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DETERMINATION OF OPTIMAL PARAMETERS OF THE PULSE WIDTH MODULATION OF THE 4QS TRANSDUCER FOR ELECTRIC ROLLING STOCK

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Досліджено режими роботи однофазного 4qs-перетворювача з широтно-імпульсною модуляцією в складі електрорухомого складу змінного струму. Розроблено методу визначення параметрів ШІМ, при яких реалізується оптимальний за критерієм мінімізації величини реактивної потужності в системі «локомотив – тягова мережа» режим роботи перетворювача.

Особливостями запропонованої методи є розділення процесу визначення оптимальних параметрів ШІМ на 2 етапи, що дозволяє видалити з імітаційної моделі непотрібні на даному етапі блоки та зменшити сумарний час моделювання. На першому етапі визначаються значення коефіцієнту потужності та струму ланки постійного струму в усьому діапазоні коефіцієнтів модуляції та зсуву між мережевим струмом та опорним синусоїдальним сигналом. Далі, з отриманого масиву даних виділяються пари значень параметрів ШІМ, за яких реалізується найвищій коефіцієнт потужності системи «електровоз – тягова мережа», та заносяться до табличною системи завдання параметрів ШІМ. На другому етапі визначається залежності електричних втрат, а, отже, й ККД, та коефіцієнту нелінійних спотворювань мережевого струму від тактової частоти перетворювачі. Визначення електричних втрат ґрунтується на обчисленні енергії, що була розсіяна протягом 1 с на IGBT-транзисторі та снаберному резисторі в залежності від миттєвих значень струму через них.

Для знаходження параметрів ШІМ за наведеною методою розроблено імітаційну модель 4qs-перетворювача, проведено ідентифікацію параметрів ШІМ перетворювача електровозу для тестової задачі. Визначено, що енергетичні показники перетворювача залежать нелінійно від трьох керуючих величин, що є параметрами ШІМ: коефіцієнту модуляції, зсуву між мережевим струмом та опорним синусоїдальним сигналом, та тактовою частоти ШІМ.

Визначено, що перетворювач з ідентифікованими параметрами ШІМ забезпечує одиничний коефіцієнт потужності тягової мережі при навантаженні більше 10 % від номінального в режимах тяги та рекуперативного гальмування.

Отримано залежність електричних втрат перетворювача та коефіцієнту нелінійних спотворень в тяговій мережі від тактової частоти ШІМ. Визначено, що раціональне значення тактової частоти лежить в інтервалі 900...2000 Гц, при цьому ККД перетворювача досягає 98...95 %, коефіцієнт нелінійних спотворень складає 12...5 %. Визначено, що виключення з силового кола снаберної ланки може суттєво зменшити сумарні електричні втрати. Встановлено, що втрати на паразитних опорах фільтрів незначні, тому їх можна не враховувати в загальному балансі втрат

Ключові слова: 4qs-перетворювач, електрорухомий склад, коефіцієнт потужності, ШІМ, імітаційне моделювання, електричні втрати

1. Introduction

Current trends in the development of electric rolling stock require the creation of modern energy-saving technologies in traction electric drives [1].

The increase of power efficiency of electrified railroads is achieved through various measures. One of the main is the use of traction drives based on promising types of traction motors, such as asynchronous [2, 3], jet [4] and others. Also, power efficiency of the rolling stock is affected by the efficiency of using traction and regenerative braking modes [5, 6], design and element base of power circuits, and so on.

A large number of goods are transported by the AC rolling stock, in which the implementation of traction and regeneration modes is complicated by the need to maintain not only a certain level of consumed or applied voltage, but also a certain phase shift between the current and voltage of the traction network. It is also desirable to ensure, if possible, low total harmonic current distortion of the traction network. The most widespread in the AC rolling stock were input traction transducers with zone-phase regulation. Due to their peculiarities, such transducers produce a large amount of reactive power and higher current harmonics, which negatively affects the power factor and electromagnetic compatibility of the rolling stock. Therefore, the work aimed at researching traction transducers with a reduced level of the reactive component and higher current harmonics of the network is considered relevant.

