Modelling and Simulation of Locomotives with Traction Induction Motors and Three Levels Converters

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Abstract: - The paper describes the mathematical models and structural diagrams of the three levels voltage-source inverter and line-side converter used on the locomotive fed from AC line. The overall structural diagram construction for the principle schemes corresponding to modern locomotives is also presented. At the end are shown the simulated waveforms of the three levels converters.

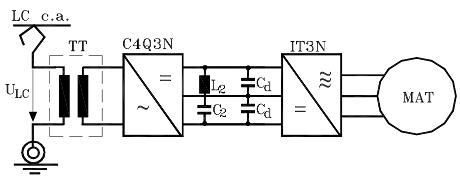
Key-Words: - modelling, locomotive, electric traction, three levels converters, simulation

1 Introduction

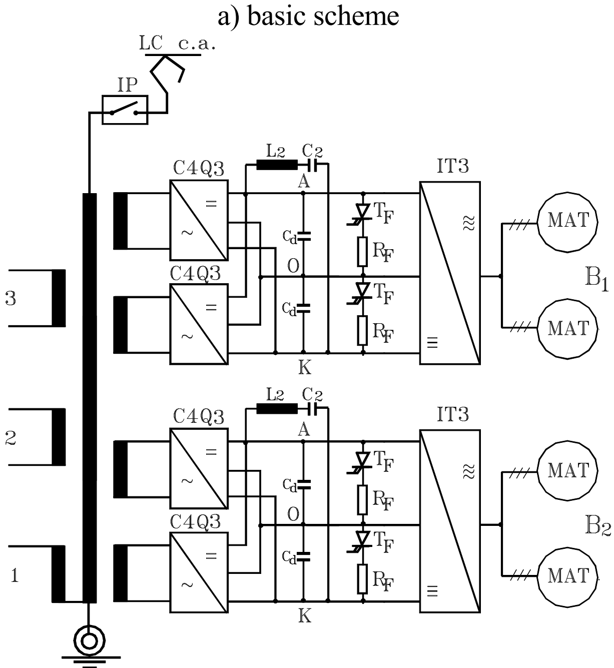
Utilization in the electric traction of the induction motor with squirrel cage it is possibly only in this feeding condition with a three-phase system by voltages of amplitudes and frequency controlled variable. This feeding type it is achieved by means of machine-side converter (CM), usually a voltage-source inverter (IT) with two or three levels (Fig.1,a).

As a rule, the main electric circuits of modern locomotive (Fig.1) ensure two conversion stages of the electric energy, the first being achieved by line-side converters and the second, by machine-side converters [1], [2], [3]. In the case of AC- line supply, the line-side converter is a four-quadrant converter (C4Q) with two (2N) or three levels (3N), associated to a voltage-source inverter (IT3N), which represents the machine-side converter (Fig.1). The modelling of such line-side converters can use the switching functions method, which offers a high generality degree.

As far as the model implementation into simulation software is concerned, the switching functions approach presents the advantages of reduced simulation time and good convergence. For three levels converters, the switching functions with three levels f_{3w} [4], [5] are used. For the modelling of different converter structures by means of switching functions, it has been considered that the switching devices are ideal, by neglecting the commutation time and forward voltage drop. Such a converter is considered ideal (without losses).



a) basic scheme



b) B_0B_0 locomotive main electric circuits

Fig.1 Basic scheme and main electric circuits used in modern locomotives with three levels converters

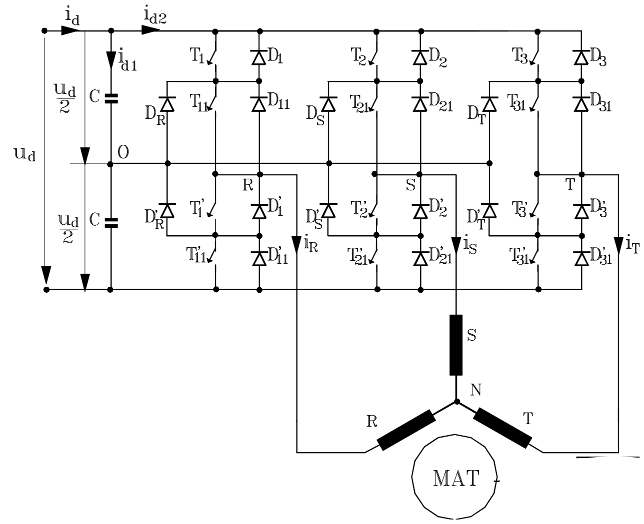


Fig.2 Three-phase voltage-source inverter with three levels (IT3N)

