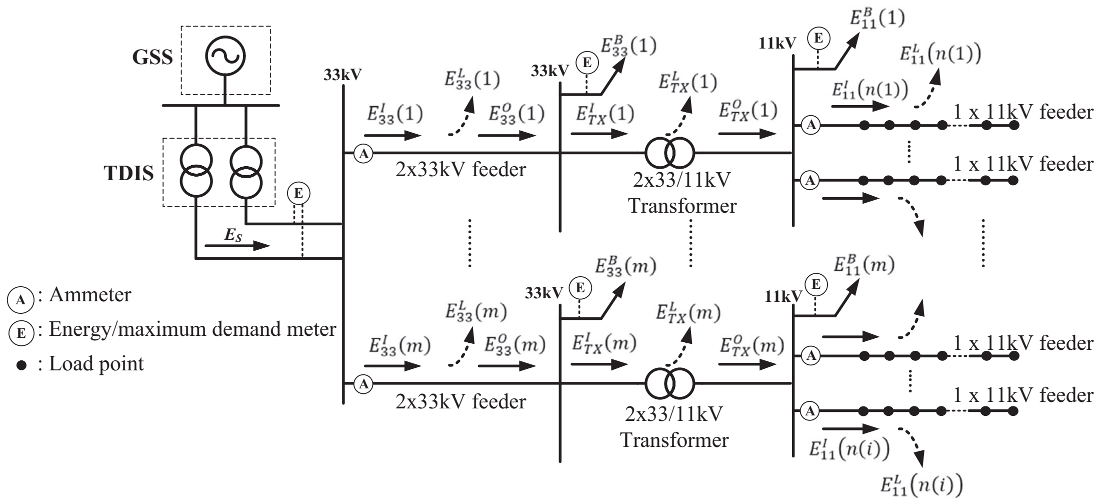

Fig. 1. Representation of energy flow in radial MV distribution network.

meters which also record PPD for revenue billing purposes. The EFM shown in Fig. 1 is based on a MV distribution network configured for security of supply where 33 kV feeders and 33/11 kV transformers are operating in parallel with single redundancy, typically referred to as N-1 contingency.

Referring to Fig. 1, equations based on energy balanced principle over a 30-day (720 h) period are formulated to describe the flow of energy through each of the 33 and 11 kV feeder, 33/11 kV transformer, and the whole MV distribution network. Eqs. (1)–(5) are related to the flow of energy from the TDIS to the 33 kV feeders. Eq. (1) is formulated to estimate the energy which flows into each of the 33 kV feeder based on the maximum current recorded by the respective feeder ammeter, its power factor (PF) and its LF. To enhance the accuracy of estimating the percentage TL for each MV component and consequently the MV network, the 30-day energy (E_S) recorded by the energy meters at the TDIS is used to satisfy the condition whereby the flow and distribution of energy into the individual 33 kV feeder should summed up to E_S. Hence, a scaling/adjustment factor, μ_{33} based on (2) is applied to satisfy the fundamental principle that the energy recorded at TDIS should be equal to the estimated total sum of energy that flows into the 33 kV feeders. Consequently, the estimated energy that flows into the 33 kV feeders previously calculated based on (1), is then adjusted by a factor μ_{33} as shown in (3).

In (4), the net energy that flows out from the respective 33 kV feeder is calculated as the difference between the estimated energy that flows into the feeder minus the TL of the feeder. TL estimation methodology using RF is discussed in detail in Section 4. The percentage of TL, defined as the inflow energy of the respective 33 kV feeder or as a group of feeders are shown in (5) and (6) respectively.

$$E^I_{33}(i) = \sqrt{3} \times I^{Max}_{33}(i) \times 33000 \times pf_{33}(i) \times \mathcal{F}_{33}(i) \times 720, \quad i = 1, \cdots, m \tag{1}$$

$$\mu_{33} = \frac{E_S}{\sum_{i=1}^{m} E^I_{33}(i)}, \quad i = 1, \cdots, m \tag{2}$$

$$E^I_{33}(i)' = \mu_{33} \times \sqrt{3} \times I^{Max}_{33}(i) \times 33000 \times pf_{33}(i) \times \mathcal{F}_{33}(i) \times 720, \quad i = 1, \cdots, m \tag{3}$$

$$E^O_{33}(i) = E^I_{33}(i)' - \Im_{33}(i), \quad i = 1, \cdots, m \tag{4}$$

$$\varepsilon_{33}(i) = \frac{\Im_{33}(i)}{E^I_{33}(i)'} \times 100\%, \quad i = 1, \cdots, m \tag{5}$$

$$\varepsilon_{33} = \frac{\sum_{i=1}^{m} \Im_{33}(i)}{\sum_{i=1}^{m} E^I_{33}(i)'} \times 100\%, \quad i = 1, \cdots, m \tag{6}$$

Equations on energy flow through the 33/11 kV transformer and its TL are shown in (7)–(9). Calculations on transformer TL are discussed in Section 4.3. The percentage of TL of the individual transformer and the group of transformers are given in (8) and (9) respectively.

$$E^O_{TX}(i) = E^O_{33}(i) - E^B_{33}(i) - \Im_{TX}(i), \quad i = 1, \cdots, m \tag{7}$$

$$\varepsilon_{TX}(i) = \frac{\Im_{TX}(i)}{\left[E^O_{33}(i) - E^B_{33}(i)\right]} \times 100\%, \quad i = 1, \cdots, m \tag{8}$$

$$\varepsilon_{TX} = \frac{\sum_{i=1}^{m} \Im_{TX}(i)}{\sum_{i=1}^{m} \left[E^O_{33}(i) - E^B_{33}(i)\right]} \times 100\%, \quad i = 1, \cdots, m \tag{9}$$

