Analysis of Indian Electricity Distribution Systems for the Integration of High Shares of Rooftop PV

Paper #2: Data Collection and Modelling

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of:

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of the Federal Republic of Germany

Project

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1. Introduction

The studies that should be conducted to analyze the impact of distributed PV generation on the distribution grid require certain amounts of data and information about the relevant grid area and its operation. A large part of the data may already be available to the distribution system operator and can thus easily be used for the necessary calculations. Depending on the technical capabilities of the operator and the progress in renewable energy development in the area, some data may be lacking. This paper on data collection is intended to shed some light on what data is necessary for a distribution grid impact study, and how gaps in the data can be closed either by the use of qualified assumptions or by additional data collection and monitoring measures.

2. Grid data

Detailed information on the grid topology and the existing assets should be largely available to the distribution system operator. However, experience shows that gaps in such data may exist, as distribution grids tend to be grown structures that are often decades old. Especially detailed data at the low voltage level may be hard to come by, and assumptions based on typical structures may be necessary. Some of the data may also be of very limited importance to the distribution system operator in daily operation and thus not immediately available, but important when setting up a simulation model.

2.1 Voltage levels and classification

The starting point of any grid impact study is the analysis of the relevant parts of the grid, coming down to the following questions:

- Which voltage levels are used for transmission and distribution in the respective area?
- How are the voltage levels classified into transmission, sub-transmission and distribution grids?
- Who owns and operates what portion of the grid, and where exactly are the division lines?
- What terminology is used by the local operators and other stakeholders? (Example: "Medium voltage" and "distribution transformer" may mean very different things in different countries.)

This information will be available to the distribution system operator, but close attention to detail should be paid to establish clear communications with all stakeholders and avoid confusion later during the project.

2.2 Topology

The focus of distribution grid analysis and simulation is determined by the grid topology that can be expected in the relevant grid area.

2.2.1 Radial topology

A radial topology consists of one or multiple feeders branching off a substation to supply load or evacuate power from distributed generation. Feeders at the same voltage level are not connected to each other (see Figure 1.) This is the simplest and most common setup for distribution grids at medium and low voltage level (< 100 kV.) At least without high shares of distributed generation, protection of radial feeders is relatively easy. Load flow is unidirectional, and simple current measurements are sufficient to locate a fault and switch the corresponding feeder off. However, at rising shares of distributed generation, fault detection may become more difficult and should thus be investigated. Moreover, radial networks are prone to voltage range violations at high load or high distributed generation than meshed networks (see Figure 2.)

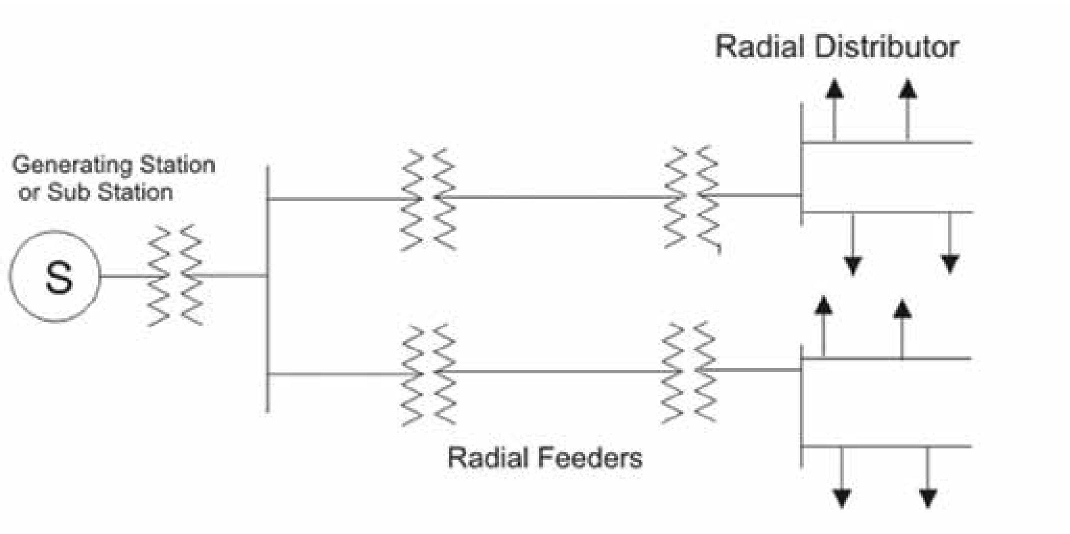

Figure 1: Radial grid topology.