2 Modelling of the Machine-Side Converter

For the modelling of the machine-side converter, that being the three levels voltage-source inverter, they are used the commutation functions with three levels [5], [6]. From viewpoint of modelling, any static converter it can be approached like a "black box" with input/output characteristics through the commutation functions intermediation. For the different structures modelling of converters by means of commutation they have been considered that the used semiconductor devices they are ideally, they are neglected both the commutations times and the voltage drop at conduction in forward direction. Such converter is ideal and it is considered without losses.

For modelling of three-phase voltage-source inverter with three levels (Fig.2) it is considered the ideal case, at which two identical capacitors they divide in equal mode the constant voltage u_d.

For modelling they are used the commutation function with three levels ”f_{3w}”:

$$f_{3w\,R,S,T} = \begin{cases} +1, & T_i, T_{i1}\,(I) \\ 0, & T_{i1}, T_i'\,(I) \\ -1, & T_i', T_{i1}'\,(I) \end{cases} \quad , \quad i=1,2,3 \tag{1}$$

Analysing the topology of three-phase voltage-source inverter with three levels (Fig.2) they can be written the equations:

$$\begin{gathered} u_{RO} = \frac{u_d}{2}\cdot f_{3wR};\; u_{SO} = \frac{u_d}{2}\cdot f_{3wS};\; u_{TO} = \frac{u_d}{2}\cdot f_{3wT}; \\ i_{d2} = i_R\cdot f_{3wR} + i_S\cdot f_{3wS} + i_T\cdot f_{3wT}; \\ u_{RN} = u_{RO} - u_{NO};\, u_{SN} = u_{SO} - u_{NO};\, u_{TN} = u_{TO} - u_{NO}; \\ u_{NO} = \frac{u_{RO} + u_{SO} + u_{TO}}{3}; \end{gathered} \tag{2}$$

On these equations basis, it is obtained the structural diagram of three-phase voltage-source inverter with three levels (Fig.3). This model have comprised in their structure the MAT traction induction motor model (both the electromagnetic part and mechanic part) [2], [6], the link with this making through the voltage ($\underline{u}_s$) and respectively by the stator current ($\underline{i}_s$) space phasors.

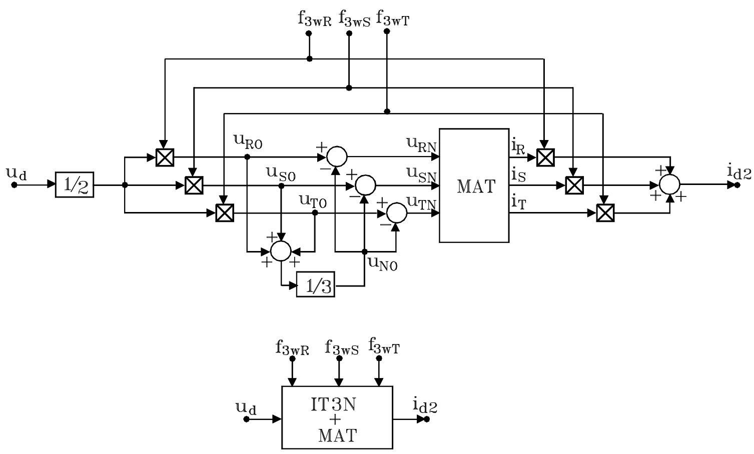


Fig.3 Structural diagram and mask block for three-phase voltage-source inverter with three levels

3 Modelling of the Four-Quadrant Line-Side Converter

In order to obtain the mathematical model of the four-quadrant line-side converter with three levels (Fig. 4), the following switching functions are used:

$$f_{3wA}=\begin{cases}+1, & T_1, T_{11}(I)\\ 0, & T_{11}, T_1'(I)\\ -1, & T_1', T_{11}'(I)\end{cases};\quad f_{3wB}=\begin{cases}+1, & T_2, T_{21}(I)\\ 0, & T_{21}, T_2'(I)\\ -1 & T_2', T_{21}'(I)\end{cases} \qquad (3)$$

