ANALYSIS OF THE PROPAGATION OF POWER QUALITY PHENOMENA USING WIDE-AREA MEASUREMENTS

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ABSTRACT

The propagation of Power Quality (PQ) phenomena through distribution networks is dependent on a number of parameters, including the characteristics of the disturbance source, impedances and configuration of the network and behaviour of loads and generators in the analysed area. Due to the large numbers of network users, estimation of disturbance levels in the network includes a large number of uncertainties.

This paper proposes a method for analysing the propagation of PQ phenomena through the distribution network based on wide-area field measurements. In the future, the method will be used to analyse the data obtained from Live-Lab - the permanent field experiment of the Dutch DSO Alliander. The analysis takes into account the state of the network, loading of substations and measurement uncertainty.

INTRODUCTION

Whereas the effects of a local Power Quality (PQ) disturbance on the PQ levels at its point of connection are often analysed, the effect of multiple disturbance sources on the wider network is not very well understood. The propagation of PQ phenomena is usually investigated using statistical analysis of a few measurement points or computer simulations based on a network model with estimated impedances of network components. Such analysis gives results with various successes for different kinds of phenomena, due to the different influences of connected users. For example, for the analysis of voltage dips and swells, the structure of loads does not lead to very high uncertainties due to the significantly lower short-circuit impedance of the upstream network. For other phenomena, the structure of loads can have a very significant influence, e.g. the influence of low-frequency response of loads on voltage flicker or the broader-frequency response of loads on harmonic distortion. For better understanding of the propagation of PQ phenomena through the network, field measurements should be performed, including the loadings of individual substations.

The propagation of PQ disturbances can mathematically be described with transfer impedances, when a set of synchronised measurements is available as described in [1]. However, most PQ analysers present in the networks are not synchronised – they perform simultaneous measurements with a significant uncertainty of the starting moment of each data window. Also, additional time aggregation is normally applied to the results (e.g. at 10 minute intervals), which adds more uncertainty to the synchronisation.

In [2], a method for analysing the sources of disturbances based on different components of the current is proposed. This method requires synchronised waveforms as inputs. Identification of harmonic sources based on a few synchronised measurement locations and state estimation was analysed in [3]. In [4] the results of some of the previously proposed methods for multi-point measurements of PQ phenomena are compared, and their drawbacks are indicated. The aggregation of many loads into a single harmonic impedance characteristic was analysed in the past, and the equivalent load model based on the measured active and reactive power is reported in [5]. This equivalent is based on the measurements in one country made in the 1980’s, and it is difficult to estimate how applicable it is to other countries and the changes of loads which happened since then.

The analysis of the propagation of PQ phenomena through distribution networks is one of the objectives of a recently started project called “Measurement Tools for Smart Grid Stability and Supply Quality Management” [6]. This paper proposes the methodology which will be used in the project, using wide-area measurements of existing PQ analysers at multiple points in the Medium Voltage (MV) network and most of the connected Low Voltage (LV) networks. Due to the large number of substations, the analysers are simultaneously recording measurements, but are not synchronised.

The method will give the opportunity of analysing the transfer of PQ phenomena through the network, taking into account the current state of the network and the loading level of each substation. Additional information about the structure of loads in each area of the network will also be used, e.g. to analyse the seasonal variations of levels caused by Combined Heat and Power (CHP) generators. Furthermore, the impact of measurement uncertainty of the different meters and sensors on the conclusions about the propagation will be investigated. Estimation of impedances of groups of loads is also possible under certain conditions (limited by the signal to noise ratio for each frequency). This makes it possible e.g. to correlate the loading levels of LV networks to the damping and/or resonances in the network, and make an update of the aggregated load model proposed in [5].

The results of such analysis are meant to be used for the following purposes: guidance for network design and locating disturbance sources, inputs for voltage quality standards, connection requirements for installations and emission limits for equipment in the future.

TEST NETWORK

The test environment for this work is Live-Lab - the permanent field experiment of the Dutch Distribution System Operator (DSO) Alliander [7]. It consists of a MV/LV network in which the primary High Voltage substation (HV/MV) and most of the secondary substations (MV/LV) are equipped with monitoring equipment of different types. The two main purposes of Live-Lab are experimenting with different types of measurement equipment and determining the possible applications using additional measurements in the distribution network.

The schematic of a part of the test network is shown in Fig. 1. The primary (HV/MV) and secondary (MV/LV) substations are indicated in the figure, together with the busbars on which PQ is monitored.

This network supplies both residential and industrial customers. Significant production of CHP generator is also present in some parts of the network (mainly supplying greenhouses).

