A TIME-DOMAIN MODEL FOR THE TWELVE-PULSE AC/DC CONVERTER

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Abstract – **This paper describes a steady-state analysis of the twelve-pulse AC/DC converter, applying the fictitious voltage source technique recently proposed. This technique consists in the strategic connection of known voltage sources so that the circuit is separated into the a linear part and a nonlinear part. Its main objective is to correct these voltage sources for which the mismatch current flowing into them are zero. The responses of the HVDC Cigre Benchmark converter have been presented and compared with the corresponding MicroTran® EMTP program.**

I. INTRODUCTION

It is becoming common to find the 3-phase AC/DC converter embedded in electric power systems. The converter usually consists of a six or twelve-pulse controlled rectifier with a controller to supply the gating pulses for the individual valves of the bridge. The converter is fed by a 3-phase AC system and it supplies power to a DC system on its load side. Connected in this manner, the converter interacts with the AC and DC systems, defined by transfers of voltage and current to both the systems.

The presence of a ripple in the DC current leads, via the control system, to switching instants of the bridge valves which are not equally spaced over one cycle and this results in large injections of harmonic currents into the AC power system. Unbalance at the fundamental frequency and/or harmonic distortion in the 3-phase AC system voltage, also lead to the generation of abnormal harmonics by the converter.

Correct modelling of the converter is therefore, essential for determining the penetration of harmonics into the AC power system.

The steady-state response of the AC/DC converter has been determined usually in the harmonic domain [1][2], though it is difficult to model the nonlinear valve behaviour. Time-domain simulation to the steady-state is computationally intensive and methods have been recently reported to accelerate the convergence to the steady-state solution [3].

In this paper, we apply a time-domain technique [4][5][6] for obtaining the steady-state response of the AC/DC converter. The technique can include the control-system representation and the v-i characteristic of the valves elements. Unbalance and harmonic distortion in the AC system voltages, if present, may also be included. The response of HVDC Cigre Benchmark, a twelve-pulse AC/DC converter, has been determined and the response waveforms are presented. The response waveforms have also been obtained with the MicroTran® EMTP program [9] and they agree well with those obtained with the new technique.

II. SOLUTION TECHNIQUE

A. Simulation of the transient response

Consider the nonlinear circuit in Fig. 1a. In the existing EMTP solution methodology, the inductor and capacitor are first substituted by their Norton equivalents consisting of resistances and fictitious current sources in parallel (Fig. 1b). The linear part of the circuit is then reduced to its Thevenin equivalent comprising a voltage source e_0 in series with the resistance R_{TH}. The voltage v_D across the nonlinear element is the solution of the equations :

$$F = v_D + R_{TH} \cdot i_D - e_0 = 0 \tag{1}$$

$$i_D = f(v_D) \tag{2}$$

The solution is approached iteratively by following the Newton-Raphson procedure :

$$\Delta v_D^k = -F \Big/ \left(\frac{\partial F}{\partial v_D} \right)^k \tag{3}$$

$$v_D^{k+1} = v_D^k + \Delta v_D^k \tag{4}$$

where k is the iteration number, and Δv_D^k is the correction to be added to the approximate solution v_D^k.

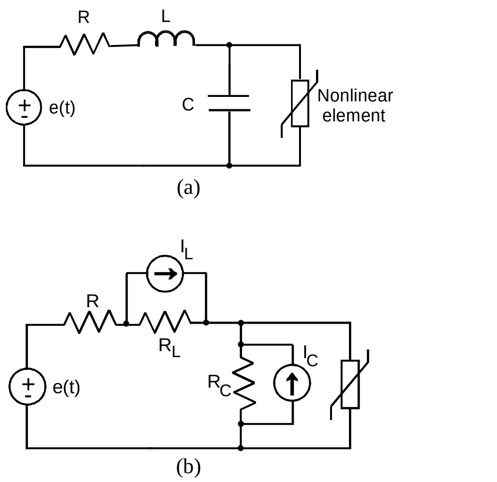


Fig. 1 : Solution method for nonlinear circuits. (a) nolinear circuit, (b) EMTP model.

