Harmonic emissions of power-electronic devices in different transmission-network operating conditions

Ambrož Božiček, Member IEEE
University of Ljubljana
Faculty of Electrical Engineering
Ljubljana, Slovenia
ambroz.bozicek@fe.uni-lj.si

Jako Kilter, Senior Member, IEEE
Tanel Sarnet, Stud. Member, IEEE
Elering AS and
Tallinn University of Technology
Department of Electrical Power
Engineering and Mechatronics
Tallinn, Estonia

Igor Papič, Senior Member, IEEE
Boštjan Blažič, Member, IEEE
University of Ljubljana
Faculty of Electrical Engineering
Ljubljana, Slovenia

Abstract – Harmonic emissions of power electronic (PE) devices connected to transmission networks are introducing new and rising trends of harmonic distortion. Analyses, which focus on assessing the harmonic levels in PE-rich power networks of the future, are mostly based on digital simulations, which require accurate models of the power system and connected devices. The simulations are usually performed with the use of EMT models, resulting in long simulation times, or the use of over-simplified load-flow models. In this paper, we propose a methodology that can be used to define accurate frequency-domain simulation models of PE devices. The models are derived by frequency-dependent multi-parameter scanning. The resulting models can be employed for harmonic load-flow simulations in different network and PE-device operating conditions. They enable the assessment of the impact of frequency-dependent network-impedance characteristics and, moreover, the effect of cross-coupling between different frequency components. The analysis is focused on high-power, high-voltage power-electronic devices, which cannot be easily measured or analyzed for harmonic characteristics. Therefore, the methodology requires detailed EMT models of the devices, which are analyzed within different operating conditions. The accurate equivalent models of PE devices represent a crucial element within the context of harmonic emission studies in large transmission networks.

Index Terms—Harmonic analysis, Power system harmonics, Power quality, Power electronics, Load modelling

I. INTRODUCTION

Transmission networks are under heavy influence of the fast development of new power electronic (PE) technologies in the field of power generation and transmission [1], [2]. Due to environmental concerns, we are facing a rapidly increasing share of renewable energy sources, as are wind and photovoltaic generation, and, consequently, high-voltage DC (HVDC) transmission is becoming an increasingly viable option for improving the network transfer capacity [3],[4]. In

addition, the tendency is also to utilize the available transmission infrastructure as much as possible, so compensation devices like STATCOM or SVC are often used in transmission systems to increase the transmission capacity and stability margins [5], which is especially essential in the offshore ac grids [6]. All mentioned devices are based on power electronics (PE), which have an impact on power quality levels in transmission systems.

The operation of PE devices depends on their electrical topologies and control algorithms. Controllers define the overall dynamics of the device, including the response to changes of the operating points or to distortions of any kind. Proper design and tuning of controllers is the main challenge of the developers of PE devices, while the strict rules of network operation, usually defined by grid codes, increase the complexity of the designs.

Strict limits for the contribution to the harmonic emissions of devices connected to different voltage levels are also defined [7]. The experiences of European TSOs show that the harmonic distortions are most critical in the networks where the short-circuit power is low and where the network consists of a high share of cables, which tend to resonate with particular harmonic components produced by PE-based renewable energy sources [8].

To cope with the expected influence of a higher share of modern PE devices on power quality in the transmission grid, digital simulation tools and models of electrical devices will have to be revised and further developed to deliver satisfactorily results in view of accuracy and viable simulation-time.

To achieve a detailed insight into the operation of the power electronic devices, detailed EMT models are regularly utilized to evaluate operation characteristics on a wide frequency bandwidth. Since the transmission system simulations with detailed EMT models of electrical elements require extremely long simulation-times to cope with analyses for different operating conditions including many PE devices, frequency-domain simulations are still the favorable tool for harmonic load-flow or stability analyses.

The frequency-domain models of PE devices are often based on simplified models. These models, used for harmonic load-flow simulations, are built in many different ways, from the simplest constant or variable current sources and basic

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Norton equivalents [9], to the complex cross-frequency dependent or so called harmonically coupled admittances [10],[11] or Norton equivalents [12],[13].

The harmonically coupled characteristics allow for representing the nonlinear device's characteristics with the cross-frequency dependent impedances with linear matrix elements. In [11], the authors present the exact equivalent model of a PE device (thyristor-based bridge converter) with the analytically derived frequency cross-coupled admittance, which utilizes linear matrix elements. However, such linear characteristics cannot be generalized for all PE devices since the admittance matrix elements might change with different operation conditions, defined by individual influential parameters.

