Single/Three-Phase Transformer with Variable Frequency for Electric Locomotives

Berzan Vladimir*, Ermurachi Iurie*, Ivanov Sergiu†

* Institute of Power Engineering, Chişinău, Republic of Moldova, berzan@ie.asm.md, ermurachi.iurie@ie.asm.md
† University of Craiova, Department of Electromechanics, Environment and Industrial Informatics, Craiova, Romania, sergiu.ivanov@ie.ucv.ro

Abstract **- Electric rail transport is positioned as environment-friendly technology that has good future prospects for development. The supply of electric rail transport from DC or AC power lines requires the use of specialized transformers that form the three-phase system in the low-voltage circuit to power this load. Solid State Transformer (SST) are very attractive for use in power systems of electric locomotives. This paper examines a new architecture for the realization of SST transformers for their use in power systems of electric locomotives. The proposed SST transformer has the bidirectional high-frequency power transmission capability and at the same time ensures multiplication of phases in the low voltage circuit. The SST transformer is a single-phase / three-phase transformer, which can be supplied both from the high-voltage DC power network and from the AC network frequently used in electric rail transport. Changing the power supply type (of the current) does not lead to changes in the topology of the SST. The transformer is designed as an object made of identical functional modules. The ferromagnetic core is made of separate portions for each functional module. This simplifies the problem of ensuring the electrical stiffness of the transformer. The transistors of the module operate at variable switching frequency, have soft switching mode. Energy conversion takes place in a single step. This ensures that losses are diminished and transformer efficiency is increased in all load regimes. Mathematical simulations have confirmed that this transformer has a very low impact on the power supply, whether the power supply is DC or AC. Under-load operation of the SST transformer does not lead to pollution of the power supply network with higher current harmonics.**

Cuvinte cheie: *transport electric feroviar, transformator electronic, construcție modulară, multiplicarea fazelor, frecvența de comutare variabilă, impact redus asupra rețelei de alimentare.*

Keywords: *electric railway transport, electronic transformer, modular construction, phase multiplication, variable switching frequency, low impact on the power supply.*

I. Introduction

The flexibility of transmission and distribution of electricity provides advantages in terms of its use in various branches of the economy. Today's electrified transport is an environmentally friendly solution, which leads to the expansion of its use both in urban areas and in interurban transport.

Rail electrical transport has a fairly long history and is a major consumer of electricity. The propulsion system can be supplied from the DC or AC mains. As a physical infrastructure for the supply of electric locomotives, the single-conductor contact line is used [1]. The working voltage of electric motors the locomotive differs greatly from the nominal voltage of the supply network. The applied voltage at the motor terminals depends very much on the train speed [1-3].

The locomotive engines must to operate stable, when is adjustable the supply voltage value (either DC or AC) [1, 2], and the power supply system has the possibility to recover the train braking energy [4, 5]. The operating mode of the traction motor must have a small impact on the currents distortion from power supply network [6]. It is also necessary to ensure the compensation of the reactive power of the traction motors in all their operating modes.[7], etc.

The need to meet complex requirements to the traction drive system leads to the use of several stages transformation parameters of the electrical energy, which influences the final energy efficiency of the locomotive propulsion system.

In the European Union (EU), the electrified rail transport [8, 9] is developing in the hardening and intensification of transport corridors. The implementation of these measures also includes the development of the power supply infrastructure based on innovations. The implementation of innovative solutions ensures the increase of the energy performance of the electric transport by diminishing the negative impact of the transport units on the environment [8].

Power electronics can provide obvious advantages in addressing the issue of increasing energy efficiency in electric transport [10-13]. This increase in energy efficiency and the increase of technical and economic indices is also characteristic of medium voltage power distribution networks [14-19], when using of the equipment at the power electronics based.

The variation of the nominal voltage values of the single-conductor contact lines (3 kV of direct current [20], 25 kV (50 Hz) [20, 21], 15 kV (16 Hz) [21] of alternating current), to creates of the difficulties in designing and using electric locomotives in different areas of electrified railways. The use of bi-system locomotives [20, 21] leads in part to overcoming these difficulties. However, these solutions can not ensure the compatibility of electric locomotives with all existing power systems.

The use of PWM technology in electrical converters ensures not only increased energy efficiency of AC and DC motors, but also solves the problem of the compatibility of electric locomotives with AC and DC power supply systems with different value of the nominal voltage.

The purpose of this paper is to explain and to argue the solution of realization of the power supply system of asynchronous motors with three phases of the electric locomotives from contact line of alternating current or the contact line of direct current with the single conductor with the adjustment of the frequency of the supply current of locomotive motors according to the speed of the train.