Referring to Fig. 1, for each set of 2 × 33 kV feeder and 2 × 33/11 kV transformer at the primary distribution substation (PDS), which is indexed from $i = 1$ to m, there are $n(i)$ out going 11 kV feeders at each PDS. At the 11 kV buses, an adjustment factor $\mu_{11}(i)$, determined from (11) is applied to adjust the total energy estimated based on (10) so that the total energy flowing out from the i^{th} 33/11 kV transformers into the set of 11 kV feeders is equal. Consequently, the estimated energy that flows into the 11 kV feeders previously calculated based on (10) is then adjusted by applying the adjustment factor $\mu_{11}(i)$ as shown in (12). The percentage TL of the respective individual and group of 11 kV feeders are given in (13) and (14) respectively.

$$E^I_{11}(j) = \sqrt{3} \times I^{Max}_{11}(j) \times 11000 \times pf_{11}(j) \times \mathcal{F}_{11}(j) \times 720, \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m \tag{10}$$

$$\mu_{11}(i) = \frac{E^O_{TX}(i) - E^B_{11}(i)}{\sum_{j=1}^{n(i)} E^I_{11}(j)}, \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m \tag{11}$$

$$E^I_{11}(j)' = \mu_{11}(i) \times \sqrt{3} \times I^{Max}_{11}(j) \times 11{,}000 \times pf_{11}(j) \times \mathcal{F}_{11}(j) \times 720, \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m \tag{12}$$

Table 1
Samples of representative MV feeder model.

RF type	Cable type	Positive sequence impedance (Ω/km)	Capacitance (μF/km)	Topology	Load distribution
F33-A1	33 kV, 630 mm^2, 3 core, Al XLPE	0.0627 + j0.1070	0.35	Single feeder	Load concentration at feeder tail
F11-A1	11 kV, 240 mm^2, 3 core, Al XLPE	0.1609 + j0.1524	0.4690	Multiple laterals	Evenly distributed along feeder
F11-A2	11 kV, 240 mm^2, 3 core, Al XLPE	0.1609 + j0.1524	0.4690	Multiple laterals	Load concentration at feeder source
F11-A3	11 kV, 240 mm^2, 3 core, Al XLPE	0.1609 + j0.1524	0.4690	Multiple laterals	Load concentration at feeder tail
F11-A4	11 kV, 240 mm^2, 3 core, Al XLPE	0.1609 + j0.1524	0.4690	No lateral	Load concentration at feeder source
F11-A5	11 kV, 240 mm^2, 3 core, Al XLPE	0.1609 + j0.1524	0.4690	No lateral	Load concentration at feeder tail

$$\varepsilon_{11}(j) = \frac{\Im_{11}(j)}{E^{l}_{11}(j)'} \times 100\%, \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m \tag{13}$$

$$\varepsilon_{11} = \frac{\sum_{j=1}^{n(i)} \Im_{11}(j)}{\sum_{i=1}^{n(i)} E^{l}_{11}(j)'} \times 100\%, \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m \tag{14}$$

Percentage TL of the whole MV distribution network is then determined based on (15).

$$\varepsilon_{SYS} = \frac{\sum_{i=1}^{m} \{\Im_{33}(i) + \Im_{TX}(i)\} + \sum_{j=1}^{n(i)} \Im_{11}(0j)}{E_S} \times 100\%, \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m \tag{15}$$

It should be noted that, with minor modifications of the energy flow equations, the EFM presented can be applied to determine energy efficiency of radial MV components and network of different voltages (e.g. 22 kV and 6.6 kV) and network configurations (i.e. feeder length, LD and number of laterals).

3. MV reference feeder model

In a real distribution system, the MV feeders and its load characteristics are never the same for every feeder. Thus, it is impossible to estimate TL on the basis of a model that includes every single feeder of the system as the process involved would be extremely time consuming and costly [36]. Hence, this motivates research works in developing simplified and generic feeder models which

