

# Modelling and Simulation of HVDC Systems Considering the Harmonics of Converter Based on Dynamic Phasors Theory

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**Abstract**—This paper proposes a dynamic phasors model of HVDC systems including the converter, DC line and control when the AC systems are symmetrical and analyses the simulation process of the proposed dynamic phasors model. The proposed dynamic phasors model can rapidly reflect the dynamic characteristics of HVDC systems including the harmonics characteristics of the converter of HVDC systems at the AC system side. Simulation results among the dynamic phasors models and EMR model are compared and the simulation results confirm the validity and accuracy of the proposed dynamic phasors model.

**Keywords**- modelling; simulation; High Voltage Direct Current (HVDC) systems; dynamic phasors

## I. INTRODUCTION

With the development of the economy and technology in the world, the HVDC systems have been constructed widely as its ability at long-distance large-scale transmission [1,2]. Especially in China, HVDC systems have been widely adopted to transmit the power from the power centre to load centre and interconnect regional power grids, and the power grid of China have become the one of the most complex AC-DC interconnected power grids in the world [3,4]. As a result, the complicated interactions among AC-DC systems are needed to be researched, and the simulation models and methods of HVDC systems for various applications are hot research topics.

The electromagnetic transient model and the electromechanical transient model of HVDC systems are the two kinds of common used HVDC models. The electromagnetic transient model can reflect the fundamental and all harmonic components of the converter, but the needed computing resources of computer is large. The electromechanical transient model can reflect the fundamental component only and need less computing resources of computer. Moreover, the simulation models of HVDC systems based on dynamic phasors theory have been researched by the researchers [5-7]. The dynamic phasors theory can build the algebraic model of the converter based on a time-varying Fourier series of the time-signals and this algebraic model can include the fundamental component and the necessary harmonic components according to the accurate requirement of the modelling and simulation [7]. So the simulation model based on dynamic phasors theory is simpler than electromagnetic transient model and can reflect more dynamic

processes than the electromechanical transient model. The balance between the simulation accuracy and the needed computing resources can be achieved by this dynamic phasors model.

The simulation models of HVDC systems considering the fundamental component of the converter only under the symmetrical condition of AC systems are presented based on dynamic phasors theory in [5,6]. The simulation models of the HVDC converter considering the fundamental component and necessary harmonic components of converter under the asymmetrical conditions of AC system are presented based on dynamic phasors theory in [7]. What's more, the dynamic phasors theory has been used in modelling and analysis of solid state transformer [8,9], thyristor-controlled series capacitor [10,11], unified power flow controller [12,13], dc-dc converters [14], multiconverter ac systems [15] and other power electronic devices or power systems with power electronic devices successfully. However, the dynamic phasors simulation model of HVDC systems considering the fundamental component and harmonic components of the converter under the symmetrical condition of AC system theory hasn't been researched and the harmonic components of the converter of HVDC systems should be considered to reflect the dynamic characteristics of HVDC systems more accurately.

In this paper, we focus on the modelling and simulation of the monopole 12-pulse HVDC systems including the converter, DC line and controller which consider the fundamental and harmonics components of the converter under the symmetrical condition of the AC system based on dynamic phasors theory to build a more thorough and accurate dynamic phasors model of HVDC systems. The following sections are organized as follows: section 2 describes the basic principles of dynamic phasors theory. Section 3 proposes the model of the monopole 12-pulse HVDC systems considering the harmonic components of the converter based on dynamic phasors theory and analyses the simulation process of the proposed dynamic phasors model. Section 4 shows the simulation results and section 5 draws the conclusions of this paper.

## II. BASIC PRINCIPLES OF DYNAMIC PHASORS THEORY

The mathematical foundation of dynamic phasors theory comes from the time-varying Fourier series [16]. For any

function,  $x(\tau)$ , in the time domain, the time-varying Fourier series of  $x(\tau)$  in the interval which is  $(t-T, t]$  is

$$x(\tau) = \sum_{k=-\infty}^{\infty} X_k(t) e^{jk\omega\tau} \quad (1)$$

$$X_k(t) = \frac{1}{T} \int_{t-T}^t x(\tau) e^{-jk\omega\tau} d\tau \quad (2)$$

where  $\omega=2\pi/T$ ;  $X_k(t)$  is the  $k$ th Fourier coefficient of  $x(\tau)$ , and is called the  $k$ th dynamic phasors. In this paper,  $\langle x \rangle_k$  is used to represent  $X_k(t)$ .