An alternative procedure results if the correction Δv_D^k is written as :

$$\Delta v_D^k = -\frac{v_D^k + R_{TH} i_D^k - e_0}{1 + R_{TH}\left(\dfrac{\partial i_D}{\partial v_D}\right)^k} = \frac{R_{TH} R_D^k}{R_{TH} + R_D^k} \cdot i_M^k \qquad (5)$$

where,

$$i_M^k = \frac{e_0 - v_D^k}{R_{TH}} - i_D^k \qquad (6)$$

and $R_D^k = \left(\dfrac{\partial v_D}{\partial i_D}\right)^k$ is the linearized (or small-signal) equivalent resistance of the nonlinear element.

If a voltage source v_D^k is connected across the nonlinear element as shown in Fig. 2a, the current flowing through this source is the mismatch current. The connection of the voltage source in parallel with the nonlinear element separates the circuit into linear and nonlinear parts. Therefore, the determination of the mismatch current is very much simplified.

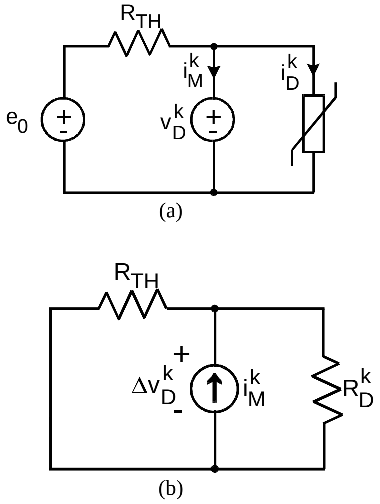


Fig. 2 : Alternative solution technique. (a) connection of fictitious voltage source, (b) calculation of Δv_D^k.

Suppose the voltage source v_D^k is substituted by the mismatch current source i_M^k with polarity reversed as shown in Fig. 2b and the nonlinear element is replaced by its linearized equivalent resistance. (Fig. 2b will be referred to as the small-signal equivalent). With the source e_0 removed, the voltage developed across the mismatch current source is the correction to be added to v_D^k. The computations may now proceed to the next iteration.

This alternative procedure may be extended to circuits with many nonlinear elements. In this case, voltage sources representing the approximate solutions are connected across each nonlinear elements and the mismatch currents through each of these sources are determined. During this analysis, the linearized equivalents of the nonlinear elements are computed and stored. The small-signal equivalent circuit is now set up with the nonlinear elements substituted by the mismatch currents. The voltages developed across the mismatch currents are the corretions to be added to the approximate solutions before proceeding to the next iteration.

B. Simulation of periodic steady-state response

Suppose the voltage source $e(t)$ in Fig. 1a is periodic. Let the waveform be represented by the vector of N equidistant time-domain samples $[e_G]$ taken over one period of the fundamental frequency of $e(t)$. The complexy valued Fourier coefficients of this waveform are given by the vector

$$[EG] = [DFT] \cdot [e_G] \qquad (7)$$

where $[DFT]$ is the matrix representing the Fourier transformation.

A periodic voltage source $[v_D]$ is connected across the nonlinear element and the periodic mismatch current through this source is

$$[i_M] = [IDFT] \cdot \{[Y_G] \cdot [DFT] \cdot ([e_G] - [v_D])\} - f([v_D]) \qquad (8)$$

where $[IDFT]$ is the matrix representing the inverse Fourier transformation, $[Y_G]$ is the diagonal matrix of harmonic impedances looking into the linear part of the circuit, and $f(\cdot)$ is the scalar nonlinear function of equation (2) operating on the time-domain samples $[v_D]$.

The waveform $[v_D]$ for which the periodic mismatch current $[i_M] = 0$ is obtained by applying the Newton-Raphson procedure :

$$[\Delta v_D]^k = \{[IDFT] \cdot [Y_G] \cdot [DFT] + f'((v_D))\}^{-1} \cdot [i_M] \qquad (9)$$

$$[v_D]^{k+1} = [v_D]^k + [\Delta v_D]^k \qquad (10)$$

where $f'([v_D])$ is the periodic, time-varying equivalent resistance of the nonlinear element. But $[\Delta v_D]^k$ is precisely the voltage waveform developed across the mismatch current source when it is injected into the parallel combination of the linear part and the time-varying equivalent of the nonlinear part.