Versatile nonlinear dependencies of PE models on different system or PE-device based operation parameters are clearly identified in [13], [14] and [15] where the data are gathered by detailed measurements or simulations of different "black-box" models of PE devices, which represents the device with unknown topology and control algorithms. Mostly, the characteristics are identified as equivalent impedances with dependencies on different parameters.

In practice, the equivalent model can be established by using the scanning method with a real hardware devices [14] - [16] or with the detailed EMT simulation models. The latter is applicable especially with the high-power, high-voltage devices due to more demanding requirements for the testing equipment.

In practice, beside the models in frequency domain, the use of more complex harmonic state-space (HSS) equivalent models of PE devices can be used for steady state and dynamic simulations [22]. However, for the development of a HSS model of a PE device the exact parameters of the passive elements, control algorithms, modulator, etc. are required. These data are mostly available only to the manufacturer (developer) of the PE device. If the detailed EMT model of a PE device is available only as a black-box model, as usually provided by the manufacturer, then the development of the HSS model is practically impossible.

Within this paper, a multi-parameter based scanning of detailed EMT models is proposed. The elements of the equivalent model defined with this approach are not constant, they depend on various parameters (PE device and network operating conditions), and deliver accurate harmonic contribution of a PE device for different operating points. The scanning results for both elements of the Norton equivalent are stored in look-up tables. The admittance is defined with a cross-frequency coupled matrix, while the current source is given with a frequency dependent vector for each individual operating condition. The more parameters are used for the definition of the operating point, the more dimensions the resultant data-matrices will have. Within the paper it is also indicated how the large amount of the obtained data could be minimized by introducing the functional dependencies of the Norton equivalent elements.

II. HARMONICS EVALUATION IN TRANSMISSION NETWORKS

The studies of harmonic emissions in transmission systems are relatively scarce in practice, which is because most of the issues, caused by harmonics, are found in distribution networks, near to non-linear loads. Nevertheless, the new experiences with high penetration of FACTS devices and high-power PE-based generation units call for harmonic studies also at transmission systems level [21].

Accurate harmonic simulations require the modelling of two distinct areas. One model describes the area of a large-scale transmission system, which is required to obtain accurate impedance characteristics. Namely, the impedance at a certain network point can be influenced by far-away elements, which is due to the relatively close electrical proximity of elements in the transmission systems. The second model describes the harmonic generating PE-devices, where accurate simulations are required to reach a satisfactory level of accuracy.

Since PE devices are becoming the main contributors to harmonic distortion, the required simulation and modeling precision must follow the minimum required simulation precision, which is relatively high with PWM voltage-source converters. Generally, the PE device can be analyzed in detail only by detailed EMT simulations in time-domain, which require high processing power and result in long simulation times. Therefore, for the steady-state simulation, simplified equivalent models in frequency-domain, as described in this paper, can replace the models of actively controlled PE devices. The accuracy of such models is the crucial point of the analyses.

The flowchart in Fig. 1 briefly explains the methodology for defining and utilizing the PE device's equivalent model in the transmission network analyses. The detailed EMT simulations of electrical networks with PE devices offer very precise results, but the time-consumption easily becomes extremely high and the simulations very impractical when multiple devices and multiple operating points need to be analyzed. Therefore, performing a systematical analysis of individual PE devices enables the development of detailed steady-state equivalent models based on the Norton equivalent. The equivalent models can be then used with harmonic load-flow simulations to deliver the simulation results much faster and still with relatively good accuracy for steady-state conditions.

Further on, the scanned elements are useful for different frequency-domain studies in transmission systems, for example, for allocation of responsibilities for harmonic emissions, or for the harmonic stability analyses, which follow the principles of defining the Nyquist stability margins (phase reserve) in the Bode plot [7], [17], [18], [21]. Stability analysis could detect also possible controller stability or interaction issues in specific operating points. The versatile devices' characteristics for different operating conditions can be used also with probabilistic analyses with Monte-Carlo simulation approach to estimate the probability of different operating scenarios, as in [19].

Fig. 1. Derivation and utilization of the equivalent “fingerprint” models of PE devices in harmonic load-flow simulations

The utilization of equivalent models is important especially for the TSOs whose main focus is the operation and reliability of the grid and not the details of individual customer’s device. Equivalent models can be easily used by TSOs in the phase of the request for connection approval of a PE device, enabling stability analyses, harmonic emissions evaluation and other steady-state analyses.

III. OVERVIEW OF TRANSMISSION SYSTEM PE DEVICES

When considering the power electronic devices, which are connected directly to the HV or EHV transmission system, we are limited to the FACTS devices, mostly the SVC, STATCOM and HVDC. However, also other PE devices, which have lower power but are connected to the transmission system in groups, may have a potentially large impact on the transmission system power quality. In this group, we can find especially large wind or solar power parks.