According to the definition of the  $k$ th dynamic phasors, dynamic phasors have the following properties:

1) Conjugate property:

$$\langle x \rangle_{-k} = \langle x \rangle_k^* \quad (3)$$

where \* denotes the complex conjugate operator.

2) Differential property:

$$\frac{d\langle x \rangle_k}{dt} = \left\langle \frac{dx}{dt} \right\rangle_k - jk\omega \langle x \rangle_k \quad (4)$$

3) Convolution property:

$$\langle x_1 x_2 \rangle_k = \sum_{i=-\infty}^{\infty} \langle x_1 \rangle_{k-i} \langle x_2 \rangle_i \quad (5)$$

4) The transformation from time domain value to dynamic phasors value:

$$\begin{aligned} \langle X \rangle_k(t) &= \frac{1}{T} \int_{t-T}^t x(\tau) e^{-jk\omega\tau} d\tau \\ &= \frac{1}{N} \sum_{n=1}^N x(t-T+n\Delta t) e^{-jk\omega(t-T+n\Delta t)} \end{aligned} \quad (6)$$

5) The transformation from dynamic phasors value to time domain value:

$$x(t) = \langle X \rangle_0(t) + 2Re \sum_{k=1}^{\infty} \langle X \rangle_k(t) e^{jk\omega t} \quad (7)$$

### III. MODELLING AND SIMULATION OF HVDC SYSTEMS

#### A. Switch Functions of the 6-Phase Converter

The 6-phase converter is the fundamental unit of the 12-phase HVDC systems and the switch functions of the 6-phase converter showing the switch status of the converter is the foundation to analyse the dynamic phasors model of the converter of the HVDC systems. Assume that the three-phase voltage at the rectifier side as shown in equation (8):

$$\begin{bmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{bmatrix} = \begin{bmatrix} V_{ra} \cos(\omega t + \varphi_{rva}) \\ V_{rb} \cos(\omega t + \varphi_{rva} - \frac{2\pi}{3}) \\ V_{rc} \cos(\omega t + \varphi_{rva} + \frac{2\pi}{3}) \end{bmatrix} \quad (8)$$

where  $V_{ra}$ ,  $V_{rb}$ ,  $V_{rc}$  are the amplitude of the three-phase voltage, and  $\varphi_{rva}$  is the initial phase angle of A-phase voltage.

The corresponding three-phase voltage switch functions,  $S_{rva}$ ,  $S_{rvb}$ ,  $S_{rvc}$ , and the three-phase current switch functions,  $S_{ria}$ ,  $S_{rib}$ ,  $S_{ric}$ , of the rectifier as shown in equation (9) and (10) respectively:

$$\begin{cases} S_{rva} = \sum_{n=1}^{\infty} A_n \cos\left(\frac{n\mu_r}{2}\right) \cos n(\omega t - \alpha_r - \frac{\mu_r}{2} + \varphi_{rva}) \\ S_{rvb} = \sum_{n=1}^{\infty} A_n \cos\left(\frac{n\mu_r}{2}\right) \cos n(\omega t - \alpha_r - \frac{\mu_r}{2} + \varphi_{rva} - \frac{2\pi}{3}) \\ S_{rvc} = \sum_{n=1}^{\infty} A_n \cos\left(\frac{n\mu_r}{2}\right) \cos n(\omega t - \alpha_r - \frac{\mu_r}{2} + \varphi_{rva} + \frac{2\pi}{3}) \end{cases} \quad (9)$$

$$\begin{cases} S_{ria} = \sum_{n=1}^{\infty} A_n \frac{\sin(n\mu_r/2)}{n\mu_r/2} \cos n(\omega t - \alpha_r - \frac{\mu_r}{2} + \varphi_{rva}) \\ S_{rib} = \sum_{n=1}^{\infty} A_n \frac{\sin(n\mu_r/2)}{n\mu_r/2} \cos n(\omega t - \alpha_r - \frac{\mu_r}{2} + \varphi_{rva} - \frac{2\pi}{3}) \\ S_{ria} = \sum_{n=1}^{\infty} A_n \frac{\sin(n\mu_r/2)}{n\mu_r/2} \cos n(\omega t - \alpha_r - \frac{\mu_r}{2} + \varphi_{rva} + \frac{2\pi}{3}) \end{cases} \quad (10)$$

where  $\alpha_r$  and  $\mu_r$  are the firing angle and the commutation angle of the rectifier respectively.

