CHOSEN ASPECTS FOR HARMONIC ANALYSIS IN DISTRIBUTION NETWORKS

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ABSTRACT

This paper presents a review of techniques for modelling and analysis of harmonic propagation in power systems with regard to the usability for small, low power harmonic producing devices. Theoretical aspects of different concepts for harmonics modelling and simulation are presented, including a discussion of advantages and disadvantages. Furthermore, research needs in the application field of low voltage distribution grids are identified.

I. INTRODUCTION

For quite some time harmonic study is a standard component of power system analysis. Nevertheless, the improvements of known algorithms as well as the development of new simulation techniques are necessary as the presence of harmonic producing equipment is still increasing. At the same time, the demand for more energy efficiency at consistent or even enhanced reliability of supply is growing. Not only that harmonics propagate through the system and result in additional losses. They also may interfere with control, communication or protective equipment. Furthermore, over current and over voltages resulting from resonances can damage equipment.

Increased application of power electronics such as HVDC converter technology, static var compensators and the widespread use of static power converters since the 1970s and the associated increased rate of harmonics led to the development of a variety of methods for the modelling of harmonic sources and network components as well as the prediction of harmonic propagation through the network and the harmonic steady state of the system.

The current development from centralized power supply to smart grids with distributed energy sources like photovoltaic systems as well as new grid participants like electric cars requires new approaches. While, so far, harmonic studies mainly concentrated on the transmission systems, now the attention is shifted also to the distribution systems including low voltage networks.

In the following a review of the current available techniques for the modelling and analysis of harmonic phenomena in AC power networks, with regard to the usability for the new areas of application, is given. The first part presents fundamental aspects of the modelling and simulation of harmonic sources, both in frequency and time domain, opposing advantages and disadvantages. A further section provides a survey of available harmonic load flow algorithms. Harmonic interaction phenomena, amplification effects as well as statistical/ probabilistic aspects are discussed in a separate section. In conclusion, research needs are identified.

II. HARMONIC ANALYSIS

A harmonic study aims at the quantification of the waveform pollution at a number of relevant points in the power system and the overall performance. Various harmonic analysis techniques are available to study the generation and propagation of harmonics. They differ in the way of problem formulation, modelling complexity as well as the solution algorithms and always constitute a compromise between the required calculation accuracy and data availability. A detailed overview of established methods can be found in [1]. Generally, frequency domain and time domain based algorithms are distinguished. The simplest technique is the frequency scan. It provides the frequency response of the power system at a certain bus or node. A one per unit sinusoidal current is assumed to be injected into a certain node of the power system and the voltage response is calculated [2]. The procedure is repeated for all relevant frequencies. Frequency scan is a useful method to determine resonance conditions in a system. Its application is limited with regard to harmonic power flow studies as it usually does not consider transfer impedances of the network.

The most commonly used technique to model harmonic sources is the current source model [3], [4], (figure 1 (a)). It reflects the injected harmonic current for undisturbed terminal voltage. The method is computationally efficient but as a drawback it has to be considered that it assumes an undisturbed terminal voltage and thus ignores interaction between the network and the equipment. Unbalanced system conditions also necessitate more detailed models. The iterative harmonic analysis (IHA) where a harmonic producing device is modelled as a supply-voltage-dependent current source is used to overcome at least the first problem. Initially, the harmonic currents are estimated. In an iterative process, each time the latest vector of harmonic currents is then used to recalculate the bus harmonic voltages [5] until

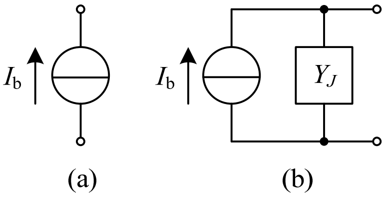

Figure 1: Simple harmonic load models (a) harmonic current source, (b) Norton equivalent

convergence is reached. Converters are usually represented by fixed harmonic current sources at each iteration step. For better convergence, a Norton equivalent can be used [3], (figure 1 (b)). The nonlinear relationship between injected harmonic currents and the corresponding terminal voltages can be formulated as

$$\underline{\mathbf{I}} = f(\underline{\mathbf{V}}), \tag{1}$$

where $\underline{\mathbf{I}}$ and $\underline{\mathbf{V}}$ represent the harmonic vectors. If the content of harmonics is relatively small, a linearization around the base working point ($\underline{\mathbf{V}}_b$, $\underline{\mathbf{I}}_b$) of the nonlinear device is possible. In this case, the $\underline{\mathbf{V}}$-$\underline{\mathbf{I}}$-dependency can be formulated as

$$\underline{\mathbf{I}} = \underline{\mathbf{Y}}_J \underline{\mathbf{V}} + \underline{\mathbf{I}}_N, \tag{2}$$

with the Norton equivalent $\underline{\mathbf{I}}_N = \underline{\mathbf{I}}_b - \underline{\mathbf{Y}}_J\underline{\mathbf{V}}_b$. and the Norton admittance matrix $\underline{\mathbf{Y}}_J$ [6]. The method may face convergence problems near sharply tuned resonances [1]. A divergence of IHA is likely in case of comparatively large system impedance or a device behaviour which is sensitive to changes in the harmonic voltage levels [7]. [7] analyses and discusses several techniques for improvement of IHA convergence.