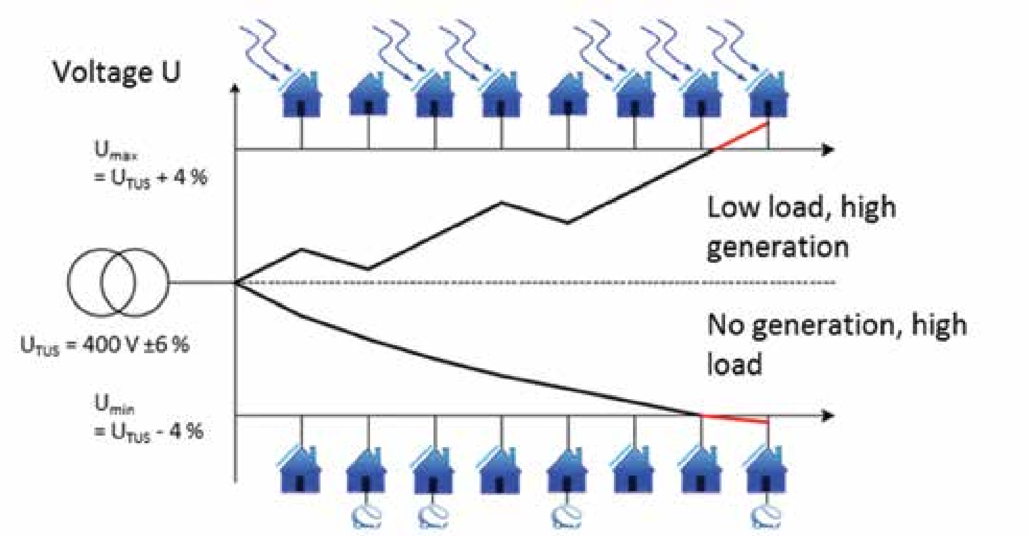

Figure 2: Typical voltage distribution along a radial feeder, with and without decentralized generation.

2.2.2 Open ring topology

Ring topology is also widely used in distribution grid and is an extension of a radial topology. It consists of radial feeders that are connected by switchgear at the end. Typically, this connection is left open to facilitate protection, but provides redundancy in case of a fault on one of the feeders, as the portion cut off by the fault can be supplied from the other side by closing the switch. Open rings are typical for medium voltage (primary distribution) grids, but can also be found at low voltage level or in sub-transmission grids. Except for the additional degree of redundancy, the behavior and expected issues are the same as in radial grids.

2.2.3 Closed rings and meshed grids

Closed ring topologies are usually not used on their own, but may occur as parts of a meshed grid (see Figure 3.) Meshed grids rarely used in distribution grids, but if so, they are used in urban areas, and may be supplied from the next highest voltage level at multiple points at once. This increases redundancy and reduces asset loading and voltage deviations, but protection in fault cases is much more complex. For the latter reason, even meshed structures are often disconnected from each other during regular operation, resulting in radial grids that can be connected to each other if the necessity arises. If meshed structures exist in the grid area to be investigated, special attention has to be paid to obtaining data on switching states (see section 2.3.5) and protection (section 2.3.6.)

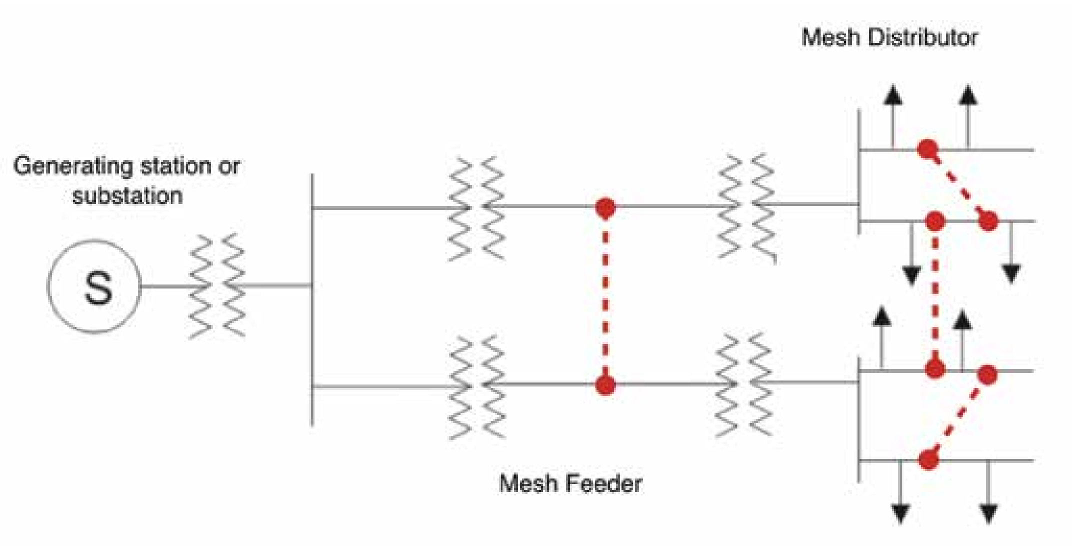

Figure 3: Meshed distribution grid (example.)

2.3 Grid assets

2.3.1 Line and cable types

Knowledge of the exact types of line and cables installed in the relevant parts of the grid is crucial for both technical and economic calculations and assessments.

The thermal rating (ampacity) is determined by the conductor material and cross section and the topology – for cables, the type of insulation also has an impact, while the ampacity of overhead lines is often limited by the maximum allowed sag of the conductor, which is in turn directly dependent on the construction and topology of poles or towers. The line and cable impedances have a direct impact on losses and voltage drop. In meshed grids, the power transfer distribution factor (PTDF), which is the sensitivity of each line to a spatial change in load/generation balance, and thus the power flow on each line, is determined by the line impedance.

Table 1: Required line and cable data.