The commutation angle  $\mu_r$  can be calculated as shown in equation (11) [7]:

$$\mu_r = \cos^{-1} \left( \cos \alpha_r - \frac{\sqrt{2} X_r i_{dr}}{E_r} \right) - \alpha_r \quad (11)$$

where  $X_r$  and  $E_r$  are the leakage reactance of the converter transformer and the no load effective value of the line voltage at the converter side respectively.

The corresponding  $k$ th Fourier coefficient of the voltage switch functions and the current switch functions of the rectifier based on dynamic phasors theory as shown in equation (12) and (13) respectively:

$$\begin{aligned}\langle S_{rva} \rangle_k &= \frac{A_k}{2} \cos\left(\frac{k\mu_r}{2}\right) e^{jk(\varphi_{rva} - \alpha_r - \frac{\mu_r}{2})} \\ \langle S_{rvb} \rangle_k &= \frac{A_k}{2} \cos\left(\frac{k\mu_r}{2}\right) e^{jk(\varphi_{rvb} - \alpha_r - \frac{\mu_r}{2} + \frac{2\pi}{3})} \\ \langle S_{rva} \rangle_k &= \frac{A_k}{2} \cos\left(\frac{k\mu_r}{2}\right) e^{jn(\varphi_{rva} - \alpha_r - \frac{\mu_r}{2} + \frac{2\pi}{3})}\end{aligned}\quad (12)$$

$$\begin{aligned}\langle S_{ria} \rangle_k &= \frac{A_k}{k\mu_r} \sin\frac{k\mu_r}{2} e^{jk(\varphi_{ria} - \alpha_r - \frac{\mu_r}{2})} \\ \langle S_{rib} \rangle_k &= \frac{A_k}{k\mu_r} \sin\frac{k\mu_r}{2} e^{jk(\varphi_{rib} - \alpha_r - \frac{\mu_r}{2} + \frac{2\pi}{3})} \\ \langle S_{ria} \rangle_k &= \frac{A_k}{k\mu_r} \sin\frac{k\mu_r}{2} e^{jk(\varphi_{ria} - \alpha_r - \frac{\mu_r}{2} + \frac{2\pi}{3})}\end{aligned}\quad (13)$$

where  $k$  is non-zero integer,  $A_k = (4/\pi k) \sin(\pi k/2) \cos(\pi k/6)$ .

### B. Dynamic Phasors Model of the Cconverter

The converter can be regarded as a modulator based on the modulation theory [15] and the relations between inputs and outputs of the 6-pulse converter linked by Y-Y transformer as shown in equation (14) and (15) respectively:

$$v_{dr,6p} = K_r (v_{ra} S_{rva} + v_{rb} S_{rvb} + v_{rc} S_{rvc}) \quad (14)$$

$$\begin{cases} i_{ra,YY} = K_r i_{dr} S_{ria} \\ i_{rb,YY} = K_r i_{dr} S_{rib} \\ i_{rc,YY} = K_r i_{dr} S_{rib} \end{cases} \quad (15)$$

where  $K_r$  is the transformation ratio of the converter transformer from the converter side to the grid side and positive direction of the AC current is from the converter bus to the rectifier.

The DC components are considered at the DC side of the converter, so the DC voltage and current consider the zero-order dynamic phasors. The zero-order dynamic phasor model of the DC voltage of the 6-pulse rectifier linked by Y-Y transformer as shown in equation (16):

$$\begin{aligned}\langle v_{dr,6p} \rangle_0 &= K_r (\langle v_{ra} S_{rva} \rangle_0 + \langle v_{rb} S_{rvb} \rangle_0 + \langle v_{rc} S_{rvc} \rangle_0) \\ &= K_r (\langle v_{ra} \rangle_1 \langle S_{rva} \rangle_{-1} + \langle v_{ra} \rangle_{-1} \langle S_{rva} \rangle_1 + \langle v_{rb} \rangle_1 \langle S_{rvb} \rangle_{-1} \\ &+ \langle v_{rb} \rangle_{-1} \langle S_{rvb} \rangle_1 + \langle v_{rc} \rangle_1 \langle S_{rvc} \rangle_{-1} + \langle v_{rc} \rangle_{-1} \langle S_{rvc} \rangle_1) \\ &= 3K_r \left| \langle v_{ra} \rangle_1 \right| A_1 \cos\frac{\mu_r}{2} \cos(\alpha_r + \frac{\mu_r}{2})\end{aligned}\quad (16)$$

where  $\left| \langle v_{ra} \rangle_1 \right|$  is the amplitude of the first order dynamic phasors of the A-phase voltage at the rectifier side.

