Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Harmonic Modeling of Multi-pulse SSSC

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***Abstract*—The aim of this paper is to propose a Dynamic Harmonic Domain model for a 24-pulse Voltage Source Converter based Static Synchronous Series Compensator. The model is developed converting a state-space system to the Dynamic Harmonic Domain, having the advantage over Time Domain models of showing the evolution in time of the harmonic components that compose each of the SSSC signals. The model takes into account the harmonic components present in the VSC waveforms. The effectiveness and precision of the model are validated against simulations carried out in industry standard Matlab/Simulink®.**

***Index Terms*— harmonics, modeling, SSSC.**

I. Introduction

DYNAMIC representation of the electrical network and its elements is usually carried out using Time Domain (TD) or Frequency Domain (FD) modeling approaches. Since linear and nonlinear elements compose the power system, both linear and nonlinear models are of interest. When dealing with nonlinear elements, using a TD approach simplifies the inclusion of nonlinearities, on the other hand, modeling nonlinearities using FD techniques is not straightforward.

Power electronics based systems are among the nonlinear elements found in electric networks; these are comprised of switching devices, resulting in a nonlinear behavior that generates harmonic components in the electric utility causing distorted voltage and/or current waveforms. Some of these power electronic based apparatus are Flexible AC Transmission Systems (FACTS), which are capable of dealing with some of the issues affecting the operation of the electric network; however, due to the commutative nature of the electronic devices used to construct them, they present a nonlinear behavior.

Most of the existing converter based FACTS devices rated above 80MVAR use either 24 or 48-pulse converters [1-5], because they exhibit several advantages over other Voltage Source Converter (VSC) configurations. Some of the key advantages include reduced harmonic content, low switching frequency and small dc capacitor rating [6].

Some of the dynamic modeling approaches for multi-pulse FACTS are *dq0* models in a stationary reference frame [5], [7-12]; Fundamental Frequency (FF) models in *abc* coordinates [5], [7-9]; and Switching Functions (SF) models also in *abc* quantities [13-16]. Fundamental Frequency and *dq0* models do not take into account harmonic components. However, from an engineering point of view, the behavior of harmonic components of signals is often of interest, especially when nonlinear elements and switching devices are modeled. Furthermore, a precise calculation of harmonic components is not only needed in steady-state operation, but also in transient-state. In this respect, SF models offer an appropriate representation of the harmonic components present in the signals of the FACTS device modeled. However, the harmonic information of the signals is not obtained from the model in a straightforward manner, therefore, a postprocessing method is needed. For steady-state calculation of the harmonic components, FFT methods can be used. On the other hand, for transient periods, harmonic information has to be calculated as it evolves in time, in this regard, the use of the Windowed Fast Fourier Transform (WFFT) has been reported [17,18].

In this paper a multi-pulse VSC based Static Synchronous Series Compensator (SSSC) model in *abc* coordinates is proposed using the Dynamic Harmonic Domain (DHD) approach [17]. In contrast to other modeling techniques, DHD approach allows a direct calculation of harmonic components of signals, thus avoiding the postprocessing, particularly in transient periods when the evolution in time of harmonics is of interest.

From a practical standpoint a direct application of the DHD modeling is in Power Quality (PQ) assessment [17,18]. Some of the PQ quantities that need to be calculated for a system are, for example, active, reactive and apparent power, as well as power factor. These quantities are defined in terms of fundamental frequency parameters when linear systems with single frequency sources are analyzed. However, when a nonlinear element is inserted in a system, for instance, an electronic device, the PQ quantities are defined based in Fourier coefficients, moreover, new quantities appear, for example, Total Harmonic Distortion (THD). In order to accurately assess PQ of a system, precise calculation of harmonic components is needed, especially during transient periods. The use of the WFFT has been reported for calculation of harmonic components during transients for signals obtained using TD models. However, comparison against the DHD is discussed in [17,18], where the disadvantages of using the WFFT are exposed. Also, a comprehensive discussion on the use of the WFFT for electric power quality assessment is presented in [19], where its drawbacks are pointed out. In addition, if selected for harmonic extraction, the adjustment of the WFFT is not a minor procedure as explained in [20,21].

In the modeling of FACTS devices and power system elements using the DHD concept, other authors have made

This work was supported in part by PROMEP.
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978-1-4244-2235-7/09/$25.00 ©2009 IEEE

their contribution [17-18], [22].

As a mean to extend the results obtained by other authors in the modeling of FACTS devices, the proposed multi-pulse VSC based SSSC DHD model is developed in order to be able to obtain the evolution in time of harmonic components of the SSSC signals, when inserted in a power system. Also, power system controllers, system protections, as well as other equipment would be facing the harmonic evolution of the SSSC signals when using DHD models. Therefore, DHD modeling of more power system elements is needed.

