METHODOLOGY FOR ANNUAL LOAD PROFILE ESTIMATION AT THE OUTGOING FEEDER OF DISTRIBUTION TRANSFORMERS IN URBAN AREAS

Simon KREUTMAYR
Augsburg University of Applied Sciences – Germany
simon.kreutmayr@hs-augsburg.de

Christoph J. STEINHART
Augsburg University of Applied Sciences – Germany
christoph.steinhart@hs-augsburg.de

Michael FINKEL
Augsburg University of Applied Sciences – Germany
michael.finkel@hs-augsburg.de

Christian GUTZMANN
SWM Infrastruktur GmbH & Co. KG – Germany
gutzmann.christian@swm-infrastruktur.de

ABSTRACT

The planning of power distribution system has to consider new trends like electromobility and power-to-x applications. These new technologies can have a massive influence on the load flow, especially by increasing penetration in urban areas with high population density. Efficient network planning requires the knowledge about current grid utilization as accurate as possible. Since the monitoring of load flow is not covering the entire medium and low voltage grid, the document provides a method for annual load flow estimation at the outgoing feeder of urban distribution transformers.

INTRODUCTION

The energy transition and the associated integration of decentralized generation units has mainly led to challenges in rural distribution grids. A raising share of renewable energy generation and increased power system efficiency shall be achieved by sector coupling of electricity, heating and mobility. The sectors are linked by technologies like electromobility and power-to-x systems [1]. In cities, large accumulations and the congestion of the mentioned applications are expected.

Motivation

Network planning should take into account the integration of this new consumers with increasing penetration. For the decision whether the new technologies can be integrated into existing network infrastructure and most efficient future network planning, the knowledge of the current load is a relevant input variable. The online monitoring and recording of the load flow, usually in distribution grids, is performed by permanently installed measuring equipment in the network level transformation high voltage (HV) to medium voltage (MV) and above. The actual load flow within a MV or LV (low voltage) network is therefore typically unknown. LV feeder at local substations (MV/LV) are often equipped with drag indicators for the estimation of the annual peak load, which can be read out locally if required. This network information was previously sufficient for HV and MV network planning.
Worst-case estimations, by summation of the current peak load and the expected additional maximum load in the future, would lead to a very conservative planning approach, since a temporal shift of the current peak load with the future additional loads can lead to an oversizing of the network components. The temporal shift of partial peak loads to the total peak load is usually taken into account with simultaneity factors. However, the determination of simultaneity factors can be difficult and requires the knowledge about the grid. More accurate investigation for the planning of efficient networks is possible with the summation of annual load profiles, which include their characteristic daily and seasonal load variations. From the sum-profile, the annual peak load for the future can be determined, which is crucial for the design of the network components.
The upgrade with permanently installed measurement equipment and online monitoring of several thousand substations (MV/LV) in a city is very expensive. Therefore, the methodology for the estimation of annual load profiles at distribution transformer is presented.

Load modelling

Standard load profiles allow the estimation of a large number of consumers. For this purpose, in Germany the VDEW standard load profiles are available. There are profiles for different types of consumers, such as household, agricultural and commercial, which can be used to model an annual load cycle. In addition, a dynamic modification of the household type is applied for consideration of seasonal fluctuations. [2] The estimation of the load with the help of the standard load profiles is possible from a number of 150 household consumers or more. [3]

Network specifications

In the considered residential grid areas about four to twelve substations (MV/LV) are located in a MV feeder, whereof one station supplies 200 to 500 households. An estimation of the transformer load with standard load profiles would thus be possible even for one distribution transformer. However, it has to be taken into account that in all areas there is a mixture of residential and commercial consumer. Since the mentioned load profiles do not include electrical heating systems, they must be additionally considered with the thermal losses of the buildings. Under these circiumstances, the investigation of the consumer structure in the regarding urban network area causes huge effort for modelling with standard load profiles. Therefore, the following methodology provides a realistic load estimation method for urban distribution transformers.