II. The Proposed Technical Solution and the Transformer Operation principle

Power transformers are a basic functional element in power systems. Transformer manufacturing technology is predominantly geared to their operation at the 50 or 60 Hz frequency, and in the case of the electrified rail transport at the frequency of $16\frac{2}{3}$ Hz, for example in some countries (Austria, Sweden, etc.) [21]. At these frequencies, the mass and volume of the transformers are quite considerable.

The development of new materials with high ferromagnetic properties, the performances in the field of power electronics can provide an essential diminution of the mass, volume and cost indices per installed power unit of the power transformers. At the same time, these constructive solutions provide other advantages, such as: the cumulating of the functions of transforming the alternating voltage parameters and multiplying the number of phases in the supply circuits of the asynchronous motors, ensuring the bi-directional energy transfer, transforming the parameters and converting the electric power into one stage, the diminution of the negative impact on the network [22, 23].

A. Electrical Equivalent Scheme of Single/Three Phase Transformer

Depending on the type of electric motors used in the propulsion system of electric locomotives, the traction transformer supplies the rectifier or also performs the phase multiplication function in the secondary circuit. The bi-system supply schemes can be considered as variable topology systems since, depending on the parameters of the contact line, the supply scheme of the circuit of propulsion motor is changes.

Phase multiplication is required when supplying asynchronous motors. This reduces the gauge, mass and cost indices of the filter system components. In this topology of the propulsion engine power supply scheme, two advantages are achieved: the use of the single-phase supply system (use of the single-conductor contact line) and three-phase AC motors.

Reaching these advantages is possible when designing the traction transformer as a Solid State Transformer (SST). When designing SST transformers, it is necessary to take into account the electrical rigidity of the insulation and the voltage values applied to the active and passive electronic components.

Ensuring the electrical stiffness of the SST transformer (as well as traditional transformers) is the fundamental issue that needs to be solved when designing them equipment of this kind. The need to meet the requirements for electrical rigidity of the transformer leads us to the modular solution of manufacturing of the SST transformer. The modular concept of power equipment manufacture can ensure compliance with the requirements of electrical rigidity, improved heat evacuation from active and passive components, as well as facilities for fixing the electronic switching devices of SST windings.

The quality and parameters of modern transistors allow them to be used as electronic devices ordered with the high value of the operation current. The concept of manufacturing the SST transformer from identical modules also has a beneficial economic aspect. Making of the transformer from the identical modules leads to a reduction in the manufacturing costs of the modules and thus of the transformer. In Fig. 1 shows the equivalent electrical scheme of the SST-type transformer with power supply from both the DC voltage network and the AC supply network, which may have different frequencies, e.g., 16.7, 50 and 60 Hz. This ensures high compatibility of proposed SST transformers with existing power supply networks of the electrified railways.

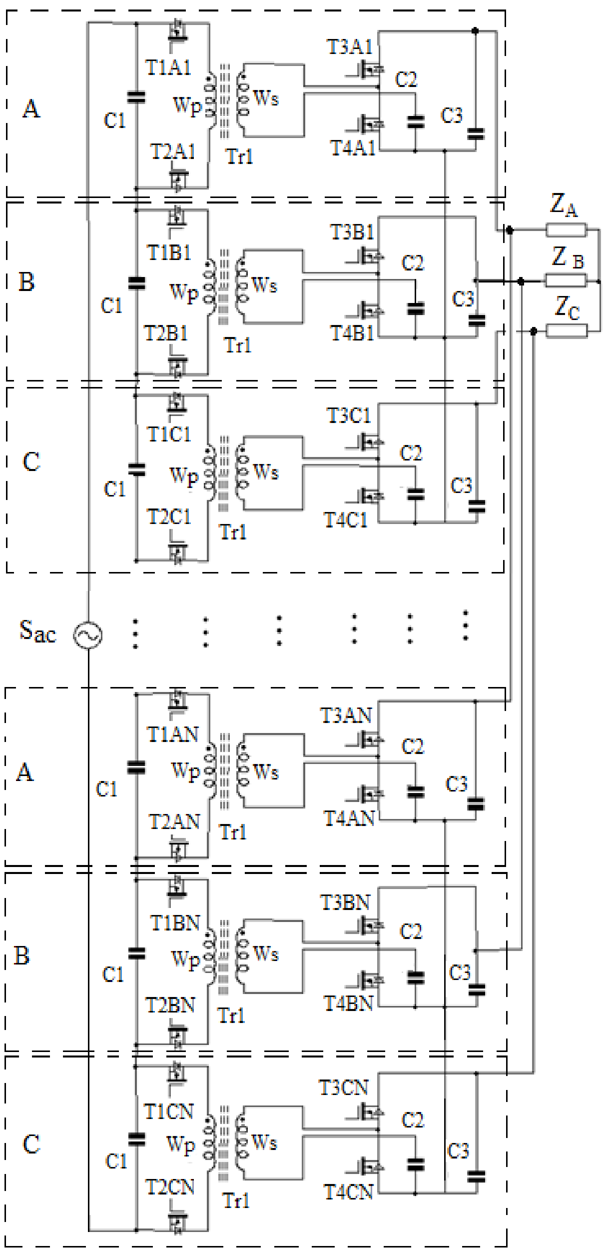

Fig. 1. Equivalent scheme of single-phase/three-phase bidirectional SST.