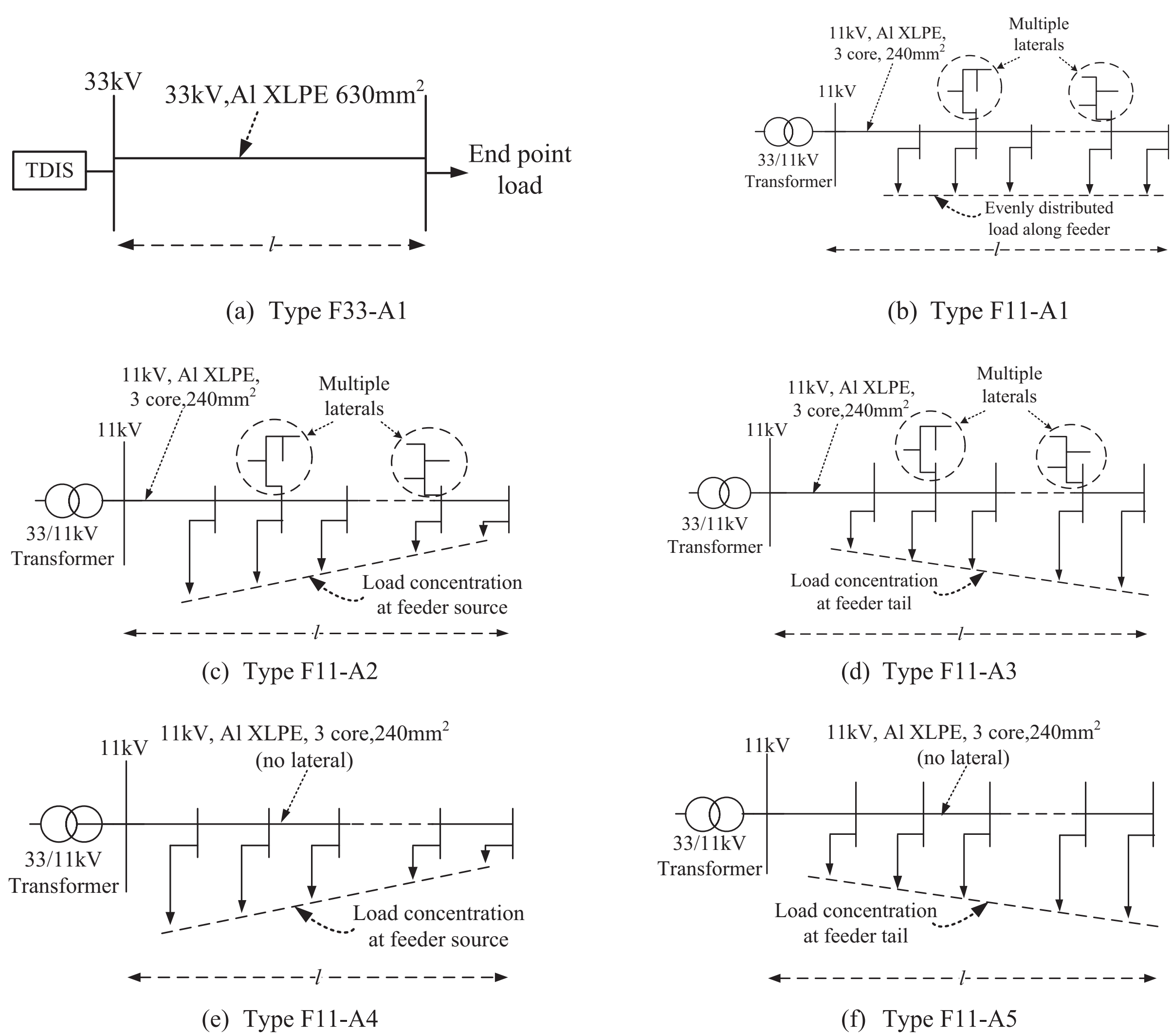

Fig. 2. (a)–(f) Single line diagram of different MV RF type.

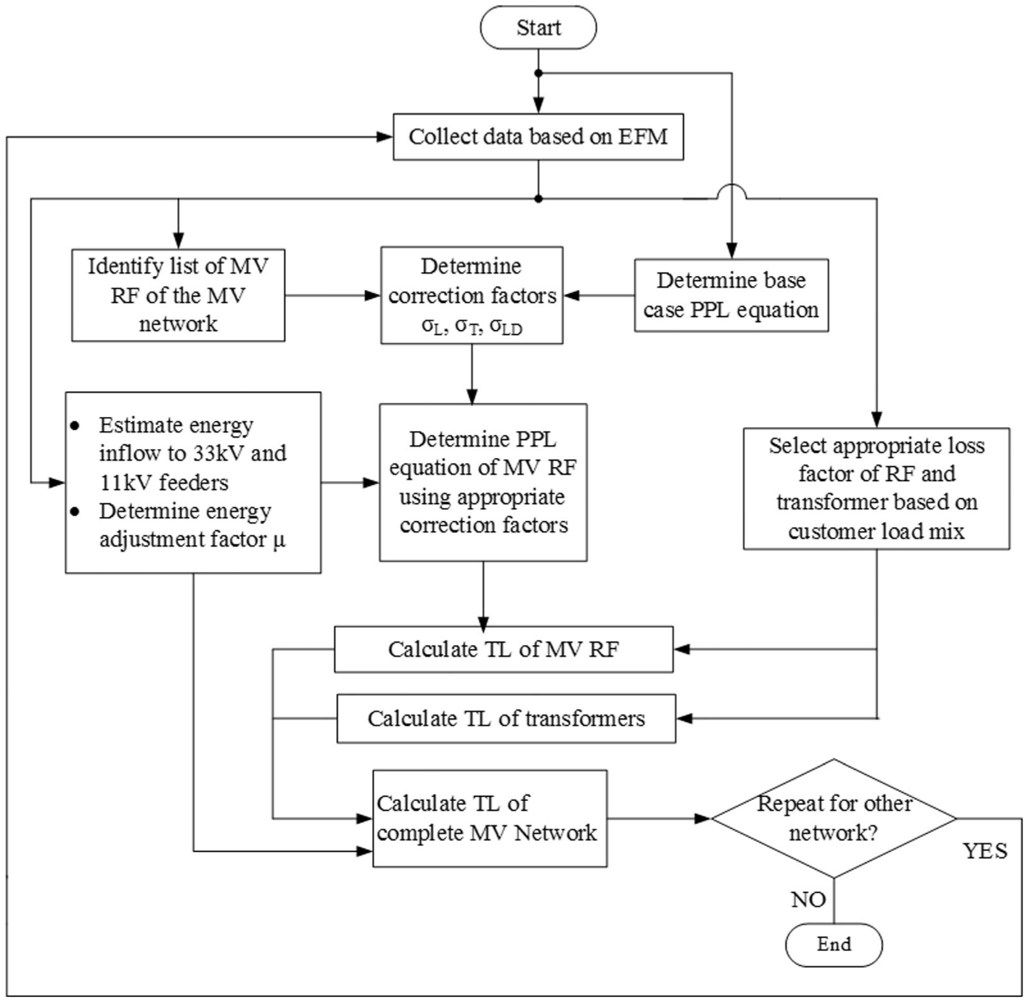

Fig. 3. Flowchart of system wide MV distribution TL estimation.