METHODOLOGY

MV outgoing feeder in cities have a well-structured regional size due to the high load density and supply a similar building structure, what results in similar load characteristics. The operational condition monitoring and permanent recording of the MV feeder panel in the substation (HV/MV) provides information about the sum behavior of all transformer stations (MV/LV) located within the MV-feeder network [4]. The overview of the methodology in Figure 1 allows an annual load profile estimation of a single distribution transformer by means of a mobile short-term measurement at LV over a few weeks, together with information of the MV feeder.

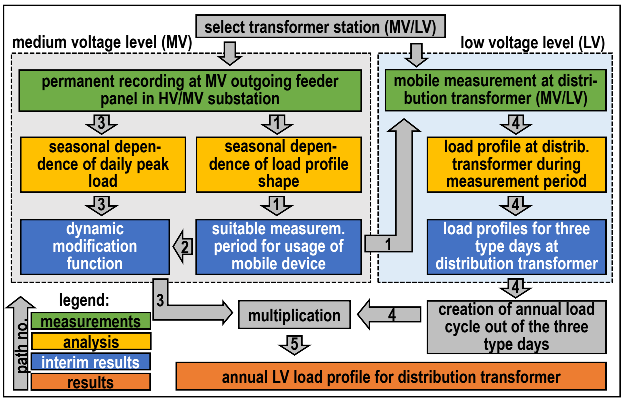


Figure 1: Overview of methodology for annual load profile estimation at the distribution transformers in urban areas

The permanent measurement recording at the MV feeder allows the determination of a suitable time for the short term measurement and the consideration of seasonal fluctuation of the load. The result is an annual load profile under consideration of seasonal impacts to the load at the desired transformer by minimization of the effort for additional measurement equipment. The methodology is described at a generic local substation (MV/LV) in an urban residential area with block and row buildings which were mainly built before 1978. For better orientation in the document, the paths 1 to 5 are defined in Figure 1.

Data analysis at MV level (path 1, 2 and 3)

Overload protection in MV networks is usually performed by monitoring the load at the outgoing feeder in substations (HV/MV). The measured load flow is archived in the examined distribution network as 15 min mean values in ampere. Therefore, records of the previous years are available for further investigations regarding to seasonal impacts in change of daily peak load and load profile shape. An almost symmetrical loading of the medium-voltage network is determined.

Suitable period for short term measurement (path 1)

This section describes suitable periods of time for usage of mobile measurement equipment with path 1. The identification of a suitable time period for the mobile device is necessary, because the short-term measurement at the LV feeder only takes place over a period of a few weeks. Afterwards, the determined profile shape of three type days is scaled with the dynamic modification function over the entire year. The measured profile shape is thus representative for the entire year. In order to obtain a tendency, when a suitable time for the measurement could be, the profile shape of at MV feeder is examined (path 1). The analysis consists of three tasks: Creation of type days (MV), Normalization of load profiles and Determination of suitable measurement period.

Creation of type days (MV)

Analogous to the standard load profiles [2], nine average type days are created from the measurement records during one year at the MV feeder. This results in profiles for a working day (WD), Saturday (SA) and Sunday / public holiday (SU) for the seasons winter, summer and transition period. The time periods are defined as follows [2]: winter 01.11. to 20.03., summer 15.05. to 14.09, transition period 21.03. to 14.05. and 15.09. to 31.10.