The difference between PE devices comes from different topology designs as well as from the control algorithms, which dictate the operation characteristics of the PE device. Fig. 2 presents some topologies of PE devices, which will also provide the reference cases for the further analyses in this paper. The first one, the SVC, consists of the passive single tuned harmonic filters (HF) and the active thyristor-controlled reactors (TCR). Due to its limited bandwidth performance, the controls are not capable of actively controlling harmonics above the second harmonic. The second device is a STATCOM with the multi-modular converter topology, which is connected to the transmission system through the step-up transformer. The utilized topology is a double star connected converter with 20 half-bridge sub-modules per arm. The modulation based on the nearest level control and selected harmonic compensation provide additional active filter functionalities to reduce the device’s output harmonic emissions. The third topology represents the full-bridge converter based on the two back-to-back connected 2-level voltage-source converters, which is the generalized (and simplified) topology for the most of solar converters and wind turbine generators (type 4). The device uses also a grid-side

filter (LCL or similar) to filter-out the switching harmonics produced by the PWM based converter.

Fig. 2. Single-line diagrams of PE devices’ topologies (SVC, STATCOM and WTG T4)

The devices are used as the reference cases to show the main differences between parameters of equivalent circuits of individual devices and to illustrate the effect of control algorithms on shaping the impedance characteristic.

IV. FREQUENCY SCANNING AND THE EQUIVALENT MODEL IN FREQUENCY-DOMAIN

Transmission system analyses are often performed in frequency domain as load-flow simulations, stability analyses, etc. A crucial point of the frequency-domain analyses is the accuracy of the utilized models. Especially the controller-based PE devices require comprehensive analyses to extract their steady-state characteristics for different operating points.

A. Definition of the operating points

To deal with PE model variability in terms of harmonic emission variations (current injections), the harmonic load-flow model has to respond to different operating points of the transmission network which are defined with the voltage conditions at the point-of-connection (POC).

Modelling of a PE devices must therefore include the dependency on the network voltage and its harmonic components. These conditions cover also the variation of the POC voltage which occurs due to the PE device current injections into the grid impedance. Therefore, from the perspective of frequency scanning of a PE device, only its response to different voltage components at the POC is important. Modelling of the PE devices partly as admittance allows it to respond to voltage variations. On the other hand, the invariant injections around individual operating point is attributed to the constant current source of the Norton equivalent.

Beside the operating points defined on the network side (POC voltage), also the PE-device itself operates at different operating points, mostly defined with the fundamental-frequency quantities as are the generated reactive or active power. However, the PE devices are built on different converter topologies using different switching modulation techniques, which causes variable harmonic contributions, dependent on several parameters (e.g. device current, POC

voltage, dc-side voltage, etc.). In addition, control algorithms of the PE devices can include several control functionalities (active filtering, different set-points, etc.) which all increase the number of possible device operating points. From a theoretical point of view, every variable parameter results in an additional set of operating points of the PE device causing additional dimension of the equivalent model and can be included in the presented model. Due to the mentioned reasons, the device's equivalent model has to be defined for an actual PE device with the actual controller.

The variable conditions of steady-state operating-points under which the PE device could operate and will be used to extract the multi-parameter Norton equivalents of PE devices are the following:

- Network-side conditions:
 - Fundamental voltage amplitude $|U_{H1}|$ at the POC,
 - Individual harmonic voltage amplitudes $|U_H|$ at the POC,
 - Phase angles of individual harmonic voltage components $\varphi(U_H)$ at the POC and
- PE-device side conditions:
 - Active or/and reactive power of device P, Q .

The PE devices show diverse dependencies on the particular parameters. Therefore, the characteristics need to be analyzed for combinations of these parameters. However, as mentioned in the introduction, some modeling approaches utilize more simple average models, considering the model to be linear or invariant to particular parameters [11],[12]. This consequently simplifies the equivalent models but cannot offer satisfactory simulation results for all possible operating conditions.

B. Operating-point dependent Norton equivalent model

The PE devices can be modeled with different equivalent models. Which one is the most suitable to describe a particular device depends on multiple aspects:

- The topology of the device (filter impedances, converter, etc.).
- Location of the point of evaluation in the network.
- Control algorithms.

