A New Concept in Power Electronics Simulation

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Abstract - Usually dynamic models for power electronic converters are only presented in general form, because a detailed system description requires great effort. Therefore, in this paper a new method in power electronics simulation is described using a graph representation of system equations. These graphs allow a detailed insight into the complex signal flow of the model. By means of the new method a three phase bridge rectifier is described.

Keywords: Power Electronics Simulation, Hybrid System, Block Diagram, State Diagram, Time Constant Method (TCM).

I. INTRODUCTION

To simulate transient phenomena in power systems all network elements have to be described by dynamic models. For many standard elements like transformers, lines and generators these models are well known [1]. The structure of other components like power electronic converters is more complicated. Different methods of simulating power electronics have been widely discussed in the literature [2-5]. But usually the authors describe only modeling strategies. The converter equations are not published in detail due to their great complexity.

This paper presents a new and systematic approach in power electronics modeling based on hybrid system theory [6]. The equations are described by graphs, which allow detailed insights into the complex signal flow. The method is characterized by

- a special ideal switch representation of semiconductor valves [7]
- the time constant method (TCM) for electrical circuit modeling [8-10] and
- arithmetic expressions of logic terms [11].

The new simulation concept is adapted to a standard power electronic circuit (three phase thyristor bridge rectifier).

II. SIMULATION CONCEPT

We consider the electrical network of Fig. 1a, which consists of

- continuous time components (RL-elements, voltage, sources) and
- discrete event components (thyristor switches).

Therefore, the power electronic circuit behaves like a hybrid system [6]. The dynamic continuous time part and the discrete event part (Fig. 1b) communicate via static interfaces. The variables of Fig. 1b have the following meaning:

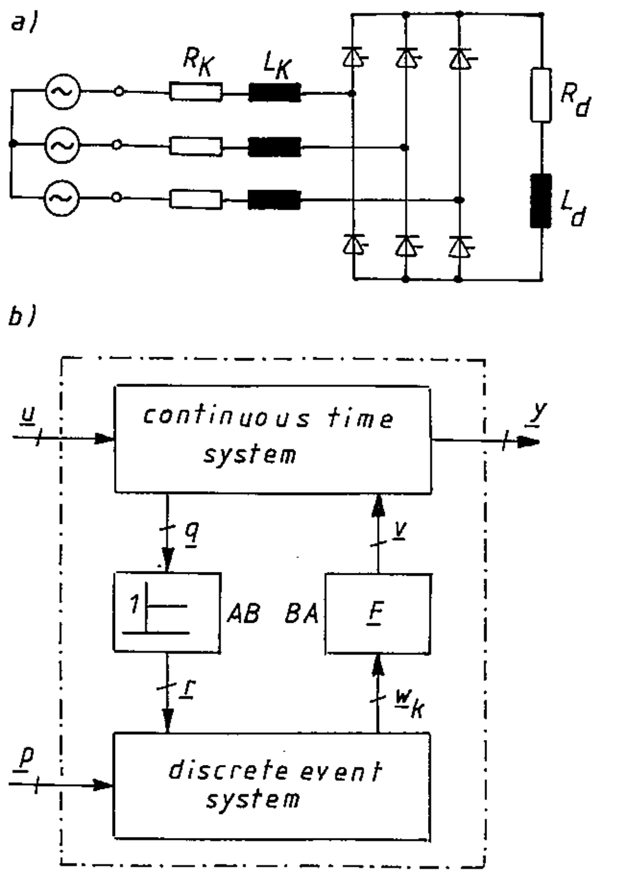


Fig. 1: Power electronic converter
AB analogue binary interface
BA binary analogue interface
a) circuit diagram
b) concept for mathematical description

continuous system

- $\underline{u}$ extern input vector (voltage sources)
- $\underline{v}$ intern input vector (defines network structure)
- $\underline{y}$ extern output vector (reactor currents)
- $\underline{q}$ intern output vector (thyristor voltages and currents)

discrete system

- $\underline{p}$ extern input vector (thyristor firing pulses)
- $\underline{r}$ intern input vector (polarity of the thyristor voltages and currents)
- $\underline{w}_k$ intern output vector (switching state of the thyristor bridge)

The vectors $\underline{p}$, $\underline{r}$ and $\underline{w}_k$ of the discrete system part consist of binary components, which are provided with the values 0 and 1:

$$p_i, r_i, w_i \in \{0, 1\}$$

By means of comparators the analogue binary (AB) interface detects the zero crossings of the valve voltages and currents. These events must be known for a correct converter simulation. A matrix $\underline{F}$ with constant coefficients describes the binary analogue (BA) interface. This block generates the switching vector $\underline{v}$, which depends on the switching state of the thyristor bridge. The vector $\underline{v}$ carries out the switching operations in the time continuous part.

