Equivalent Circuits of Power Electronic Converters

D. Nelles C. Tuttas

Department of Electrical Power Engineering
University of Kaiserslautern, D-67653 Kaiserslautern
E-Mail: dnelles@e-technik.uni-kl.de
E-Mail: tuttas@e-technik.uni-kl.de

Abstract - **Models for power electronics become very complex, if instantaneous quantities of voltages and currents have to be considered. Therefore, the coupling of power electronics to electromagnetic transients programs is usually done by iterative algorithms. An equivalent circuit description avoids this disadvantage. Seen from the power system, an electronic converter behaves like a linear circuit, which can simply be integrated into the transmission network. The nonlinearities are summarized in a voltage source. If explicite integration methods are used in system simulation, the voltage source is an additional input variable of the network.**

Keywords: Power Electronics, Equivalent Circuit, Transients Modeling, Power Systems

I. INTRODUCTION

Today, power electronic converters are not only installed at the load side but also at the transmission side of power systems (FACTS elements). Therefore, it exists a demand to modeling power electronics in dynamic power system simulators. Usually, two different time ranges are considered [1]:

- long time range (s ... min)
- short time range (ns ... ms)

The long time range is used for stability studies. The power system is described in the frequency range below the fundamental ac frequency of 50/60 Hz. Only the rms values of the network variables (voltages, currents) are of interest. In this time range, it is usual to model power electronics like classical components (transformers, lines) by equivalent circuits [1-3]. This measure simplifies its integration into existing power system simulation programs.

Electromagnetic phenomena in transmission networks have to be researched in the short time range. Here, modeling of power electronics becomes more difficult, because the instantaneous network variables are considered. The integration of a power electronic model into an electromagnetic transients program is usually solved by iteration algorithms. But his procedure can be avoided. Also in the short time range it is possible to describe a power electronic converter by an equivalent circuit. The equivalent circuit behaves like a Thévenin element and can be connected easily to a power system.

II. CIRCUIT DESCRIPTION

Two types of power electronic converters are considered:

- a forced commutated circuit with a voltage source inverter (Fig. 1a) and
- a line commutated circuit with a diode bridge rectifier (Fig. 1b).

In power system simulation usually snubber circuits and dynamic effects in the semiconductors are neglected. Because of this, the electronic valves behave like controlled switches. With these assumptions, Fig. 2a describes the power electronic converters of Fig. 1. If the voltages u_{PE1} and u_{PE3} are known, an equivalent circuit description becomes possible (Fig. 2b). The power electronic converters are represented by simple Thévenin elements, whose inner voltage vector $\mathbf{u}_{PE} = [u_{PE1}\ u_{PE3}]^T$ is calculated in the background with the input and state variables of the system.

$$\mathbf{u}_{PE} = \mathbf{f}\,(\mathbf{u}; \mathbf{i}) \tag{1}$$

$$\mathbf{u} = [u_1\ u_3]^T \tag{2}$$

$$\mathbf{i} = [i_1\ i_3]^T \tag{3}$$

In (1) to (3) only two phases have to be considered, because in the network a zero sequence system is not possible. The determination of the inner voltage vector $\mathbf{u}_{PE}$ is presented in the following.

A. Voltage Source Inverter

The circuit of Fig. 2a contains of six switches. Therefore, $2^6 = 64$ different switch positions (switching states) are theoretically possible. But in the voltage source inverter of Fig. 1a only 8 switching states are allowed during normal operation (Table 1). All other states are characterized by a short circuited dc capacitor or interrupted ac currents and have to be avoided.

Fig. 3 shows the signal flow graph to calculate the inner voltage. An ac/dc and dc/ac-converter represent the behaviour of the switches. The dc network is modeled by a transfer function.

The ac/dc-converter transforms the ac current vector $\mathbf{i} = [i_3\ i_3]^T$ into the dc current i_d. This variable depends on the switch currents (Fig. 2a):

$$i_d = i_{v1} + i_{v2} + i_{v3} \tag{4}$$

The dc/ac module converts the dc voltage u_d into the ac voltage vector $\mathbf{u}_{PE} = [u_{PE1}\ u_{PE3}]^T$. This vector is influenced by the switch voltages (Fig. 2a):