In most cases, the high-power PE devices operate as the sources of active or reactive power, which represents a current source at constant fundamental voltage, at least for the fundamental harmonic component. On the other hand, harmonic and other high-frequency current components are usually initiated by several causes: distortion defined by PWM-based voltage at the output of voltage source converters, which reflects the switching frequency-related harmonic components, and the components caused by nonlinear-modulation characteristics during the voltage zero crossing. These distortion effects can be characterized as voltage sources. The other significant cause for the distortion is the sensitivity of the control algorithms to distortions of the voltage at the POC, which can lead to the generation of additional current harmonics, if correct filtering measures are not applied. The nature of the distortion source for these causes can be correctly represented with a combination of the

constant harmonic current and constant harmonic voltage source. However, due to the nature of the PE devices and networks, the current and voltage harmonic sources that are connected to the POC through a relatively large impedance (series reactor, transformer) in comparison to the network impedance, tend to behave as current sources [20]. For this reason, we find the Norton equivalent circuit as the most suitable for describing the operation of the controlled PE devices.

The Norton equivalent circuit (Fig. 3) consists of two frequency-dependent elements, the current source and the admittance. For each operating point, the current source generates constant harmonic emissions, while the impedance represents the sensitivity of the model (PE device) to the grid-side voltage harmonics causing additional harmonic current injections of the modeled device.

The admittance of the equivalent model usually represents the passive grid-side elements of the PE device as well as the influence of the actively controlled voltage source converter. The converter could eventually operate in a four-quadrant region and can recreate, at least in the limited controllable range, the behavior of passive elements. For this reason, both, passive impedances and controls influence the admittance of the Norton equivalent.

C. EMT model frequency scanning

To define the characteristics of the equivalent Norton circuit, the detailed EMT simulation model of the PE device has to be available. The model scanning is based on the frequency-sweep analysis of the EMT models under different operating conditions in the steady state operation. The procedure is schematically represented in Fig. 4.

The PE device is connected to a voltage source. In the first step, the EMT model is tested under initial (ideal) conditions with undistorted voltage source connected to the point of connection (POC). In the second step, we observe the response of the PE device to particular constant voltage harmonic components. However, in a real electrical system, the voltage distortion at the bus is also the function of the feedback harmonic injections of the observed PE device. This feedback influence creates new operating conditions at the bus, which causes new injections from the PE device. Therefore, it is important to scan as many as possible operating conditions of the PE device in order to be able to use it with satisfactory accuracy with iterative harmonic load-flow simulations.

Fig. 3. Basic scheme of the multi-parameter Norton equivalent circuit

Fig. 4. Algorithm for the multi-parameter frequency scanning of the EMT model of PE devices

The scanning of the EMT model for an individual operating point in steady state is performed in a time-interval of at least 10 fundamental periods, which gives the 5 Hz resolution for the FFT results. If necessary, higher resolution can be utilized by using a larger sampling window. To reach the high accuracy of the scanned equivalents, the EMT simulation time-step during scanning must be sufficiently low to produce accurate high-frequency responses of the PE device and to minimize the simulation background noise that can deteriorate the scanned characteristics of the device.

The PE device's harmonic-current response $\Delta \underline{I}$ to the voltage excitation $\Delta \underline{U}$ with different harmonics, as shown with (1), are used for extraction of the admittance values $\underline{Y}_{eq}$ (2). Both, $\Delta \underline{I}$ and $\Delta \underline{U}$, are the vectors defining a change of the PE device current and POC voltage on a wide, discrete frequency range.

The undistorted voltage $\underline{U}_f$ which causes initial current injections $\underline{I}_f$ of the PE device, and the admittance $\underline{Y}_{eq}$ are used to define the value of the Norton current source, which is properly recalculated with (4) for the fundamental frequency

component to exclude the influence of the admittance at individual frequency.

$$\Delta \underline{I} = \begin{bmatrix} \Delta I_{f1} \\ \Delta I_{f2} \\ \dots \\ \Delta I_{fi} \\ \dots \\ \Delta I_{fm} \end{bmatrix} \quad \Delta \underline{U} = \begin{bmatrix} \Delta U_{f1} \\ \Delta U_{f2} \\ \dots \\ \Delta U_{fi} \\ \dots \\ \Delta U_{fm} \end{bmatrix} \quad (1)$$

$$\underline{Y}_{eq} = \frac{\Delta \underline{I}}{\Delta \underline{U}} \quad (2)$$

$$\underline{Y}_{eq} = \begin{bmatrix} Y_{f1,f1} & Y_{f1,f2} & \dots & Y_{f1,fj} & \dots & Y_{f1,fn} \\ Y_{f2,f1} & Y_{f2,f2} & \dots & Y_{f2,fj} & \dots & Y_{f2,fn} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{fi,f1} & Y_{fi,f2} & \dots & Y_{fi,fj} & \dots & Y_{fi,fn} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{fm,f1} & Y_{fm,f2} & \dots & Y_{fm,fj} & \dots & Y_{fm,fn} \end{bmatrix} \quad (3)$$

$$\underline{I}_{eq} = \underline{I}_{init} - \underline{Y}_{eq} \underline{U}_{init} \quad (4)$$