Fig. 1b models the basic structure of a power electronic circuit. Further components like firing pulse generators and superimposed controllers are not considered in this paper.

III. SYSTEM DESCRIPTION

A. Continuous time part

The continuous time system of Fig. 1b is now described in more detail. Fig. 2 shows the considered power electronic circuit in a modified version. Due to the thyristor switches the structure of the network is variable. For simulation it is better to transform the variable structure circuit into a constant structure circuit. This is possible, if the ideal thyristor switches are described by their valve voltages u_{vi} and currents i_{vi} ($i = 1, ..., 6$).

In Fig. 2 the resistor R_K of the commutation reactor is divided into two terms [8-10]:

$$R_K = R^0 + R^* \tag{1}$$

The time constant T_0 of the R^0L_K-elements is equal to the load time constant T_d:

$$R^0 = \frac{L_K}{T_0} = \frac{L_K}{T_d} = R_d \frac{L_K}{L_d} \tag{2}$$

A second resistor R* is necessary to meet the correct system parameters:

$$R^* = R_K - R^0 = R_K - R_d \frac{L_K}{L_d} \tag{3}$$

Seen from the nodes 1^0, 2^0 and 3^0 the network of Fig. 2 consists of switches and RL-elements with the same time constants. The voltages of the nonconducting thyristors can be calculated as a function of the input variables u_{12}^0 and

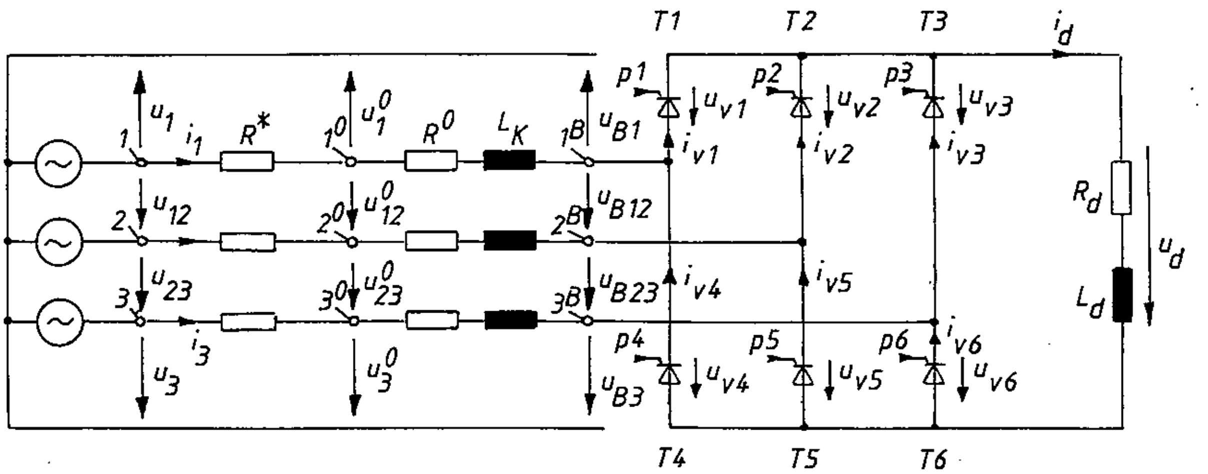


Fig. 2: Modified circuit diagram

u_{23}^0. This becomes possible, because the RL-elements form frequency independent voltage dividers [7]. With

$$\begin{bmatrix} u_{12}^0 \\ u_{23}^0 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ -1 & -2 \end{bmatrix} \cdot \begin{bmatrix} u_1^0 \\ u_3^0 \end{bmatrix} \tag{4}$$

we make the following assumptions in determining the valve voltages (Fig. 2)

$$\begin{bmatrix} u_{v1} \\ u_{v2} \\ u_{v3} \\ u_{v4} \end{bmatrix} = \begin{bmatrix} v_1 & v_5 \\ v_2 & v_6 \\ v_3 & v_7 \\ v_4 & v_8 \end{bmatrix} \cdot \begin{bmatrix} u_{12}^0 \\ u_{23}^0 \end{bmatrix} \tag{5}$$

$$\begin{aligned} u_{v5} &= u_{v1} - u_{v2} + u_{v4} \\ u_{v6} &= u_{v1} - u_{v3} + u_{v4} \end{aligned} \tag{6}$$