The DHD model for the SSSC is derived based in a 24-pulse VSC multi-pulse configuration. The proposed model takes into account the appropriate VSC configuration, as well as its transformer arrangements for magnetic coupling and phase shifting; gate pulse patterns for the commutating devices are also considered in the model.

This work focuses in the multi-pulse arrangement due to it is a suitable configuration for the implementation of FACTS devices. A comparison of various converter topologies is given in [6]; the authors compare only line frequency switching configurations excluding the fast frequency switching ones, like PWM, because power dissipation during conduction and switching severely limits the switching frequency used. Switching losses is one of the causes that make line frequency switching converters preferable over fast switching configurations, for power system applications like FACTS.

The paper is organized as follows. The second section provides fundamentals to understand the multi-pulse VSC topology, which is the arrangement used in this paper. The third section presents basics about DHD modeling. The fourth section gives the SSSC modeling in DHD. And finally, section five shows a comparison between waveforms carried out using the DHD SSSC model and industry standard Matlab/Simulink®.

II. MULTI-PULSE VSC TOPOLOGY

The objective of a VSC is to generate a three phase ac voltage using a dc voltage. The basic 6-pulse VSC configuration is shown in Fig. 1. The frequency, as well as the angle, of the three phase voltage generated by a 6-pulse VSC configuration like the one depicted in Fig. 1, is determined by the gate pulse pattern of the commutating devices shown in Fig. 2. The amplitude of the three phase ac voltage is determined by the magnitude of the dc voltage, v_{dc}.

Signals gs_1, gs_2, gs_3, gs_4, gs_5 and gs_6 are gate pulses of switches S_1, S_2, S_3, S_4, S_5 and S_6 in Fig. 1, respectively. The gate signals can only take values of 0 or 1 for the switching devices to be *off* or *on*, respectively.

The *on-off* sequence depicted in Fig. 2 applied to the 6-pulse VSC shown in Fig. 1 results in phase, v_{a6}, and line, v_{ab6}, voltages for phase *a* like the ones exhibited in Fig. 3.

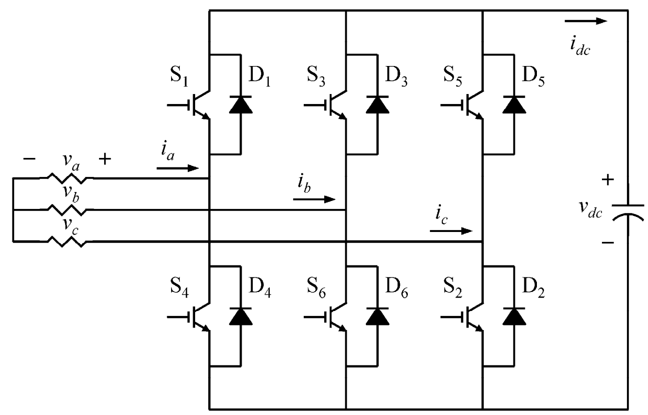

Fig. 1. Configuration of 6-pulse VSC.

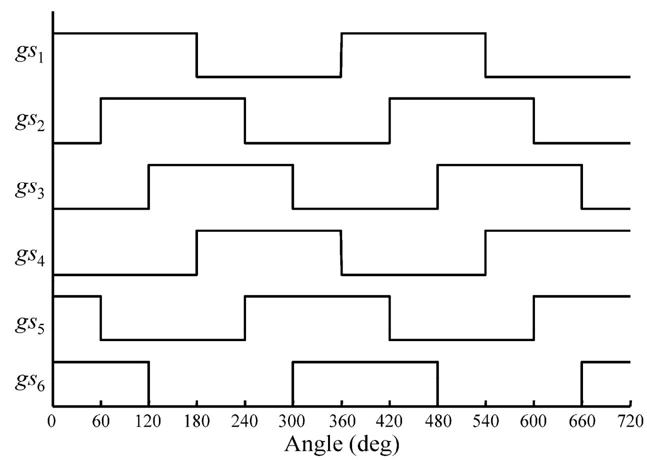

Fig. 2. Gate pulse pattern of 6-pulse VSC.

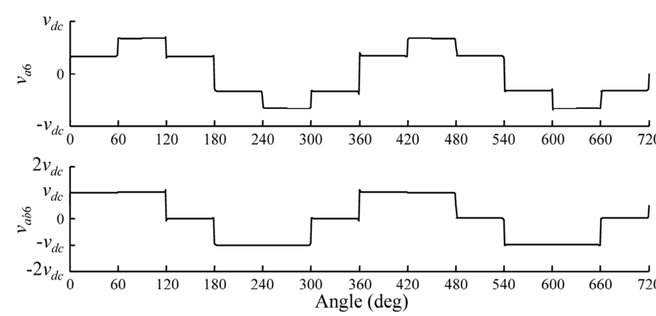

Fig. 3. Phase and line voltages of 6-pulse VSC.