The high compatibility of the proposed SST transformer, capable of stable operation with different types of contact networks (DC and AC), fully solves the problem of the operation of electric locomotives in the electrified rail systems, which have been designed and constructed according the different requirements of true design standards for the contact network. The economical benefits of the manufacturing solution of SST transformers in the proposed topology can extend beyond the electrified transport branch. Transformers of this type can be used to power equipment and electric machines of different uses, eg household appliances (air conditioners, washing machines, heat pumps, etc.), due to their elasticity of operation with different sources of power, without the use of specialized additional equipment for connecting the supply network and the respective load.

B. Solution for constructive realization of the transformer

The SST transformer is based on the functional modules, which is noted as A, B, and C and which have an identical architecture. The WP primary windings of these modules are connected in series and WS secondary windings of the A, B and C modules which belonging to the secondary circuit are connected in parallel through the bridges formed by the T3, T4 transistors and C2 and C3 capacitors. This connection topology of the modules ensures the connection of the mains voltage and rated voltage of the SST transformers. The clusters of modules, which are more clearly visible for WS winding circuits, will be perceived as phases of the SST transformer.

The transistors T1 and T2 of the modules which form the phases A, B, and C, they work with phase difference equal to 120 degrees electric. The fulfillment of this condition ensures the formation of a three-phase alternating current system, used to supply the asynchronous traction motors of the electric locomotive. Transistors T1 and T2 have the switching function of the primary coils of the SST transformer, which are located on three columns of the ferromagnetic core. The columns and ferromagnetic yokes are spatially located. The ferromagnetic columns formed by the ferromagnetic cores of the Tr1 modules are made with an air space. The columns and modules are spatially located on the vertices of the equilateral triangle (Fig.2). This basic column structure provides minimal consumption of ferromagnetic materials and provides space for mounting the transistors, which features power switching devices.

In Fig. 3 shows the layout scheme of the transformer windings SST, the Wp and Ws coils of the modules groups A, B and C, which form a functional element which we defined as phase. The core of the ferromagnetic core is made of air gap, which is occupied by the electrical insulation of the transformer.

In Fig. 3 the following notations are used in order to explain the constructive realization of the phase of the SST transformer: 1 - the modules connected to the mains supply; 2- the modules that connect to the task; 3- the ferromagnetic elements of the typical modules; 4- electrical insulation between of the typical modules, which is also used to form the air gap in the transformer column Tr1.

The insulation class is determined by the highest voltage value of either the primary circuit or the secondary circuit of the SST transformer. In the transformer being examined, this is the voltage of the AC power supply.

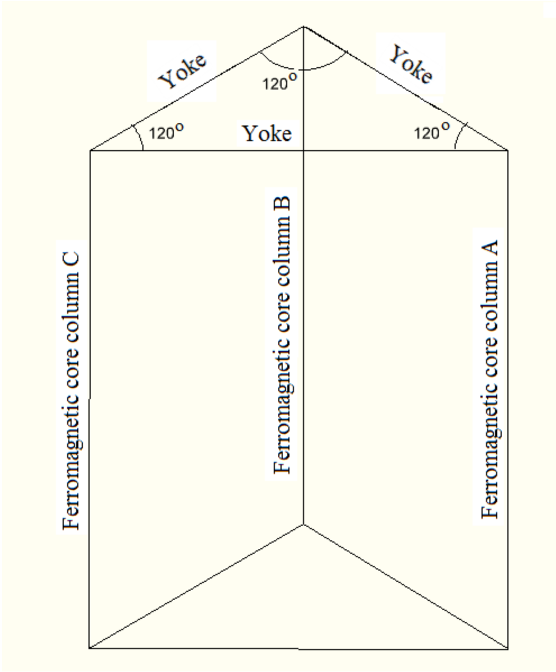

Fig.2. Schematic of the spatial location the columns of the ferromagnetic core of the SST transformer.

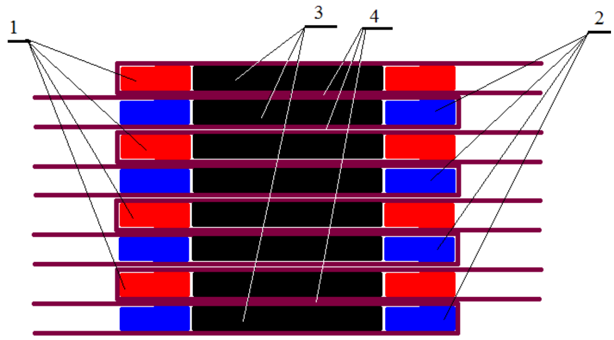

Fig.3. The scheme of placed the coils of the SST transformer phase on the ferromagnetic core column.