The valve currents (Fig 2) are analogously defined

$$\begin{vmatrix} i_{v1} \\ i_{v3} \end{vmatrix} = \begin{vmatrix} v_9 & 0 \\ 0 & v_{10} \end{vmatrix} \cdot \begin{vmatrix} i_1 \\ i_3 \end{vmatrix} \tag{7}$$

$$\begin{aligned} i_{v2} &= i_d - i_{v1} - i_{v3} \\ i_{v4} &= -i_1 + i_{v1} \\ i_{v5} &= i_1 + i_3 + i_{v2} \\ i_{v6} &= -i_3 + i_{v3} \end{aligned} \tag{8}$$

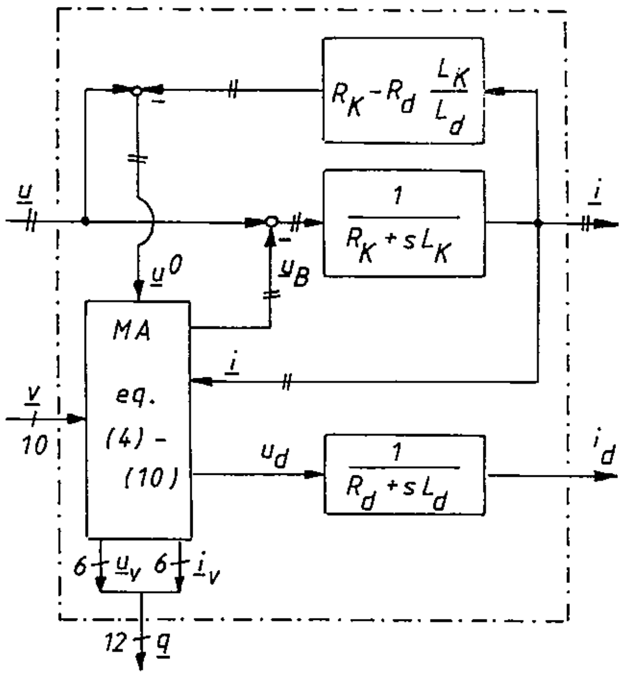
The variables v_1 to v_{10} are components of the switching vector $\underline{v}$ (Fig. 1b) and depend on the switching state of the thyristor bridge (section III.C).

With the known valve voltages also the bridge voltages and the load voltage u_d can be calculated (Fig. 2):

$$\begin{bmatrix} u_{B12} \\ u_{B23} \\ u_d \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} u_{v1} \\ u_{v2} \\ u_{v3} \\ u_{v4} \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} u_{B1} \\ u_{B3} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & -2 \end{bmatrix} \cdot \begin{bmatrix} u_{B12} \\ u_{B23} \end{bmatrix} \tag{10}$$

The electrical circuit of Fig. 2 can be transformed into a block diagram (Fig. 3), which represents the dynamic equations of the continuous time part [7]. Transfer functions model the linear RL-elements, while the thyristor switches



$\underline{u} = [u_1\ u_3]^T;\ \underline{u}_B = [u_{B1}\ u_{B3}]^T;$

$\underline{u}^0 = [u_1^0\ u_3^0]^T;\ \underline{i} = [i_1\ i_3]^T$

Fig. 3: Block diagram of the continuous time part

are expressed by the nonlinear block MA. This block is defined by (4) - (10) and consists of multipliers and adders (MA-net). For simulation it is sufficient to take only two phases of the ac side of the converter into consideration.

B. Discrete event part

The discrete event part of a power electronic model (Fig. 1b) describes the switching sequences of the network. The power electronic converter of Fig. 2 contains 6 thyristors. Therefore, $2^6 = 64$ different switching states are possible. In the normal operation mode (symmetric voltage sources, symmetrically fired thyristors, small commutation reactors, no multiple commutations) this number is reduced to 13 states.