Table 2
Base case polynomial coefficients.

Base case type	Base case parameters				Base case polynomial coefficients			
	Cable type	Length (km)	Topology	LD	a_B	b_B	c_B	d_B
33 kV	630 mm^2, 3 Core, Al XLPE	10	Without lateral	Point load at feeder end	0.000001	0.000623	0.000198	0.000203
11 kV	240 mm^2, 3 Core, Al XLPE	10	Without lateral	Evenly distributed along feeder	0.000075	0.005755	0.000691	0.000166

Table 3
Accuracy of the base case polynomial.

Voltage	Feeder PPD (MW)	Feeder PPL (kW)		Difference in PPL between estimation and load flow simulation (%)
		Estimation from base case polynomial equation	Load flow simulation	
33 kV	4.32	11.055	11.069	0.13%
	8.64	45.644	45.753	0.24%
	14.4	129.523	130.034	0.39%
11 kV	0.855	3.829	3.857	0.72%
	1.425	11.085	11.100	0.14%
	2.850	46.678	46.667	0.02%

statistically represents a group of feeders known as reference network (RN) of the real system [24,37]. The TL analysis of each RN could then be benchmarked or inferred to other feeders in the large network with similar generic characteristics [29,33].

In this paper, the goal is to establish an accurate estimation of the energy which flows through the MV feeders of diverse characteristics without the need to repetitively model and perform load flow simulations for each and every feeder. Hence, a set of representative

Table 4
Correction factors of MV RF.

Feeder of interest characteristics		PPL Correction factor, σ	
Feeder length	l km	$0.1 \times l$	σ_L
Topology	One lateral	0.991	σ_T
	Two laterals	0.951	
	Three laterals	0.859	
Load distribution	Concentration at feeder source	0.678	σ_{LD}
	Concentration at feeder tail	1.485	

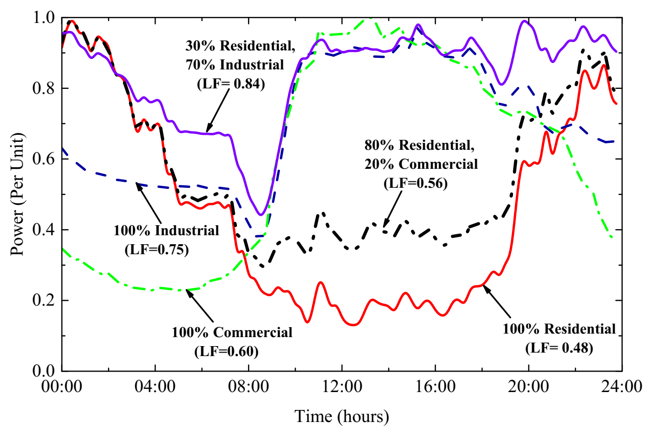

Fig. 4. Load profile curves and LF.

Table 5
Samples of LF with different customers load compositions.

MV feeder	Load composition (%)			LF	Supply zone demographic
	Residential	Industrial	Commercial		
X	10	10	80	0.65	Business centre
Y	20	70	10	0.78	Commercial and Industrial (mixed)
Z	80	0	20	0.56	Residential

Table 6
Validation of TL estimation.

11 kV feeder	LF	Feeder length (km)	TL for 30-day period (MWh)		Difference between estimation and load flow simulation (%)
			Estimated using analytical equations	Load flow simulation	
A	0.457	20	12.056	12.796	−5.78
B	0.702	11	30.280	29.386	3.04
C	0.652	15	24.091	24.775	−2.76
D	0.802	6	9.114	9.219	−1.14
E	0.555	8	14.660	14.123	3.81

reference feeder (RF) which captures the principal and typical characteristics of feeders from real network were developed for the purpose of estimating TL of the feeders. As an illustration, as shown in Table 1, are samples of MV RF based on real 33 kV and 11 kV feeders which were developed using statistical analysis presented in [38,39]. Single line diagrams of the MV RF are shown in Fig. 2.

4. MV distribution network TL estimation methodology

Equations on energy flow in radial MV distribution network were formulated based on the principles of EFM as discussed Section 2. Estimation of TL for the whole MV distribution network as shown in Fig. 1 is divided into four parts: (a) Computation of TL for the 33 kV feeders; (b) Computation of TL for the 33/11 kV transformers; (c) Computation of TL for the 11 kV feeders; and (d) Computation of TL for the whole MV distribution network based on the EFM and the associated input data from energy meters at TDIS, bulk supply points, and feeder ammeters. A flow chart to estimate TL of a MV radial distribution network based on EFM, RF, peak power loss (PPL), LF and LsF is shown in Fig. 3.