Inspecting Fig. 3 it can be seen that even though these 6-pulse voltages are ac waveforms, they are not sinusoidal; this is due to a high harmonic content present in them.

In order to reduce this harmonic content of the resulting voltages, higher pulse configurations are needed, so as to cancel specific harmonic components. These multi-pulse arrangements are achieved combining several 6-pulse VSC in order to produce an output voltage with reduced harmonics. As a result, combining two 6-pulse VSC a 12-pulse configuration is attained and two 12-pulse converters achieve a 24-pulse topology. Due to the reduced harmonics of the 24-pulse VSC, this is a configuration suitable for use on the power system [1-3]. For a thorough description of a 24-pulse VSC see [23].

III. DHD Basics

The basic idea of the DHD is that a system described by a set of Ordinary Differential Equations (ODE) can be transformed to an alternative representation called the Dynamic Harmonic Domain, which is based on the approximation of the system by Fourier series over a period of the fundamental frequency.

A feature of the DHD representation is that a Linear Time Periodic (LTP) system is converted to a Linear Time Invariant (LTI) one.

For instance, consider the LTP state-space system given by,

$$\begin{aligned} \dot{x}(t) &= a(t)x(t) + b(t)u(t) \\ y(t) &= c(t)x(t) + d(t)u(t) \end{aligned} \tag{1}$$

In (1), for example, $a(t)$ is defined as,

$$a(t) = a_{-h}e^{-jh\omega_0 t} + \cdots + a_{-1}e^{-j\omega_0 t} + a_0 + a_1 e^{j\omega_0 t} + \cdots + a_h e^{jh\omega_0 t} \tag{2}$$

where h is the highest harmonic component considered and ω_0 is the fundamental frequency of the system.

Representing the elements of (1) by their Fourier series, the set of ODE can be transformed to an alternative DHD representation that yields,

$$\begin{aligned} \dot{\mathbf{X}} &= (\mathbf{A} - \mathbf{S})\mathbf{X} + \mathbf{BU} \\ \mathbf{Y} &= \mathbf{CX} + \mathbf{DU} \end{aligned} \tag{3}$$

where the variables of (1) are now vectors with coefficients related to the harmonic components of their instantaneous signals, for instance,

$$\mathbf{X} = \left[X_{-h}(t) \cdots X_{-1}(t)\ X_0(t)\ X_1(t) \cdots X_h(t)\right]^{\mathrm{T}} \tag{4}$$

Matrix $\mathbf{S}$ is the operational matrix of differentiation given by,

$$\mathbf{S} = diag\left[-jh\omega_0 \quad \cdots \quad -j\omega_0 \quad 0 \quad j\omega_0 \quad \cdots \quad jh\omega_0\right] \tag{5}$$

The coefficient matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$ have a Toeplitz structure with entries related to the harmonic order of their time domain counterparts, for example,

$$\mathbf{A} = \begin{bmatrix} A_0 & A_{-1} & \cdots & A_{-h} & & & & \\ A_1 & \ddots & \ddots & \ddots & \ddots & & & \\ \vdots & \ddots & \ddots & \ddots & \ddots & A_{-h} & & \\ A_h & \ddots & \ddots & A_0 & A_{-1} & \ddots & \ddots & \\ & \ddots & \ddots & A_1 & A_0 & \ddots & \ddots & A_{-h} \\ & & A_h & \ddots & \ddots & \ddots & \ddots & \vdots \\ & & & \ddots & \ddots & \ddots & \ddots & A_{-1} \\ & & & & A_h & \cdots & A_1 & A_0 \end{bmatrix} \tag{6}$$

Another feature of the DHD representation is that the steady-state of the system can be directly computed from (3), and becomes,

$$\begin{aligned} \mathbf{X} &= (\mathbf{S} - \mathbf{A})^{-1}\mathbf{BU} \\ \mathbf{Y} &= \mathbf{CX} + \mathbf{DU} \end{aligned} \tag{7}$$

The steady-state calculation of the system obtained from (7) can be used to initialize the DHD representation for simulation purposes; moreover, the steady-state conditions can be transformed to instantaneous variables for the initialization of the corresponding TD simulation.