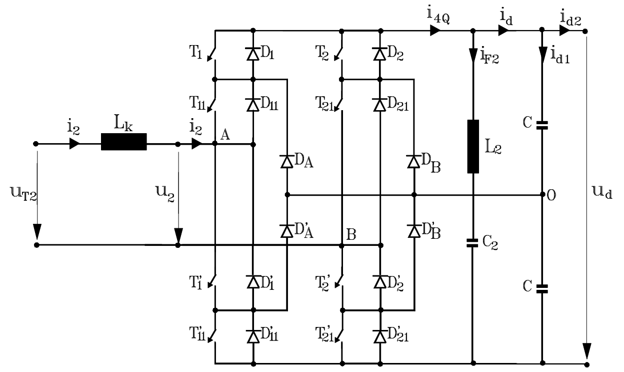


Fig.4 Structure of the four-quadrant line-side converter with three levels C4Q3N

By means of these functions, the following voltage and current expressions, respectively, can be written:

$$u_{AO}=\frac{u_d}{2}\cdot f_{3wA};\quad u_{BO}=\frac{u_d}{2}\cdot f_{3wB}$$
$$u_2=u_{AB}=u_{AO}-u_{BO}=\frac{u_d}{2}\cdot(f_{3wA}-f_{3wB})=\frac{u_d}{2}\cdot f_{3wAB} \qquad (4)$$

$$i_{4Q}=i_2\cdot f_{3wA}-i_2\cdot f_{3wB}=i_2\cdot(f_{3wA}-f_{3wB})=i_2\cdot f_{3wAB} \qquad (5)$$

With reference to the electric circuit of Fig.4, the following equations can be added to (4) and (5):

$$u_{T2}=L_k\cdot\frac{di_2}{dt}+u_2$$
$$i_{4Q}=i_{F2}+i_d;\quad i_d=i_{d1}+i_{d2}$$
$$u_d=L_2\cdot\frac{di_{F2}}{dt}+\frac{1}{C_2}\cdot\int i_{F2}\,dt \qquad (6)$$
$$i_{d1}=\frac{C}{2}\cdot\frac{du_d}{dt}$$
$$u_2=\frac{u_d}{2}\cdot f_{3wAB};\quad i_{4Q}=i_2\cdot f_{3wAB}$$

Based on the above system of equations, the structural diagram and mask block of the four-quadrant line-side converter with three levels are obtained in Fig.5. The input quantities are:

- u_{T2}, the voltage from the transformer secondary;
- i_{d2}, the input current from the inverter (machine-side converter);
- the switching functions, which allow the four-quadrant operation control of line-side converters, being generated by the traction control system. The DC-link voltage u_d represents the output quantity for the four-quadrant line-side converters and, in the same time, the input quantity for the inverter (machine-side converter) model.

4 Structural Diagrams for AC Locomotives

With the obtained structural diagrams, as well as the mask blocks of other components of the main electric circuit, it is possible to build the structural diagrams for the modern locomotives fed from AC contact line having the main circuit schemes given in Fig.1.