4.1. PPL estimation of MV RF

Real MV feeders in the distribution network can be classified and represented using RF based on the feeder PPD, length, cable size, LD and topology. One of the advantages of modelling PPL equations of MV feeders based on its RF is that, the power loss at PPD of the feeders could be estimated using a set of generalised parameters associated with the RF. By modelling the MV RF and performing load flow simulations, a mathematical relationship between PPL and PPD is obtained. For the load flow simulation, the voltage at the reference/slack bus is set and regulated at 1.05 p.u. Using regression method, the base case feeder PPL equation is established as a cubic polynomial as shown in (16).

$$\wp_B = f_B(\rho) = a_B\rho^3 + b_B\rho^2 - c_B\rho + d_B \qquad (16)$$

Variable ρ in (16) is the PPD of the feeder, while a_B, b_B, c_B and d_B are the polynomial coefficients for the base case MV RF. The network parameters of the base case feeders and its polynomial coefficients are as shown in Table 2. The accuracy of estimating PPL for the two (2) base cases were validated against PPL obtained from time series load flow simulation. The validation results indicate a difference of less than 1% as shown in Table 3.

PPL of feeders with different characteristics from the base case is estimated by applying correction factors to the base case polynomial coefficients as shown in (17). Three correction factors, σ_L, σ_T and σ_{LD} which are associated with feeder length, topology and LD respectively are multiplied with the base case polynomial coefficients to obtain the PPL equation of the feeder of interest, $\wp_F$ as shown in (17).

$$\wp_F = f_F(\rho) = \sigma_L \cdot \sigma_T \cdot \sigma_{LD} \times \{a_B\rho^3 + b_B\rho^2 - c_B\rho + d_B\} \qquad (17)$$

As feeder PPL is directly proportion to its length, and with the base case feeder length fixed at 10 km, the feeder length correction factor, σ_L is therefore equal to $0.1 \times l$, where l is the length of the feeder of interest. Correction factors, σ_T and σ_{LD} which are associated with the feeder topology and load distribution respectively are obtained from load flow simulations results. The associated feeder characteristics and its correction factors are summarized as shown in Table 4.

4.2. Estimation of technical losses in MV RF

TL in MV feeders can be obtained from time series simulations of the feeder and its load profile. While the TL results obtained might be accurate, the approach is not efficient to determine TL of MV networks on a system wide level. Based on the LsF expression shown in (18), TL of the feeder of interest over a 30-day period can be calculated from its corresponding PPL equation using (19) [14,17,40].

$$\mathcal{L} = \alpha \cdot F + (1 - \alpha) \cdot F^2 \qquad (18)$$

$$\Im = \wp_F \times \mathcal{L} \times 720 \qquad (19)$$

Table 7
Sensitivity analysis for different LsF coefficient, α.

Feeder LF	Feeder load composition (%)			LsF coefficient, α					
				0.1	0.15	0.2	0.25	0.3	0.35
	Residential	Industrial	Commercial	% difference between estimated and simulated TL					
0.457	100	0	0	18.5	14.1	9.8	5.5	1.1	3.2
0.506	90	0	10	11.6	7.7	3.8	0.2	4.1	8.1
0.556	80	10	10	6.8	3.3	0.1	3.5	7.0	10.4
0.611	70	20	10	3.6	0.7	2.2	5.1	8.0	10.9
0.660	10	10	80	9.4	7.1	4.8	2.5	0.2	2.1
0.702	0	100	0	2.9	0.9	1.1	3.0	5.0	7.0
0.752	50	30	20	1.9	0.3	1.3	2.9	4.4	6.0
0.802	30	30	40	4.0	2.8	1.6	0.5	0.7	1.8
Average difference (%)				7.34	4.61	3.09	2.90	3.81	6.19

Table 8
Summary of system wide losses estimation equations for MV distribution network.

Network components/MV network	Percentage of energy losses equations
Individual 33 kV feeder	$\varepsilon_{33}(i) = \frac{\Im_{33}(i)}{E^{I}_{33}(i)'} \times 100\%, \quad i = 1, \cdots, m$
33 kV network	$\varepsilon_{33} = \frac{\sum_{i=1}^{m} \Im_{33}(i)}{\sum_{i=1}^{m} E^{I}_{33}(i)'} \times 100\%, \quad i = 1, \cdots, m$
Individual 33/11 kV transformer	$\varepsilon_{TX}(i) = \frac{\Im_{TX}(i)}{\left[E^{O}_{33}(i) - E^{B}_{33}(i)\right]} \times 100\%, \quad i = 1, \cdots, m$
33/11 kV transformers	$\varepsilon_{TX} = \frac{\sum_{i=1}^{m} \Im_{TX}(i)}{\sum_{i=1}^{m} \left[E^{O}_{33}(i) - E^{B}_{33}(i)\right]} \times 100\%, \quad i = 1, \cdots, m$
Individual 11 kV feeder	$\varepsilon_{11}(j) = \frac{\Im_{11}(j)}{E^{I}_{11}(j)'} \times 100\% \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m$
11 kV network	$\varepsilon_{11} = \frac{\sum_{j=1}^{n(i)} \Im_{11}(j)}{\sum_{i=1}^{n(i)} E^{I}_{11}(j)'} \times 100\% \quad j = 1, \cdots, n(i), \quad i = 1, \cdots, m$
MV network	$\varepsilon_{SYS} = \frac{\sum_{i=1}^{m} \{\Im_{33}(i) + \Im_{TX}(i)\} + \sum_{j=1}^{n(i)} \Im_{11}(j)}{E_S} \times 100\% \quad j = 1, \cdots, n(i), i = 1, \cdots, m$