Therefore, the iterative procedure consists in connecting periodic voltage sources across each nonlinear element and calculating the steady-state mismatch currents through these sources. At the same time, the linearized, periodically time-varying equivalents of the nonlinear elements are computed. The mismatch currents are the excitations to be applied in the small-signal equivalent circuit and the nonlinear elements are replaced in this circuit by their linearized equivalents. The steady-state voltages developed across the mismatch currents are the corrections to be added to the periodic voltage sources before going to the next iteration.

III. SIMULATION OF THE TWELVE-PULSE HVDC CONVERTER

A. Transient response of the HVDC converter

The Fig. 3 (last page) shows the twelve-pulse HVDC Cigre Benchmark converter (more details in [7]) with the fictitious voltage sources e_{A1}, e_{B1}, e_{C1}, e_{AB2}, e_{BC2}, e_{LD1} and e_{LD2} connected according to the technique described above. Though there are twelve nonlinear elements in this circuit, the seven voltage sources are sufficient to separate the converter into linear parts comprising the AC and DC power systems and a nonlinear part comprising the twelve valves.

Analysis of the linear parts gives the currents i_{ST1A}, i_{ST1B}, i_{ST1C}, i_{ST2A}, i_{ST2C} and i_{D1}. The currents i_{NA1}, i_{NB1}, i_{NC1}, i_{NA2}, i_{NC2}, i_{ND1}, i_{ND2} and the linearized equivalents of the valves are obtained from an analysis of the nonlinear part of the circuit. The nonlinear module has voltage sources $e_{AB1} = e_{A1} - e_{B1}$, $e_{BC1} = e_{B1} - e_{C1}$, e_{AB2} and e_{BC2} connected on the AC side and the voltage sources e_{LD1} and e_{LD2} connected on the DC side, as shown in Fig. 4a. The currents i_{NA1}, i_{NB1}, i_{NC1}, i_{NA2}, i_{NC2}, i_{ND1} and i_{ND2} are determined by applying the proposed technique in a recurrent manner. The voltage sources e_{ND1} and e_{ND2} are connected across one of the valves from each bridge (Fig. 4a). The voltages and currents of all the valves are now calculed and the mismatch currents δi_{ND1} and δi_{ND2} flowing into the sources are determined. The small-signal equivalent for the nonlinear module is then established as shown in Fig. 4b. The voltages across the mismatch current sources are the corrections to be added to the sources e_{ND1} and e_{ND2}. Convergence is obtained in a few iteractions.

The mismatch currents flowing into the voltage sources e_{A1}, e_{B1}, e_{C1}, e_{AB2}, e_{BC2}, e_{LD1} and e_{LD2} are given by (Fig. 3) :

$$\delta i_{kN1} = i_{ST1k} - i_{Nk1} \text{ , to } k = A, B, C \qquad (11)$$

$$\delta i_{AB2} = -i_{ST2AB} + i_{ST2CA} - i_{NA2} \qquad (12)$$

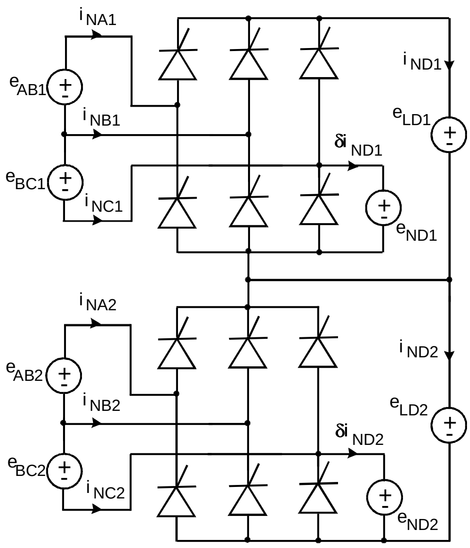
$$\delta_{BC2} = -i_{ST2BC} + i_{ST2CA} + i_{NC2} \qquad (13)$$