The use of the concept of manufacturing the SST transformer from typical unitary modules also has an advantage, which is the possibility of using different dielectric materials to ensure electrical rigidity. Thus, the air gap can be formed as a result of the use electrical isolation of the unit modules. The air gap has the dimensions of the electrical insulation thickness of the modules, which are mounted vertically, forming the respective columns of the ferromagnetic core of the transformer.

For the formation of the transformer insulation system, rigid mechanical materials can also be used. These structural elements can be made from both organic and non-organic insulating materials. Since the voltage applied to the winding terminals is the proportionally distributed to the number of the unit modules, it is possibilities of the use standard insulating components may be used, which are manufactured in accordance with the permissible working voltage of the transistors of the modules. The use of standard insulating elements leads not only to the simplification of the SST transformer assembly technology, but also to the reduction of manufacturing costs.

As standard components can be used when designing modules, there is a possibility to use different types of insulation, including industrial-grade ceramics. The type of ferromagnetic material used depends on the switching frequency of the transistors of the SST transformer. At frequencies up to 5 kHz, it is reasonable to use traditional ferromagnetic materials (electro technical steel). At higher frequencies the multicomponents crystalline ferromagnetic materials with high magnetic characteristics are competitive for the manufacture of transformers with high performance indices.

The energy transfer between the Wp primary windings and the W_S secondary windings side of the Tr1 transformer takes place at high frequencies. This reduces the mass, volume and consumption of active materials in the SST transformer (copper, ferromagnetic materials, insulation).

The switching of the transistors takes place in soft switching mode at variable frequencies of the PWM regime. As a result, energy losses in the transistors of the modules are reduced. This leads to a reduction in total energy losses in the converter, which contributes to increasing the energy efficiency index of the SST transformer [24].

C. The control algorithm of transistors of the SST transformer

The modular units A, B, C of the electronic transformer is including the primary circuit and the secondary circuit. The primary circuit from consists of the capacitors C1, transistors T1, T2 and Wp coils. The secondary circuit consists of WS coil and T4 (Fig.1), capacitors C2, C3 and transistors T3.

The alternative single-phase voltage is applied to the transformer input. Transistors T1A1, T2A1; T1B1, T2B1; T1C1, T2C1; ...; T1AN, T2AN; T1BN, T2BN; T1CN, T2CN belong to the functional modules which is the noted A, B and C. The T1 transistors work on the positive alternation of the input voltage, and the transistors T2 on the negative alternation. Transistors T1 and T3 operate synchronously and T4 is closed during this time. When closing transistors T1 and T3, transistor T4 is the opens.

For the negative alternation the transistors T2 and T4 operate synchronously and the transistor T3 is closed. The T1A1 and T2A1 transistors work in two ways. In the first mode, the transistor operates with a variable switching frequency. This PWM mode lasts 240 electrical degrees. In this 120 electrical degree mode, the transistor is permanently open.

Modules which belonging to groups A, B, and C operate with phase difference equal to 120 electrical degrees.

The three-phase voltage appears on the C3 capacitors of modules A, B and C. In order to form the three-phase voltage on the C3 capacitors, it is necessary that the transistors T3 and T4 be switched according to the law, which is described by the relationship:

$$f_{com} = \left(u_{AB} / U_{m.AB} \right) * f_{PWM} , \tag{1}$$

where: f_{com} - the switching frequency of the transistors in the working cycle with duration of the 240 electrical degrees; $U_{m.AB}$ - is the amplitude of the network voltage of a three-phase secondary circuit (load); u_{AB} - instantaneous value of line voltage of the secondary circuit; f_{PWM} - the switching frequency of the transistors, which is determined by the allowable switching frequency of the transistors used in the primary and secondary circuitry of the electronic transformer.

The law of the control pulse frequency change of the transistors T3 and T4 of the inverter is shown in Fig. 4 (see diagrams of parameter f for modules A, B and C). The control algorithm for the first mode and the second mode of operation of the transistor groups T3 and T4 is illustrated by the diagrams of Fig. 4 (see VT1, VT2 for modules A, B and C).