IV. DHD Model of Multi-pulse SSSC

The SSSC DHD representation is obtained using a TD SF model that represents harmonic components present is the SSSC signals. The TD SF SSSC model is derived using the system of Fig. 4 [23,24]. The figure shows the SSSC equivalent circuit connected in series to a transmission line. On the ac side the SSSC is characterized by a three phase series connected sinusoidal voltage source that represent its voltage injections for phases a, b and c denoted by v_a, v_b and v_c, respectively. The impedance $R+j\omega_0 L$ combines the common influence of both, series coupling transformer and transmission line between sending and receiving end nodes denoted by subscripts s and r, respectively. The dc side of the SSSC is represented by a current source connected to a capacitor. Shunt connection of a resistance enables representation of converter losses in the circuit.

Obtaining the system equations along with their corresponding SF, and rearranging in state-space form the TD SF SSSC model yields,

$$\dot{\mathbf{X}}_{\mathrm{TD}} = \mathbf{A}_{\mathrm{TD}}\mathbf{X}_{\mathrm{TD}} + \mathbf{B}_{\mathrm{TD}}\mathbf{U}_{\mathrm{TD}} \tag{8}$$

where the subscript TD stands for time domain model, and the vectors and matrices are given by,

$$\mathbf{X}_{\mathrm{TD}} = \begin{bmatrix} i_a \\ i_b \\ i_c \\ v_{dc} \end{bmatrix}, \mathbf{U}_{\mathrm{TD}} = \begin{bmatrix} v_{sra} \\ v_{srb} \\ v_{src} \\ 0 \end{bmatrix}, \mathbf{B}_{\mathrm{TD}} = \begin{bmatrix} \frac{1}{L_a} & 0 & 0 & 0 \\ 0 & \frac{1}{L_b} & 0 & 0 \\ 0 & 0 & \frac{1}{L_c} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B}_{\mathrm{DHD}} = \begin{bmatrix} \frac{1}{L_a}\mathbf{I} & & & \\ & \frac{1}{L_b}\mathbf{I} & & \\ & & \frac{1}{L_c}\mathbf{I} & \\ & & & \mathbf{0} \end{bmatrix}$$

$$\mathbf{A}_{\mathrm{TD}} = \begin{bmatrix} -\frac{R_a}{L_a} & 0 & 0 & -\frac{a_{14}}{L_a} \\ 0 & -\frac{R_b}{L_b} & 0 & -\frac{a_{24}}{L_b} \\ 0 & 0 & -\frac{R_c}{L_c} & -\frac{a_{34}}{L_c} \\ \frac{a_{41}}{C} & \frac{a_{42}}{C} & \frac{a_{43}}{C} & -\frac{1}{CR_C} \end{bmatrix}$$

Coefficients a_{14}, a_{24}, a_{34}, a_{41}, a_{42} and a_{43} represent the SF of the SSSC model as given in [23,24].

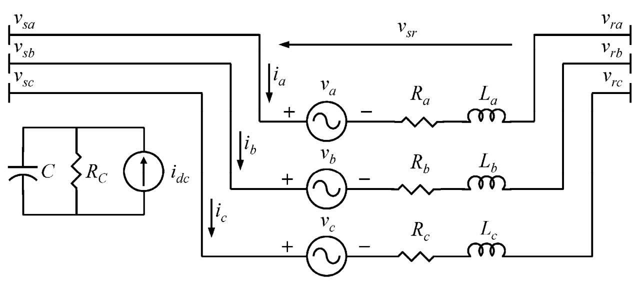

Fig. 4. SSSC equivalent circuit connected in series to a transmission line.

The TD state-space SSSC model in (8) can be transformed to a DHD representation following the procedure given in section III. The DHD model of the SSSC becomes,

$$\dot{\mathbf{X}}_{\mathrm{DHD}} = (\mathbf{A}_{\mathrm{DHD}} - \mathbf{S})\mathbf{X}_{\mathrm{DHD}} + \mathbf{B}_{\mathrm{DHD}}\mathbf{U}_{\mathrm{DHD}} \tag{9}$$

where the subscript DHD stands for dynamic harmonic domain model and the vectors and matrices are given by,

$$\mathbf{X}_{\mathrm{DHD}} = \begin{bmatrix} \mathbf{I}_a \\ \mathbf{I}_b \\ \mathbf{I}_c \\ \mathbf{V}_{dc} \end{bmatrix}, \mathbf{U}_{\mathrm{DHD}} = \begin{bmatrix} \mathbf{V}_{sra} \\ \mathbf{V}_{srb} \\ \mathbf{V}_{src} \\ \mathbf{0} \end{bmatrix}$$

$$\mathbf{A}_{\mathrm{DHD}} = \begin{bmatrix} \mathbf{A}_{11} & & & -\frac{1}{L_a}\mathbf{A}_{14} \\ & \mathbf{A}_{22} & & -\frac{1}{L_b}\mathbf{A}_{24} \\ & & \mathbf{A}_{33} & -\frac{1}{L_c}\mathbf{A}_{34} \\ \frac{1}{C}\mathbf{A}_{41} & \frac{1}{C}\mathbf{A}_{42} & \frac{1}{C}\mathbf{A}_{43} & \mathbf{A}_{44} \end{bmatrix}$$