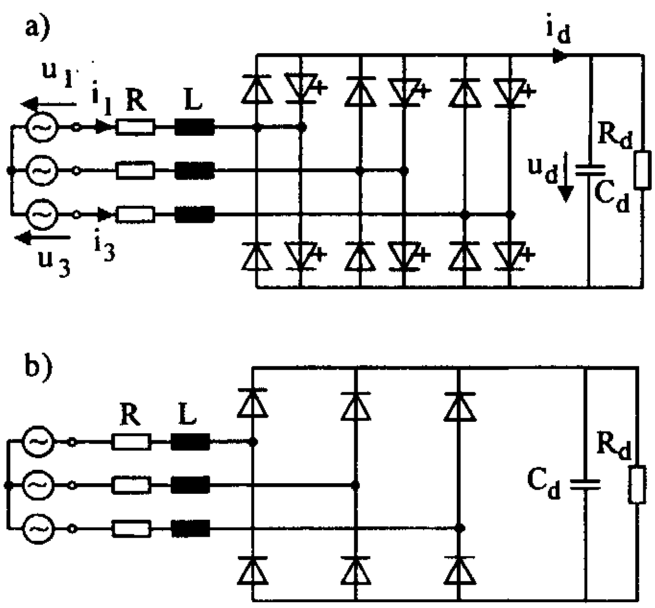

Fig. 1: Considered power electronic circuits
a) forced commutated converter
b) line commutated converter

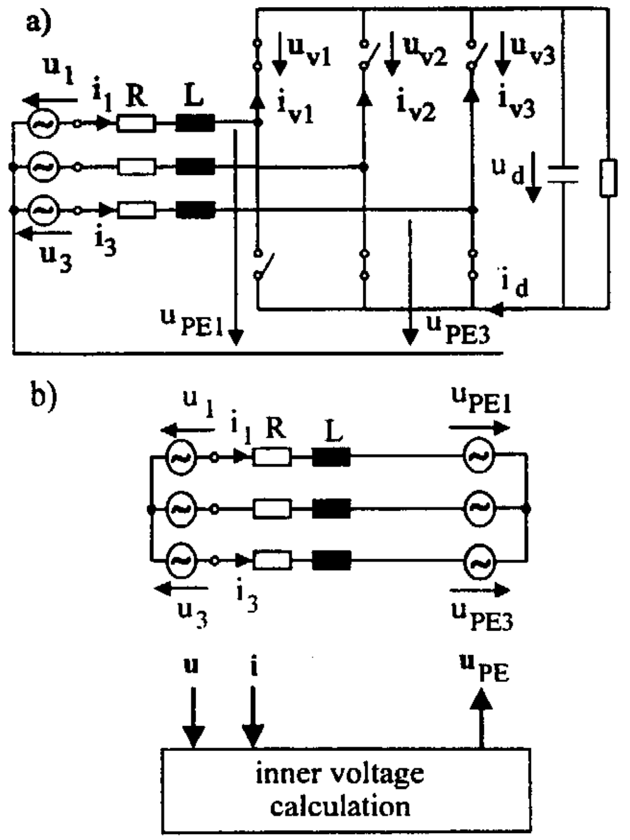

Fig. 2: Modeling of power electronic circuits
a) circuit with switches
b) equivalent circuit (ac side)

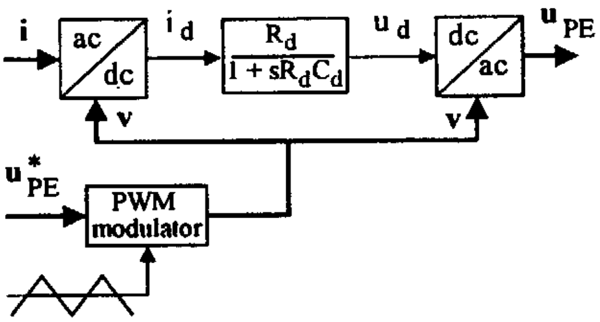

Fig. 3: Inner voltage calculation for the voltage source inverter

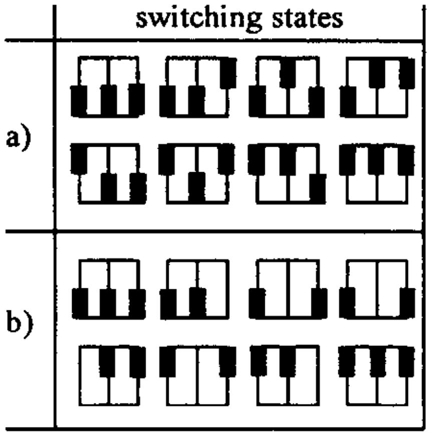

Table 1: Switching states
(▌ conducting branch, | blocking branch)
a) allowed states (converter of Fig. 1a)
b) impossible states (converter of Fig. 1b)