$$\delta i_{LD1} = i_{ND1} - i_{D1} \qquad (14)$$

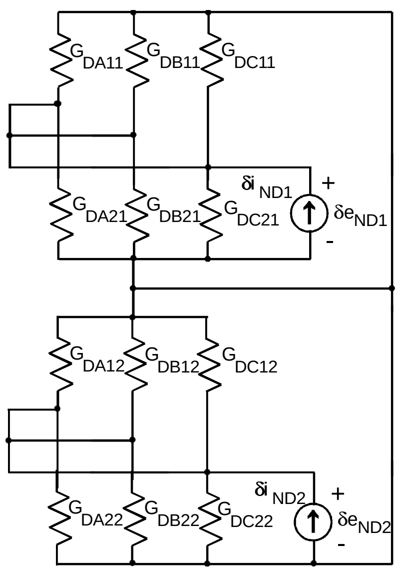
$$\delta i_{LD2} = i_{ND2} - i_{D1} \qquad (15)$$

and these are excitations for the small-signal equivalent circuit for the HVDC converter, which is shown in Fig. 5 (last page). The voltages across the mismatch current sources in this circuit are the corrections to be added to the voltages e_{A1}, e_{B1}, e_{C1}, e_{AB2}, e_{BC2}, e_{LD1}, e_{LD2} and the next iteration commences. The objective is to determine the fictitious voltage sources for which the mismatch current are zero or less than given tolerance. The test for convergence is based on suitable norm for the mismatch current waveforms (such as the rms value). The procedure converges when the norm of each mismatch current is below a specified tolerance.

It should be observed that there are two nested iterative loops in the algorithm. The main iterative loop deals with the progressive reduction of the mismatch currents. Within each of these iteractions is another iterative loop for determining the currents in the nonlinear part of the converter circuit.



(a)



(b)

Fig. 4 : Analysis of the nonlinear part of the HVDC converter. (a) model for nonlinear part, (b) small signal equivalent.

B. Steady-state response of the HVDC converter

The voltages sources $e_{A1}(t)$, $e_{B1}(t)$, $e_{C1}(t)$, $e_{AB2}(t)$, $e_{BC2}(t)$, $e_{LD1}(t)$ and $e_{LD2}(t)$ are now periodically time-varying. The periodic steady-state of the linear parts is obtained either from na analysis in the time domain or in the frequency domain, in case the linear part is frequency-dependent. This analysis provides the currents $i_{ST1A}(t)$, $i_{ST1B}(t)$, $i_{ST1C}(t)$, $i_{ST2A}(t)$, $i_{ST2C}(t)$ and $i_{D1}(t)$. The nonlinear part, however, is analysed in the time domain and the periodic steady-state currents $i_{NA1}(t)$, $i_{NB1}(t)$, $i_{NC1}(t)$, $i_{NA2}(t)$, $i_{NC2}(t)$, $i_{ND1}(t)$, $i_{ND2}(t)$ and the time-varying equivalent resistances of the valves are determined. The periodic mismatch currents $\delta i_{AN1}(t)$, $\delta i_{BN1}(t)$, $\delta i_{CN1}(t)$, $\delta i_{AB2}(t)$, $\delta i_{BC2}(t)$, $\delta i_{LD1}(t)$, $\delta i_{LD2}(t)$ flowing through the fictitious voltage sources are subsequently computed.

The steady-state small-signal equivalent circuit for the HVDC converter is identical to that shown in Fig. 5. However, the excitations for this circuit are the periodic mismatch currents and the valve elements are replaced by periodically time-varying resistances. It should be observed that the small-signal equivalent circuit is linear, even though it is time-varying. Its steady-state response and stability of this response may be determined with one iteration of the Aprille-Trick algorithm [8]. The periodic steady-state voltages across the mismatch current sources in the small-signal equivalent circuit are the corrections to be added to the voltage sources and the next iteration commences. The test for convergence is now based on a siutable norm for the mismatch current waveform (such as the rms value). The procedure converges when the norm of each mismatch current is below a specified tolerance.

IV. RESULTS AND DISCUSSION

The steady-state responses of the HVDC Cigre Bechmark converter [7] were computed using the fictitious voltage source technique. An IBM-PC compatible microcomputer with a 200 MHz processor was used in all computations. The number of time-steps per fundamental period was chosen to be 512, which besides being adequate for the transient responses, conveniently allows the harmonic analysis of the steady-state waveforms using the FFT. Double precision arithmetic was used in all the simulations.