$$\mathbf{A}_{11} = -\frac{R_a}{L_a}\mathbf{I} - \mathbf{S}, \mathbf{A}_{22} = -\frac{R_b}{L_b}\mathbf{I} - \mathbf{S}, \mathbf{A}_{33} = -\frac{R_c}{L_c}\mathbf{I} - \mathbf{S}$$

$$\mathbf{A}_{44} = -\frac{1}{CR_C}\mathbf{I} - \mathbf{S}$$

Vectors $\mathbf{I}_a$, $\mathbf{I}_b$, $\mathbf{I}_c$, $\mathbf{V}_{dc}$, $\mathbf{V}_{sra}$, $\mathbf{V}_{srb}$ and $\mathbf{V}_{src}$ are of the form (4).

Matrices $\mathbf{A}_{14}$, $\mathbf{A}_{24}$, $\mathbf{A}_{34}$, $\mathbf{A}_{41}$, $\mathbf{A}_{42}$ and $\mathbf{A}_{43}$ have a Toeplitz structure as in (6), and are populated with the harmonic content of a_{14}, a_{24}, a_{34}, a_{41}, a_{42} and a_{43}, respectively.

V. Simulation Results

In order to assess the effectiveness and precision of the 24-pulse VSC based SSSC DHD model, comparison of signals is carried out using industry standard Matlab/Simulink® and the proposed multi-pulse SSSC DHD model.

Simulations are accomplished using the schematic circuit of the SSSC shown in Fig. 4 with the following parameters: R=10Ω, L=700mH, C=2200μF and three phase peak line voltages $v_s=V_m\angle 30^{\circ}$ and $v_r=V_m\angle 0^{\circ}$, $V_m = 230\sqrt{2}/\sqrt{3}$ kV, for a utility system frequency of 60Hz, resistances and inductances of the three phases are equal to R and L, respectively. No control is included in the system; in order to maintain the dc voltage magnitude, the appropriate SSSC control angle is used. The simulations are carried out in the capacitive operating mode, which is the normal operating mode for a SSSC.

A. Steady-state simulations

As a first example, comparison is given for simulations that suppose that the transient response has already passed and that the steady-state of the system remains. The example considers a dc capacitor voltage of 25kV. Harmonic components of the signals for the DHD model are achieved in a straightforward manner whereas harmonics for the TD Matlab/Simulink® waveforms are obtained with the use of the FFT. Harmonic components of all graphs are normalized in magnitude and frequency by the 60Hz fundamental component.

Waveforms of SSSC output voltage of phase *a*, v_a,, SSSC current of phase *a*, i_a, and capacitor voltage v_{dc}, are shown in Fig. 5, 6 and 7, respectively.

SSSC instantaneous waveforms are easily calculated using the DHD model solution and show good agreement when compared with signals obtained with Matlab/Simulink®, this corroborates the performance of the SSSC DHD model. This is also confirmed in Fig. 8 and 9 where the harmonic content of v_a and v_{dc} are shown for both TD and DHD simulations. The magnitudes and order of the harmonic components are comparable between them, verifying the behavior of the instantaneous signals.

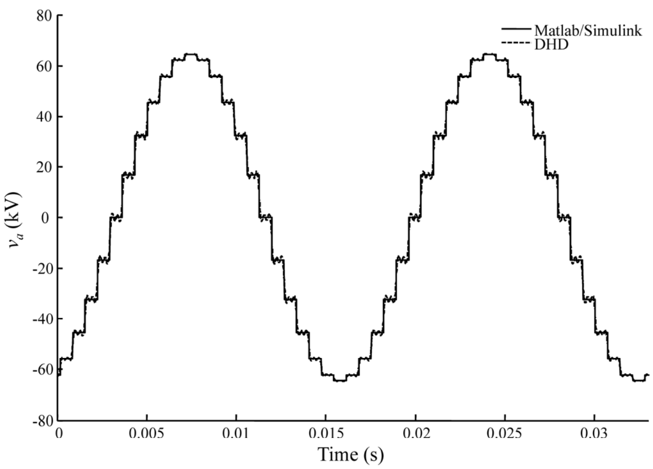

Fig. 5. Steady-state SSSC output voltage for phase *a*.