2. Literature review and problem statement

To ensure high power efficiency of the modern AC rolling stock, various technical means providing optimum values of all three above-stated parameters are used. Such means are systems with active bootstraps [7, 8], four-quadrant transducers [9, 10], reactive power compensators [11, 12]. The most widespread is the use of four-quadrant transducers (4qs transducers), as those that do not require additional transducers and have high power characteristics.

The detailed design and operating principles of 4qs transducers are given in [9, 10, 13–17]. In [9, 13], theoretical principles of construction are considered, calculation schemes and mathematical description of processes in the transducer are given, and the test simulation of the transducer in the traction and regenerative braking mode is performed. It is determined that the operating modes of the transducer are set by the value of the shift between the network current and the reference sine-wave signal, as well as the modulation depth of the reference signal. However, in these works, the dependence of the energy parameters of the transducer on the control quantities is not determined, only recommendations for the construction of controllers are given.

In [10], the simulation of the motion of several locomotives along the section of the AC electrified road is performed, power loss in 4qs transducers in the traction mode is determined, and the comparison of the calculated results with the experimental results is made.

In [14], the mathematical model of a single-phase bridge transducer with the discharge diode as a part of the AC electric rolling stock with commutator traction motors is developed. The values of modulation frequency and depth, providing the power factor greater than 0.9 and the total harmonic distortion in the power network are determined. Electromagnetic processes at three values of modulation frequency (900, 1,200, 1,800 Hz) are investigated.

In [15], the mathematical description of the transducer and the structure of the control system of the modulation depth and phase shift between the network current and the reference signal is given. As a result of the test simulation, the efficiency of the proposed control system is confirmed, however, such a system is characterized by complexity and low accuracy of maintaining the power factor, and requires a large number of calculations in real time. Also, no methodology for determining the coefficients of the PI controllers of the control system is given in the work.

In [16], the control algorithm of the active input rectifier of the IGBT-based electric locomotive is given, simulation of the “traction substation – traction network – electric locomotive” system is carried out. It is determined that when using the proposed transistor rectifier, the power factor is higher than when using a thyristor rectifier and is at least 0.95. However, the secondary current and voltage of the traction transformer are essentially non-sine-wave, which leads to the generation of higher current harmonics in the traction network.

In [17], the active rectifier control system, the individual circuits of which maintain the traction motor current and the traction network power factor, is proposed. It is determined that the control system is capable of maintaining the power factor equal to one at currents larger than a certain value; at lower currents, the power factor maintenance circuit is disabled. Problems of synchronization of the reference sine-wave signal with the traction network current are considered.

The literature review allows concluding that the use of the transistor active rectifier or 4qs transducer greatly improves the power factor of the traction network compared to the traditional thyristor rectifier. However, in the literature, except [14], there is no determination of the effect of clock frequency on the transducer efficiency and total harmonic distortion. The problem of direct maintenance of the power factor at the level of one is solved in [17], but the question of maintaining the maximum possible factor at low currents is not considered. In the literature, the traction mode is mainly considered, the regenerative braking mode is considered insufficiently, which does not allow using the obtained results for the construction of a complete control system of the input transducer.

3. The aim and objectives of the study

The aim of the work is to develop a method for determining the parameters of pulse-width modulation, which set the operating modes of the 4qs transducer, which ensure high power efficiency in the traction and regenerative braking modes throughout the range of operating currents.