Parameter	Remarks
Length	
Coordinates	Start and end substation
Rated voltage U_n [kV]	Essential parameters.
Ampacity I_r [kA]	
Rated short-time current [kA]	
Conductor type	OHL only. Can be used to calculate ampacity and short time current, otherwise not strictly necessary.
Maximum allowed conductor sag	
Max. Operational Temperature [°C]	
Temperature Coefficient [1/°C]	
Cable type	Cable only. Can be used to calculate ampacity and short time current, otherwise not strictly necessary.
Insulation	
Topology (air or ground)	

Parameter	Remarks
Resistance R' [Ohm/km]	This data is essential for modelling, but may not be available to the grid operator. In this case, it can be calculated if the conductor type and OHL/ cable topology is known.
Reactance X' [Ohm/km]	
Capacity C' [µF/km]	
Conductance G' [µS/km]	
Number of Circuits on Tower	OHL only. Strictly necessary if line impedance data is unavailable, as it can be calculated from these parameters
Number of Earth Wires on Tower	
Symmetry of conductors on tower	
Distance between towers	

2.3.2 Transformers

In meshed grids, transformer impedances have a significant impact on the distribution of load flows and must thus be known to the modeler. In radial or ring structures, which occur more commonly in distribution grids, this is not the case, however, voltage and losses on a feeder are directly dependent on the types of transformers installed.

Generally, the technical data given on the nameplate of each transformer should provide the information needed to create a sufficiently accurate simulation model (see Table 2.)

Table 2: Technical data provided on transformer nameplate.

Parameter	Remarks
Rated apparent power S_r [MVA]	For three winding transformers, ratings may vary for the three voltage sides
Rated primary voltage U_{r_HV}	
Rated secondary voltage U_{r_LV}	Three winding transformer data should also include rated tertiary voltage
General winding configuration	
Short circuit voltage u_k [%]	Necessary for the calculation of voltage drop over loaded transformer
Commissioning date	If data is unavailable, assumptions may be based on the state of the art at the date of commissioning/manufacture of the unit
Copper losses P_{Cu} [kW]	
No-load current i_0 [%]	
No-load losses P_0 [kW]	

Special attention should be paid to tap changing transformers. Most transformers in a power system will be equipped with tap changers to adjust the voltage on the secondary side according to load level, except for low voltage transformers, which may, at times, have a fixed ratio. However, there are different types of tap changing transformers that are typically used.

On-load tap changing transformers are mostly used in the high and medium voltage levels. The transformer ratio can be adjusted in loaded state. This may be done automatically (via computer control) during operation, which allows for active automated voltage control. A typical application of such a transformer is the link between transmission and distribution grid, while medium voltage transformers within the distribution grid are often manually controlled. This can be done remotely – allowing for capabilities similar to an automatically operated transformer, albeit slightly more cumbersome – or on site by switching. The latter is often done only seasonally, leaving the transformer at a fixed ratio for long stretches of time.

Off-load tap changing transformers need to be unloaded and switched off to change the ratio. This type of transformer is usually used in medium and low voltage networks. The ratio is typically set to a value deemed appropriate to the specific application and left there for the life of the unit. This means that off-load tap changing transformers provide no means of operational voltage control.

Table 3: Types of transformers in distribution systems.

Transformer type	Typical application
On-load tap changing, automatic voltage control	HV/MV and MV/MV applications – voltage can be continually controlled during operation
On-load tap changing, remote controlled	HV/MV and MV/MV applications – voltage set points can be changed remotely
On-load tap changing, manually controlled	MV/MV and MV/LV applications – voltage set points are typically changed only seasonally
Off-load tap changing	MV/LV applications, ratio is re-set only at revisions, if at all
Fixed ratio	MV/LV applications, rare

Considering this multitude of possibilities of transformer operation, clear communications must be established to identify the units in the grid correctly. Especially for on-load tap changing transformers, the operational regime used must also be determined, for transformers that are not or only rarely switched, the set points used must be established.

In case of a lack of measured load data, transformer ratings are a good indicator of the load levels that can be expected, especially for low voltage transformers.

2.3.3 Generators

Data on existing distributed generators necessary for the setup of a simple load flow simulation model should at least include the rated power (both unit rating and inverter rating for inverter based generation), the possible reactive power range and the reactive power control regime (fixed ▯, Q/U control, ▯/U control etc.) should be known. The generation patterns as explained in section 3.1.3 are of interest as well. If no measured generator data is available, inclination, azimuth and efficiency (PV) or power curves (wind) should be procured (see section 3.3.)

For further studies, information on properties such as fault current contribution, fault ride through behavior, operational ranges for voltage and frequency should also be provided. If a valid grid code was applicable at a unit's commissioning (or approval) date, such information is found in the grid code requirements.

2.3.4 Compensation

Reactive compensators may be used for additional voltage control in substations with known voltage deviation issues. This may be the case in distribution grids with long feeders and/or high load. If such compensators are installed in the relevant grid area, data on their type (L, C, RLC, power electronics, etc.) should be provided, as well as their reactive power output and their switching or voltage control regime.

2.3.5 Switching states

With the redundancy provided by multiple parallel transformers and multi-busbar systems, which are typically used at least in the substations connecting the distribution grid to the transmission or sub-transmission grid, the knowledge of switching states used during normal operation becomes important. Usually, there are multiple ways of how a distribution grid can be supplied, but only one will be used during normal operation, while other switching options become relevant only during faults, emergencies or asset revisions (see Figure 4 for an example.) The same is often true for ring or meshed grid structures which are run with open switches during normal operation, but can be connected to each other in certain situations. The criteria that trigger switching operations must also be established for a correct analysis.