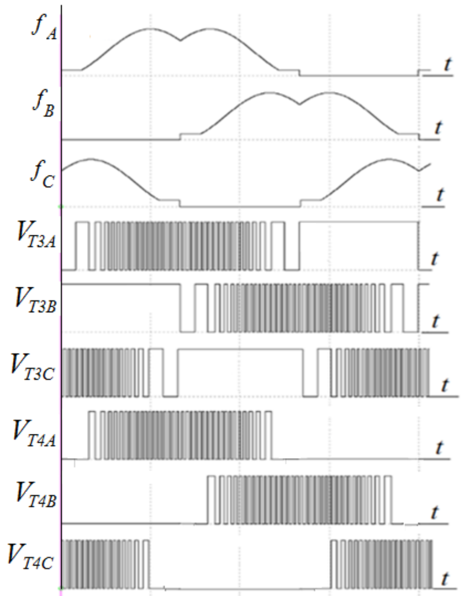

Fig. 4. The law of command pulse generation

The transistors operate at a variable switching frequency for 2/3 time duration from period of the three-phase current of the secondary circuit and the remaining 1/3 from period of the signal, the transistors do not work in the PWM mode. During the second regime the transistors are fully opens. This ensures a reduction of the switching losses for the transistors of the electronic transformer. This is a very important aspect in improving the energy efficiency of this device. As a result, this leads to a decrease in the temperature loads of the module's active and passive elements.

In the electronic transformer (Fig. 1), the bidirectional power transmission of the power flow is ensured in a single step of converting the electric energy. This is a powerful solution for the power supply system of electric locomotives. In the same context, the energy storage capacitors are excluded in the SST transformer. Capacitors C1, C2, and C3 have the function of the filtering of the higher current harmonics, which occur as a result of the switching of the transistors. As a result, the capacity of the capacitors is small, and the low total cost of these capacitors is decided. This is also a factor contributing to the increase in SST transformer performance indices.

D. The principle of operation of the SST transformer

The processes in the SST transformer modules A, B and C are similar, but these processes are time-shifted with phase difference angles equal to 120 electrical degrees. Based on this we will present the description of the working cycle for a module only. The description of the working principle of the SST transformer will be performed for the most difficult mode of operation. This mode corresponds to the instantaneous of the maximum power transfer power value that takes place at the maximum instantaneous voltage value $u_{ac} = U_{m.ac}$ of the source Sac for the positive voltage alternation.

The concept of the switching algorithm of the SST transformer transistors is described in the paper [15]. However, the operation of the proposed single-phase/ three-phase transformer has some peculiarities. In this context we will describe in more detail the working cycle of this transformer. The diagram of the working cycle is shown in Fig.5.

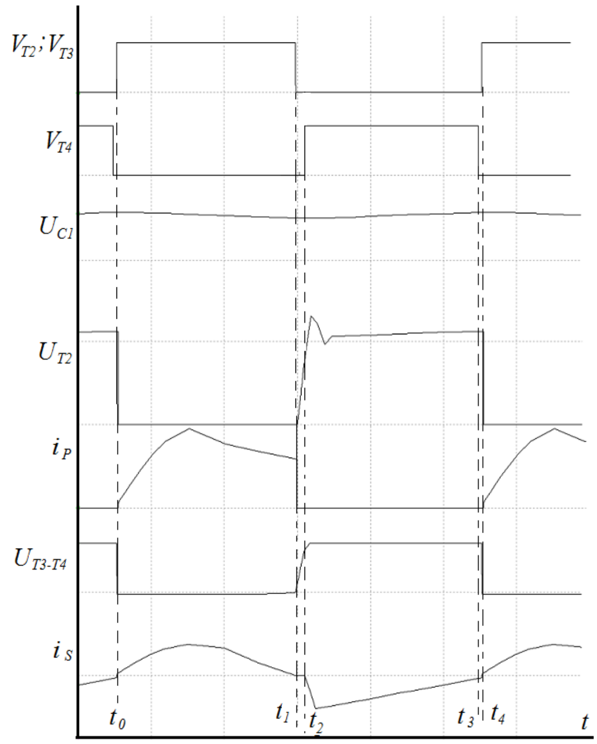

Fig. 5. Diagram of switching processes of transistors of the SST transformer for the zero switching mode (ZCS mode).

In Fig. 3 the following notations of the parameters, which describing the process of operation of the SST transformer are used: V_{T2}-the control pulse applied to the transistor T2; U_{C1}-voltage across capacitor C1 of the primary circuit; U_{T2} - collector voltage of transistor T2; i_p - the current in the primary winding WP coil of the module; UT3-T4 - voltage at the common switching point of the T3-T4 transistors in the secondary circuit; i_s - the current in the WS coil winding.

At the time t_0 is applied control pulse VT2 to transistor T2 the (Fig. 5). At the opening of the transistor T2, at time t_0 (Fig. 5), the circuit is formed: C1- inner diode of the transistor T1-coil Wp-transistor T2-C1. Under the action of the U_{C1} voltage of the capacitor C1 in this circuit, the current i_p in the primary winding Wp of the transformer Tr1 appears. When occurs the current i_p in the Wp winding, as a result of the common magnetic field between the Wp and Ws windings, there is appear of voltage in the Ws winding, which leads to the appears of the current i_s in the circuit WS-T3-C3-C2-Ws. As a result of this process, the energy from the capacitors C1 and C2 is transferred directly to the capacitor C3.

