TECHNICAL LOSSES ASSESSMENT IN DISTRIBUTION SYSTEMS WITH REDUCED MEASUREMENT CAPABILITIES

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ABSTRACT

In the recent years, the electricity Regulators want to reduce the energy cost and to raise the energy efficiency by curtailing the energy losses, particularly in the MV and LV distribution networks. The definition of an adequate methodology for the calculation of the energy losses in the distribution system is crucial for both the Regulator and the Distribution Companies (DISCOs). The assessment of the energy losses in distribution systems with reduced measurement capabilities (fast developing countries) is usually performed by resorting to simplified methods of calculation or to the simple difference between purchased and billed energies. This approach may provide too imprecise or inaccurate results. Better accuracy can be achieved with the methodology illustrated in this paper.

INTRODUCTION

The increase in energy efficiency by curtailing the energy losses, particularly in the MV and LV distribution networks, is a goal pursued worldwide for environmental (low carbon society) and economical reasons (cost of fuel). The definition of an adequate methodology for the calculation of the energy losses in the distribution system is then crucial for both the Regulator and the Distribution Company (DISCO): Regulators need it to make recommendations and to arrange feasible loss reduction targets, and DISCOs use it to assess planning solutions that boost the energy efficiency of the electricity system. Obviously, the two counterparts should agree with such a methodology in order to avoid any friction while evaluating the distribution system's performance.

In fast developing countries, the calculation of the energy losses is not a simple task due to the shortage of measurements available. Often DISCOs do not have SCADA systems and the only yearly measurements come from the Transmission System Operator (TSO) within the invoices of the purchased energy. Sometimes, few sample measurements for short periods exist in the MV/LV substations (typically to estimate the peak demand) and on the LV customers (from sporadic Power Quality studies). Moreover, the allocation of the LV customers to the corresponding MV/LV substation is a critical issue because the network and the commercial databases are not linked (generally, it is known the list of supplied customers per geographical area, district or village, but not per distribution transformer).

In this context, the assessment of the energy losses is approximated with simplified approaches. In the MV system, where the distribution network topology is generally known and load flow analyses can be executed, the yearly energy losses are calculated at the peak (derived from the TSO measurements and allotted to the single distribution transformer) and corrected by applying the Loss Load Factor (LLF). Even if the LLF can be calculated directly from the TSO yearly measurements (when available), most usually it is reckoned from the global Load Factor (LF) of the whole DISCO's system:

$$LF = \frac{W}{P_{\max} \cdot T}$$

and approximated with the formula:

$$LLF = a \cdot LF + \left(1 - a\right) \cdot LF^2$$

where W is the whole energy absorbed in the period T (typically one year), P_{max} is the maximum demand registered in the same period, and a is a coefficient that depends on the shape of the demand profile (a = 1 for a flat profile and a = 0 for a profile with a sharp peak and a fairly steady demand in the rest of the time). Typically, the coefficient a is chosen in the range 0.1÷0.3. For the LV system, due to the lack of a complete network description and the high number of feeders also for a small MV system, generally the energy losses are simply estimated by subtracting the MV energy losses from the difference between the overall purchased energy and the total energy billed to the customers.

The application of this classical approach in conditions of reduced measurement capabilities may provide inaccurate results. Indeed, the adoption of a unique LLF tends to produce energy losses values often overestimated and not correlated to the single MV feeders. Moreover, the LV energy losses, obtained as simple difference between the energies purchased and billed, are affected by the Non Technical Losses (electricity theft and meter tampering) that often are not negligible in the considered scenario. Thus, in order to boost the quality of the energy losses

estimation, in this paper some improvements are illustrated. Firstly, the energy losses are always estimated by means of suitable load flow calculations. Secondly, the load is modelled by representative daily profiles, desisting from the single point calculation (at the peak) and the adoption of the LLF. Finally, the network modelling is distinct between MV and LV systems, due to the different levels of data available: in MV exact models of the actual feeders are used, while for LV representative networks are created.