The monopole 12-pulse rectifier is the series connection of two 6-pulse rectifiers with equal average voltages. So the zero-

order dynamic phasors model of the DC voltage at the 12-pulse rectifier side as shown in equation (17):

$$\langle v_{dr,12p} \rangle_0 = 2 \langle v_{dr,6p} \rangle_0 \quad (17)$$

According to analysis of the harmonic currents of the rectifier at the grid side, the AC currents of the 6-pulse rectifier linked by Y-Y transformer at the grid side and the 6-pulse rectifier linked by Y-Δ transformer include the fundamental component, the 5th, 7th, 11th and 13th harmonic components. The amplitudes and phase angles of the fundamental component and the 11th, 13th harmonic components of these AC currents are the same, and the 5th, 7th harmonic component cancel out each other. So the dynamic phasors model of the AC currents of the 12-pulse rectifier at the grid side includes the ±1th, ±11th and ±13th-order dynamic phasors, and the -1th, -11th and -13th-order dynamic phasors can be obtained by the 1th, 11th and 13th-order dynamic phasors based on the conjugate property of the dynamic phasors. What's more, the 1th, 11th and 13th-order dynamic phasors can be obtained by the 1th, 11th and 13th-order dynamic phasors of the AC current at the grid side of the 6-pulse rectifier linked by Y-Y transformer.

According to the modulation theory, the 1th, 11th and 13th-order dynamic phasors of the A-phase current of the 6-pulse rectifier at the grid side as shown in equation (18):

$$\begin{aligned}\langle i_{ra,YY} \rangle_1 &= K_r \langle i_{dr} S_{ira} \rangle_1 = K_r \langle i_{dr} \rangle_0 \langle S_{ira} \rangle_1 \\ \langle i_{ra,YY} \rangle_{11} &= K_r \langle i_{dr} S_{ira} \rangle_{11} = K_r \langle i_{dr} \rangle_0 \langle S_{ira} \rangle_{11} \\ \langle i_{ra,YY} \rangle_{13} &= K_r \langle i_{dr} S_{ira} \rangle_{13} = K_r \langle i_{dr} \rangle_0 \langle S_{ira} \rangle_{13}\end{aligned}\quad (18)$$

where  $\langle i_{dr} \rangle_0$  is the zero-order dynamic phasor of the DC current at the rectifier side.

So the 1th, 11th and 13th-order dynamic phasors of the A-phase current of the 12-pulse rectifier at the grid side as shown in equation (19):

$$\begin{aligned}\langle i_{ra} \rangle_1 &= 2 \langle i_{ra,YY} \rangle_1 \\ \langle i_{ra} \rangle_{11} &= 2 \langle i_{ra,YY} \rangle_{11} \\ \langle i_{ra} \rangle_{13} &= 2 \langle i_{ra,YY} \rangle_{13}\end{aligned}\quad (19)$$

The dynamic phasors models of the B-phase and C-phase current of the 12-pulse rectifier at the grid side are similar with the dynamic phasors model of the A-phase current, and the dynamic phasors model of the inverter is also similar with the dynamic phasors model of the rectifier.

### C. Dynamic Phasors Model of the DC Line

The time domain model of the DC line of the monopole 12-pulse HVDC systems as shown in equation (20):

$$\begin{aligned}
 L_d \frac{di_{dr}}{dt} &= v_{dr,12p} - v_{dc,12p} - \frac{R_d}{2} i_{dr} \\
 L_d \frac{di_{di}}{dt} &= v_{dc,12p} - v_{di,12p} - \frac{R_d}{2} i_{di} \\
 C_{dc} \frac{dv_{dc,12p}}{dt} &= i_{dc}
 \end{aligned} \quad (20)$$

where  $v_{di,12p}$  and  $v_{di,12p}$  are the DC voltages at the rectifier side and the inverter side respectively,  $v_{dc,12p}$  is the DC voltage of the capacitor located in the middle of the DC line,  $i_{dr}$  and  $i_{di}$  are the DC currents at the rectifier side and the inverter side respectively,  $i_{dc}$  is the DC current of the capacitor.