The dynamic switching behavior of a power electronic circuit can be modeled by a state diagram, which visualizes the switching sequences. Fig. 4 shows the state diagram for the considered three phase bridge in the normal operation mode. A state is represented by a circle and characterized by the conducting thyristors. In state 1 the valves T1 and T6 (see also Fig. 2) are switched on. A transition from state 1 to state 7 is only possible, if the event e_{71} occurs. An event is depicted by a line with an arrow.

The graph of Fig. 4 can be transformed into nonlinear binary difference equations:

$$\begin{bmatrix} w_1 \\ \vdots \\ w_{13} \end{bmatrix}_{k+1} = \begin{bmatrix} e_{11} & \cdots & e_{113} \\ \vdots & & \vdots \\ e_{131} & \cdots & e_{1313} \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ \vdots \\ w_{13} \end{bmatrix}_k \qquad (11)$$

or

$$\underline{w}_{k+1} = \underline{E}\left(\underline{r}, \underline{p}\right) \underline{w}_k \qquad (12)$$

In (11) the variables w_1 to w_{13} represent the 13 switching states of the systems. State 1 is characterized by $w_1 = 1$ and $w_i = 0$ ($i = 2, \ldots 13$). The binary event variables e_{ij} ($i = 1, \ldots, 13$; $j = 1, \ldots 13$) depend on the vectors $\underline{r}$ and $\underline{p}$ (Fig 1b) and can be determined, if the components of the vector $\underline{q}$ are given (Fig. 2):

$$\underline{q} = \left[u_{v1}, \cdots u_{v6}, i_{v1} \cdots i_{v6}\right]^T \qquad (13)$$

This vector is transformed via comparators (Fig. 1b) into the binary vector $\underline{r}$:

$$\underline{r} = \left[r_1 \cdots r_6, r_7 \cdots r_{12}\right]^T \qquad (14)$$

The components r_1 to r_{12} indicate the polarity of the corresponding valve voltages and currents. A transition from state 1 to state 7 is only possible (Fig. 4), if

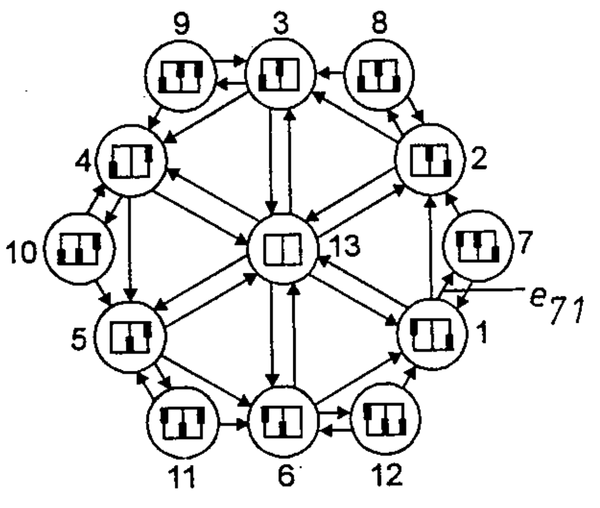


Fig. 4: State diagram of the discrete event part (▬ conducting, — nonconducting valve)

- the valve T1 is conducting ($i_{v1} > 0 \rightarrow r_7 = 1$) and
- the valve T2 is blocking ($u_{v2} < 0 \rightarrow r_2 = 0$) and
- the valve T2 is fired ($p_2 = 1$).

Therefore, the event variable e_{71} is determined by

$$e_{71} = r_7\left(1 - r_2\right) p_2 \qquad (15)$$

If the conditions mentioned above are fulfilled, the variable e_{71} becomes $e_{71} = 1$, otherwise it remains $e_{71} = 0$.

With analogous considerations all other event variables can be calculated. The most elements of the event matrix $\underline{E}$ are zero due to the graph of Fig. 4.

C. BA-interface

The BA-interface determines the switching vector $\underline{v}$, which depends linearly to the state vector $\underline{w}_k$ and carries out the switching operations in the continuous time part:

$$\underline{v} = \underline{F}\, \underline{w}_k \qquad (16)$$

Now it is shown, how the elements of the (10 x 13)-matrix $\underline{F}$ can be calculated.