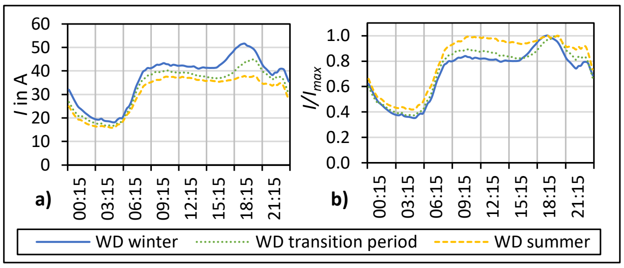


Figure 2: Seasonal change in load profile at MV feeder during working day: a) absolute profiles, b) normalized profiles

Figure 2 a) presents the shape of WD-load profile and its seasonal change. In this section, the focus is on the change in profile shape (path 1). It can be seen that the evening peak is significantly more distinctive in WD winter than in WD summer, whereas the load is almost constant between midday and evening in WD summer.

Normalization of load profiles

With normalization of the daily load profiles to its maximum value in Figure 2 b), the comparison of profile shape between winter, summer and transition period is possible. Due to the creation of three type days for the LV feeder in the following chapter, the comparison is exclusively valid within a WD, SA or SU. If the analysis shows no major differences in seasonal profile shape, the measurement time of the mobile measurement plays a minor role. Nevertheless, the determination of the load level of the considered local substation becomes more accurate, if the measurement period takes place at a relevant time slot for further investigations.

Determination of suitable measurement period

With the comparison of load profiles in Figure 2, the following approaches for a suitable measurement period for the mobile measurement at the LV feeder can be followed. Depending on the application, there are many options as shown in Table 1.

Table 1: Examples of suitable measurement period in LV

Examples for expected condition at certain period in season	**Exemplary case**
Current annual peak load (Figure 3)	January
Peak load of additional future load ➔ Highest load growth	depends on the investi-gations
Total peak load out of current and additional future load ➔ Future peak load	
Highest utilization factor ➔ Worst case related to profile shape by scaling with dynamic modification function	summer

If there is a current annual peak load in winter and the total annual peak load in future is expected to be shifted into summer (e.g. due to massive growth of air conditioning), there could be a suitable measurement period for the mobile measurement in summer for accurate system modelling.

Dynamic modification function (path 2 and 3)

This chapter describes the creation of the dynamic modification function in path 3 which is essential for modelling seasonal fluctuation in daily peak load. Therefore, the change in daily peak load is examined with the 15 min mean values of current flow at the MV feeder at substation (HV/MV) again, which supplies the local substation (MV/LV). The analysis is divided into three tasks: Identification of daily peak load, Normalization of peak load, Creation of dynamic modification function.

Identification of daily peak load

The daily peak load is considered individually for the three type days working day (WD), Saturday (SA) and Sunday / public holidays (SU) within one year.

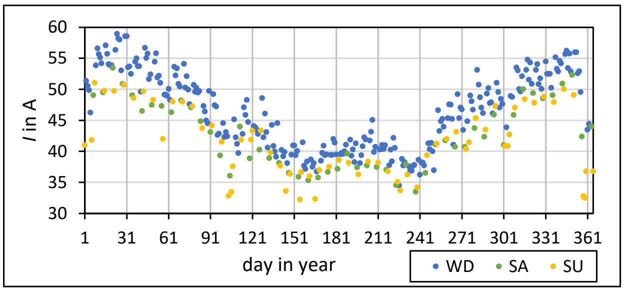


Figure 3: Identification of daily peak load at MV feeder

(In areas with a large share of commerce and industry, only weekdays and Saturdays are taken into account for further investigation due to the comparatively weak load on Sundays and public holidays). Figure 3 shows the identified daily peak load out of the 15 min mean value recording of the MV feeder current from 2017. It can be seen, that the peak load at the MV feeder during working days raises up to 60 A in winter and decreases to 30 A during Sundays in summer. The level of daily peak load at Saturdays and Sundays is a bit weaker compared to working days. Therefore, the separate normalization of the three type days in the next section enables a common consideration of the seasonal dependency, independent of the different load levels.