v			i_v		
v_1	v_2	v_3	i_{v1}	i_{v2}	i_{v3}
0	0	0	0	0	0
0	0	1	0	0	i_3
0	1	0	0	i_2	0
0	1	1	0	i_2	i_3
1	0	0	i_1	0	0
1	0	1	i_1	0	i_3
1	1	0	i_1	i_2	0
1	1	1	i_1	i_2	i_3

Table 2: Valve currents (converter of Fig. 1a)

$$\mathbf{u}_{PE} = \begin{bmatrix} u_{PE1} \\ u_{PE3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & 1 \\ -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} u_{v2} - u_{v1} \\ u_{v3} - u_{v2} \end{bmatrix} \quad (5)$$

$$\mathbf{u}_{PE} = \begin{bmatrix} u_{PE1} \\ u_{PE3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} u_{v1} \\ u_{v2} \\ u_{v3} \end{bmatrix} \cdot (6)$$

The voltages and currents of the semiconductor valves depend on the switching state. They are listed in Table 2 and 3. The 8 allowed switching states are coded by the binary vector $\mathbf{v} = [v_1\ v_2\ v_3]^T$, which is generated from an external signal source, the PWM modulator of the voltage source inverter (Fig. 3). Table 2 describes together with (4) the ac/dc converter while Table 3 represents in combination with (6) the dc/ac converter.

The contents of Table 2 and 3 can be expressed by simple algebraic equations [4]. Therefore, a non-linear equation describes the dc/ac converter:

$$i_d = (v_1 - v_2)\, i_1 + (v_3 - v_2)\, i_3 \quad (7)$$

The ac/dc module is represented by

$$\mathbf{u}_{PE} = \begin{bmatrix} u_{PE1} \\ u_{PE3} \end{bmatrix} = \frac{u_d}{3}\begin{bmatrix} 2\,v_1 - v_2 - v_3 \\ -v_1 - v_2 + 2\,v_3 \end{bmatrix} \quad (8)$$

The equations (7) and (8) show that both converters are independent on the valve voltages and currents.

B. Diode Bridge Rectifier

The inner voltage calculation of the diode bridge rectifier (Fig. 1b) is more complicated due to two reasons:

1. The number of switching states which have to be considered is higher than that one for the voltage source inverter. The 8 impossible combinations which are characterized by diode currents with negative polarity are listed in Table 1.

2. The switching state is not determined by an external signal source but by the polarity of the diodes voltages and currents. Therefore, these

variables have to observed. A diode is switched on, if its anode voltage becomes positive, and switched of, if its anode current tends to negative polarity.

Fig. 4 shows the signal flow graph of the inner voltage calculator. It is possible to describe also the ac/dc-and the dc/ac converter by tables. But this is only recommended for power electronics with a low number of switching states [5]. If 12- or 24-pulse rectifiers are considered the number of theoretically possible switching states is extremely high ($2^{12} = 4096$ or $2^{24} = 16,7 \cdot 10^6$). Then, the table concept with an a priori calculation of all valve voltages and currents is not practicable. Therefore, in [6, 7] a new method is proposed which allows an online calculation of all needed variables.

Referring to (4) an ac/dc conversion is not possible without knowledge of the valve currents. These variables are determined by means of an ohmic network (R-net) which is shown in Fig. 5.

Switched resistors R_{vi} (i = 1, ..., 6) represent the diodes:

$$R_{vi} = \begin{cases} R_{min} \ll 1; \text{ diode is conducting} \\ R_{max} \gg 1; \text{ diode is blocking} \end{cases} \quad (9)$$

The modeling of semiconductors by switched resistors is not new but in this approach the resistors do not influence the time constants of the electrical circuit [7]. Therefore, the elements R_{vi} are called virtual resistors.