TECHNICAL LOSSES CALCULATION METHODOLOGIES

Technical Losses (TL) occur naturally and consist mainly of power dissipation in electricity system components such as lines, transformers, and measurement systems. In general, they can be separated into so-called fixed and variable losses. The fixed losses are those due to the magnetisation currents of transformers and reactors, which are also referred to as *iron losses*. They occur all year round (outages are generally neglected) and they are independent from the load but they depend on the square of the voltage applied to the equipment. The variable losses are those caused by the flow of current through the different items of equipment on the network, and are also termed *copper losses*. They are proportional to the component's resistance and to the square of the current flowing through it.

The gross amount of distribution system losses (MV and LV) can be easily determined by the difference between the total energy purchased from the transmission system and the total energy sold to the customers. However, this value includes also the Non-Technical Losses (NTL) and it cannot provide disaggregated information about which part of the system is more responsible for the losses.

Therefore, AC load flow studies are necessary to assess technical losses. In order to perform this kind of calculation, two steps are necessary: the definition of the MV network model and the characterization of the load in each consumption point (MV/LV substation).

Due to the large extension of a national distribution system in respect of the transmission one (number of feeders and nodes), often the analyses are executed by resorting to few representative networks: firstly, network's attributes are identified and calculated from the network database, then the distribution feeders is grouped into few representative classes defined on the basis of the network's attributes, and finally a representative network for each class is selected from the actual networks or it is created with the average values of these attributes in the class [1]-[2]. For the LV network this approach is always adopted, due to its huge dimension also in small national distribution systems. Instead, in fast developing countries, the scale extent of a national MV network can allow performing the AC load flow calculations directly on the actual network. Therefore, considering also the different completeness levels of the specific network databases, it is proposed to execute the calculations with representative networks for the LV system and on the actual feeders for the MV system.

Compared to the network model, the characterisation of the load is a harder task, because in a distribution system the number of load points per network is high and the information on the individual loads is often partial and limited to the peak value. As aforementioned, with these circumstances copper losses are estimated by applying the concepts of Load Factor and Loss Load Factor.

The international best practice for losses calculation is denoted by two main features:

1. *The representation of the load by means of daily profiles*: every supply point (single LV customer or MV/LV substation) is modelled through daily load patterns, discretized on hourly basis and representative of the load behaviour in the whole year.
2. *The definition of the daily load profiles starting from the bottom of the system*: for the LV customers, specific categories of consumption are identified and characterised by representative profiles derived from real measurements; for the MV supply points, the profiles are derived from real measurements of big customers with dedicated transformer or from the load aggregation of the representative LV networks.

The main shortage in the DISCOs distribution system databases (particularly in fast developing countries) is the knowledge and the characterisation of their electricity demand. Indeed, the main source of data is the measurements of the yearly current profiles absorbed from the transmission grid, provided by the TSO to the DISCOs for the billing of the purchased energy. Distribution SCADA systems are generally absent or planned to be installed in the future. Few spot measurements of LV and MV customers may exist, with different time frames (from a single day to several weeks) and granularities (from 1 second to 1 hour). Moreover, MV customers (those with dedicated transformers) are not commonly associated with the relative MV/LV substation in the network database.

Despite these limitations, the definition of daily load profiles is possible and it is proposed as improvement of TL assessment methodology. Then, the bottom-up approach is adopted for the LV system, where the load has been modelled by defining standard daily profiles of few categories of consumption. Instead, for the MV system, it has been decided set aside temporarily the bottom-up definition of the load and to propose an improved top-down approach. It is based on the only today's available measurements (yearly sequence of current at the beginning of each MV feeder), which are used to derive some representative daily profiles suitably scaled to each MV supply point (*load allocation*). The bottom-up approach, potentially able to produce more accurate results, can be adopted in the future with an improved knowledge of the load in the MV system.

MV Technical Losses assessment

As aforementioned, for relative small national MV distribution system the calculations can be executed directly on each actual feeder. The main issue in the definition of the network model is the completeness of the network component database: often the electrical parameters of the oldest components are missing. This problem can be overcome by adopting standard values taken from the technical Literature available.

Once the network model has been created, the load representation in each feeder is obtained by following a top-down approach (Figure **1**).