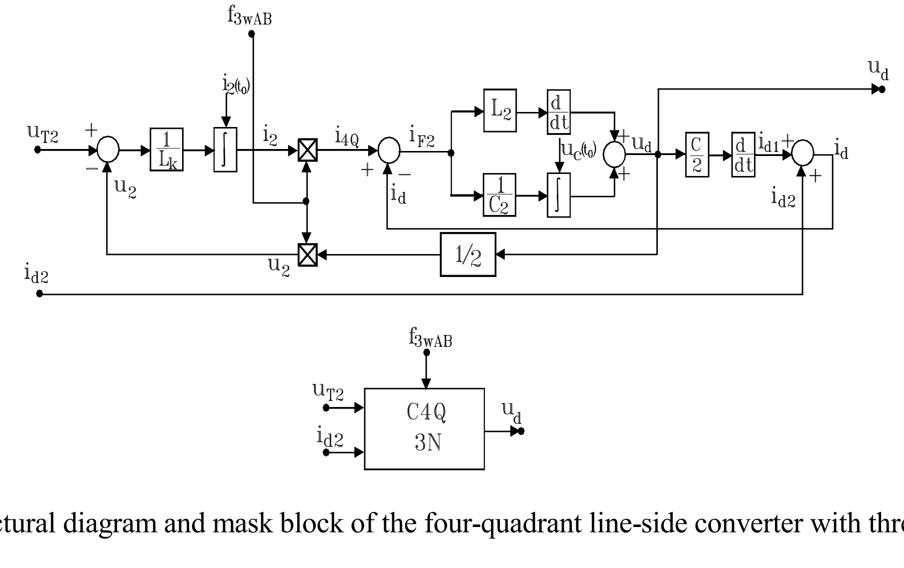


Fig.5 Structural diagram and mask block of the four-quadrant line-side converter with three levels

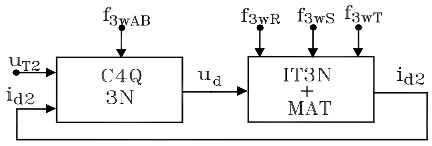


Fig.6 Structural diagrams
of the main electric circuits of Fig.1 a)

The locomotives with traction induction motors fed from the AC contact line they have obligatory two conversion phases, through the existence of network converter (four quadrant converter). The basic scheme modelling of the traction induction motor feeding (Fig.1., a) it can make easily by means of the mask blocks of the four quadrant converter with three levels („*C4Q3N”*) and of the voltage-source inverter fed traction induction motor („*IT3N+MAT”*) [2], [6]. It is obtained thus the structural diagram (fig.6) having like input variables the u_{T2} (voltage from the transformer secondary) as well as the switching functions of those two converters. The output variables can be considered anything among variables from the mask blocks inside, depending on the studies regime or the possibly connections with other sub-systems.

For the structural diagram construction of the entire main circuit, corresponding to a high-speed train (Fig.7), the previous diagram it is multiplied of four time (the total numbers of motors) and they are written the proportionality relations what they describe the traction transformer working. For the identification of the blocks and of the quantities corresponding to those four traction secondary they have been used superior indexes. Like input and output variables they have been considered those which interact with the contact line, the u_{LC} voltage and the i_{LC} current absorbed by the train. For obtainment of this from behind, given the previous cases, it was necessary the utilization, from the four quadrant converters inside, of the $i_2^{(i)}, i = 1,4$ currents from the traction transformers secondary.

5 Simulink Model

Based on the presented structural diagram (fig.6), its SIMULINK model has been achieved, as shown in Fig.8. They are obtained the identical SIMULINK model from viewpoint topology with associated structural diagram.

Using this SIMULINK model (Fig.8), the operation of a four-quadrant line-side converter together with a voltage-source inverter with two levels and a traction induction motor has been simulated (fig. 9).