Since the transformer is made with an air gap, the energy accumulation process takes place in the magnetic field of the Tr1 transformer. The direct transfer and energy accumulation process in the Tr1 transformer magnetic field of the modules lasts until the closing of the transistor T2 (see diagram din Fig. 5; time t_1). After time t_1, the voltage across transistor T2 increases. At the equal voltage of the transistor T2 and the capacitor C1 (time t_2) opens the inner diode of the transistor T4. At the same time t_2, the command pulse V_{T4} is applied to transistor T4. As a result, the Ws-C2-T4-Ws circuit is formed, in which the current i_s changing its polarity, and the energy accumulated in the magnetic field of the transformer (predominantly the air gap) is transferred to the capacitor C2. This process takes place up to time t_3. At time t_3, the V_{T4} control pulse of the T4 transistor is removed. Next, at the time t_4, the V_{T2} and V_{T3} control pulses are again applied to the transistors T2 and T3. The energy transfer process in charge is repeated.

In order to exclude the short circuit in the T3 and T4 transistors, the time difference of the closing and opening processes (the times t_3 and t_4) of the T3 and T4 transistors must be greater than the closing time of the transistor T3.

At time t_1, after removing the V_{T2} control pulse, it is observed that the transistor T2 closes at the voltage of the transistor U_{T2} close to zero (Fig. 5). The transistor T2 is connected to the near-zero current (see Fig. 5 for t_0, i_p and U_{T2}). This ensures the absence of shock current leakage through the common circuit of the T3 and T4 transistors as well as the occurrence of overvoltages at the switching of the transistors. Another beneficial effect is that the switching of the transistors to voltage and current close to zero reduces the switching losses during transformer operation, including under load.

III. Simulation the Operating Modes of the SST Transformer

A. Mathematical model of mode simulation

In Fig. 6 it presents the mathematical model of simulation of the operating modes of the SST transformer at its supply from the DC network and the single-phase AC network. We consideration as a reference parameters the voltage of power supply network, which has the value of 25 kV (whether of DC voltage, or the AC voltage with the frequency 16.7 and 50 Hz). The simulations were performed for two types of three-phase asynchronous motors, which have a nominal operating frequency of 50 or 200 Hz.

For the mathematical simulations of the operating mode were selected as controlled parameters: the voltage U and the current I of the input circuit, the voltages and the currents I_a, I_b, I_c of the phases of the three-phase output circuits.

Simulation of the operation mode of the transformer SST was performed in the relative unit system for both the input and output parameters of the SST transformer modeled.

The control impulses of the transistors of the modules of different groups have a phase difference of 120 electrical degrees and form a three-phase system. Depending on the current value of the instantaneous output voltage, the control pulses have variable frequency [14]. The switching frequency of the SST transformer transistors depends on the instantaneous value of the supply voltage of the primary circuit (high voltage). In fact, this moment is a key moment, which explains the non-sensitivity of the proposed transformer to the type of power supply. As a result, we obtain equipment that is indifferent to the type of power supply, whether it is DC or AC.

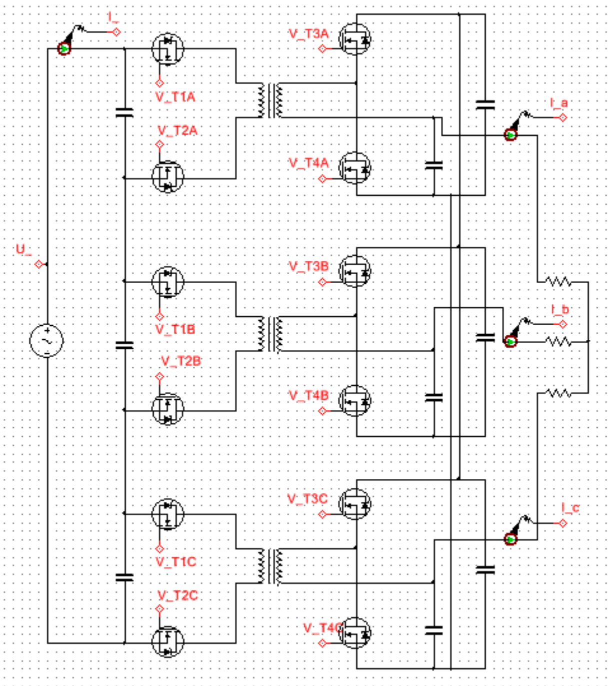

Fig.6. Model for simulating the operation modes of the SST transformer

B. Simulation of SST transformer mode of function at DC power supply

The output frequency of the SST transformer is used as the output parameter. Selecting this parameter is a consequence of the fact that propulsion engines of electrical locomotive operate at variable speeds. This ensures different train speeds according to traffic requirements. When executing the simulations, the law of the asynchronous motor speed control was selected as the law of U / f, where U - the three-phase AC output voltage generated by the SST.