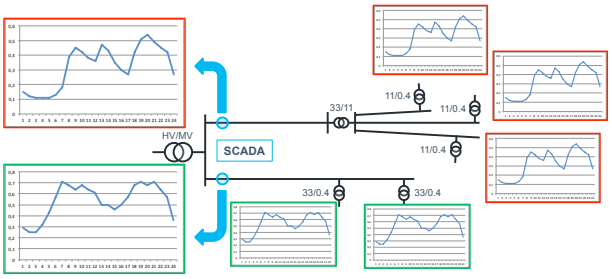

Figure 1 – Top-down approach: allocation of the measured profile at the beginning of the feeder in each supply point.

By using the measurement of the current at the beginning of each feeder, provided by the TSO's SCADA system on a yearly basis, a limited number of daily profiles is created that approximates the whole annual electric energy absorbed by the feeder. Even if different behaviours exist, the analysis of the feeder demands shows in general a difference between the workdays and the weekends. Also seasonal differences appear in the peak demand during the year. Therefore, a number of periods can be identified that better represent the yearly variation of the electricity demand, in terms of season and day of the week. Then, the days of the year are grouped into these periods and a representative daily profile is derived for each period by calculating the average current in all the 24 hours of a day. By so doing, the annual behaviour of the feeder demand is approximated through a reduced but significant number of points.

The choice of the representative profiles should be a good compromise between the precision and the simplicity of the calculation. Indeed, it is obvious that by using the entire annual sequence of measured currents (8760 samples), the results have the highest precision. On the other hand, performing 8760 load flow calculations for each feeder would be an excessive time-consuming procedure, making unfeasible the direct estimation of the technical losses on the real MV distribution network. If too few profiles were chosen, the approximation could become strong and compromise the quality of the results.

As example, in Figure **2** the representative daily profiles of a real MV feeder of a Middle East country are depicted. Ten patterns have been identified: the workdays, the Fridays and the Saturdays of summer, winter and spring-autumn, plus a special daily profile for the Ramadan period.

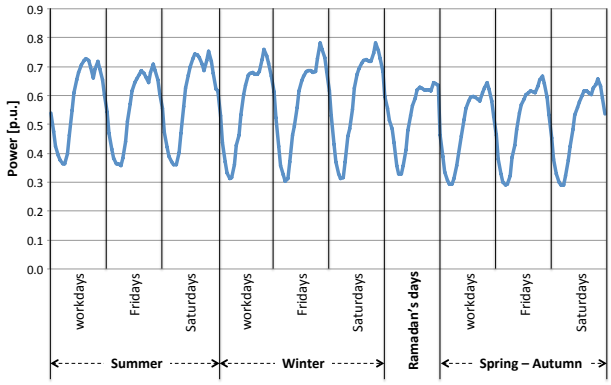

Figure 2 – Example of the definition of the representative daily profiles for a MV feeder.

For the specific example, it can be recognized the higher demand of the winter (maximum peak) and summer seasons in respect to the rest of the year. The summer daily profile is characterised by two peaks, one in the morning and the other in the evening, with the first one higher than the second during the workdays, maybe due to the operation of the air-conditioning units. The Ramadan's representative daily profile is clearly lower if compared to the other days of the same season (summer), with the peak demand shifted to the night.

Since the distribution transformers are included in the MV network model, the load allocation is typically applied to the LV side of the transformer. In this way, the fixed and variable losses of the transformers can be assessed automatically by any commercial software used to execute the load flow calculations. However, this choice should be avoided because it emphasizes the overestimation of the technical losses inherent the top-down philosophy. Indeed, the measurements at the beginning of each feeder include all losses; thus, when these measurements are allocated to the load points, the represented demand is higher than the real one and the difference increases if the allocation is executed further away (electrically speaking) from the point of measurement (beginning of the MV feeder). For this reason, it is proposed to allocate the load at the MV side of the transformers and to assess their TL "manually" by using the results of the load flow calculations.