The admittance characteristic (3) is defined as a spectrum of current response for each excitation voltage frequency. Thus, the cross-influence between different frequency components can also be evaluated by defining the frequency cross-coupling admittance as a division of the i -th current frequency component and j -th excitation voltage frequency component (5).

$$Y_{fi,fj} = \frac{\Delta I_{fi}}{\Delta U_{fj}} \quad (5)$$

where:

- f_j is the excitation voltage frequency and
 - f_i current response frequency,
- both defined for negative and positive frequencies.

The frequency scanning takes into account also the unbalanced operation of the three-phase systems by considering the positive and negative sequence components. The zero sequence components can be neglected in most cases, considering that the zero sequence current cannot propagate from PE device to the network. The cross-frequency dependence of the admittance is therefore defined also between the positive and negative sequences of individual frequency components.

In principle, the scanning procedure is very time-consuming and generates a relatively large amount of data, especially because of a high number of operating points for which the EMT model of the PE device needs to be scanned. On the other hand, the use of the equivalent PE device models (based on scanning results) is very simple and straightforward and enables fast harmonic load-flow simulations. In cases when multiple devices of the same type

are utilized in the network (e.g. wind turbines), only one equivalent model is sufficient for modelling.

Due to the expected increase of the number of PE devices in future transmission systems, which contribute significantly to harmonic levels, the frequency scanning procedure targets mostly higher harmonics. However, the control algorithms of PE devices can lead also to unpredicted behavior in the subsynchronous frequency range, therefore, a similar frequency scanning can be performed also for the lower frequencies. The voltages and currents of a PE device within this range are mostly influenced by the dynamics of the control algorithm controlling the fundamental frequency components.

V. FREQUENCY DEPENDENT EQUIVALENT CIRCUITS - EXAMPLES

In this section, the multi-parameter based scanning of the PE devices' EMT models will provide examples of scanned equivalent models of different PE devices. Due to the multi-dimensional and complex values of the obtained results, the graphical representation of the Norton equivalents will be limited to 3-dimensions, which gives the possibility of showing the influence of only two parameters at a time. Other parameters for the particular operating point are kept constant. The admittances and current values of the Norton equivalent are complex values represented with amplitude and phase angle. In most of the graphs herein, only the amplitude will be shown and the frequencies up to 2 kHz will be analyzed. The elements of the equivalent circuits are given in symmetrical components for positive and negative sequences (frequencies).

All the variables of the equivalent circuits are shown in the normalized, per-unit scale. The base values for the voltage and current are the amplitudes of the nominal voltage at POC and nominal current of the PE device respectively. The base admittance is the phase-wise admittance that produces nominal current at nominal voltage at POC.

A. Scanned characteristics of the Norton equivalent under different operating conditions

1) SVC

The particular SVC consists of passive elements, the two harmonic filters (HF), and active component, the thyristor-controlled reactor (TCR).

In one of the defined operating points, the SVC operates only with the harmonic filters. The scanned Norton admittance of this case is shown in Fig. 5a. The second case represents the characteristics with the influence of the TCR (Fig. 5b). Fig. 5a shows the admittance of a purely passive linear circuit, which is evident due to presence of only diagonal elements (no cross-frequency influence), which are symmetrical for positive and negative sequences. Due to linear passive elements, the admittance characteristic would remain identical also for other network-based operating points (different operating voltage or harmonic voltage). However, this is mostly not true for other nonlinear PE devices. In Fig. 5b, the new operating point of the SVC (different reactive power) causes that, the diagonal components are not

symmetrical for the two sequences (positive and negative). This is caused by the influence of the controlled TCR, which influences the fundamental and the 2nd harmonic components. The fundamental component is influenced asymmetrically for the positive and negative sequence, which is a clear indication of different controls for positive and negative sequence of the fundamental frequency component. The TCR is causing also some cross-frequency influence that can be seen from the presence of the non-diagonal elements, but these are rather small.

The scanning algorithm defines also the Norton current source, which is zero for all frequency components in the 1st case with only passive harmonic filters (Fig. 5a). In the 2nd case (Fig. 5b), the TCR generates a constant harmonic current contribution, which is shown in Fig. 5c.