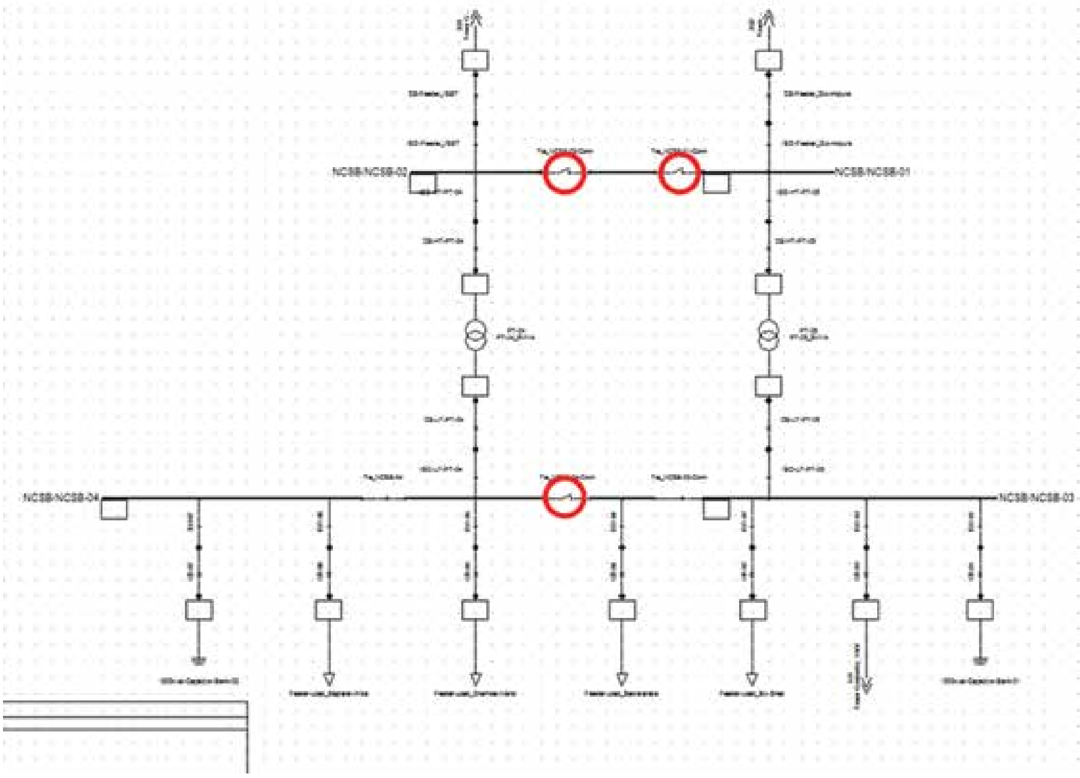

Figure 4: Substation diagram with tie breakers marked in red open during normal operation. In case of an outage of one or more assets, the parallel branch could be supplied by closing one or more of the switches.

2.3.6 Protection

Most distribution grids were designed with uni-directional power flows in mind, thus as load-only grids. With the introduction of distributed generation, grid protection settings designed for such grids may have to be updated. For example, if a short circuit happens on a feeder, distributed generation connected between protection and fault location may feed power into the fault and lower the short circuit current measured by the protection device, resulting in a delay or even a failure of the device to disconnect. Installed protection and exact settings should be provided by the grid operator to assess the adequacy of the protection regime, identify possibly arising issues and develop solutions.

2.4 Diagrams and maps

Although this information could be provided in other forms as well (Excel sheets, simulation models etc.), substation diagrams at least of larger substations supplying more than one feeder are usually essential to the understanding of the grid topology, switching and protection. Such diagrams must be provided by the grid operator, as even with on-site visits and photographs of the substation, the exact topology is difficult to establish. For the exact same reason, the grid operator will usually be able to provide this information.

Diagrams and maps of the grid and grid area may not be strictly necessary for the analysis, but facilitate understanding of the topology and its peculiarities. This can include single-line diagrams (SLD) of the grid area, maps which include the line/cable topologies, or simply geographic coordinates of substations so the grid topology can be recreated using mapping tools such as GIS systems, Google Maps or OpenStreetMap.

2.5 Grid models

Analysis of the grid is generally less time consuming if the operator – or a third party – has already set up a model of the grid in a simulation software. Even if a different software is to be used for the study, most simulation tools allow the structured export of all grid data into different formats. This can either be imported by other software or at least facilitates the setup of a new model as all data is available in one place in a structured way.

However, this does not eliminate the need for grid and generator data, as modelling is always prone to errors. Cross-checking the model with real data is advisable, even if a full model validation is not possible.

3. Operational data

3.1 Measured operational data

If available, measured operational data from the relevant grid area greatly facilitates modelling and improves the quality of model and results. Relevant data includes measurements of voltage, current, active and reactive power at different points in the grid in different time resolutions (preferable: hourly or sub-hourly) during normal operation, but also data from events in the grid such as outages and restarts.

Measurements can either be available as outputs of SCADA systems or other monitoring mechanisms, or they can be procured through a project specific measuring campaign using Phasor Measurement Units or similar devices. Necessary data and typical availabilities are specified in Table 4 and elaborated on in the following. Simplifications and assumptions will typically have to be made at some point, depending on the focus of the analysis to be conducted.

Table 4: Measured operational data for grid modelling and simulation.

