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

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ABSTRACT

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
$E_{33}^{B}(i)$	energy recorded by energy meter of 33 kV bulk customers connected at the i^{th} primary distribution substation (PDS)
$E_{11}^{B}(i)$	energy recorded by energy meter of 11 kV bulk customers connected at the i^{th} PDS
$I_{33}^{Max}(i)$	maximum current recorded by the i^{th} 33 kV feeder ammeter
$I_{11}^{Max}(j)$	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
$E_{33}^{I}(i)$	energy inflow to the i^{th}33 kV feeder
$E_{33}^{I}(i)'$	adjusted energy inflow to the i^{th} 33 kV feeder
$E_{33}^{O}(i)$	energy outflow from the i^{th} 33 kV feeder
$E_{TX}^{I}(i)$	energy inflow to the i^{th} 33/11 kV transformer
$E_{TX}^{O}(i)$	energy outflow from 33/11 kV transformer
$E_{11}^{I}(j)$	energy inflow to the j^{th} 11 kV feeder
$E_{11}^{I}(j)'$	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_{TX}^{NL}	33/11 kV transformer no-load loss
P_{TX}^{FL}	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