In each iteration of the Newton-Raphson procedure, only a fraction of the correction is added to the approximate solution, i.e., $v_D^{k+1} = v_D^k + q\Delta v_D^k$, where $0 < q \le 1$. The optimum value of q is obtained from an one-dimensional search. This procedure increases the computational time but assures convergence.

Initial waveforms for the periodic voltage sources $e_{A1}(t)$, $e_{B1}(t)$, $e_{C1}(t)$, $e_{AB2}(t)$, $e_{BC2}(t)$, $e_{LD1}(t)$ and $e_{LD2}(t)$ are required for determining the steady-state responses. For this purpose, the start-up trasient is calulated over several periods. In the case of the AC system voltages are balanced and undistorted, was necessary 14 transient periods to compose the estimative voltage sources. Typically, less than 15 periods of start-up transient is computed and the steady-state requires 1 to 2 iterations. Mismatch current tolerance has been set at 10^{-5}.

The parameters values used for the HVDC converter have been obtained from [7]. The HVDC converter was operated in the simulations with constant delay angle $\alpha = 15^\circ$. The fire instants are sincronised with the AC system voltages natural fire angles directly applied in the bridges.

Fig. 5 shows the steady-state response waveforms of the AC subsystem and Fig.6 shows the steady-state response waveforms of the CC subsystem. Both cases the AC system voltage are balanced and undistorted.

Figs. 7 and 8 show the response waveforms when the AC system voltages are unbalanced and distorted. In this case the AC system phase voltages in pu are given by :

$$EG_{AN}=\mathrm{Sin}\omega t+0.071\mathrm{Sin}(\omega t+1.034)+0.11\mathrm{Sin}(3\omega t-0.439)+ +0.102\mathrm{Sin}(3\omega t+1.357) \quad (16a)$$

$$EG_{BN}=\mathrm{Sin}(\omega t-2.0944)+0.071\mathrm{Sin}(\omega t+3.1284)+0.11\mathrm{Sin}(3\omega t- -2.5334)+0.102\mathrm{Sin}(3\omega t+3.4514) \quad (16b)$$

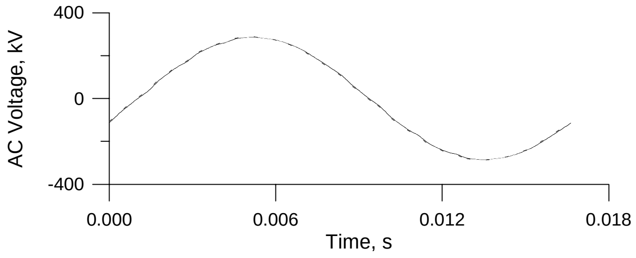
$$EG_{CN}=\mathrm{Sin}(\omega t+2.0944)+0.071\mathrm{Sin}(\omega t-1.0604)+0.11\mathrm{Sin}(3\omega t+ +1.6554)+0.102\mathrm{Sin}(3\omega t-0.7374) \quad (16c)$$

The examples presented above have also been simulated with the MicroTran®-EMTP [9]. Figs. 7 and 9 show the response waveforms for the two cases described above, obtained after 19 and 22 periods of start-up transient computation for undistorted and distorted cases, respectively. The agreement is satisfactory.

V. CONCLUSIONS

A general approach for determining the transient and steady-state responses of twelve-pulse AC/DC converter has been described. Besides being rapidly convergent, the proposed technique allows the inclusion of detailed device models in the computations. Another advantages of the proposed technique is the relative ease with control systems may be included in the analysis.

The responses of a typical HVDC converter have been presented and they agree well with the corresponding responses obtained with the EMTP.