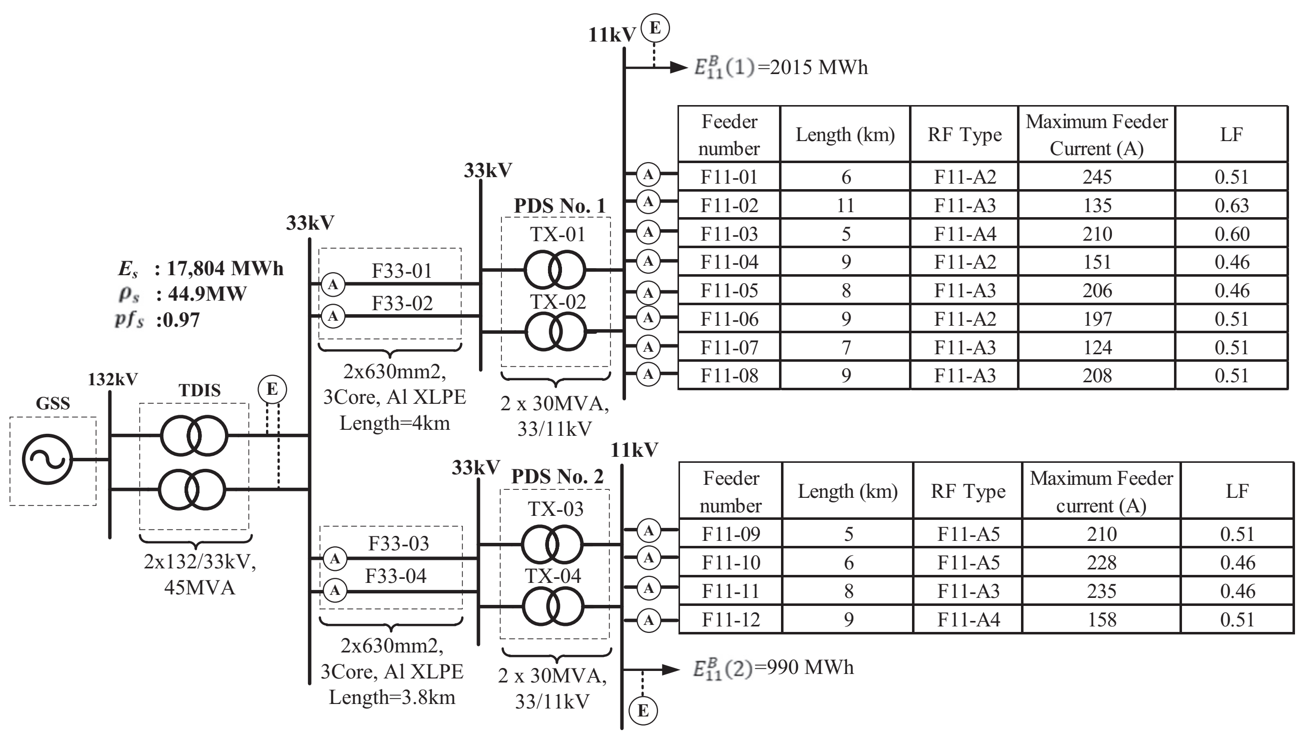

Fig. 5. Case study network.

Table 9
Inflow energy to 33 kV feeders.

E_s = 17,804 MWh					
33 kV Feeder	Maximum feeder current (A)	PF	LF	PPD (MW)	Estimated energy inflow (MWh)
F33-01	258	0.97	0.62	14.30	6376.87
F33-02	258	0.97	0.62	14.30	6376.87
F33-03	165	0.97	0.48	9.15	3170.09
F33-04	165	0.97	0.48	9.15	3170.09
Total				46.90	19093.90

Table 10
Estimation of TL in 33 kV feeders.

33 kV Feeder	Adjusted energy inflow (MWh)[Note 1]	Length (km)	PPL (MW)	LsF	TL (MWh)	TL (%)
F33-01	5946.12	5.2	0.066	0.442	21.159	0.36
F33-02	5946.12	5.2	0.066	0.442	21.159	0.36
F33-03	2955.95	3.5	0.018	0.294	3.801	0.13
F33-04	2955.95	3.5	0.018	0.294	3.801	0.13
Total	17804.13				49.921	

Note 1: Adjusted with $\mu_{33} = 0.93$.

Table 11
Inflow energy and estimation of TL in 33/11 kV transformers.

33/11 kV Transformer	Energy inflow (MWh)	PPD (MW)	Capacity factor	No-load losses (MWh)	Full load losses (MWh)	TL (MWh)	% TL
TX-01	5924.96	14.238	0.44	10.8	19.461	30.261	0.511
TX-02	5924.96	14.238	0.44	10.8	19.461	30.261	0.511
TX-03	2952.15	9.130	0.29	10.8	8.002	18.802	0.637
TX-04	2952.15	9.130	0.29	10.8	8.002	18.802	0.637
Total	17754.21			43.20	54.93	98.13	

The LsF shown in (18) is dependent on the feeder LF and coefficient α. While α is between 0.15 and 0.3 [15,16,18], feeder load factor (LF) can vary between 0 and 1.0, and is influenced by the load profiles of customers connected to the feeder. Typical daily load profiles of residential, industrial and commercial customers are shown in Fig. 4. LF representing different customers' load compositions can be derived from statistical analysis of large data sets [41–43]. Table 5 shows samples of LF with different customers' load compositions that have been identified based on supply zone demography provided by the power utility company.

Table 12
Inflow energy and estimation of TL in 11 kV feeders.