To achieve the aim, the following objectives were accomplished:

– to develop a method of identification of the PWM parameters of the 4qs transducer, which ensures high power efficiency in the traction and regenerative braking modes throughout the range of operating currents;

– to develop a simulation model of the 4qs transducer in the AC electric locomotive;

– to determine optimum values of the coefficients of modulation and shifts between the network current and the reference sine-wave PWM signal for the entire range of currents in the traction and regenerative braking modes of the electric locomotive;

– to investigate the dependence of power loss in the transducer elements and total harmonic distortion on the transducer clock frequency and to select its rational value.

4. Basic provisions of the developed method of identification of optimum parameters and rational clock frequency of PWM of the transducer

As a power part of the 4qs transducer, a two-tier design, the equivalent circuit of which is shown in Fig. 1 is the most commonly used in practice.

A table system of setting the pulse-width modulation parameters, shown in Fig. 2, is proposed. Such a system uses pre-calculated values of the coefficients of modulation K_M

and shifts between the network current and the reference sine-wave signal K_S for the entire range of currents in the DC link.

The proposed method consists of the following steps:

Step 1. Simulation of the transducer at different coefficients of modulation and shift between the network current and the reference sine-wave signal. According to the simulation results, the dependences of the power factor in the traction network on the coefficients of modulation K_M and shift between the network current and the reference sine wave signal K_S, with K_M varying within (0…1), K_S – in the range of (0…1) for the regenerative braking (–1…0) and traction mode were obtained. At this step, part of the model that determines power loss in the transducer elements is disabled.

Step 2. Based on the results of step 1, determination of the modulation and shift coefficients, providing the maximum power factor in the traction network at different currents of the DC link. Entering the obtained pairs of values in the table of the control system of the electric locomotive transducer.

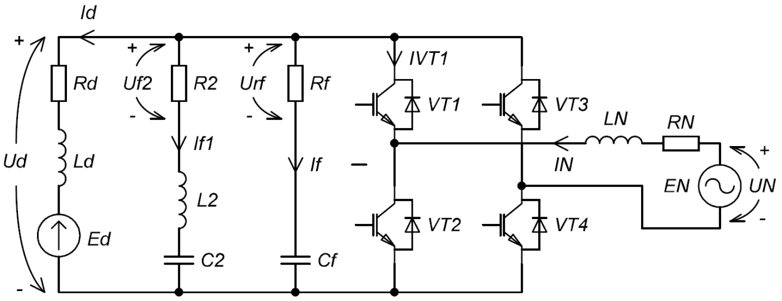


Fig. 1. Equivalent circuit of the 4qs transducer

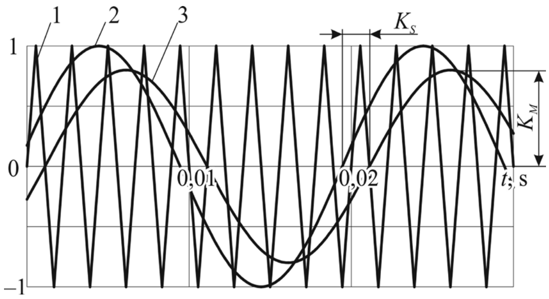


Fig. 2. PWM parameters of the transducer. The figures are: 1 — sawtooth clock signal, 2 — traction network current, 3 — reference sine-wave signal

Step 3. Determination of power loss in the transducer elements and total harmonic distortion of the network current at different values of the clock frequency. Selection of the rational value of clock frequency. At this step, the table of modulation and shear coefficients obtained in ste 2 is used, part of the model defining their optimum values is disabled.