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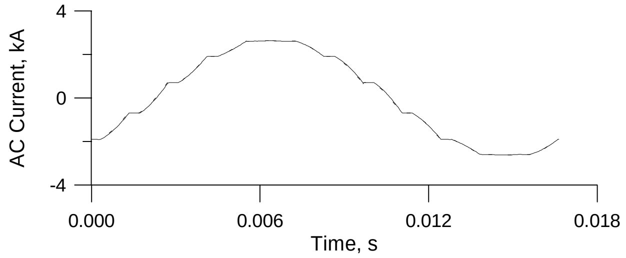
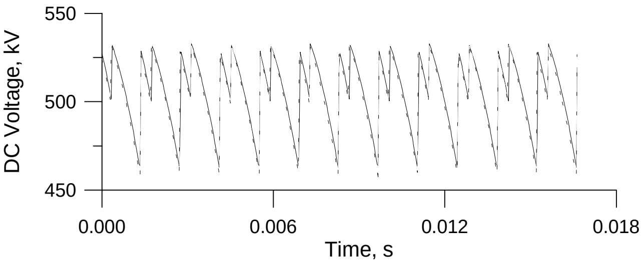


(b)

Fig. 5 : Response waveforms for AC subsystem (balanced and undistorted case). (a) AC voltage, (b) AC current. (—) Model, (- - -) MicroTran®.



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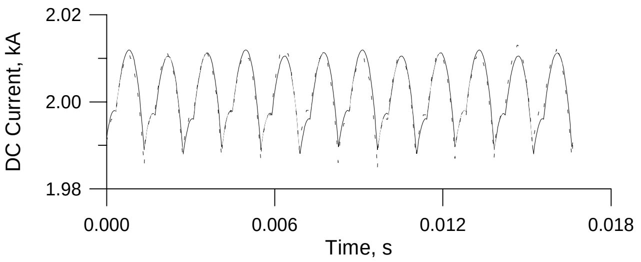
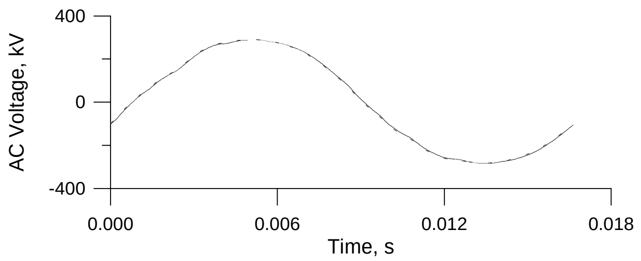


(b)

Fig. 6 : Response waveforms for DC subsystem (balanced and undistorted case). (a) DC voltage, (b) DC current. (—) Model, (- - -) MicroTran®.



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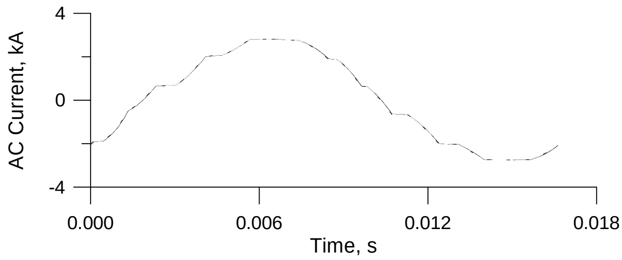
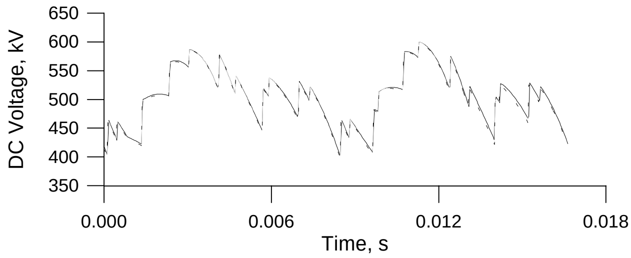


(b)

Fig. 7 : Response waveforms for AC subsystem (unbalanced and distorted case). (a) AC voltage, (b) AC current. (—) Model, (- - -) MicroTran®.



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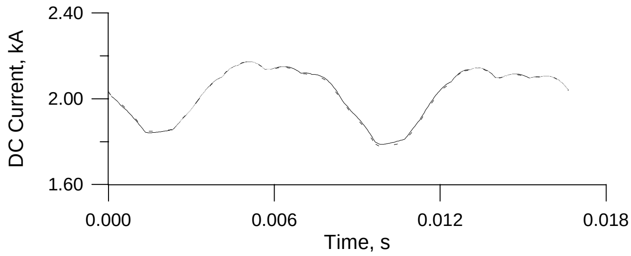

(b)

Fig. 8 : Response waveforms for DC subsystem (unbalanced and distorted case). (a) DC voltage, (b) DC current. (—) Model, (- - -) MicroTran®.