Normalization of peak load

The identified peak currents (Figure 3) are normalized to the average values of the peak loads during mobile measurement at LV feeder due to path 2. In this example, the mobile measurement took place in calendar week 5 and 6. Thus, the normalization currents $I_{\text{norm WD}}$, $I_{\text{norm SA}}$ and $I_{\text{norm SU}}$, are calculated for the three type days WD (10 values), SA (2 values) and SU (2 values). Afterwards, the normalization regarding to calendar week 5 und 6 for the 365 values of peak current is executed in Figure 4 with DP1.

Creation of dynamic modification function

The point cloud DP1 in Figure 4, after normalization of the currents of Figure 3, should be described by a function now. A polynomial of 6th order, which is approximated by regression analysis, provides a good replication of the seasonal dependency, also in cases where the highest annual load occurs in summer (case is not presented in this paper). Due the used mathematical approximation method, the function has a rough drift off at the border areas, caused by weak load in the holidays between Christmas and New Year (Figure 4, f1). Furthermore, there is an offset at the transition between December and January which may be caused by different temperature levels in winter 16/17 and 17/18.

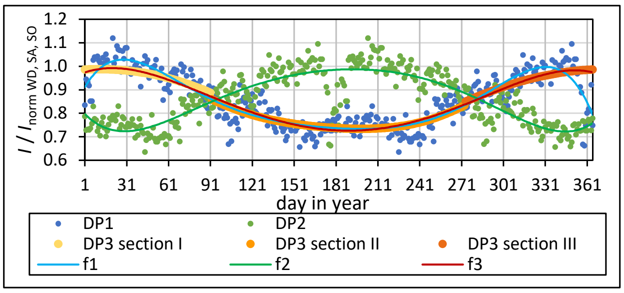


Figure 4: Creation of dynamic modification function

The data points are processed as described in the following section and Figure 4 to smooth the mentioned effects:

- Composition of dataset DP2 with DP1:
  - Split dataset DP1 between the days 182 and 183 into section A (1 to 182) and B (183 to 365)
  - Time shift of 182 day of section A to the right
  - Time shift of -182 day of section B to the left

  (Section A and section B have changed its position to get dataset DP2 out of DP1)
- Creation of polynomial function f2 out of DP2
- Composition of DP3, consisting of three sections, with data points of the mentioned days of f1 and f2:
  - Section I (day 1-91) 🡐 f2, day 183-273
  - Section II (day 92-273) 🡐 f1, day 92-273
  - Section III (day 274-365) 🡐 f2, day 92-182
- Creation of polynomial function f3 out of DP3

Function f3 in Figure 4 shows the developed dynamic modification, whose equation is shown below together with the parameter for the example in Table 2.

$$x(t) = x_0 \cdot (a_6 \cdot t^6 + a_5 \cdot t^5 + a_4 \cdot t^4 + a_3 \cdot t^3 + a_2 \cdot t^2 + a_1 \cdot t + a_0)$$

Table 2: Polynomial of dynamic modification function

Legend of function		a	Parameters of Example
x(t)	Dynamic value of the annual profile	0	9,71498540865418·10^{-01}
		1	2,16609518840298·10^{-03}
x_0	Static value of the annual profile	2	-6,37447973732225·10^{-05}
		3	3,94644637894899·10^{-07}
t	Current day of the year (January 1st to December 31st)	4	-1,13041027178397·10^{-09}
		5	2,02061467664811·10^{-12}
		6	-1,90836531203009·10^{-15}

Data analysis at LV level (path 4)

The load profile of the substation is recorded at the LV outgoing feeder with the help of a mobile measurement device over a measurement period of few weeks, to measure each type day at least two times. For static investigations in network planning and network utilization according to [5] a RMS interval of 15 min is sufficient. The active and reactive power of the fundamental frequency are recorded by the sum of the three phases. The consideration of reactive power is necessary, especially when examining voltage problems [3]. Alternatively, apparent power and phase angle can be analyzed.

Load profiles for three type days at LV feeder (path 4)

This section describes the creation of three type days out of the mobile short term measurement in path 4. This consists of the tasks Creation of three type days and Data compression. Afterwards a sensitivity analysis regarding to the load modelling is presented.