5. Description of the developed simulation model of the 4qs transducer in the AC electric locomotive

To identify the PWM parameters, the simulation model of the input traction 4qs transducer is developed in Matlab-Simulink, its general structure is shown in Fig. 3

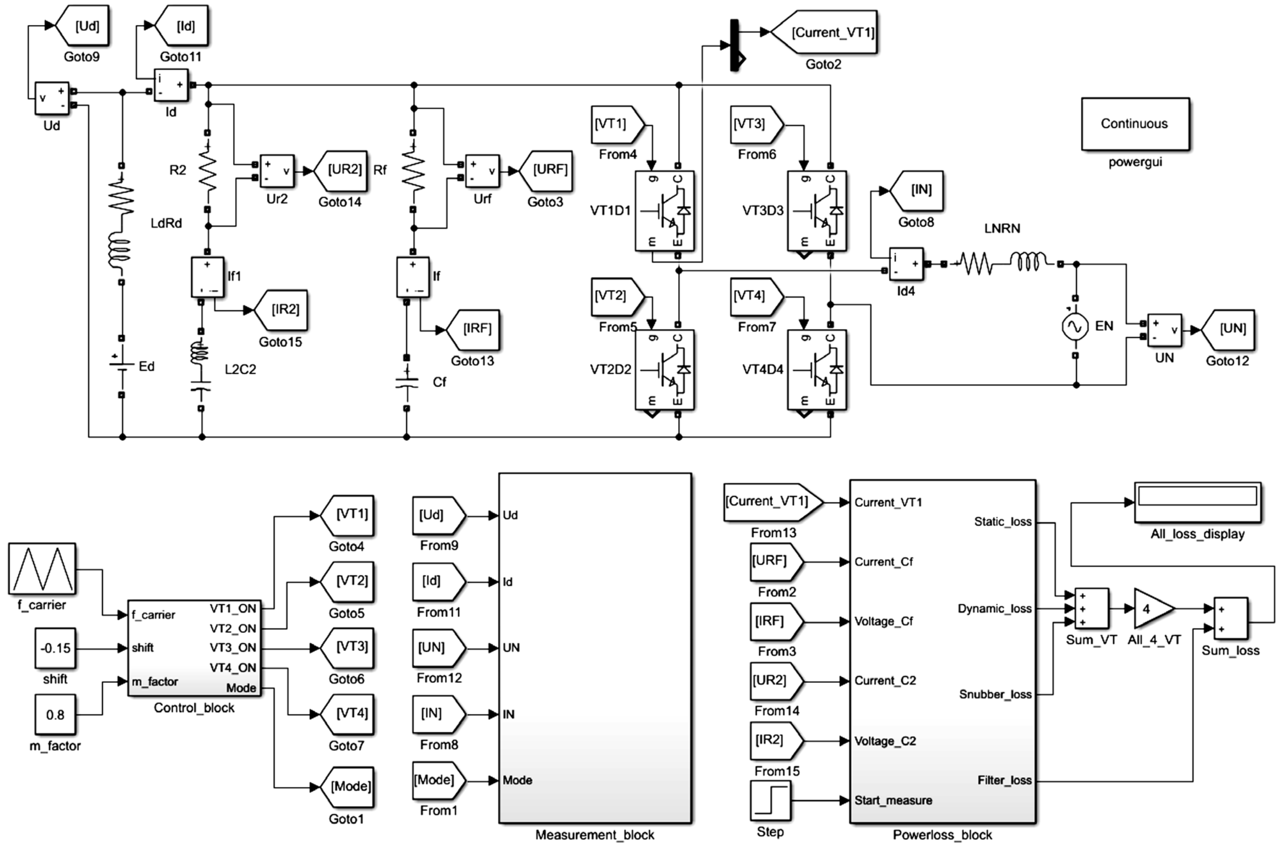


Fig. 3. General structure of the simulation model of the 4qs transducer

The model uses the method of generating control signals of IGBT transistors described in [9]. The comparison of the sawtooth clock signal with the reference sine-wave signal for controlling the transistors of one rack, and with the reverse reference sine-wave signal for controlling the transistors of another rack is used. Fig. 4 shows the diagrams of generating control signals with the modulation coefficient equal to 1.