In [8] and [9] a model is proposed which represents non-linear loads by a so called crossed-frequency harmonic admittance matrix $\underline{\mathbf{Y}}$. The elements $\underline{Y}_{jk}$ in equation (3) relate a harmonic current of order k to the harmonic voltage of order (j). Their parameterisation is based on physical measurements, see [8].

$$\begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \\ \cdots \\ \underline{I}_M \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & & \underline{Y}_{1N} \\ \underline{Y}_{21} & \underline{Y}_{22} & & \underline{Y}_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ \underline{Y}_{M1} & \underline{Y}_{M2} & \cdots & \underline{Y}_{MN} \end{bmatrix} \begin{bmatrix} \underline{V}_1 \\ \underline{V}_2 \\ \cdots \\ \underline{V}_N \end{bmatrix} \tag{3}$$

The model was tested and validated for several single-phase non-linear loads, such as fluorescent discharge lamps. It is conceivable to use it within an iterative frequency domain algorithm. A challenge is to be seen in the phase dependency of the matrix elements as well as in the fact that each operating point of a device requires a separate matrix. As a possible solution [10] shows the implementation of a phase dependent admittance into a computationally efficient tensor based frequency coupling matrix. An advantage of the method is that the harmonic source can be considered as a “black box”. A detailed knowledge of e.g. the converter behaviour is not necessary.

Weak systems with significant harmonic distortion may require a more in-depth representation of system nonlinearities in time domain. Time domain methods typically use a set of differential equations or state equations to represent the system elements and the harmonic sources. Usually, they are more accurate than the iterative frequency domain methods. Mostly, the techniques are far developed and implemented in various software tools such as PSCAD®/ EMTDC^{TM}. Simulations of non-linear effects in the time domain are time consuming. Not all methods can be included in harmonic power flow analysis. Therefore, often they are not the preferred means of harmonic study. Nevertheless, there are some approaches to reduce complexity and thus computation time by using e.g. dynamic equivalents of the network and switching functions of converters [11].

III. HARMONIC POWER FLOW

Harmonic power flow methods are usually a reformulation of the conventional load flow including nonlinear device behaviour. Mathematically, a network equation and a set of device equations at fundamental and harmonic frequencies are to be solved. The network representation can be realised either by an admittance matrix or in form of power flow equations. For the device equations there is a spectrum from simple current sources up to complex control-variable dependent circuits [1]. A review of the different harmonic power flow formulations with required data, unknowns and equations is presented in [12]. Most available methods base on calculations in frequency domain. Time domain methods have the disadvantage that conventional load flow constraints such as constant power specifications at load buses cannot be included. The frequency domain procedures can be classified according to figure 2.

The simplest method is harmonic penetration (HP). It neglects any harmonic interaction between network and the non-linear device, i.e. the harmonic voltages at the terminals have no influence on the load behaviour. The injected currents are calculated as a function of the fundamental bus voltage and parameters of the non-linear device. The voltage nodes method is used to get the harmonic voltages. As non-linear devices are in fact sensitive to harmonic voltages, the application of the HP method entails the risk of overestimation of their pollution effect [12].

For improvement the HP can be extended by an iterative harmonic analysis with the Gauss-Seidel algorithm. The last values of the harmonic voltages are used to renew the injected currents. In turn, the currents are used to derive the

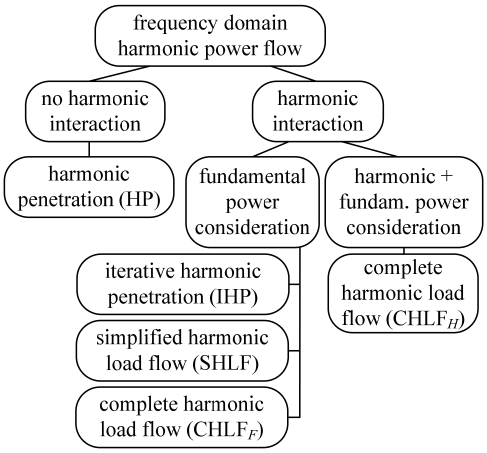

Figure 2: Classification of harmonic power flow methods (following [12])

voltage harmonics. Despite possible convergence problems the iterative harmonic penetration method (IHP) is limited by the assumption that the conventional power flow solutions are unaffected by the introduction of harmonics.
With the simplified harmonic load flow method (SHLF) two Newton-Raphson procedures are executed consecutively. First a conventional power flow with non-linear loads included as PQ loads is performed. Second step is a harmonic analysis for a network reduced to the buses with non-linear devices. It corrects not only harmonic voltages but also the fundamental voltage. As a result of the network reduction for the harmonic analysis for power consumption the SHLF only takes into account the fundamental frequency.