Data	Typically available	Additional requirements
Voltage, HV	Voltage at all busbars through SCADA system	Sufficient
Voltage, MV	Voltage at secondary side of HV/MV transformer	Sufficient for modelling. For model validation, measurements from other locations in the grid (feeder end) may be useful.
Voltage, LV	None	
Load, HV	Power flow through HV/MV transformer	Active and reactive power measurements may be available, can be used for model validation
Load, MV	Peak load at MV/LV transformers	Feeder load time series (active power) are often available for MV. For LV grids, only peak load may be available, if at all.
Load, LV		

3.1.1 Analysis of medium voltage / primary distribution grids

Medium voltage grids connect the high voltage transmission or sub-transmission grids with the low voltage supply for the end customer, thus distributing electricity regionally. Medium voltage grids typically use voltages between 10 and 50 kV (66 kV in some places, but this could also be considered sub-transmission) depending on the size of the area to be covered. Radial and open ring structures are dominant, but meshed grids may also appear in urban areas.

Besides the detailed topology and asset data described in section 1, a range of operational data is needed to assess the impact of rising PV shares on an MV grid section. Typically, a selected grid area is analyzed in detail, using a simulation model with low voltage grids and other MV grid sections connected to the selected areas being represented by their load equivalents (see Figure 5.) Starting from the point of connection to the high voltage grid, the following operational data is required for grid modelling (marked in green in Figure 5):

- Time series of voltage measurements at the secondary side of the HV/MV transformer. Typically, the HV/MV transformer is the last instance of voltage control. The voltage here is the supply voltage for the entire distribution grid area, and real life measurements are necessary to establish the impact of distribution grid load on the voltage and assess the adequacy of voltage control at this point.
- If there are any additional means of active voltage control in the grid – reactive compensation, or other automatic on-load tap changing transformers – voltage measurement time series at the connection points of those are necessary, as well as detailed information on the operating regimes (see section 2.3.)
- Time series of active and reactive power flows through the HV/MV transformer, for the same reason mentioned in the previous bullet points.

- Time series of active and reactive power flows through the transformers connecting lower voltage levels. This can be, as shown in Figure 5, a lower medium voltage level, or directly the low voltage grid. In the former case, measurements are usually available from the grid operators monitoring systems, while in the latter case, detailed low voltage load data may often be unavailable. In this case, data should be approximated using peak load data (if available), transformer ratings and/or standard load profiles (see section 3.2.)

With this data available alongside the grid topology and asset information, a setup of a power flow simulation model is possible – the flows and voltages in the grid are a result of the supply voltage, the voltage control mechanisms, the load and the grid properties. Assuming there are no errors in the calculation parameters, the model should now deliver reasonably accurate results.

For cross-checking and validating results, more detailed data is of course useful. Especially voltage measurements at different points in the grid can be beneficial, as well as active and reactive power flows on lines and through MV/MV or MV/LV transformers. The cost-benefit ratio of conducting a measurement campaign for the sole reason of collecting this data may be questionable, but if a campaign is already within the scope of the project, the following points will be of interest:

- Voltage time series downstream of the last instance of voltage control, to check voltage results from simulations. As the end of a feeder experiences the largest voltage swings, it is advisable to measure voltage there.
- Load time series of one or more low voltage grids (MV side of transformer) or individual low voltage feeders (LV side), if possible with active and reactive power component.

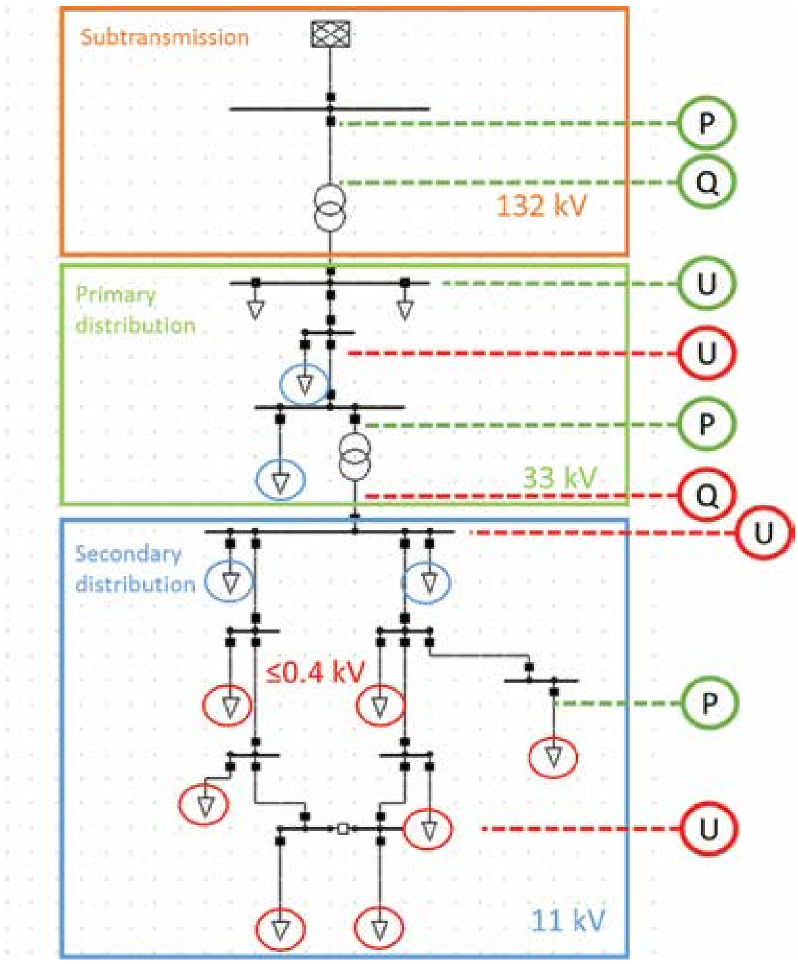

Figure 5: Necessary (green) and optional (red) measurements for a medium voltage grid analysis.