Fig. 5. Frequency based cross-coupled Norton admittance characteristic (a, b) and Norton current source (c) defined on the wide harmonic spectrum for the SVC in two operating points, without and with TCR
Two operating points ($U: 1$ pu, $Q_{TCR}: =0$ (a), $\neq 0$ (b), $|U_h|: 0.5\%$, $\phi(U_h): 0^\circ$)

It can be concluded that the SVC is expressing more or less diagonal components, which are practically equal for positive sequence and negative sequence impedances for the frequencies higher than 50 Hz. This is the case with dominant passive elements. The fundamental, 50 Hz component, and the second harmonic (100 Hz) are the controlled components and therefore the impedance is not equal for both sequences (Fig. 5b).

2) STATCOM

PE devices that are based on voltage source converters show a lower influence of the passive elements and therefore higher asymmetry among the sequences and higher cross-frequency influence. The following case presents the STATCOM, topologically shown in Fig. 2.

The particular model of the STATCOM is based on the multi-modular converter in the double star topology. To the grid, it is connected only through a series reactance (transformer and arm reactors) which defines the basis for the admittance characteristic of the equivalent model. The scanned equivalent Norton admittance (with the frequency cross-coupling) for STATCOM is shown in Fig. 6. The correlation, as expected, is highest between the diagonal components, but, in comparison to the SVC results, the non-diagonal components show large cross-frequency influence. The diagonal components follow the impedance characteristics defined by the series phase-reactance of the device, which is modified by the influence of the active control algorithm that controls the VSC output voltage and consequently the output power. The particular analyzed controller includes active filtering control of the STATCOM output current (harmonic-self-compensation, HC). In particular, the HC consists of the controller for 5th, 11th, 17th and 23th negative sequence and 7th, 11th, 13th and 19th positive sequence harmonics.

If the frequency cross coupling is neglected, then only the diagonal components of the equivalent admittance matrix are extracted. The two cases of the Norton equivalent circuit for STATCOM with and without HC are shown in Fig. 7.

Fig. 6. Frequency based cross-coupled impedance characteristic of the wide harmonic spectrum of the STATCOM for single operating point
Single operating point (U:1pu, Q:1pu, |Uh|:0.5%, $\varphi(U_h):0^\circ$)

Fig. 7. Diagonal components of the admittance matrix for positive and negative sequence and current source components of the STATCOM equivalent model, all defined for a single operating point with and without harmonic controls (HC)

Single operating point (U:1pu/Q:1pu, |Uh|:0.5%, $\varphi(U_h):0^\circ$)

The scanning results of the two cases with different control algorithms (Fig. 7) show a big change of the value of the admittance at the selected controlled harmonic components. Lower admittance represents lower sensitivity of the PE device to voltage harmonic distortion at the POC. On the other hand, the presence of the harmonic controls can even lead to an increase of the uncontrolled harmonic components, which is identified in Fig. 7 (e.g. at 600 Hz or 700 Hz for positive seq. components). However, the characteristics can be influenced by tuning of the individual harmonic controllers in order to gain a narrower band of influenced frequencies while taking into consideration the limited dynamics of the harmonic control.

With the Norton current source, the fundamental frequency current component reaches the value of around 2 pu. The rest of the current, which reduces the resultant output current of the PE device to 1 pu (which is the operating point), is generated by the admittance at the fundamental frequency. Higher harmonic current source components are relatively small for both sequences and reach maximally 1%.

B. Complex-value characteristics of the Norton equivalent under different operating conditions

Each Norton equivalent model consists of admittance and current source, which are both complex values, defining the amplitude and phase angle of individual frequency components. The Norton admittance and current source must be defined as phasors to allow for accurate harmonic load-flow simulation with respect to the analyses of the harmonic cancellation and harmonic stability issues [7].

An example of the current and admittance phasor position in the complex plane is shown in Fig. 8a and 8c for the 5th harmonic component of the STATCOM in 90 different operating points. The same phasors are shown also in Fig. 8b and 8d, which gives a more detailed insight into the probability of the phasor distribution in the complex plane. From this figure, the prevailing phase angles of operating conditions can be identified.

On the other hand, as shown in the Fig. 8a, the prevailing phase angles may be identified also for different combinations of the operating conditions. The three diagonal groups of operating conditions, as marked with the dotted ellipse, show the tendency of amplitude and phase angles correlation with specific combination of the reactive power and POC voltage. The particular correlation might be just one of many, which could be useful in case of minimization of the equivalent models as explained in the section D.