The corresponding dynamic phasors model of the DC line as shown in equation (21):

$$\begin{cases}
 L_d \frac{d\langle i_{dr} \rangle_0}{dt} = \langle v_{dr,12p} \rangle_0 - \langle v_{dc,12p} \rangle_0 - \frac{R_d}{2} \langle i_{dr} \rangle_0 \\
 L_d \frac{d\langle i_{di} \rangle_0}{dt} = \langle v_{dc,12p} \rangle_0 - \langle v_{di,12p} \rangle_0 - \frac{R_d}{2} \langle i_{di} \rangle_0 \\
 C_{dc} \frac{d\langle v_{dc,12p} \rangle_0}{dt} = \langle i_{dc} \rangle_0
 \end{cases} \quad (21)$$

#### D. Dynamic Phasors Model of the Controller

The controllers at the rectifier side and at the inverter side use the constant current controller and constant voltage controller respectively, and both sides install the voltage dependent current controller. The constant current controller at the rectifier side and constant voltage controller at the inverter side provide the firing angle for the rectifier and inverter respectively.

According to dynamic equations of the constant current controller, the dynamic phasors model of the constant current controller as shown in equation (22) to (24):

$$\frac{d\langle x_{ri} \rangle_0}{dt} = -\frac{1}{T_{ri}} \langle i_{dr} \rangle_0 + \frac{1}{T_{ri}} i_{drref} \quad (22)$$

$$\beta_{ri} = -K_{ri} \langle i_{dr} \rangle_0 + K_{ri} i_{drref} + \langle x_{ri} \rangle_0 \quad (23)$$

$$\alpha_r = \pi - \beta_{ri} \quad (24)$$

where  $K_{ri}$  and  $T_{ri}$  are the proportionality constant and integral constant of the constant current controller respectively,  $i_{drref}$  is the reference value of the DC current of the constant current controller,  $\beta_{ri}$  and  $\alpha_{ri}$  are the advanced firing angle and firing angle of the constant current controller respectively.

The dynamic phasors model of the constant voltage controller is similar with the dynamic phasors model of the constant current control. The cooperation among the controllers refers to [17]. Combining the dynamic phasors model of the rectifier, the dynamic phasors model of the

inverter, the dynamic phasors model of the DC line with the dynamic phasors model of the controller, the dynamic phasors model of HVDC systems considering the harmonics of the converter can be obtained.

#### E. Simulation Process of the Proposed Dynamic Phasors Model of HVDC Systems

The input values and the output values of the proposed model are the time domain values of the A-phase voltage and the time domain values of the DC voltages, DC currents, AC currents at the grid side respectively, and the dynamic phasors are used during the simulation process of the model. The interconversion between the time domain value and dynamic phasor are needed. The conversion from time domain value to dynamic phasors can be achieved based on equation (6), and the conversion from dynamic phasors values to time domain values of the DC voltage, DC current and AC current at the grid side can be achieved as shown in equation (25) to (27).