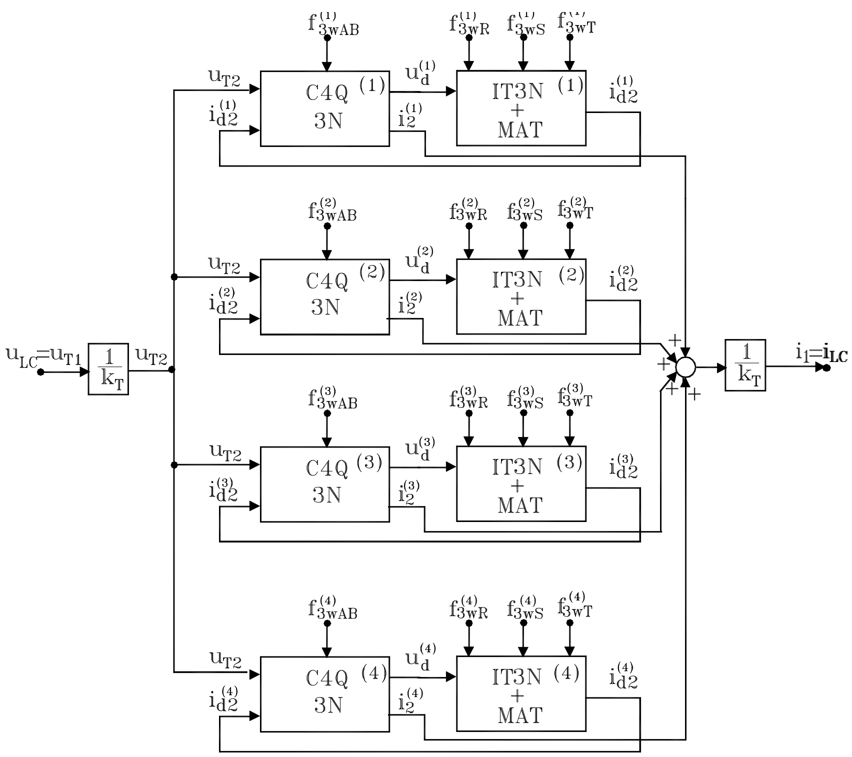


Fig.7 Structural diagrams
of the main electric circuits (B_0B_0 locomotive)

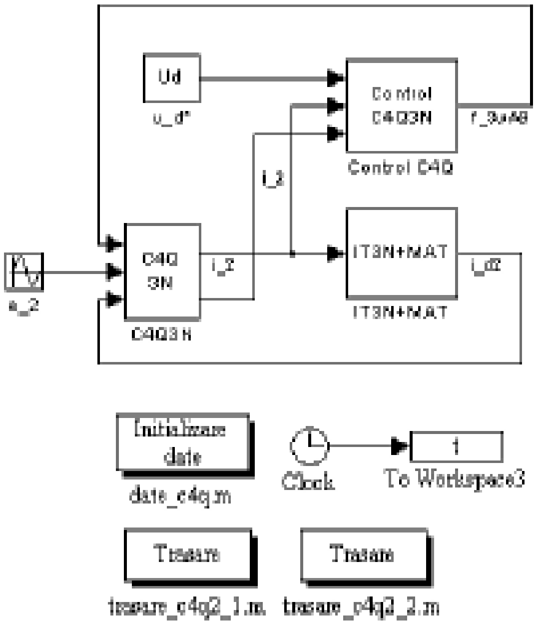


Fig.8 SIMULINK model
of the main electric circuits of Fig.1 a)

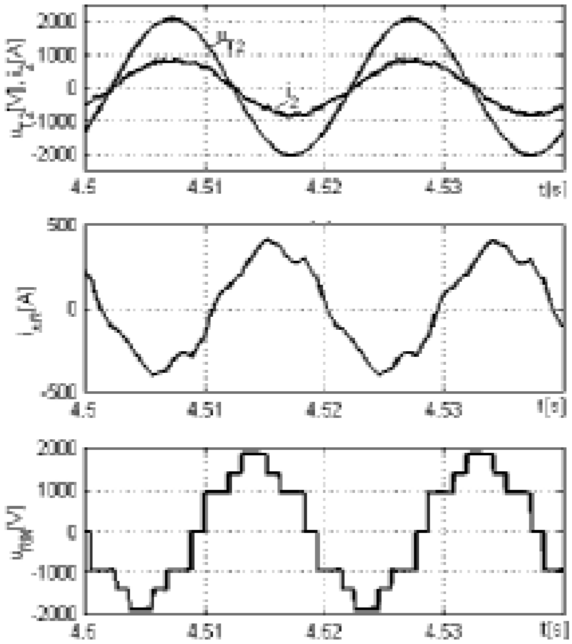


Fig.9 Waveforms of simulated system quantities

6 Conclusions

The imposed specific features of the utilization in electric traction of equipments used in modern locomotives fed from AC contact line can be studies by means of the simulation. In this context it is necessarily a mathematical modelling consorted of the structural diagrams obtainment what permit the immediate implementation within the framework of a simulation soft like MATLAB- SIMULINK. With the obtained structural diagrams, as well as the mask blocks of other components of the main electric circuit, it is possible to build the structural diagrams for the locomotives with traction induction motors fed from AC contact. It is observed the facile modality by achievement of the structural diagram corresponding to a complex circuit from viewpoint topology. Otherwise, it is achieved a construction on four levels, easy to study modified and implemented in a simulation soft like MATLAB-SIMULINK. It is possibly, the integration of this diagram in to another more complex, how it would be that which it is studied the interaction between the traction substation and motor electric vehicles, too.

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