Once defined the representative profiles, they are assigned to each MV load point of the feeder and scaled proportionally to local characteristics that help to distinguish one transformer from the other (the measured peak demand, the measured energy consumption or simply the nominal rate of the distribution transformer). In details, for each hour of the representative daily profiles the current is allotted to the ith substation by multiplying with the following scale factor, as in (1):

$$k_i = \frac{A_i}{\sum_{j=1}^{N_{TR}} A_j} \qquad (1)$$

where A_i is the local characteristic of the ith substation and N_{TR} is the number of substations in the examined feeder.
The extension to the whole year of the load flow results is obtained by multiplying the variable losses in the calculated hours ($TL^{(Cu)}{}_h$) for their equivalent number of days in the year (h_eqv_p), as in (2):

$$TL_{MV}^{(Cu)} = \sum_{f=1}^{N_{feeder}} \left[\sum_{p=1}^{N_{profiles}} h\_eqv_p \cdot \left(\sum_{h=1}^{24} TL_{f,p,h}^{(Cu)} \right) \right] \quad (2)$$

where N_{feeder} is the number of feeders in the DISCO's MV distribution network and $N_{profiles}$ is the number of representative profiles.
The total Technical Losses of the MV system is finally determined by calculating the fixed losses associated to all the distribution transformers.

LV Technical Losses assessment

As stated before, it is generally unfeasible to perform load flow calculations on the entire actual LV network, and the resort to representative networks become necessary. Two alternatives are possible:

1. a small number of actual LV network can be selected as representative of the whole system, or
2. artificial representative networks can be created from all the accessible data.

The second option is more suited to the situation of the majority of fast developing countries, because the knowledge of the LV system is often not sufficient for implementing the first option.
The requirement of assuring an easy extension of the results to the whole LV system has brought to the identification of the MV/LV transformer rate as the key attribute of the LV representative networks. Indeed, generally, it is not exactly known the whole number of LV feeders. Thus, it is preferable to not create representative networks based on single feeders, because it could become difficult to determine the number of feeders included in each representative class and used to expand to the whole class the results obtained for the average feeder (representative of the class). On the contrary, the exact number of distribution transformers is known from the complete MV network database.
Therefore, the LV system has been classified in terms of the nominal rate of the distribution transformers and the representative network has been created as average system among the networks supplied by all the MV/LV substations included in each class. In other word, the LV representative network is not referred to a single feeder but to all the feeders supplied by a transformer. The extension of the results on a single representative network can be estimated by multiplying them with the number of similar transformers included in the same class.
For the definition of a representative network, two features have to be identified: the network topology and the network load. The design of the LV representative network topologies is illustrated below in five steps.

1. *Collection of available data* – All the available data for the LV system are collected and organized in a single database: the transformer's rate, the type of LV feeders (only overhead lines – OH, only overhead cables – ABC, only underground cable – UG, mixed construction), the number of substations (from the MV database), the number of LV feeders per substation (from the available LV database), the number of line sections for each type of feeder, the number of branches per node (gives information on the number of derivations), the number of line sections per derivation, the lengths of line sections (differentiated per type of conductor), the cross-sections of the conductors.
2. *Arrangement of the collected data* – the LV feeders are grouped and classified on the basis of the supplying MV/LV transformer and on the type of feeder (OH, ABC or UG). For each group it is also evaluated the incidence within the LV database (percentage of occurrence), in order to avoid the definition of a representative network with a negligible impact on the LV Technical Losses.
3. *Definition of representative classes* – the groups formed in step 2 are now aggregated in representative classes. The aggregation considers similar transformer rates, the homogeneity of the feeder type, and the overcoming of a minimum percentage of occurrence (higher than 1%).
4. *Extraction of statistics* – Once all the available data of the LV network have been classified, some statistics (minimum, average and maximum values) of the main network attributes are calculated.
5. *Definition of representative networks* – First of all, the representative network is characterized with the most frequent MV/LV transformer's rate (highest occurrence in the class). Then, by using the statistics obtained in step 4, the average values of the network attributes are used to create the network topology.

It must be noted that, if the DISCO has the availability of good LV network database, the application of this procedure is easy and immediate; otherwise, it requires a longer implementation period for the data collection from some sample field measurements combined with the experience of the DISCO's engineers.
The LV electric load modelling should start from the available DISCO's measurements of LV customers in different categories, collected during previous measurement campaigns. If these data are insufficient, they can be integrated by standard daily load patterns derived from the available scientific Literature, in order to define at least the shape of the consumption. The procedure is illustrated with the following six steps.