$$v_d(t) = \langle v_d \rangle_0(t) \quad (25)$$

$$i_d(t) = \langle i_d \rangle_0(t) \quad (26)$$

$$\begin{aligned}
 \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} &= \begin{bmatrix} \langle i_a \rangle_1(t) \\ \langle i_b \rangle_1(t) \\ \langle i_c \rangle_1(t) \end{bmatrix} e^{j\omega t} + \begin{bmatrix} \langle i_a \rangle_{-1}(t) \\ \langle i_b \rangle_{-1}(t) \\ \langle i_c \rangle_{-1}(t) \end{bmatrix} e^{-j\omega t} + \begin{bmatrix} \langle i_a \rangle_{11}(t) \\ \langle i_b \rangle_{11}(t) \\ \langle i_c \rangle_{11}(t) \end{bmatrix} e^{j11\omega t} \\
 &+ \begin{bmatrix} \langle i_a \rangle_{-11}(t) \\ \langle i_b \rangle_{-11}(t) \\ \langle i_c \rangle_{-11}(t) \end{bmatrix} e^{-j11\omega t} + \begin{bmatrix} \langle i_a \rangle_{13}(t) \\ \langle i_b \rangle_{13}(t) \\ \langle i_c \rangle_{13}(t) \end{bmatrix} e^{j13\omega t} + \begin{bmatrix} \langle i_a \rangle_{-13}(t) \\ \langle i_b \rangle_{-13}(t) \\ \langle i_c \rangle_{-13}(t) \end{bmatrix} e^{-j13\omega t} \\
 &= 2Re \left\{ \begin{bmatrix} \langle i_a \rangle_1(t) \\ \langle i_b \rangle_1(t) \\ \langle i_c \rangle_1(t) \end{bmatrix} e^{j\omega t} + \begin{bmatrix} \langle i_a \rangle_{11}(t) \\ \langle i_b \rangle_{11}(t) \\ \langle i_c \rangle_{11}(t) \end{bmatrix} e^{j11\omega t} + \begin{bmatrix} \langle i_a \rangle_{13}(t) \\ \langle i_b \rangle_{13}(t) \\ \langle i_c \rangle_{13}(t) \end{bmatrix} e^{j13\omega t} \right\}
 \end{aligned} \quad (27)$$

The simulation method of the proposed model is to use implicit trapezoidal integration method to difference the dynamic phasors models of DC line and controller, then combine the differencing dynamic phasors models of DC lines and controller with the dynamic phasors models of the converters to simulate. The simulation flow chart of the proposed model is shown in Fig. 1, the dynamic phasors model of the controller delays the dynamic phasors models of the converters and the DC line one simulation step.

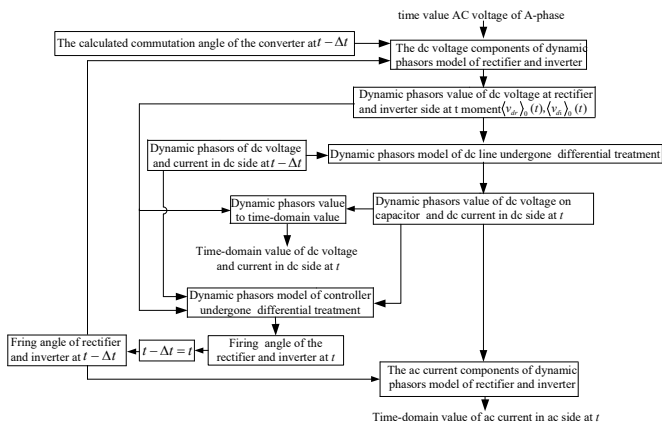


FIGURE I. SIMULATION FLOW CHART OF PROPOSED MODEL

#### IV. SIMULATION ANALYSIS

##### A. Simulation Test System

The simulation test system is the monopole 12-pulse HVDC systems shown in Fig. 2. The parameters of the test system are shown as following: the frequency of the AC systems is 50 Hz, the effective values of the line voltages of the AC system source at the rectifier and the inverter side are 382.87kV and 215.05kV respectively, the ratios of the converter transformers at rectifier and inverter side,  $1/K_r$  and  $1/K_i$ , are 345/213.46 and 230/209.23 respectively, the capacities of the converter transformers at the rectifier and the inverter side are 603.73MW and 591.79MVA respectively, the per-unit value of the leakage reactance of the converter transformer are 0.18p.u.. The rated voltage and current of the HVDC systems are 500kV and 2kA respectively, the resistance of the DC line is  $5\Omega$ , the smoothing reactances of the DC lines at the rectifier and the inverter side are 0.5968H respectively, the capacitor in the middle of DC line is 50uF. The reactive power compensation devices and 11th and 13th harmonic filters are installed at rectifier and inverter side. The constant current controller and the constant voltage controller are used at the rectifier and inverter side respectively, and voltage dependent current controllers are installed at both sides.

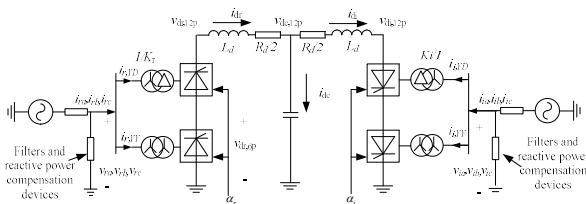


FIGURE II. THE MONOPOLE 12-PLUSE HVDC SYSTEMS

The simulations of the proposed model and the dynamic phasors model proposed in [6] of the test system are achieved by programming in MATLAB, and corresponding EMT simulation is achieved in PSCAD/EMTDC. The simulation steps of the dynamic phasors model and EMT model are 100  $\mu$ s and 50  $\mu$ s respectively.