PDS no 0.1

Bulk feeder energy (MWh) = 2015.00
Bulk feeder PPD (MW) = 4.00
Overall load mixed: 70% residential, 30% commercial

11 kV Feeder	Energy inflow (MWh)[Note 2]	Peak power demand (MW)[Note 2]	PPL (MW)	LsF	TL (MWh)	TL (%)
F11-01	1582.48	4.43	0.0471	0.32	10.79	0.68
F11-02	1090.97	2.44	0.0476	0.46	15.72	1.44
F11-03	1600.24	3.80	0.0285	0.42	8.54	0.53
F11-04	881.40	2.73	0.0248	0.27	4.85	0.55
F11-05	1202.44	3.73	0.0960	0.27	18.73	1.56
F11-06	1272.44	3.57	0.0389	0.32	8.92	0.70
F11-07	800.93	2.24	0.0293	0.32	6.72	0.84
F11-08	1343.49	3.76	0.1058	0.32	24.23	1.80
Total	9774.39				98.49	

PDS no 0.2

Bulk feeder energy (MWh) = 990.00
Bulk feeder PPD (MW) = 1.96
Overall load mixed: 95% residential, 5% commercial

11 kV Feeder	Energy inflow (MWh)[Note 3]	Peak power demand (MW)[Note 3]	PPL (MW)	Loss factor	TL (MWh)	TL (%)
F11-09	1302.24	3.80	0.063	0.32	14.43	1.11
F11-10	1277.72	4.13	0.090	0.27	17.48	1.37
F11-11	1316.95	4.25	0.126	0.27	24.62	1.87
F11-12	979.78	2.86	0.029	0.32	6.57	0.67
Total	4876.69				63.10	

Note 2: Adjusted with $\mu_{11}(1) = 0.98$; Note 3: Adjusted with $\mu_{11}(2) = 0.94$.

Table 13
Summary of TL estimation.

MV component	Total inflow energy (MWh)	TL (MWh)	TL (%)
33 kV Feeders	17804.13	49.92	0.28
33/11 kV Transformers	17754.21	98.13	0.55
11 kV Feeders	14651.08	161.60	1.10
Total		309.64	1.74

The accuracy of estimating TL of MV feeders using (18) and (19) were validated against results obtained from 15 min time interval load flow simulation as shown in Table 6. The percentage difference between analytical estimation results and simulation results ranges from −5.78% to 3.81%.

Additionally, different values of α were investigated to determine its influence on the accuracy of estimating TL using analytical Eqs. (18) and (19). In Table 7, sensitivity analysis on α indicates that the average percentage difference between analytical estimation results and simulation results is minimum when $\alpha = 0.25$.

Specifically, TL of 33 kV feeders were determined based on (20)–(23). In (20), LsF of the 33 kV feeders were derived from LF which are dependent on the load mixed connected to the feeders. It should be noted that in (21), PPD of the 33 kV feeders are determined based on the maximum current recorded by the feeder ammeters as indicated in the EFM shown in Fig. 1. Feeder PF is obtained from statistical analysis of load data from the utility.

PPL of 33 kV feeders are calculated using the base case cubic polynomial function and appropriate correction factors as shown in (22). As the 33 kV feeders are double circuits operating in parallel with lumped load at feeder-end, the correction factor associated with feeder length (σ_L) is applied to compensate for the change in PPL of its base case. In (23), TL of the 33 kV feeders are determined from its PPL and LsF for a 30-day period.

$$\mathcal{L}_{33} = \alpha \cdot \mathcal{F}_{33} + (1-\alpha) \cdot \mathcal{F}_{33}^2 \tag{20}$$

$$\rho_{33} = \sqrt{3} \times I_{33}^{Max} \times 33000 \times pf_{33} \tag{21}$$

$$\wp_{33} = \sigma_L \times \{a_{33B}\rho_{33}^3 + b_{33B}\rho_{33}^2 - c_{33B}\rho_{33} + d_{33B}\} \tag{22}$$

$$\Im_{33} = \wp_{33} \times \mathcal{L}_{33} \times 720 \tag{23}$$

In (24)–(27), the TL of 11 kV feeders are determined using equations identical to the 33 kV feeders, except with the inclusion of correction factors associated with feeder topology (σ_T) and load distribution (σ_{LD}) as shown in (26). The 11 kV feeder maximum current is obtained from the respective feeder ammeter as shown in (25), whereas its PF is based on statistical analysis of load data.

$$\mathcal{L}_{11} = \alpha \cdot \mathcal{F}_{11} + (1-\alpha) \cdot \mathcal{F}_{11}^2 \tag{24}$$

$$\rho_{11} = \sqrt{3} \times I_{11}^{Max} \times 11000 \times pf_{11} \tag{25}$$

$$\wp_{11} = \sigma_L \cdot \sigma_T \cdot \sigma_{LD} \times \{a_{11B}\rho_{11}^3 + b_{11B}\rho_{11}^2 - c_{11B}\rho_{11} + d_{11B}\} \tag{26}$$

$$\Im_{11} = \wp_{11} \times \mathcal{L}_{11} \times 720 \tag{27}$$

4.3. Estimation of TL in 33/11 kV transformers

TL of the 33/11 kV transformers are determined based on (28) [14,44,45]. Power losses in transformers are divided into fixed loss, P_{TX}^{NL} which is iron/no load loss, and variable loss, P_{TX}^{FL} which is copper/load loss. Iron loss and copper loss are obtained directly from manufacturer's specifications. The capacity factor (δ) is derived from the PPD of the respective transformer.

$$\Im_{TX} = \left[P_{TX}^{NL} + \left(\delta^2 \times P_{TX}^{FL}\right)\right] \times 720 \tag{28}$$

4.4. Estimation of TL in MV distribution network

The ultimate goal of estimating TL in the MV network is to determine the percentage of energy lost in the MV network and its components as an indicator of the network performance in terms of its energy efficiency. Relevant equations derived in Section 2 to calculate percentage TL are summarized and reproduced as shown in Table 8.