Creation of three type days

The mobile measurement record provides the data in the 15-minute measurement interval to create type days for working day (WD), Saturday (SA) and Sunday / public holiday (SU). At least two load profiles for the type day SA and SU, as well as ten load cycles for the WD are available for the creation of the type days with a measurement period of two weeks.

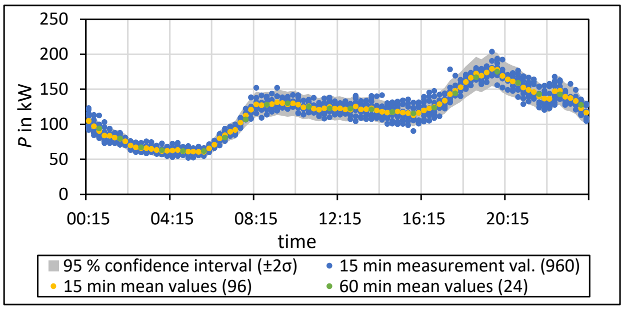


Figure 5: Creation of type day WD with evaluation

Within this period, it is possible to identify greater deviations between the same type days, which are caused by highly volatile load and generation. If the load profiles have an acceptable matching, an average load profile of each type day in active and reactive power is determined. Otherwise, the volatile influences do not allow the application of the methodology. Figure 5 shows the 15 min values (blue) of the active power over the ten measured working days with the averaged load profile (yellow).

Data compression

Since data compression from 15 min to 60 min (Figure 5, green) time interval hardly causes any loss of information, an annual load cycle with 365 days requires 8760 data points. The data basis of the standard load profiles mainly consists of hourly load cycles, too [2]. Figure 6 shows the developed load profiles for active and reactive power for the three type days.

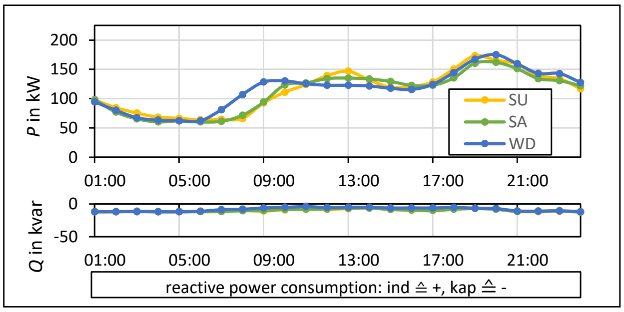


Figure 6: Development of three type days in active and reactive power for working day (WD), Saturday (SA), Sunday (SU)

The investigated station has its peak load for all three type days at approximately 7 pm with 170 kW. Reactive power (capacitive) remains below 15 kvar throughout the day, resulting in an active power factor cos (φ) close to 1 at the exemplary LV feeder.

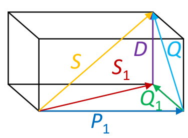
Sensitivity analysis

The sensitivity analysis focuses to the scattering of the measurement data by creating the average load profile at the LV feeder and to the additional grid load, caused by harmonics to reactive power.

The measurement values at the LV feeder (Figure 5, blue) show an approximately symmetrical scattering around the average load profile (yellow) with a coefficient of determination R^2 of 0.94. The grey marked area shows the 95 % confidence interval of the active power over ten working days with a determined deviation $\pm 2\sigma$ to the mean load profile with ±13,9 %.

Since the reactive power of the harmonics is neglected so far, the additional effect to grid load with the measurement data of the exemplary substation is examined. Table 3 shows in a three-dimensional representation the relationships between active, reactive and apparent power.