##### B. Simulation Results

The dynamic processes among the built models under the following disturbances of AC and DC systems are analysed.

Case 1: Disturbance of DC system - the DC current order changes from 1 to 0.6 p.u. at 2s.

Case 2: Disturbance of AC system – the magnitude of the AC voltage at the rectifier side are reduced by 5% at 2 s, these changes may occur due to remote faults [6].

The A-phase current from the commutation bus to the DC system at the rectifier side, the commutation bus AC voltage of A-phase at the rectifier side and DC current at the rectifier side are shown in Fig.3 to 5, where  $i_{raEMT}$ ,  $v_{raEMT}$ ,  $i_{drEMT}$  are the AC current, AC voltage and DC current simulation results got by the EMT model,  $i_{raDP}$ ,  $v_{raDP}$ ,  $i_{drDP}$  and  $i_{raP}$ ,  $v_{raP}$ ,  $i_{drP}$  are the AC current, AC voltage and DC current simulation results got by the dynamic phasors model proposed in this paper and the dynamic phasors model proposed in [6] respectively.

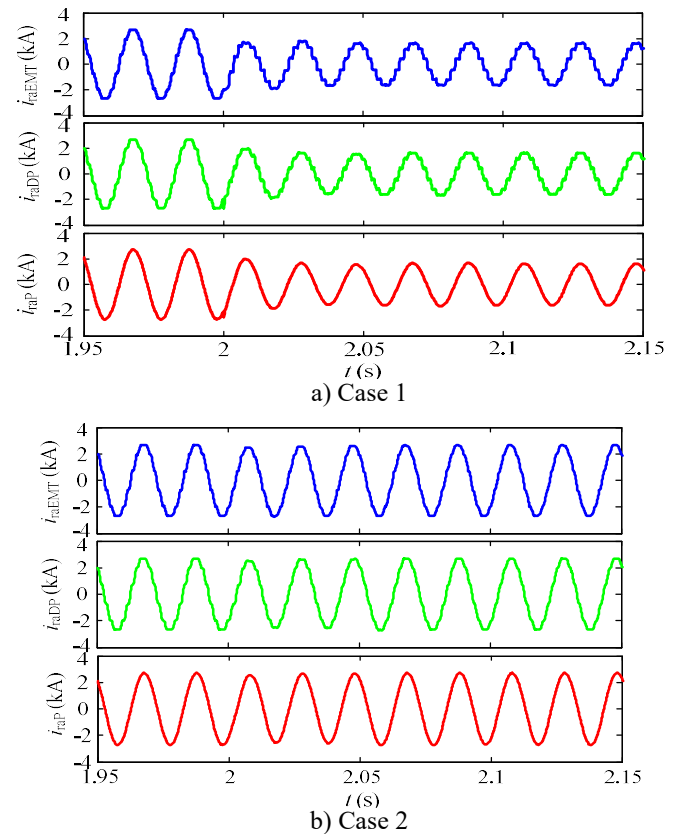


FIGURE III. AC CURRENT SIMULATION RESULTS

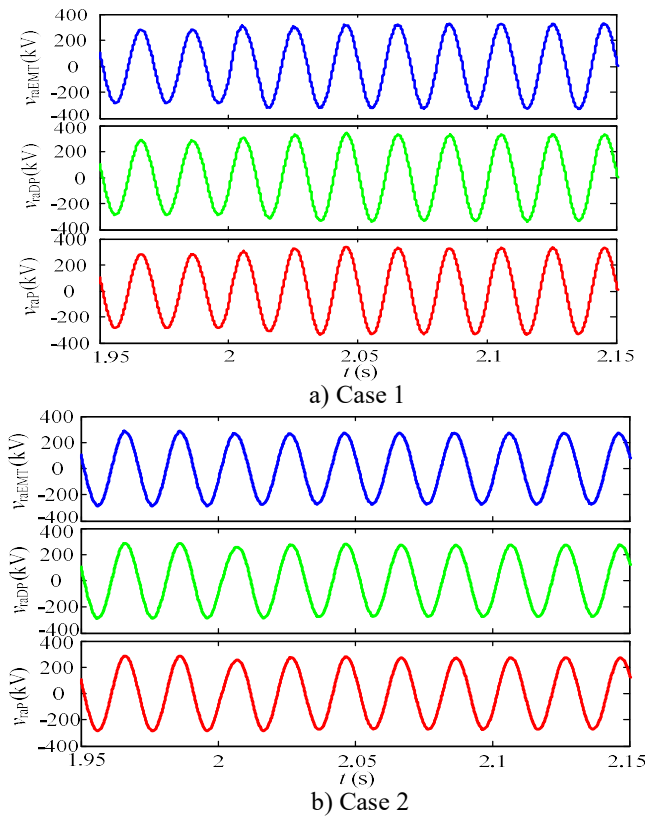


FIGURE IV. COMMUTATION BUS AC VOLTAGE SIMULATION RESULTS

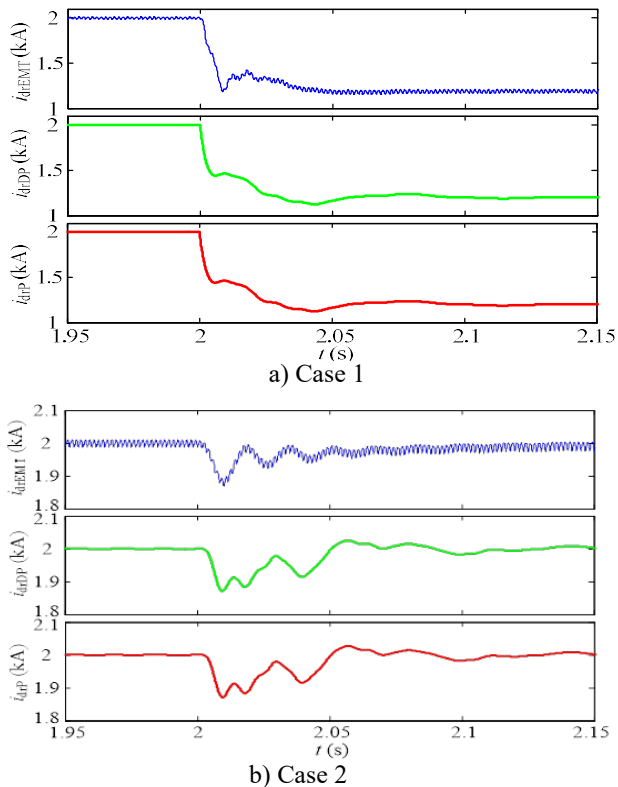


FIGURE V. DC CURRENT SIMULATION RESULTS

The simulation results shown in Fig. 3 to 5 show that the proposed dynamic phasors model can reflect the dynamic process of HVDC systems including the harmonic characteristics of the converter at the AC system better than the dynamic phasors model proposed in [6]. What's more, the dynamic phasors model and EMT model aren't achieved in the same platform, but the dynamic phasors model as algebraic model is simpler than the EMT model, the simulation step used in dynamic phasors model is larger than the simulation step used in EMT model, and the detailed analysis that the dynamic phasors model can reduce the simulation time effectively is analysed in [7], so the dynamic phasors model can improve the simulation speed and reduce the simulation time.

## V. CONCLUSION

In this paper, the dynamic phasors model of the monopole 12-pulse HVDC systems including the converter, DC line and controller which considers the fundamental and harmonics components of the converter under the symmetrical condition of AC systems is built based on the dynamic phasors theory and the simulation process of the proposed model is analysed. The simulation of the proposed dynamic phasors model is achieved by programming in MATLAB, and the comparative analyses among the simulation results of the proposed dynamic phasors model, the dynamic phasors model proposed in [6] and EMT model are made.

The comparative analyses among the simulation results show that the proposed dynamic phasors model can reflect the dynamic characteristics of HVDC systems including the harmonic characteristics of the converter at the AC system under the disturbances of AC and DC systems when the dynamic phasor model of converter which is an algebraic model and the large simulation step are used. This paper advances the application of dynamic phasors theory in the modelling and simulation of HVDC systems.

## VI. ACKNOWLEDGEMENTS

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