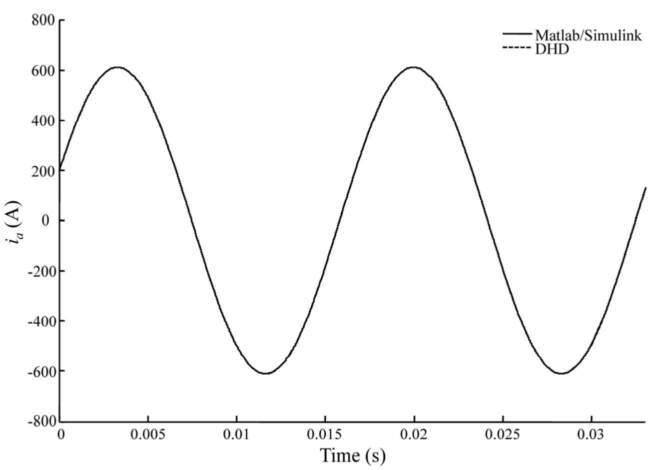

Fig. 6. Steady-state SSSC current for phase *a*.

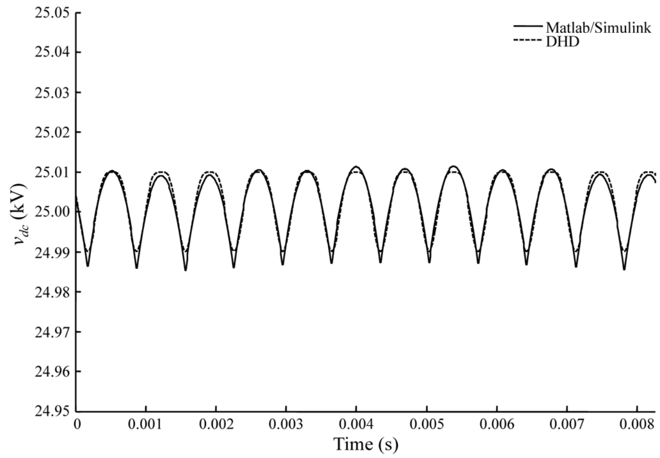

Fig. 7. Steady-state SSSC capacitor voltage.

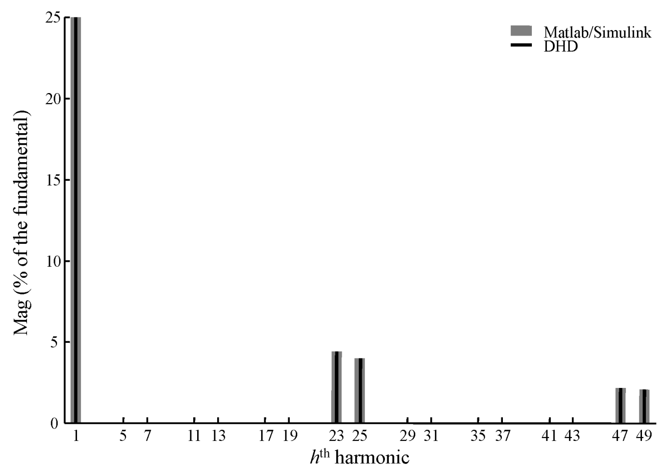

Fig. 8. Harmonic content of steady-state SSSC output voltage for phase *a*.

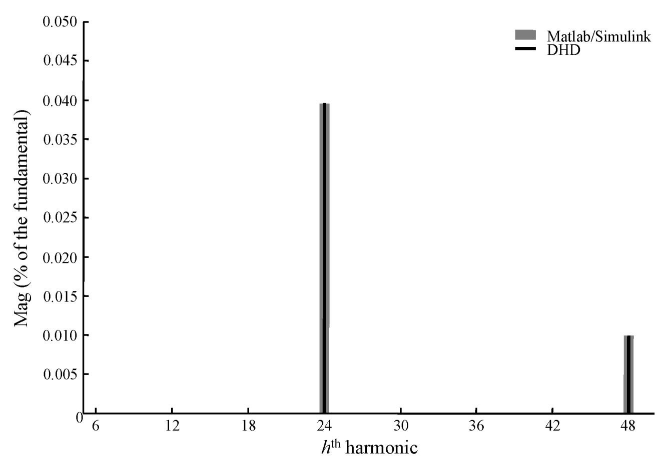

Fig. 9. Harmonic content of steady-state SSSC capacitor voltage.

Although signals carried out using Matlab/Simulink® and the DHD model are not equal, they are very similar. In both cases the harmonic components appear at the same frequencies, with almost the same magnitudes.

B. Transient-state simulations

In order to fully verify the behavior of the DHD model, comparison is given for simulations in the transient-state. This case supposes a dc capacitor voltage of 25kV as an initial condition. Harmonic components of the signals for the DHD model are obtained in a straightforward manner from the signals coefficients.

In the example it is considered that the system starts in steady-state and after a given time a step change in the SSSC control angle is applied causing the increase of the capacitor voltage. After 0.05s the control angle is modified again causing the diminishing of the dc voltage, 0.05s later a final adjustment of the control angle is given in order for the capacitor voltage to return approximately to its initial steady-state condition.