Table 3: Relation between active, reactive and apparent power

Legend		Graphic [6]
P_1	Active power	
Q	Total reactive power	
S	Total apparent power	
Q_1	Reactive power of fundamental frequency	
S_1	Apparent power of fundamental frequency	
D	Reactive power of harmonics	

The methodology has considered S_1 so far, which is composed by P_1 and Q_1. However, S is relevant for the thermal load and is connected with a right-angled triangle to S_1 and D. The difference between S and S_1 is approximately 6 kVA with nearly constant level over the entire measurement period of two weeks.

Creation of annual load profile (path 5)

The aim of the methodology is to create a complete annual load cycle for active and reactive power, which reflects both the load level and profile shape together with the seasonal load fluctuation as accurately as possible. The three type days are strung together (path 4) to an annual static load profile. Consequently, a typical week consists of five type days working day, one Saturday and one Sunday. The type day Sunday is also applied for public holidays. Afterward, the static annual load profile (path 4) is multiplied by the dynamic modification function (path 3). Depending on the investigations, which are carried out with the annual load cycles, the influences of the distortion in reactive power as well as the scattering by creation of the dynamic modification function and load profiles for type days have to be considered. By taking into account the mentioned effects, a safety margin of 10 % is added to the dynamic load profile of the exemplary LV feeder. Figure 7 presents the developed annual load profile of active and reactive power.

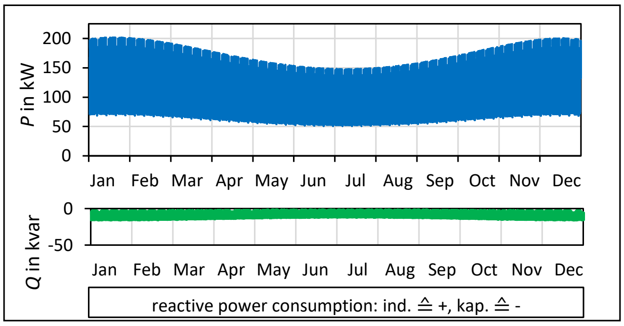


Figure 7: Annual load cycle of exemplary LV feeder at distribution transformer

The daily maximum load in winter drops from 200 kW to 150 kW in summer. The daily minimum load drops from 70 kW to 50 kW. The reactive power hardly changes. The profile shape within one day is depicted in Figure 6 by taking into account the dynamic modification factor and the mark up for additional influences.

SUMMARY AND BENEFITS

The methodology presents a comparable easy method for annual load flow estimation at individual urban distribution transformer. The permanent recording at the MV feeder allows predictions to seasonal load fluctuations. This enables the determination of a dynamic modification function (path 2 and 3, Figure 1) as well as the definition of a suitable measurement period for the mobile device at the LV feeder (path 1). This LV measurement provides the actual profile shape and load level over the measurement period of a few weeks for the creation of three type days (path 4). Finally, an annual load cycle is created out of the three type days, which is multiplied by the dynamic modification function (path 5). Even the partial results of the methodology show interesting information for network planning. The dynamic modification function indicates the load fluctuation over the season and gives the network planer an idea of higher or lower load at certain times. Mobile short-term measurements are also used in low voltage level in order to check free distribution capacities. Depending on the measurement period during the year, the load level and profile shape may fluctuate caused by seasonal influences. Suitable period of times for short-term measurements are presented in the document. This can be relevant in the design of load management systems e.g. for charging stations of electromobility.

VALIDATION AND OUTLOOK

For the validation of the methodology, a long-term measurement is currently taking place at the LV feeder in selected exemplary local substations. The results of the methodology will be compared with the real annual load profile, when the measurement is completed. Already with customer-owned substations (MV/LV), a good matching is achieved between the real annual load profile and the profile which is modeled with the described methodology. A validation with customer systems is possible due to registering load profile measurement which is prescribed from a certain size of power system. However, customer systems can have larger deviations from typical system behavior, therefore the evaluation is not particularly representative. If the methodology provides an adequate accuracy, the upgrade to intelligent substations MV/LV with permanently installed measurement equipment can be avoided for network planning.

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