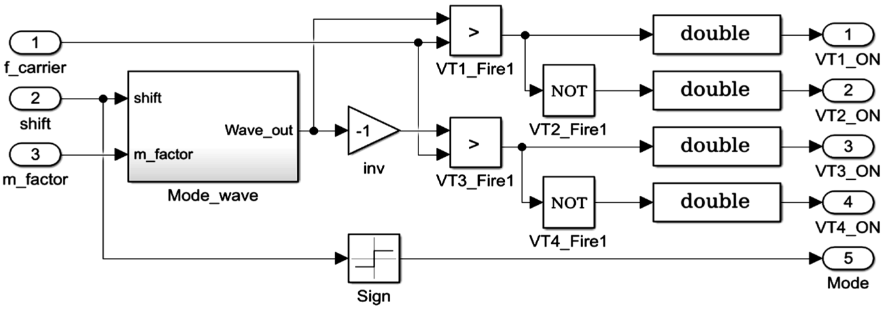


Fig. 5. System of generation of PWM signals of the 4qs transducer

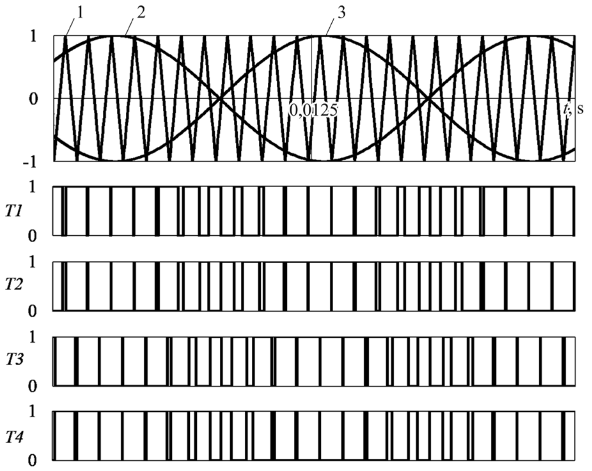


Fig. 4. Generation of control signals of IGBT transistors. 1 – sawtooth clock signal, 2 – reference sine-wave signal, 3 – reverse reference sine-wave signal, T1…T4 – control signals of the corresponding transistors

The generation unit of PWM signals of the transducer is implemented with the help of the Control_block block, the input parameters of which are the sawtooth clock signal, the shift between the network current and the reference sine-wave signal, and the modulation coefficient. The output parameters are signals for the opening of IGBT transistors and transducer mode (traction or regenerative braking). The output signals are generated by the method described in [9], the general view of the block is shown in Fig. 5.

To display the power characteristics of the transducer, obtained as a result of the simulation, the Measurement_block block is designed (Fig. 6).

The voltage and current of the DC link Ud, Id are transferred to the Votage filter and Current filter, respectively, which allocate a constant component from the signal and give to the U_DC_Link, IDC_Link indicator. The product of the constant components is equal to the power in the DC link and is displayed on the DC_Power indicator.