3.1.2 Analysis of low voltage / secondary distribution grids

Simulative analysis of a full MV grid with detailed models of all attached LV grids is usually too complex for the scope of a distribution grid study[1]. In MV grid simulation, LV grids are thus usually represented by their load equivalents. If measured data is available, time series of load at the primary side of the MV/LV transformer is sufficient – if there is no data available, this would be subject of a measuring campaign, or the approximations described in section 3.2.

Properties of low voltage grids themselves differ from those of medium voltage grids in a few important points. Grid topologies may be more diverse, as low voltage grids are often grown structures, and different planning or expansion principles may be used depending on country, region and load structure. In many European countries, MV/LV transformers are rather large, even in rural areas, supplying settlements or even whole villages, with line lengths of typically a few hundred meters, multiple parallel low voltage feeders and three phase connections to every customer. In the US and Central America, distances covered by medium voltage grids are typically longer due to the lower population density. Low voltage transformers are smaller and low voltage line lengths shorter, often with end customers being supplied with only one phase.

Moreover, low voltage grids may be of radial, open ring or meshed topology. Meshed grids are usually only used in urban areas, but may then also be supplied from the MV grid at multiple points at once. This increases redundancy and reduces asset loading and voltage deviations, but protection in fault cases is much more complex. For the latter reason, even meshed structures are often disconnected from each other during regular operation, resulting in radial grids that can be connected to each other if the necessity arises.

In any way, neither MV nor LV grids traditionally have no means of actually controlling the power flow (except for load shedding which should be reserved for emergency situations, being usually of radial configuration. To some degree, this may change with the introduction of decentralized generation or storage. LV grids, however, usually have no capability of controlling the voltage. On-load tap changing MV/LV transformers are commercially available, but currently usually employed in areas with already high PV penetration where integration studies have already been conducted.

Considering the role of LV grid analysis within a distribution grid study, a decision must be taken on whether actual simulation and/or detailed analysis of LV grids is actually necessary and/or feasible within the scope of the study. In urban or sub-urban grids with high load density and short line lengths, asset overloading will be the main concern for integration of large PV shares, while voltage deviations will most likely be less problematic. Overloading issues in short radial grids, however, can usually be addressed without grid simulations, based on the known load and generation carrying capacity of lines, cables and transformers.

In more rural grids with low load, but potentially high PV feed-in (prime example: rural Germany with agricultural customers, very low daily but large roof spaces that can be used for PV), the actual behavior the voltage in the grid at high PV penetrations and thus reversed power flows may become more interesting, to the point where grid simulations may become necessary. Especially voltage control strategies in LV grids with more than one parallel feeder supplied by the same transformer and differing load/PV characteristics may be difficult to assess without simulations.

1 Such models do exist at, for example, some German and French distribution grid operators, who use them not primarily for simulation, but also for planning and monitoring. The cost-benefit ratio of setting up such a model for the sole purpose of a PV integration study is questionable.

3.1.3 Generation data

If there is already any decentralized generation in the grid area in question, generation data must be procured as far as it is available. If data is not available to the grid operator – which may be possible especially for net-metered generation, as only generated energy, but not power is measured – approximated generation data can be obtained from weather data of the area, as described in section 3.3.

Generation data – measured or calculated – is of course useful for the modelling of future additional generation, the impact of which is to be studied. However, data from existing generation is also included in the feeder load measurements described in sections 3.1.1 and 3.1.2, which strictly speaking are net load / residual load measurements. To obtain the actual load values, the generation patterns must be subtracted from the load.

Generation connected to the distribution grid can usually include single wind turbines or small wind parks (MV grid), small and micro CHP units (MV and LV grid) and roof mounted PV units (MV and LV grids.) Measured generation data should be in time steps of 15 minutes or less, to avoid cutting off real peaks (linear interpolation) or creating artificial, non-realistic peaks (spline interpolation.)

3.1.4 Event data

Stability, defined as the capability of a system to return to steady state operation after a disturbance, is a system issue that cannot be assessed by distribution grid analysis alone. However, historical measured data (voltage and current/power) may be useful within a distribution grid study for the evaluation of the adequacy of protection and fault ride through regimes, as well as for the assessment of outages and their impact on economics and feasibility of distributed generation.

3.2 Load profiles and load estimation

As described in sections 3.1.1 and 3.1.2, there may be gaps in the load data. A common problem is that load time series are measured for a distribution feeder at the medium voltage level, but exact information on the load of the individual substations connected to the feeder are missing. Often, only peak demand, or the transformer rating can be obtained. In this case, the planning and load forecasting criteria used by the operator should be analyzed along with the available data and used to create a reasonable estimate of load distribution. This data may include:

- Time series of load at some point (feeder connection point);
- Peak load data for other points in the grid;
- Grid asset ratings (especially transformers);
- Customer types supplied in each individual area, often based on tariffing ("60 % residential, 30 % commercial, 10 % agricultural");
- Customer types as estimated from maps or GIS data of the area;
- Grid planning and load forecasting criteria used by the operator.