Comparison of signals between DHD model and Matlab/Simulink® is given in Fig. 10, 11 and 12, where waveforms of SSSC output voltage of phase a, v_a, SSSC current of phase a, i_a, and capacitor voltage v_{dc}, are shown, respectively.

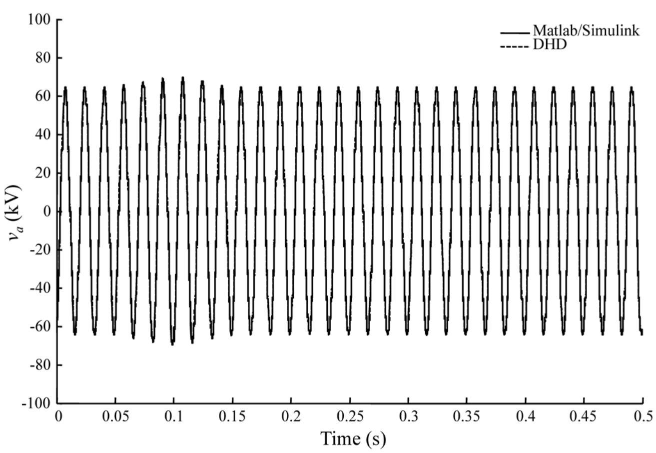

Fig. 10. Transient-state SSSC output voltage for phase a.

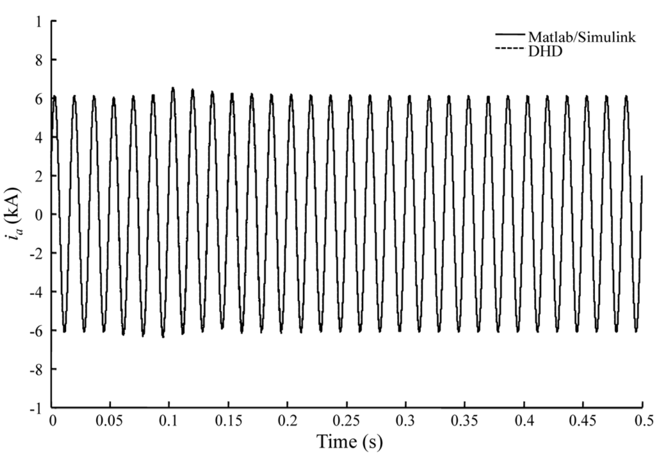

Fig. 11. Transient-state SSSC current for phase a.

SSSC instantaneous waveforms are easily calculated using the DHD model solution and show good agreement when compared with signals obtained with Matlab/Simulink®, this corroborates the appropriate performance of the SSSC DHD model.

In order to show one of the features of the DHD modeling, the evolution in time of the harmonic content of the signals v_a, i_a and v_{dc}, depicted in Fig. 10, 11 and 12 is obtained from the DHD SSSC model. The harmonic components are achieved in an easy way from the signals coefficients of the DHD SSSC model.

The harmonic content of v_a, i_a and v_{dc} is shown in Fig. 13, 14 and 15, respectively. Where h refers to harmonic number, for instance, h=0 denotes dc, h=1 stands for fundamental component and so on.

It can be seen, from the initial steady-state period, that the order and magnitude of the harmonics found in Fig. 13 and 15, match the ones shown in Fig. 8 and 9, respectively. However, as the transient period appears, the harmonic components start evolving with the transient response until they reach a new steady-state, approximately at the same value as the initial one.

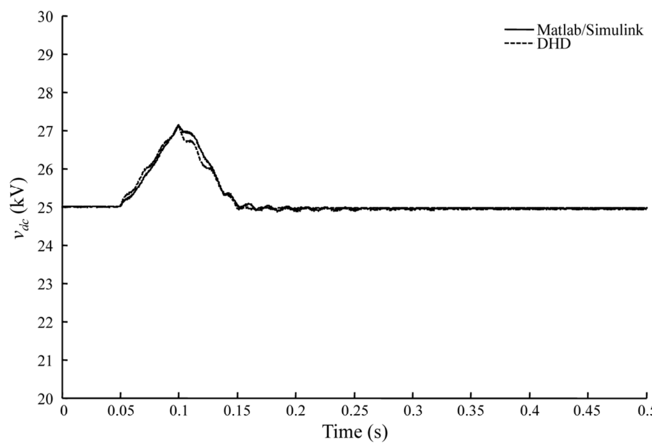

Fig. 12. Transient-state SSSC capacitor voltage.