VI. REFERENCES

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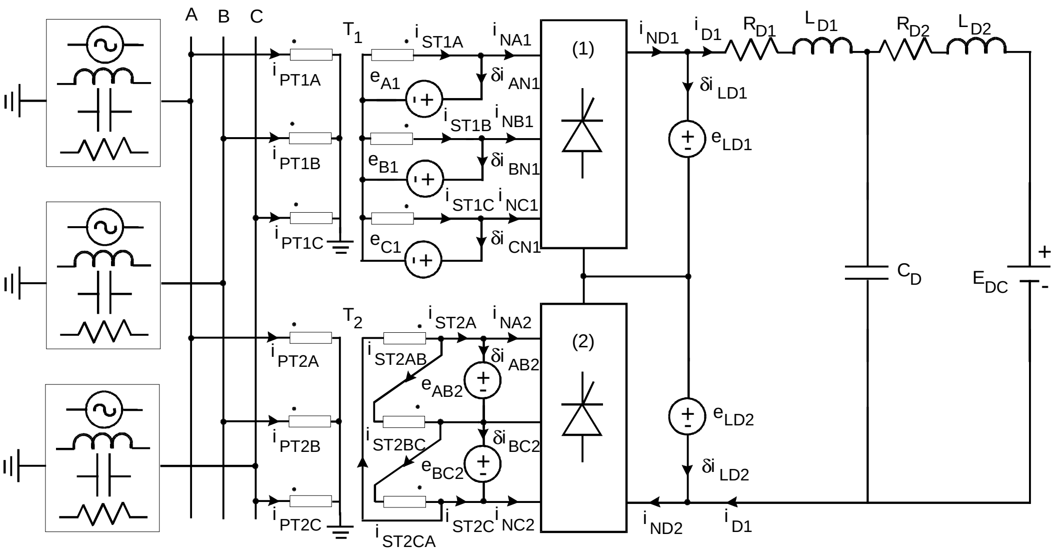

Fig 3 : Twelve-pulse AC/DC converter.

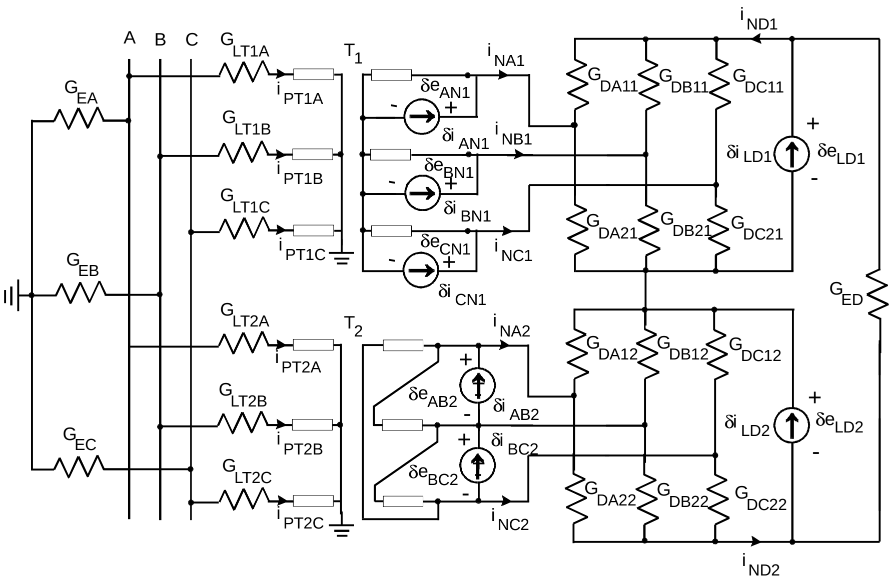

Fig. 5 : Small-signal equivalent circuit of the HVDC converter.