In switching state 1 (Fig. 4) the thyristors T1 and T6 connect the dc load to the terminals 1 and 3 of the three phase voltage source. From the terminals 1^0, 2^0 and 3^0 (Fig. 2) we see the network of Fig. 5. Due to (2) the RL-elements obtain the same time constants. Therefore, it is possible to determine all valve voltages and currents with respect to (5) and (7)

$$u_{v1} = 0 \qquad (17)$$

$$u_{v2} = u_{12}^0 - \left(L_K / L_d + 2\, L_K\right)\left(u_{12}^0 + u_{23}^0\right) \qquad (18)$$

$$u_{v3} = u_{v4} = \left(L_d / L_d + 2\, L_K\right)\left(u_{12}^0 + u_{23}^0\right) \qquad (19)$$

$$i_{v1} = i_1 \qquad (20)$$

$$i_{v3} = 0 \qquad (21)$$

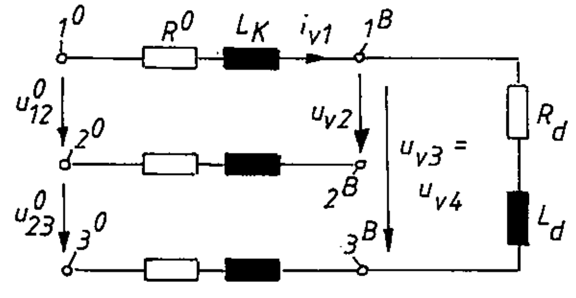


Fig. 5: Calculation of valve voltages in state 1

From (17) - (21) the switching variables v_1 to v_{10} can be derived. Then the elements of the first column of matrix $\underline{F}$ are described by

$$\begin{bmatrix} f_{11} \\ f_{21} \\ f_{31} \\ f_{41} \\ f_{51} \\ f_{61} \\ f_{71} \\ f_{81} \\ f_{91} \\ f_{101} \end{bmatrix} = \begin{bmatrix} 0 \\ \left(L_d + L_K\right) / \left(L_d + 2\,L_K\right) \\ L_d / \left(L_d + 2\,L_K\right) \\ L_d / \left(L_d + 2\,L_K\right) \\ 0 \\ -L_K / \left(L_d + 2\,L_K\right) \\ L_d / \left(L_d + 2\,L_K\right) \\ L_d / \left(L_d + 2\,L_K\right) \\ 1 \\ 0 \end{bmatrix} \qquad (22)$$

The other switching states represented by the other colums of $\underline{F}$ can be determined in the same way [7].

IV. SIMULATION

The presented modeling concept is tested by digital simulation. Fig. 6a shows the dynamic behavior of the considered bridge rectifier changing from the rectifying mode into the inverter mode. If the firing angle α is switched from 0° to 150°, the load voltage u_d changes its polarity. When the load current i_d becomes zero the bridge converter is blocking.

Fig. 6b shows the system behavior, if the firing angle is changed from 0° to 165°. Now inverter instability occurs twice, because the commutation voltage is too small.