Additional monitoring locations, both permanent and temporary, are foreseen during the project. Permanent measurement instruments are various types of PQ analysers, complying to the IEC 61000-4-30 standard [8], and the temporary measurement points will at shorter time intervals be monitored by custom data-acquisition systems with a possibility of recording waveforms for longer time intervals (without synchronisation).

APPROACH OF THE ANALYSIS

Simultaneous but not synchronised data is not appropriate for the calculation of transfer impedances in the network, but it can be used for the calculation of equivalents at each individual busbar (secondary substation). These equivalents, determined for the same time periods, can then be used for creating load equivalents (for each type of phenomenon) and for analysing the influence of loading levels on the propagation of PQ levels, e.g. based on the changes of harmonic impedance characteristics of individual busbars.

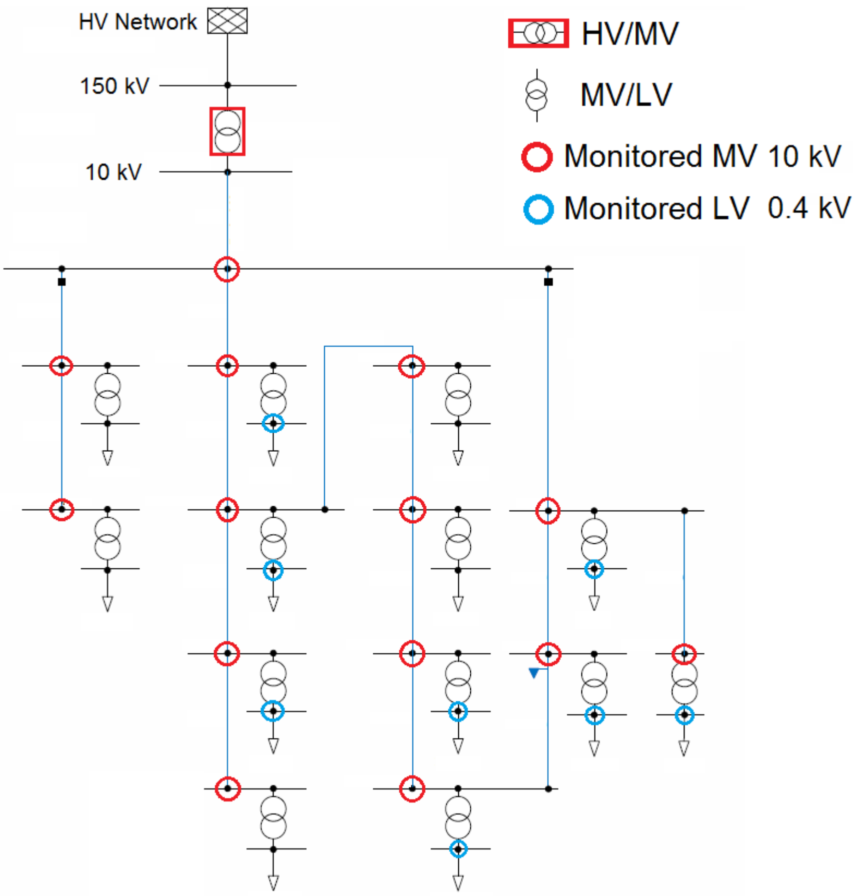

Fig. 1 Schematic of the MV/LV network within the Alliander Live-Lab, including the busbars with PQ monitoring

The measurements should include the characteristic time periods – e.g. day/night, working day/weekend, summer/winter. Power dependent models are most convenient for application, because DSOs typically have good predictions of power consumptions during the year, but not of the emission levels.

The simultaneous measurements of a later time period make it possible to validate the results of a computer simulation based on the aggregate equivalents, derived from the data covering at least one year (to cover all seasons). For better reliability of calculations, the models can later be updated with the data of more years.

The following sub-sections deal with the types of PQ phenomena for which a significant amount of data is expected during the project: voltage variations, harmonic distortion, voltage flicker and unbalance.

Voltage variations

Voltage magnitude variations are an often analysed phenomenon which can be well analysed with good predictions of the load and generation. The DSOs typically have good predictions of the load variations, , but the problem of voltage magnitude variations is again becoming relevant due to the changes caused by the local generation in distribution networks.

The impact of distributed generation on voltage variations, primarily CHP in the Live-Lab test network, will be analysed based on the measurement of power flows and voltage magnitudes. Limitations arise from the limited possibility to separate the local generators from the load in the measurements.