5. Case study

In this case study, the TL estimation proposed approach is applied to a utility MV distribution network to estimate its TL over a 30-day period. The network consists of four (4) 33 kV feeders, four (4) 33/11 kV transformers, and twelve (12) 11 kV feeders. The network parameters and its load information are shown in Fig. 5. Energy recorded by the energy meter at the TDIS over a 30-day period is 17.804 MWh, on a maximum demand of 44.9 MW, and average PF of 0.97 lagging. The energy recorded at the 11 kV bulk supply points are 2015 MWh and 990 MWh, on a peak demand of 4.0 MW and 1.96 MW respectively. The overall load mixed for the network based on power demand is approximately 80% residential, with the remainder 20% commercial. LF and LsF for the feeders are then estimated based on the given load mixed.

6. Results and discussion

Results of the case study are organized in three parts: (a) Energy inflow to the network components; (b) TL in the network components; and (c) Percentage TL of the network components and MV network. Inflow energy to the 33 kV feeders based on feeder current, PF and LF are shown in Table 9. The adjusted inflow energy using energy adjustment factor, and the estimated TL in the 33 kV feeders are shown in Table 10. Tables 11 and 12 show the TL of the 33/11 kV transformers and 11 kV feeders respectively. Summary of the MV network TL is shown in Table 13. Table 14 shows a comparison between results obtained by the utility and

Table 14
Comparison with results from local power utility.

Month	Recorded energy at TDIS (MWh)	Recorded peak power demand at TDIS (MW)	Recorded total 11 kV bulk energy (MWh)	Estimated total MV TL (%)		
				Provided by utility company	Proposed method	Difference
M1 Note 4	17804.13	44.88	3005	1.61	1.74	0.13
M2	18993.73	50.77	2956	1.73	1.93	0.20
M3	18765	48.46	3117	1.69	1.90	0.21

Note 4: Details shown in this case study.

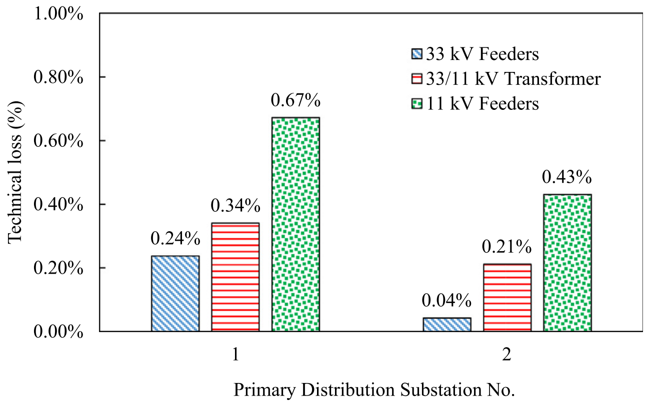

Fig. 6. Breakdown of TL according to the PDS.

the proposed method. The breakdown in TL according to the PDS is shown in Fig. 6.

As observed from Table 14, TL of the MV network obtained based on the proposed method is in close agreement with TL provided by the utility company. Based on three (3) samples, M1, M2 and M3, the difference in percentage is between 0.1% and 0.3%. The TL results are provided by the utility company based on their specialised in-house software to compute TL of its network in all its supply zones. The verification of TL in a MV network is generally difficult to establish in certainty as there are many different parameters which influence the calculations. However, TL results obtained based on the proposed approach shows consistency with changes in the feeder characteristics. For example, it can be observed that feeders which ranked high in TL are long feeders with high peak power demand, such as F11-11, F11-08 and F11-05; whereas feeders which are ranked low in TL are short feeders with low peak demand such as F11-03, F11-12, and F11-01. It is also observed from Table 12, that load distribution along the feeder has a significant impact on the percentage TL of the feeder. For example, feeder F11-03 has a percentage TL of 0.53% compared to F11-09 which has a percentage TL of 1.11%, even though both feeders are of the same length and PPD. The higher percentage of TL in feeder F11-09 is primarily due to its load concentration at feeder tail.

The process of estimating TL could be repeated on MV network which feed different supply zone. As shown in Tables 9–13, assessment of TL for each MV feeder could be done system wide for all its supply zones.

7. Conclusions

The proposed analytical approach of using RF to estimate TL in MV network (with unidirectional power flow) at system wide level is shown to be efficient, robust and could adopted to perform TL estimation for different types and configurations of MV distribution network and components. In the case study, it is shown that, by first classifying every MV feeder in the network according to the RF characteristics, TL in any radial MV network could be estimated on a monthly basis. TL results of MV distribution system/network estimated on a regular basis are useful to monitor the TL trend in the network. Operational plan in terms of reconfiguring the network by changing normal off points could be formulated to minimize TL of MV feeders. Additionally, TL in the MV network could be useful input for decision making in network augmentation. The proposed approach of estimating TL could be applied to develop test network for utility and the regulator to assess TL of MV network.

Future research work could be extended to include estimation of TL for low voltage network and MV network with bidirectional power flow due to penetration of distributed generation.

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