In [13] a modification of the conventional power flow with included non-linear device consideration and harmonic voltage calculation is proposed. The method is referred to as complete harmonic load flow. It provides a simultaneous resolution of power constraints, harmonic current balance and state equations of the non-linear devices. The formulation allows a consideration of power consumption for fundamental as well as harmonic frequencies since a system reduction is not required. However, the algorithm is single-phase in nature and thus only applicable if the network features symmetrical operating conditions. Unbalanced systems need to be studied using a three-phase model with appropriate neutral and ground circuits. A multiphase modelling allows e.g. the analysis of zero sequence-harmonics produced by three-phase transformers or the assessment of non-characteristic harmonics generated under unbalanced conditions [1]. In a perfectly balanced system harmonics of order h = 1, 7, 13, ... are purely positive sequence, while those of order h = 5, 11, 17, … are purely negative sequence. Triplens are purely zero-sequence. In an unbalanced system, any harmonic may appear in any sequence [14].

IV. HARMONIC INTERACTION PHENOMENA

A non-linear load supplied by an ideal sinusoidal voltage causes harmonic currents that flow through the impedances of the power system, thereby producing harmonic voltage drops. The original voltage waveform is modified and the current harmonic behaviour of the non-linear device changes. So, the propagation of harmonics in power systems depends on the characteristics of the harmonic sources themselves as well as on the interaction with the linear network components. In literature various methods for dealing with the harmonic interaction between AC and DC side of converters especially in conjunction with HVDC systems exist, e.g. [15]. Harmonic currents generated by HVDC terminals, dc drives or adjustable speed drives are different as the components connected to the converter output vary. A comprehensive overview for modelling of converters in harmonic simulation, mainly for frequency domain, is given in [3], while the time-domain method presented in [11] allows prediction of the harmonic propagation as a result of interaction among several converters by representing the converters by their switching function.
In medium- and low-voltage range the influence of waveform and peak values of supply voltages on harmonic currents generated by transformers, fluorescent and other gas discharge lightening, arc furnaces and similar devices is higher than for electronic switching devices [1]. Thus, it is not sufficient to model the first-mentioned devices as voltage independent harmonic current sources but necessary to take into account the actual non-linear V-I-characteristics. For steady-state analysis a linearization around operating points is conceivable.
Beyond the interaction between a harmonic source and the network it is also desirable to model the attenuation as well as amplification effects of harmonics from several sources in the system. As harmonics add vectorially the resulting harmonic distortion levels highly depend on the phase angles. Often, measured total harmonic distortions in distribution level are much lower than what is expected from a harmonic power flow study. A reason can be found in aggregation of non-linear devices .The huge number of small single-phase non-linear loads in a low-voltage system, such as static power converters for electronic equipment, small adjustable speed drives, etc. inhibits detailed harmonic power flow studies. Conventionally, the collective effect is received by summation of their single effects ignoring possible harmonic cancellation due to manufacturing tolerances and disparate use of the devices. Energy efficient lights and household electronic appliances are often simply modelled as parallel harmonic current sources with known magnitude and phase angle [16]. An investigation of attenuation and diversity effects for systems with distributed harmonic sources is documented in [17].

V. RESEARCH NEEDS

One of the most challenging aspects concerning the harmonic power flow in distribution networks, especially in low-voltage range, is the huge number of possible harmonic sources and sinks with relatively low rated power each. Frequently, the harmonic amplitudes are small and the phase angles differ in a wide range. Statistical or probabilistic models are indispensable for consideration of group effects. Moreover, linear loads such as incandescent lamps, heaters and motors which act as damping elements for propagating harmonics and influence the resonance frequency of the system [18] must be included in the modelling. As the number and specific position of this equipment is usually not known in detail not only a state estimation process but also an adequate stochastic model is required. In [19] a methodology in developing a stochastic/ probabilistic model based on harmonic field measurements is proposed.
Along with the target of sustainable energy supply the number of photovoltaic (PV) inverters is steadily increasing. Experiences in networks with high penetration of PV

generation showed that the inverters switched off undesirably or increased their harmonic emission considerably. Responsible for these effects are parallel and series resonance phenomena between the network and the PV inverters. If one of the harmonics generated by the PV inverter corresponds which either the parallel or the series resonance frequency, very high resonance voltages/ currents attenuated only by the associated network and load resistances, will occur. Mostly, parallel resonance caused by small PV inverter current harmonics trips the PV systems [20]. Not least, a detailed knowledge about resonance conditions in a system is desired in the design and rating of filters.

VI. CONCLUSIONS

In near future, an efficient operation of the electrical system up to the low-voltage range with only a minimum of faults will be only possible bearing in mind the influence of harmonics. Existing phenomena like resonance effects due to PV inverter harmonics are expected to be enhanced by new grid components like electric car chargers as well as the generally increasing number of power electronic devices.

As been described in the paper, there already exist a large number of methods of modelling harmonic sources and propagation. The challenges coming along with current grid developments need to be analyzed by combination and extensions of these methods.

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