In Fig. 7 and Fig. 8 it presents the diagrams of the currents I_a, I_b, I_c from the phases of the three-phase secondary circuit of the SST transformer, in the case of supplying this transformer from the DC network. These diagrams are constructed for two frequency values of the three-phase output circuit of the SST transformer: 25 and 50 Hz. Note that the output frequency changes slowly depending on the speed of the train movement. The alternating current frequency in the secondary circuit of the SST transformer is regulated in broadband $0 < f < f_{max}$, where f_{max}- is determined by the parameters of the asynchronous motor.

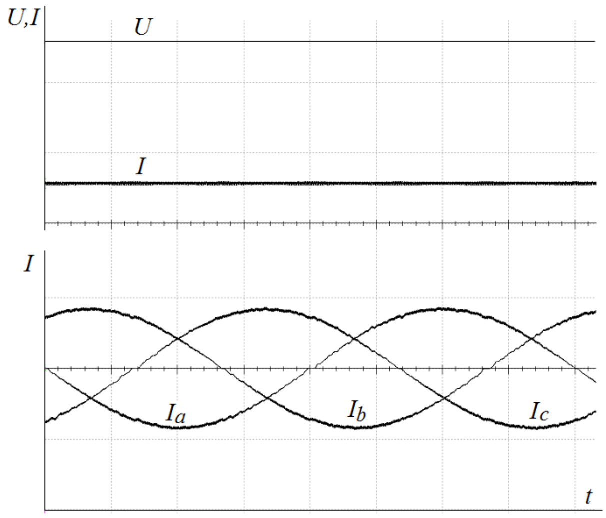

Fig.7. Input voltage U and current I, the output phase currents I_a, I_b, I_c of the SST transformer at the frequency of 25 Hz (relative units)

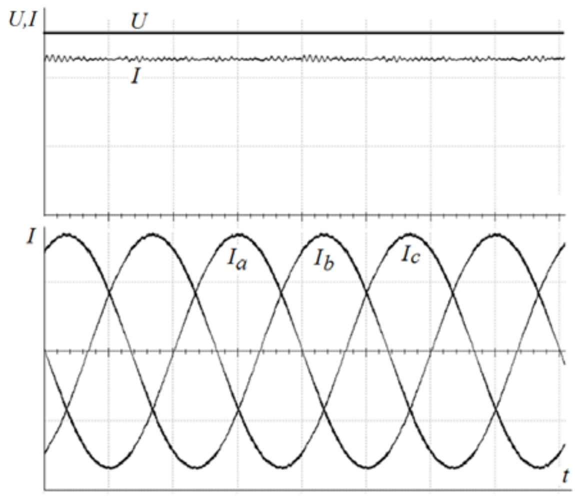

Fig.8. Input voltage U and current I, the output phase currents I_a, I_b, I_c of the SST transformer at the frequency of 50 Hz (relative units)

It can be noticed that as a result of the speed regulation according to the U/f law, the current absorbed by the three-phase asynchronous motor is proportional to the secondary circuit frequency. Increasing the frequency from 25 Hz to 50 Hz leads to a doubling of the stator current and voltage of this motor. The electromagnetic power of the asynchronous motor has increased about 4 times, reflecting of the current increased on the DC network (Fig. 7 and Fig.8). This result is correlated to the principle of ensuring the balance between the asynchronous motor's electromagnetic power and the power absorbed from DC network at the frequency increase of the current in the secondary circuit of the transformer.

At the DC power supply of the SST transformer in the output circuit we have a three-phase symmetric system. This symmetry is preserved for the entire frequency shift band, depending on the train speed. The distortion of the current curve absorbed by the SST transformer from the DC supply network is small and poorly influenced by the load regime for the entire frequency adjustment band in the three-phase output circuit.

C. *Simulation of SST transformer mode of function at AC power supply*

In Fig. 9-11 shows curves of the phase current I_a, I_b, I_c of the SST transformer, when feeding it from the AC power network at 16.7 and 50 Hz. The proposed SST transformer is not susceptible at the changing the frequency in the network supply and can be used in case of power supply of other frequency (random), which are available at the moment. When simulating the operation mode of the SST transformer, in the case of the supply from the single-phase AC network, the law of frequency regulation in the three-phase output circuit determined by the U/f ratio was also used.

In the case of supplying the SST transformer from the single-phase AC power, the values of the three-phase system output currents have variable values, which are determined by the current instantaneous value of the supply voltage. The variation of currents in the output circuit is periodic for all phases (Fig. 9-11) and is determined by the frequency of the primary circuit of the SST transformer.