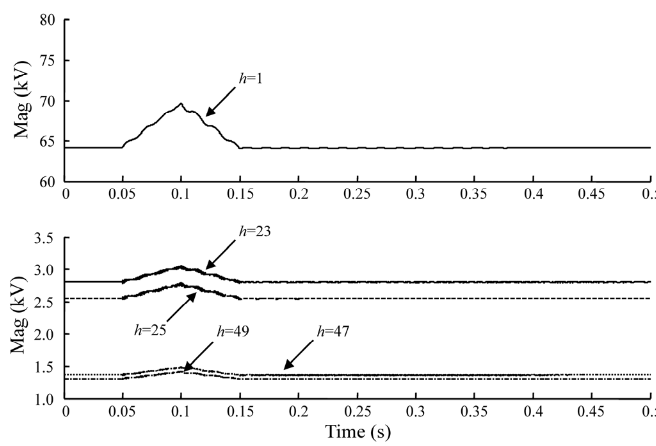

Fig. 13. Harmonic content of transient-state SSSC output voltage for phase a.

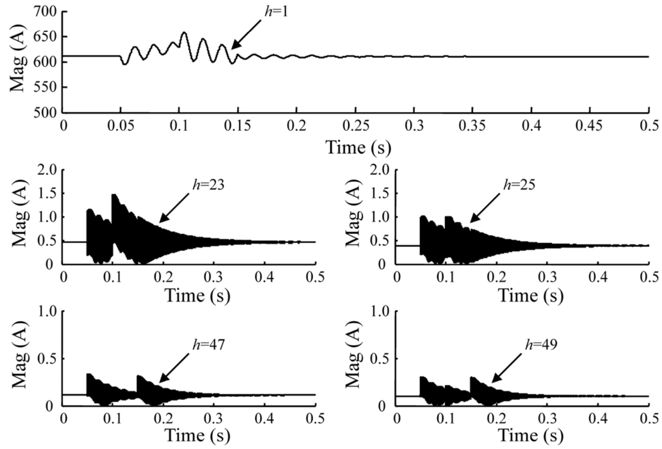

Fig. 14. Harmonic content of transient-state SSSC output current for phase *a*.

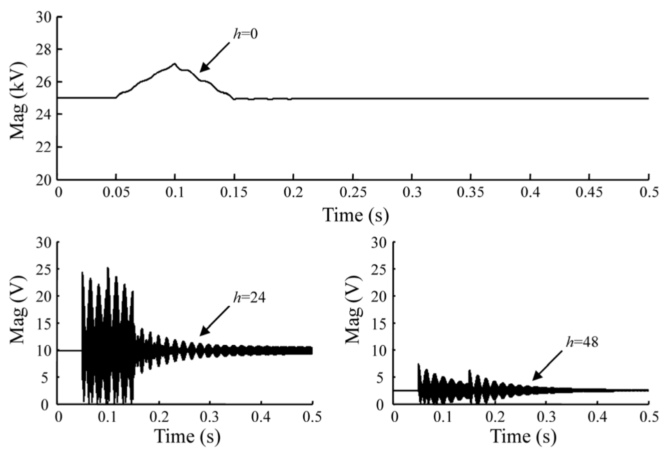

Fig. 15. Harmonic content of transient-state SSSC capacitor voltage.

As in the steady-state comparison, even though signals obtained with Matlab/Simulink® and the DHD model are not equal they are very similar. However, the disparity in the signals is small enough to assess the proper behavior of the DHD model. As a result it can be assumed that the simulations using the DHD model give adequate results and are accurate enough to be used in FACTS studies.

Once the DHD modeling has been assessed and gives adequate results, it is capable of dealing with studies where the power system has an SSSC embedded and, for example, a harmonics analysis is of great importance. Moreover, the proper calculation of the harmonic components as they evolve in time can help in various tasks, such as, tuning of controls, adjustment of protections, etc.

VI. Conclusions

The paper proposes a multi-pulse VSC based SSSC DHD model. The model is compared with simulations obtained with Matlab/Simulink® showing good results.

The DHD model is intended to better represent the behavior of a SSSC from a harmonic point of view, especially the evolution in time of the harmonic components in the SSSC signals.

It should be noted that the dimension of the DHD representation is larger than the TD state-space counterpart. This could lead to computationally demanding simulations if the number of harmonics considered in the study is high. Furthermore, since the DHD method decomposes a TD set of ODE to a DHD set of ODE based on its harmonic components, a time step should be given for the ODE solver. The determination of the time step is in direct relation to the highest harmonic component considered. Therefore, the size of the time step and the number of harmonics included determine the accuracy of the DHD representation.

In spite of the fact that DHD leads to a computationally demanding simulation, the accuracy of the information obtained, especially in transient state, is of great interest in various applications. As aforementioned, one of the uses is in PQ assessment.

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VIII. Biographies

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