Out of the R-net of Fig. 5 all valve currents can be determined. The diode current i_{v1} for instance is described by

$$i_{v1} = \frac{R_{v4}}{R_{v1} + R_{v4}} i_1 \quad (10)$$

A special block „switching state determination" delivers the virtual resistors [6]:

$$\mathbf{v}_r = [R_{v1}, \ldots, R_{v6}]^T \quad (11)$$

For this purpose, the valve currents $\mathbf{i}_v$ have to be observed.

v			u_V		
v_1	v_2	v_3	u_{v1}	u_{v2}	u_{v3}
0	0	0	u_d	u_d	u_d
0	0	1	u_d	u_d	0
0	1	0	0	u_d	0
0	1	1	u_d	0	0
1	0	0	0	u_d	u_d
1	0	1	u_d	0	u_d
1	1	0	0	0	u_d
1	1	1	0	0	0

Table 3 Valve voltages (converter of Fig. 1a)

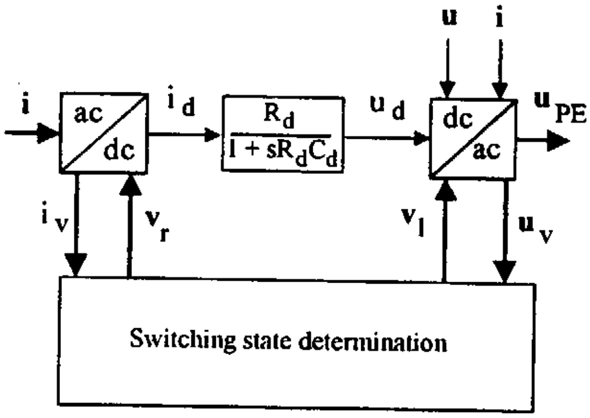

Fig. 4: Inner voltage calculation for the diode bridge rectifier

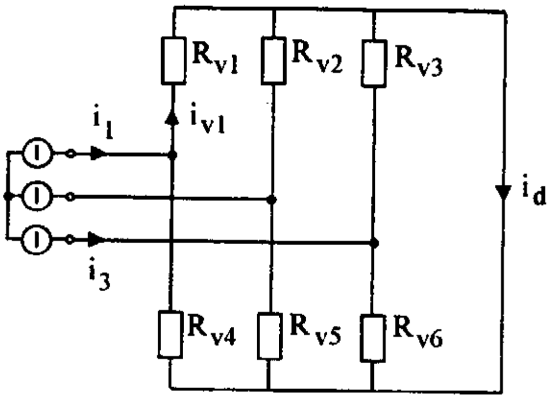

Fig. 5: R-net for valve current calculations

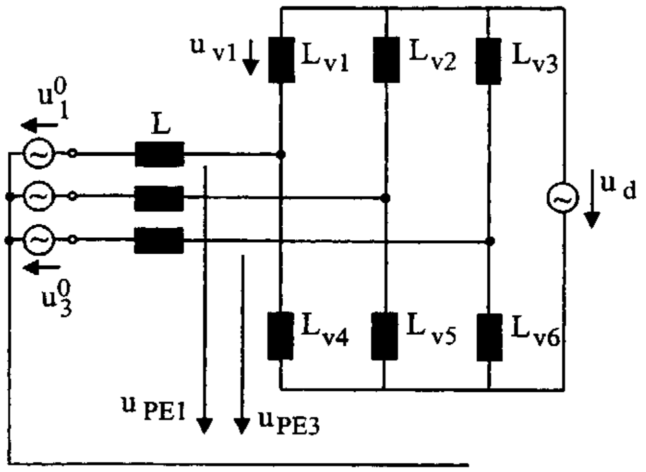

Fig.6 : L-net for valve voltage calculations

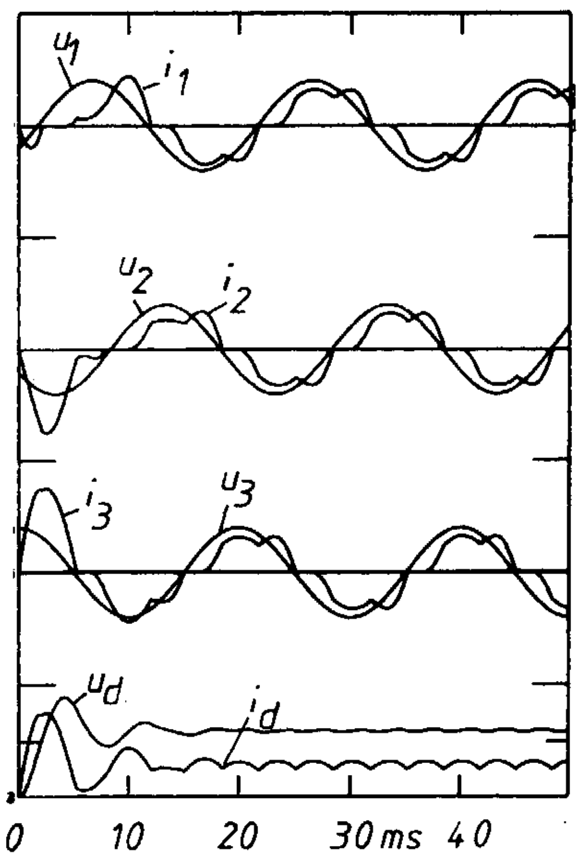

Fig. 7: Dynamic behaviour of the line commutated converter

A dc/ac conversion is not possible without knowledge of all valve voltages $\mathbf{u}_v$ (Fig. 4). Therefore, the semiconductors are modeled by switched inductances (L-net). In Fig. 6 the inductors L_{vi} ($i = 1, ..., 6$) represent the diodes:

$$L_{vi} = \begin{cases} L_{min} \ll L; \text{ diode is conducting} \\ L_{max} \gg L; \text{ diode is blocking} \end{cases} \quad (12)$$

The input variables of the L-net are the modified network voltages $\mathbf{u^0} = \mathbf{u} - \mathbf{R}\,\mathbf{i}$ and the dc voltage u_d. The representation of semiconductors by switched inductances is well known but in this approach the additional inductances do not increase the order of the differential equations which have to be solved. Therefore, these elements are called virtual inductances [6, 7].

The network of Fig. 6 allows the calculation of all valve voltages $\mathbf{u}_v = [u_{v1}, ..., u_{v6}]^T$ and the determination of the desired ac voltage vector $\mathbf{u}_{PE} = [u_{PE1} \;\; u_{PE3}]^T$ without solving differential equations. Only static matrix equations have to be handled [6, 7]. The vector $\mathbf{v}_l$ delivers the virtual inductances

$$\mathbf{v}_l = [L_{v1}, \ldots, L_{v6}]^T \quad (13)$$

The above considerations show that the simulation of a line commutated converter takes greater effort than the simulation of a forced commutated converter. The switching instants are not only determined by an external signal source but also by the input and state variables of the circuit.