Fig. 8. Phasors of the a) b) Norton current and c) d) admittance for the 5th harmonic component of the STATCOM in different operating conditions
90 operating points (U : 0.9 to 1.1 pu / Q : -1 pu to 1 pu, $|U_h|$: 0.5%, $\phi(U_h)$: 0°)

C. Examples of other PE devices' frequency scans

To illustrate the difference between equivalent models of PE devices with different topologies, the frequency scanning has been performed also for the EMT models of other important PE devices that are considered in the analyses of the transmission systems. These are wind turbine generators

of type 3 and 4 (WTG T3, T4), the converters for battery storage or photovoltaic generators (BS, PV), and the HVDC.

In order to improve the readability, the scanning results in Fig. 9 show only the diagonal elements of the frequency cross-coupled equivalent admittance matrices and the constant current injections of the Norton equivalent current source. The characteristics are scanned for five operating points, defined with different power set points (P or Q) at constant voltage at the POC (1 pu). Additionally, the scanning resolution is increased to 1 Hz. The admittance and current source characteristics are drawn within the same graph, giving the opportunity to identify the variability of the characteristics within different frequency ranges for all operating points and both sequences (pos. and neg.). All analyzed devices from Fig. 9 are based on voltage source converters, which are connected to the network through different passive coupling impedances.

Generally, it can be identified that the admittance characteristics follow the admittance of the grid-side coupling passive elements (reactors, filters), while the control algorithm influences and consequently changes the admittance at the selected frequencies to meet the control objectives. Admittance characteristics are different for positive and negative sequence components in the lower frequency range, which is caused by different control approaches for the positive and negative sequence components.

Operating in the constant power mode for single operation point means that by slight changing the voltage at POC, the admittance current will have to respond to maintain constant power, which is identified with the higher value of the corresponding admittance in the Norton equivalent.

The characteristics of the Norton current source vary with different operating points, especially with the fundamental frequency components. The elements of the equivalent model vary also at higher frequency components, which is evident especially with the injected current component (marked with x for individual operating point) for the particular cases. In most cases, the highest amplitudes of current source harmonics are found at the 5th and the 7th harmonic, at the switching and at sideband harmonics. These reflect the special characteristics of the converter as well as the control and modulation techniques. By changing the operating point of the PE devices, the variation can be identified for both admittance and current source characteristics, which proves the necessity for parametrized (multi-parametrized) scanning of the PE devices.

D. Minimization of the equivalent model

The characteristics of the equivalent Norton model are defined with the multidimensional complex matrices of the current source and admittance, with one dimension for each parameter that defines the operating points. This gives rather large amount of data describing a single device. To reduce the size of data (if necessary) it is possible to extract the average functional dependencies of the characteristics for individual operating points. However, doing this could result in the increase of the model calculation burden and utilization complexity.

Fig. 9. Frequency scans of different high-power PE devices: a) WTG type 4, b) WTG type 3, c) HVDC, d) STATCOM, e) Battery converter; Norton admittance and current source is shown for different operating points

5 operating points (U: 1 pu, Q or P: min to max in 5 points, $|U_h|: 0.5\%$, $\varphi(U_h): 0^\circ$)

The model of the PE device can be very comprehensive as shown for single operating point in e.g. Fig. 6 (with frequency cross-coupled dependencies). Usually, the software which offers harmonic load-flow simulations tend to perform only the decoupled harmonic calculation for the components of the same frequency with cross-coupling limited only to the fundamental frequency. For any further cross-frequency dependency simulations, a simulator must be customized to be able to perform iterative loops for harmonic load-flows. However, in most cases, only the reduced models of PE devices without frequency cross-coupling are utilized. This reduces the utilized data size significantly but also introduces certain level of inaccuracy, especially with the nonlinear controlled PE devices.

E. Comparison of WTG Type 4 manufacturer's black-box models

To show the diverse characteristics of PE models a comparison of several available industrial black-box EMT models of the WTG Type 4 (with nominal power ranging from 2.7 to 6 MW) has been carried out. The competitive devices mostly offer similar performance characteristics related to the fundamental frequency power, while the harmonic contribution, as shown further on, is diverse.

Fig. 10 shows the harmonic spectra of the measured current injections of the three black-box models (manufacturer A, B and C) and one model developed for the purpose of the Migrate project (model M). The testing was performed for all devices under the same conditions regarding the grid characteristics, fundamental frequency control mode and operating point.

Fig. 10. Current injection range of the black-box EMT models of WTG T4 developed by three different manufacturers and one developed for the Migrate project purposes

5 operating points (U: 1 pu, Q: min to max in 5 points, $|U_h|: 0.5\%$, $\varphi(U_h): 0^\circ$)

The measured current injection ranges prove diversity of the harmonic spectra and of the model parameters. Some models show presence of characteristic harmonics and high damping of all other harmonics (e.g. model B), while the others produce a different harmonic contribution.