3.2.1 Standard load profiles

Load profiles for customer classes are developed for the forecast of daily electricity demand in hourly or sub-hourly steps over a larger area, with the goal of balancing load and generation and procuring enough power at each point in time. An example of standard load profiles with seasonal variation used by operators in Germany is given with the BDEW H0 in Figure 6. Similar profiles exist for groups of commercial and industrial customers. Load profiles vary by country, region and operator. However, the actual load profiles especially of private households are highly stochastic and often do not resemble a standard load profile. Only if a certain larger number of customers is aggregated using the individual profiles, they typically add up to something similar to the forecast profile.

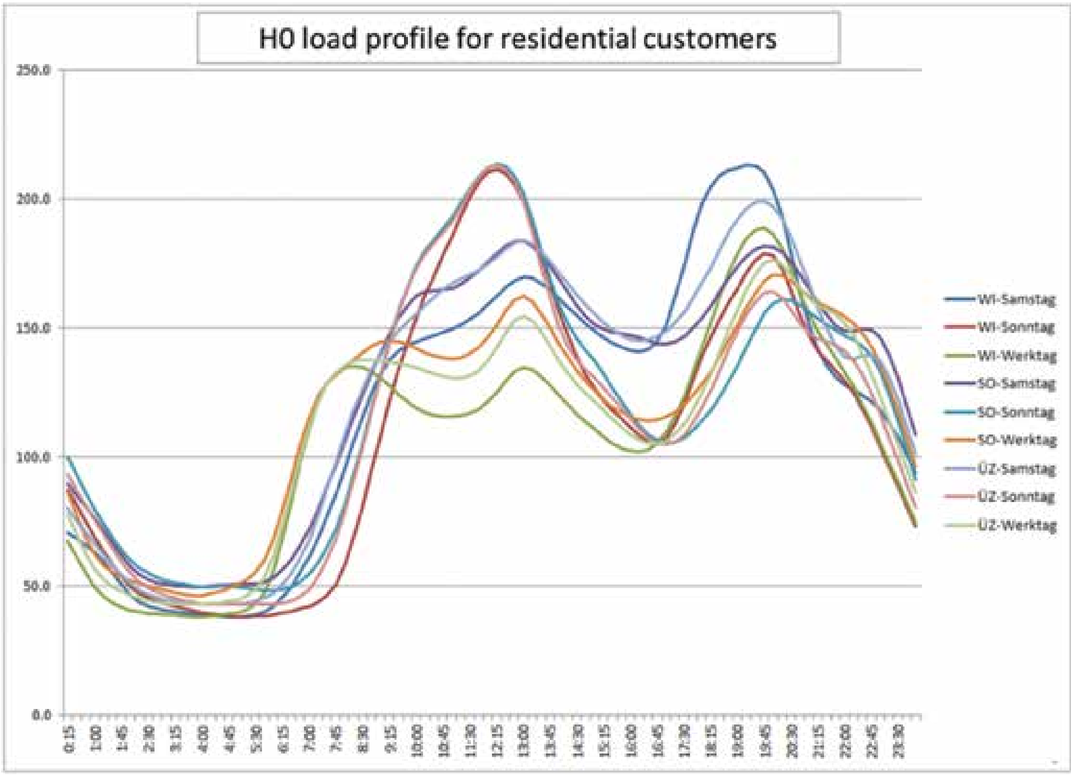

Figure 6: Load profile used for residential customers in Germany as example of a standard load profile.[2]

3.2.2 Coincidence factors

The coincidence factor is defined as the ratio of the maximum load that actually occurs and the maximum theoretical load, for a single customer, a distribution area or an entire power system:

$$f_{coincidence} = \frac{\sum_{i=1}^{n} \text{Load}_i}{\sum_{i=1}^{n} \text{Max (Load)}_i}$$

This factor is used in the dimensioning of power system assets and generation capacity. For example, a private household may have electrical devices of a combined maximum load of 18 kW connected, but experience shows that typically, no more than 3 kW will be consumed at the same time. The devices in the household are thus assigned a coincidence factor of 3/18 = 0.17, and the connection of the household is dimensioned for 3 kW.

The same is applicable when dimensioning a distribution grid: Each household may draw a peak load of 3 kW at some point, but the chance that all households do this at the same time decreases with the number of households according to Figure 7 or a similar curve. A grid with 10 customers at 3 kW each and a coincidence factor of 0.25 must thus be designed to supply a peak load of 7.5 kW.

Coincidence factors both at connection and at system level are already included in standard load profiles.

2 Legend from top to bottom: Winter Saturday, Sunday and weekday, Summer Saturday, Sunday and weekday, Spring/Autumn Saturday, Sunday and weekday.