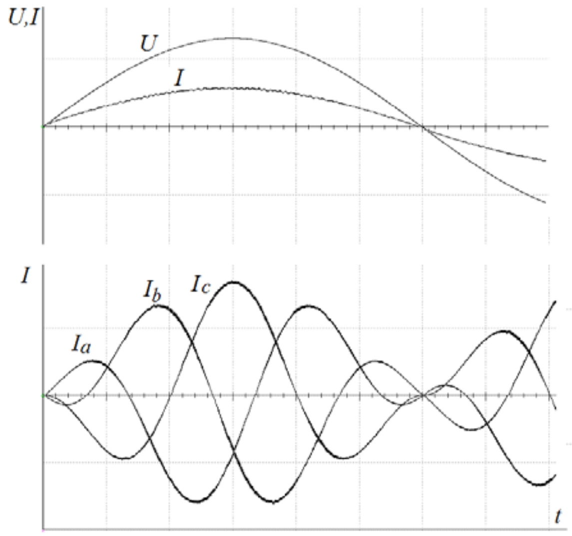

Fig. 9. Input voltage U and current I to SST power supply from single phase AC at 16.7 Hz and the curves of the output phase currents I_a, I_b, I_c, which has of the frequency 50 Hz (relative units)

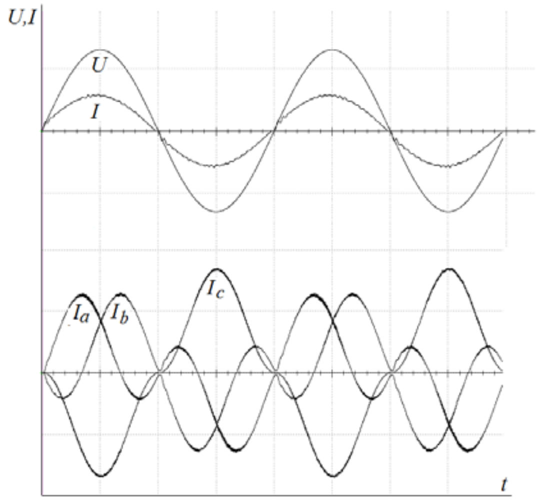

Fig. 10. Input voltage U and current I to SST power supply from single phase AC at 50 Hz and the curves of the output phase currents I_a, I_b, I_c , which has of the frequency 50 Hz (relative units)

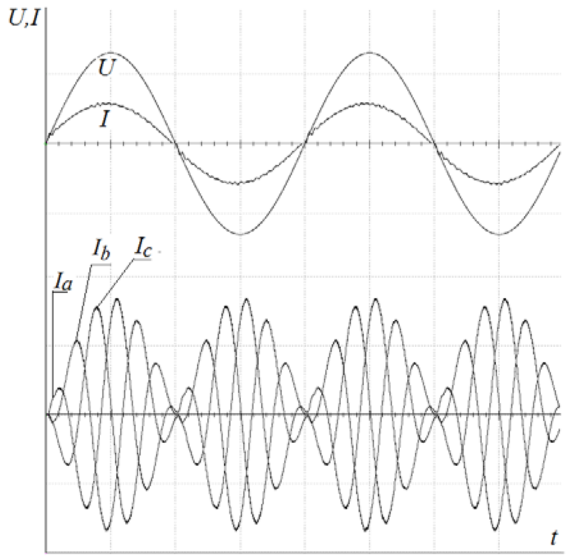

Fig. 11. The input voltage U and current I to SST power supply from single phase AC at 50 Hz and the curves of the output phase currents I_a, I_b, I_c , which has of the frequency 200 Hz (relative units)

The variation of currents in the output circuit is periodic for all phases (Fig. 9-11) and is determined by the frequency of the primary circuit of the SST transformer. The instantaneous torque value of the asynchronous motor has a variable character over time over the half period of input voltage. However, the torque moment formed by the three-phase current system always has the same sense and does not lead to the variation of the motion speed of the train propelled by these asynchronous motors.

IV. Conclusions

1. It has a new architecture of the realization of a SST transformer with power supply from the DC and/or AC network. Frequency in the single-phase supply network of the SST transformer may have any value and may deviate over time. In the SST transformer, the electrical energy conversion takes place in a single step, multi-

plying the number of phases in the output circuit. The transistors of the SST transformer work at variable frequency with soft switching, which allows to reduce the losses and increase the energy efficiency indices of the transformer.

2. It was proposed to construct the SST transformer from the identical functional modules including the medium/high voltage circuit (input) and the low voltage AC circuit. The manufacturing of the ferromagnetic core from the separate parts allows simplification of the problem the insurance of electrical rigidity of the SST transformer and allows for a high degree of flexibility in the manufacture of the SST transformers with different voltage and power from identical modules.
3. Mathematical simulations have confirmed that this trans-former has a very low impact on the power supply, whether the power supply is DC or AC. Underload operation of the SST transformer does not lead to the pollution of the power supply network with higher current harmonics, whether the power supply network is DC or single-phase AC.

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Firs author –40%

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