The fact that the devices of the same type can cause very different harmonic injections requires for precise selection and definition of harmonic load-flow simulation models, which must base on the scanning results of each individual PE device's EMT model. Only in such way, we will be able to reach the desired diverse operation characteristics of the PE devices and to produce more credible simulation results of the transmission system simulations.

VI. APPLICATIONS USING THE EQUIVALENT MODELS

The most basic use of the equivalent models of PE device are the harmonic load-flow calculations in the frequency domain. These calculations use an iterative approach to reach steady-state conditions at an individual frequency. The iterative process includes also the variation of the operating point of all voltage dependent elements. This is also the case with the defined multi-parameter PE-device equivalent models.

The equivalent models are described by the frequency cross-coupled elements of the Norton impedance matrix. Therefore, the harmonic load-flow calculations require multiple iterations within the full frequency-range to reach steady-state conditions that include also cross-frequency coupling. The cross-coupled elements reveal important interaction between individual frequency components. One example is the coupling between the positive and negative sequences at an individual frequency or between harmonic pairs of the order $3n \pm 1$ (e.g. -250 Hz and +350 Hz, which are the 5th and the 7th harmonic, respectively). These harmonics tend to express coupling in case of the controls in the 50 Hz frequency domain.

A. Study case with an equivalent PE device model

The study case that we describe in this section, briefly illustrates the use of the equivalent models of PE devices for probabilistic assessment of harmonic levels in transmission networks. The advantage of the equivalent models is their simplicity of use in harmonic load-flow simulations, which allows for fast simulations that can be repeated several times for different operating conditions, as is the case with the Monte-Carlo (MC) simulations. Namely, to address all the variability of PE device operation and network operating conditions MC simulations can be used, which enable to take into account the different probabilistic functions describing device and network operation. This approach enables also calculations with many PE devices in the network, increasing only the complexity of sampling from many probability distributions.

In the analyzed study case, the connection of a STATCOM to a real transmission system model was studied. The equivalent model of the STATCOM was defined for several operating points, based on the reactive power injection and POC voltage (Fig. 8). The STATCOM was used for voltage control at the POC. The probabilistic distribution

of the required STATCOM reactive power (Fig. 11b) was therefore based on the annual historical data of the voltage profile at the analyzed transmission system bus (Fig. 11a) and the reactive power defined as a function of the voltage at the POC (Fig. 11a). Finally, to perform the harmonic analysis, the equivalent STATCOM model has been used to perform a high number of harmonic load-flow simulations where the network operating points were sampled from the POC voltage probability distribution. As a result of the probabilistic harmonic analysis, Fig. 11c and d represent the annual probability distribution of the 5th harmonic current injections of the equivalent Norton model and the resultant 5th harmonic voltage at the POC of the analyzed transmission network.

Further analyses could include networks with much higher number of PE devices or deal with additional variation of the operating conditions (e.g. variable background harmonic distortions). In such cases, the statistical analysis based on the Monte-Carlo simulation approach is required to present the simulation results in a probabilistic manner, which seems to be a viable approach to deal with the expected harmonic distortion of the future networks.

Fig. 11. Probabilistic density a) of the voltage profile at the connection point of the STATCOM and the dependency of the STATCOM power; probabilistic density of the b) STATCOM power, c) 5th harmonic current of STATCOM and d) resultant probabilistic density of the 5th harmonic network voltage component.

VII. CONCLUSIONS

One of the important aspects with the massive integration of the power electronic devices (PE) into the transmission system is the power quality in view of harmonic emissions. The challenge that arises is the adequate representation of PE devices for harmonic studies. PE devices can be modeled within EMT simulations in time-domain, resulting in time-consuming calculations. The second option are harmonic load-flow simulations in frequency domain, where the accuracy of device representation is of crucial importance. For this reason, the methodology of frequency-domain based multi-parameter models of PE devices was proposed in this

paper. The approach enables to conduct simulations that require modelling of large transmission systems and precise representation of PE devices in terms of harmonic components generation.

Generalized, multi-parameter dependent models of PE devices that can be extracted from the EMT models have been presented in the paper. The scanning results indicate that in order to deal with high precision models and simulations of PE devices in view of harmonic emission at the transmission system, the multi-parameter dependencies of the model must be taken into account. The applicability of the proposed approach was illustrated with the use of the STATCOM equivalent model for probabilistic assessment of harmonic levels in a real transmission network.

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