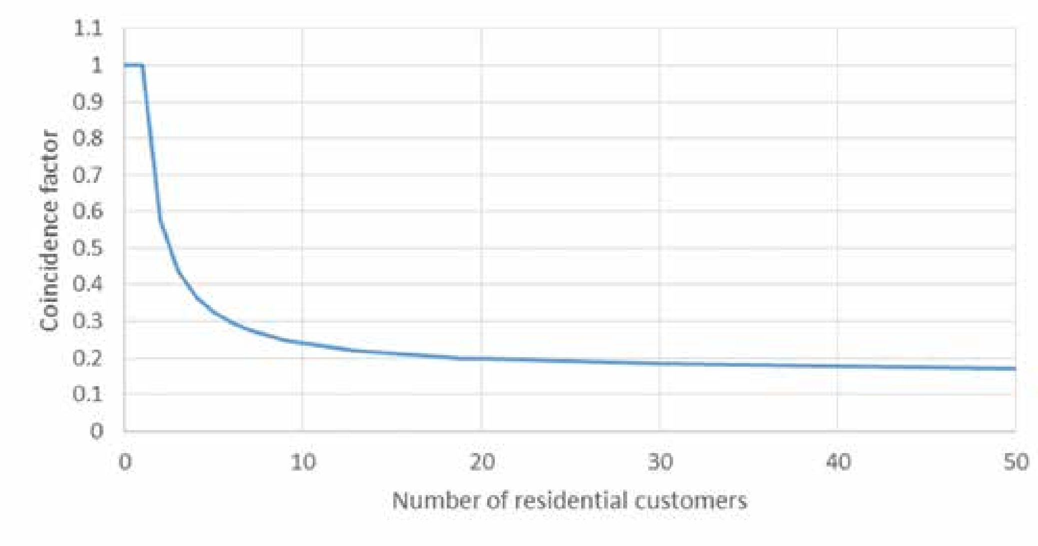

Figure 7: Decrease of coincidence factor at increasing number of customers in rural Austria.

3.3 Weather data

With some capacity of distributed generation already installed in the grid area in question and generation data available, it may be assumed that new generation will experience very similar generation patterns. However, this may be subject to some inaccuracy as technology develops and future generators may have varying properties:

- Azimuth and inclination of existing PV units may not be optimal, leading to daily generation patterns deviating from the typical case;
- Newer PV units may be more efficient, but equipped with smaller converters for peak shaving, leading to a higher energy yield, but lower peak power compared to old units of similar size;
- Modern wind turbines may display completely different windspeed-power curves than old ones.

For this reason, it is advisable to collect and analyze weather data not only in case of a lack of generator data, but in any case to eliminate error sources.

3.3.1 Solar irradiance

Solar irradiance (also: insolation) data as measured by weather stations is given as Global Horizontal Irradiance (GHI), which is defined the amount of terrestrial irradiance falling on a surface horizontal to the surface of the earth. It is either measured with a reference PV cell, or calculated from direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI):

$$GHI = DHI + DNI \cdot cos\theta_Z$$

For PV units, power output can be estimated from GHI, inclination and azimuth. If measurements from locations close to the planned generation sites exists, this may be used directly. If a weather station is located outside a city, but PV will be installed in the city, air pollution through fog, smog and dust may impact power output significantly, especially in tropical areas. In warm areas, panel temperature may also play a role, which is dependent on wind speed and air temperature.

3.3.2 Wind speed and direction

Wind speed and direction are of course needed to calculate wind turbine output, which is done with power curves as displayed in Figure 8. Wind speed will also affect the power output of PV panels by cooling effects.

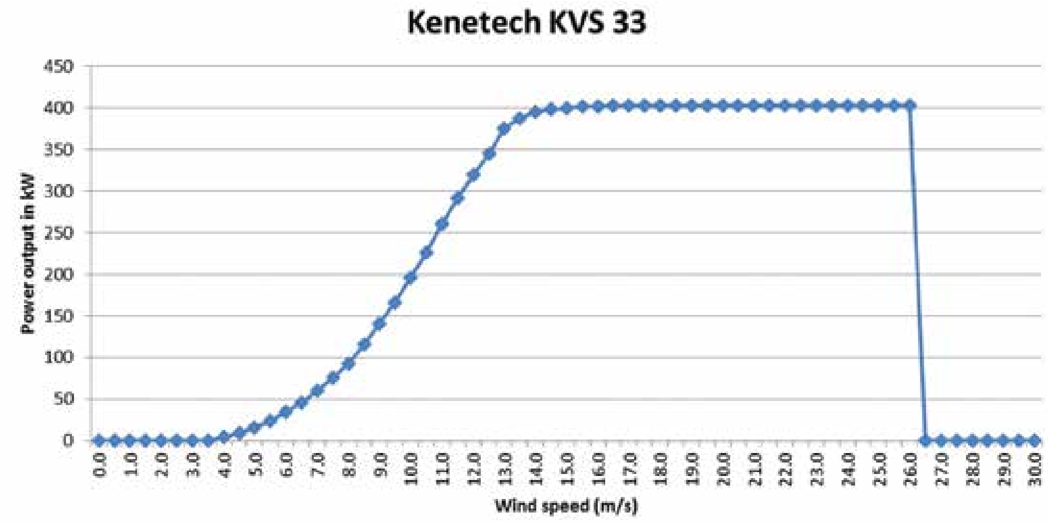

Figure 8: Power curve of a Kenetech KVS33, one of the first full converter wind turbines in the 1990s. Modern wind turbines have similarly shaped, but often steeper curves.

3.3.3 Air temperature

Depending on the type of panel used, the output voltage of a PV panel will decrease by 0.2 – 0.4 % per K increase of panel temperature, resulting in lower power output and thus lower efficiency. As a first approximation, panel temperature can be estimated to be the same as the temperature of the surrounding air. In reality, differences may be significant, as direct insolation heats the (dark) panel, while wind will have a cooling effect.

3.3.4 Air pollution

Smog, fog and dust may reduce PV power output, especially in urban and/or tropical areas. The impact can be evaluated by comparing GHI data from non-affected areas to GHI data and PV output from affected areas.

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