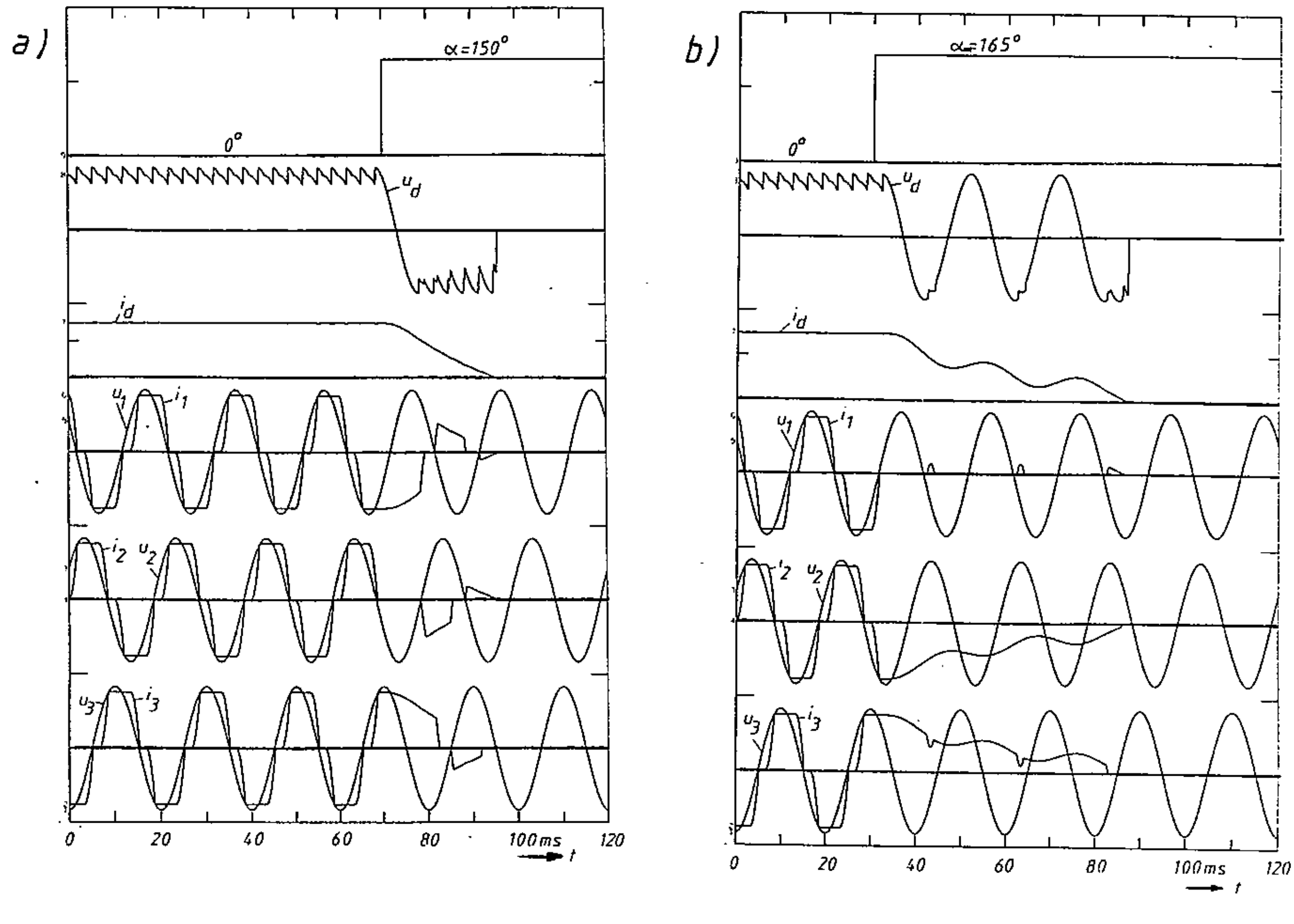


Fig. 6: Bridge changes from rectifier into inverter mode
a) without inverter instability
b) with inverter instability

The presented simulation concept describes exactly the system behavior in the normal operation mode. To study the power electronic circuit also under abnormal conditions as well, all 64 switching states must be taken into consideration. Then 64 x 64 = 4 096 events occur and the dimensions of the matrices $\underline{E}$ and $\underline{F}$ increase. This effect can be avoided by two measures:

- Until now, the thyristor bridge of Fig. 1a is considered as a six switch system (Fig. 4). If the circuit is decomposed into six subsystems of one thyristor, only 2 x 2 x 6 = 24 events occur, i.e. in the 12 x 12-matrix $\underline{E}$ 24 elements are different from zero.
- Until now, the switching vector $\underline{v}$ is precalculated and stored in the columns of the matrix $\underline{F}$ (section III.C). If this procedure is replaced by an online calculation, the matrix $\underline{F}$ is no more necessary. The vector $\underline{v}$ can be determined out of a linear algebraic equation system with constant structure. More details are given in a later paper.

These modifications allow the simulation of power electronic circuits with high pulse number. The program architecture is simpler than in the widely used EMTP [12]. Here, all semiconductor valves are modeled by ideal mechanical switches. Due to the variable structure representation of power electronics the network equations have to be modified after each switching operation.

V. CONCLUSION

A power electronic converter can be defined as a hybrid system consisting of two types of dynamics: continuous time dynamics and discrete event dynamics. Both dynamic parts communicate via static interfaces. The above model structure allows a systematic description of all types of power electronic circuits. The system equations are visualized by a block diagram for the continuous time part and by a state diagram for the discrete event part. These graphs can easyly be interpreted and give detailed insights into the complicated signal flow of the system.

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