1. *Measurements' collection* (for each kind of loads).
2. *Measurements' synchronization* – generally the data available are not correlated in time (simultaneous), because they come from measurements of different projects. For this reason, it's important to define a unique time frame in order to combine the

measurements of the single loads and create a statistical behaviour of the demand for each category of consumption. If the measured period is quite long (months), the measurements are aligned on the basis of the date (useful to catch the seasonal changes). If the measured period is shorter (a week or few weeks), the alignment is made on the basis of the day of the week, in order to capture the weekly variations of the demand between workdays and weekend.

3. *Measurements' classification* – due to the reduced number of measurements available, usually only three main categories of LV consumption have been defined: residential, commercial and industrial.
4. *Definition of the standard consumption patterns* – By following the load modelling of the MV system, the same number of representative daily profiles has to be created as average of the samples for each category. If the available measurements capture only the weekly but not also the seasonal variations, the load profiles are duplicated for the other seasons.
5. *Determination of the number of customers* – The number of customers in each representative network is estimated from the loading assigned to the representative transformer. Moreover, these numbers have to match the macro-figures of the distribution system, like the total number of LV customers and the share of consumption among load categories.

The setting of the transformer loading is crucial for a correct estimation of the LV technical losses. Typically, DISCOs characterize their distribution transformers in terms of yearly energy consumption or maximum demand. The load supplied by each representative transformer is estimated as the average (*arithmetic mean*) of the peak currents (or energy consumption) registered for all the transformers with the same rate. This characterization for the technical losses calculation is acceptable when the dispersion of the current's samples is small (all the values are concentrated around the mean). When the dispersion is big, it underestimates the contribution to the losses of the higher current's values, because the losses depend on the square of the current.

This issue arises from the traditional approach, followed in the planning studies, of adopting the (arithmetic) mean value of the load for the losses calculation [1]. This choice simplifies the AC load flow calculation, because the mean value of the combination of some loads (current in the network's branches) is simply the arithmetic combination of the mean values of the individual component loads. A rigorous solution of this issue should require the modification of the load flow calculation to evaluate the quadratic mean of the current that flows in each line section: it needs a statistical representation of each load and the application of a probabilistic load flow.

However, with a condition of reduced measurement capabilities (as considered in this paper), the definition of such sophisticated models is troublesome. Therefore, the chosen solution has been to overestimate the transformer loading by resorting to the *quadratic mean* of the measured load peaks. In this way, the number of LV customers of the representative networks is bigger, compensating the underestimation of the load flow calculations and providing a better assessment of the losses. Sometimes, the DISCO could not have a reliable characterisation of the transformers' loading. In this case, a possible answer is the calculation of the quadratic mean of the peak demands that derive from the top-down allocation of the yearly current profile measured at the beginning of each MV feeder (from the TSO's SCADA).

Finally, other two parameters related to the electrical energy demand have great influence on the LV Technical Losses: the load unbalancing and the power factor. If no specific characterisation of the actual load unbalance is available, the single-phase LV customers can be connected to the representative networks alternatively in each phase, producing a small-normal unbalance. Obviously, a 4-wires load flow calculation has to be applied. For the power factor, it must be considered the common lack in fast developing countries of specific connection rules that penalize the customers with high absorption of reactive power (low power factors). Consequently, also the electrical appliances available in the market of those countries are not certified for high levels of efficiency. This situation produces very low power factor in the LV distribution network, often around 0.75 ÷ 0.80, that must be modelled in the LV representative networks.

CONCLUSIONS

In the paper, it has been shown that, even in case of distribution systems with reduced measurement capabilities, precise and rigorous methodologies can be applied for the assessment of Technical Losses. They can be based on the adoption of daily load profiles for the representation of the electrical demand and the definition of suitable representative networks (in particular for the LV system). A bottom-up approach for the identification of the MV load should be preferable with respect to the top-down, but it requires putting on field specific measurement campaigns.

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