Harmonic distortion

The propagation of harmonic distortion is usually analysed in the frequency domain, based on the harmonic load-flow. The spectra (including magnitudes and phase angles) of disturbing currents are used as inputs, and impedances are modelled based on the network and load equivalents, e.g. the CIGRE aggregated load model which is dependent on the load power [5]. In case that insufficient information is available of the disturbance sources, a summation approach and coefficients are proposed in IEC 61000-3-6 [9], for making an aggregated disturbance source.

The general applicability of the above-mentioned aggregated load model and summation coefficients will be analysed based on the measured data. The load model will be analysed by correlating the measured power values with the harmonic impedance values calculated from harmonic voltage and currents. This approach is limited to the locations and time-intervals where and when impedance calculations are possible, as explained in [10]. At some of the substations, waveform recording can be used for this function as well (simultaneous but not synchronised with the PQ analysers). This will allow using shorter time-intervals for impedance calculation - e.g. using several cycles of the signals during which the distortion levels are higher. This is advantageous over the aggregated (e.g. 10 minute) values obtained from the standard PQ analysers, since it will allow for more accurate results.

The summation coefficient for harmonic current will be analysed based on measurements of the total current of a transformer and the currents of the individual feeders. Many of the substations in the test network are equipped with instruments which measure all individual feeders on the LV side of the transformer, and additional locations can be covered with portable equipment.

The analysis will be limited to the harmonic orders which have significant measured values of both voltages and currents, as it is expected that a significant part of the 2.5 kHz range will have measured levels lower than the uncertainty of measurement equipment together with the transducers, for most of the time.

Voltage flicker

The propagation of voltage flicker is well understood for a known single flicker source, e.g. calculating flicker based on the known current variations and impedances of lines and transformers. Furthermore, the effect of directly coupled induction motors on the reduction of flicker levels is described in [11], and the summation method and coefficient for multiple sources is proposed in [9]. However, modelling of the flicker emission of large groups of loads, e.g. commercial and small industrial buildings, still needs additional research.

In this project, the emission of aggregated loads (all loads of a LV feeder or a whole secondary substation) will be characterised based on the variations of the maximum RMS values of the voltage and current during the aggregation interval, and the short-term flicker coefficient (P_{st}) and powers during the same time interval. The usual approach for reporting voltage and current magnitude variations is based on the aggregated 10/12 cycle RMS values during the observation interval (e.g. 10 minutes), as defined in the IEC 61000-4-30 [8]. However, most PQ analysers make the maximum and minimum 10/12 cycle values available as well. Additionally, at some of the substations, waveform recording is foreseen to obtain better insight into the connection between the magnitude variations and P_{st}.

The above-mentioned magnitude variations can be correlated to the power and P_{st} values, to create aggregated equivalents of certain types of loads. Based on the same measurements, the flicker summation coefficient can be analysed, and its applicability to the groups of loads found within the test network.

Voltage unbalance

Voltage unbalance can be considered with the same methodology as harmonic distortion of one order. Based on the measured negative- or zero-sequence component of the current and the impedances of network components, the propagation can be analysed based on the load-flow of this component. With long-term measurements of load powers and negative- and zero-sequence components of load currents, generalised emission models can be derived, for the available load types.

One of the characteristics of a typical distribution network in the Netherlands is that there are no major sources of voltage/current unbalance (except for traction supplies which are not present in the test network). Also, due to the relatively short cable lengths, relatively low values of voltage unbalance were measured in the past years. This may lead to an unacceptably high uncertainty of unbalance calculations, and a need to exclude them from the end results.

CONCLUSIONS

The paper proposes a methodology for analysing the propagation of PQ phenomena in distribution networks based on wide-area measurements. The methods will be applied to the simultaneous PQ measurements from the Live-Lab test network of the Dutch DSO Alliander, which is equipped with PQ analysers in the primary and most of the secondary substations. In the first phase, simultaneous measurements will be performed for different PQ parameters. If necessary or helpful, truly synchronized measurements or waveform measurements might be performed and analysed as well.

The method will give the opportunity of analysing the transfer of PQ phenomena through the network, taking into account the current state of the network and the loading level of each substation. The aggregated models of load groups, dependent on the loading level, are expected as the main outcome of the analysis. The results of the analysis are meant to be used as guidance for network design, and inputs for the relevant standards.

Acknowledgments

This work is carried out as part of a joint European research project called “Measurement Tools for Smart Grid Stability and Supply Quality Management” with 17 participating research institutes [6]. The project is part of the European Metrology Research Program (EMRP), which is jointly funded by the EMRP participating countries within EURAMET and the European Union. Additional funding is received from the Dutch Ministry of Economic Affairs.

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