III. POWER SYSTEM MODELING

Today, there exist a lot of software like PSPICE, SABER or SIMPLORER, which allows the simulation of power electronic circuits under transient conditions. For power systems with power electronics program packages like EMTP and NETOMAC are available. But the dynamic behaviour of power electronics in power systems can also be calculated by means of standard simulation software like MATLAB/SIMULINK.

For this purpose, the proposed equivalent circuit description brings a lot of advantages. It leads to a clear separation between power system and power electronic modeling. The electronic converter behaves like a linear component. All nonlinearities are summarized in an inner voltage source. This voltage source can be calculated in the background, using the matrix operation algorithms of MATLAB. With explicite integration methods no algebraic loops occur and no differentiations are necessary connecting a power electronic converter to a power system.

Fig. 7 shows a simulation result with the line commutated converter of Fig. 1b. The circuit is free of energy and switched on to the voltage source. The network parameters are

$$R_d = 1, \quad X_{Cd} = (\omega C_d)^{-1} = 1, \quad X = \omega L = 0.1,$$
$$R = 0.01, \quad \omega = 100\,\pi\, s^{-1}$$

The diodes are modeled by virtual impedances:

$$R_{v\,min} = 10^{-3}, \qquad R_{v\,max} = 10^{3},$$
$$X_{v\,min} = 10^{-4}, \qquad X_{v\,max} = 10^{4}$$

The converter behaves like a third order system. All eigenvalues are not critical for the simulation. The worst case is given, if all diodes are blocking. Then the minimal time constant is calculated by T = 6 ms [7].

IV. CONCLUSION

Power electronic devices with forced and line commutation can be modeled in the short time range by Thévenin elements as equivalent circuits. This description simplifies is integration into an electromagnetic transients program. Seen from the ac network side, a power electronic converter behaves like a linear element. All nonlinearities are found in a separated procedure which calculates the inner voltages of the Thévenin element. In this program part, the semiconductor switches have to be modeled. The electronic valves should be represented by virtual impedances, which do not decrease the time constants of the network, do not increase the order of the differential equations and allow a constant structure system simulation.

V. REFERENCES

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