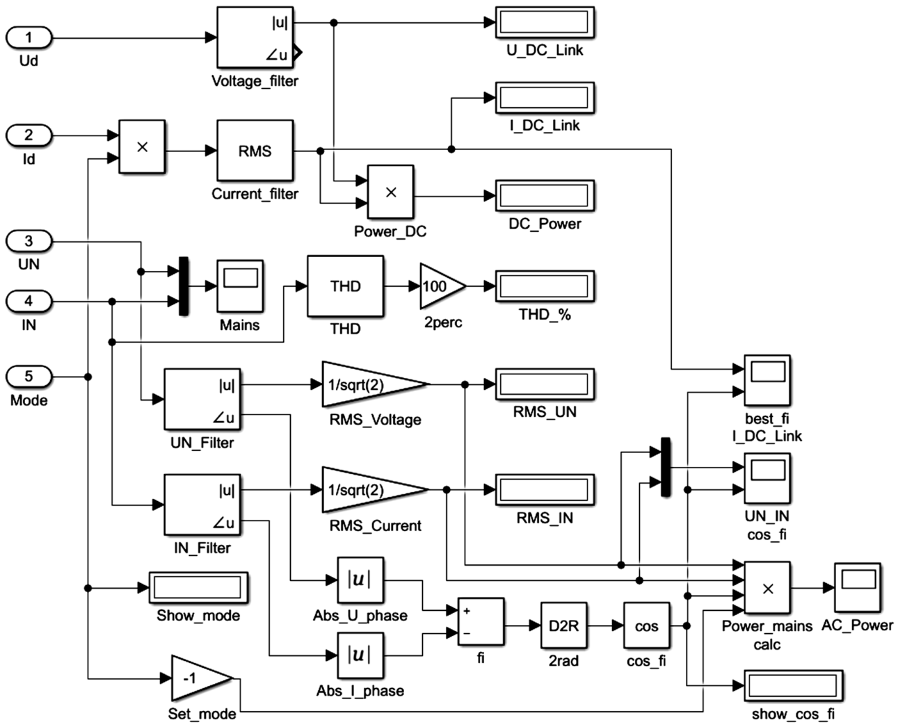


Fig. 6. Measuring and display system of the 4qs transducer characteristics

The secondary voltage and current of the transformer UN, IN are transferred to the UN_filter, IN_filter filters, which allocate the first harmonic amplitude and angle from the signal on the vector diagram. The RMS values of the first harmonic amplitudes are displayed on the RMS_UN, RMS_IN indicators. The THD block measures the total harmonic current distortion of the traction network, which quantitatively characterizes the anharmonicity of current caused by the pulse nature of the transducer. The value of the determined THD in percent is displayed on the THD_% indicator.

The difference between the absolute values of angles on the vector diagram of the secondary current and voltage of the transformer is equal to the angle of shift between the voltage and current of the traction network, the cosine of which is determined by the cos_fi block. By multiplying the RMS values of the secondary voltage and current of the transformer, the power factor obtained in the cos_fi block and the Set_mode coefficient taking into account the operating mode of the transducer, we obtain the active power consumed or given to the network by the 4qs transducer. The best_fi I_DC_link oscilloscope displays the obtained DC links and the power factor in the traction network at given PWM parameters: the shift between the network current and the reference sine-wave signal and the modulation coefficient.

Power loss in the transducer elements is calculated by the Powerloss_block block, shown in Fig. 7. This block allows determining the loss of the IGBT transistors of the transducer and parasitic resistance of the filter elements. In order to reduce the simulation time, the loss only of one of the four transducer transistors is calculated, the total loss is determined as loss of one transistor multiplied by 4.

Power loss of the IGBT transistor consists of the transistor and freewheeling diode conduction loss, transistor switching loss, freewheeling reverse recovery loss diode and snubber loss, if present. The block of determination of IGBT transistor loss is shown in Fig. 8.

Loss determination is based on the calculation of the energy dissipated within 1 s on the IGBT transistor and the snubber resistor. The calculation of the energy dissipated on the transistor is carried out in accordance with instantaneous currents through the transistor or freewheeling diode by the method given in [18].

Reference dependences are provided in the graphical form, quadratic or cubic regressions obtained as a result of the approximation of graphically displayed functions are used in the simulation. The transistor crystal temperature during the simulation is assumed to be constant and equal to 100 °C.

For the calculation of static loss of the transistor and freewheeling diode, the IGBT_CONDUCTION_LOSSES and DIODE_CONDUCTION_LOSSES blocks, respectively, are used, their arrangement is shown in Fig. 9. The reference dependence of direct voltage drops of the diode and collector-emitter junction in the on-state state on current is given in the voltage_drop block.

Dynamic loss of the transistor is calculated in the IGBT_SWON_SWOFF_LOSS block, as shown in Fig. 10. Dynamic loss of the freewheeling diode is calculated in the DIODE_REEVERSE_RECOVERY_LOSS block, shown in Fig. 11.

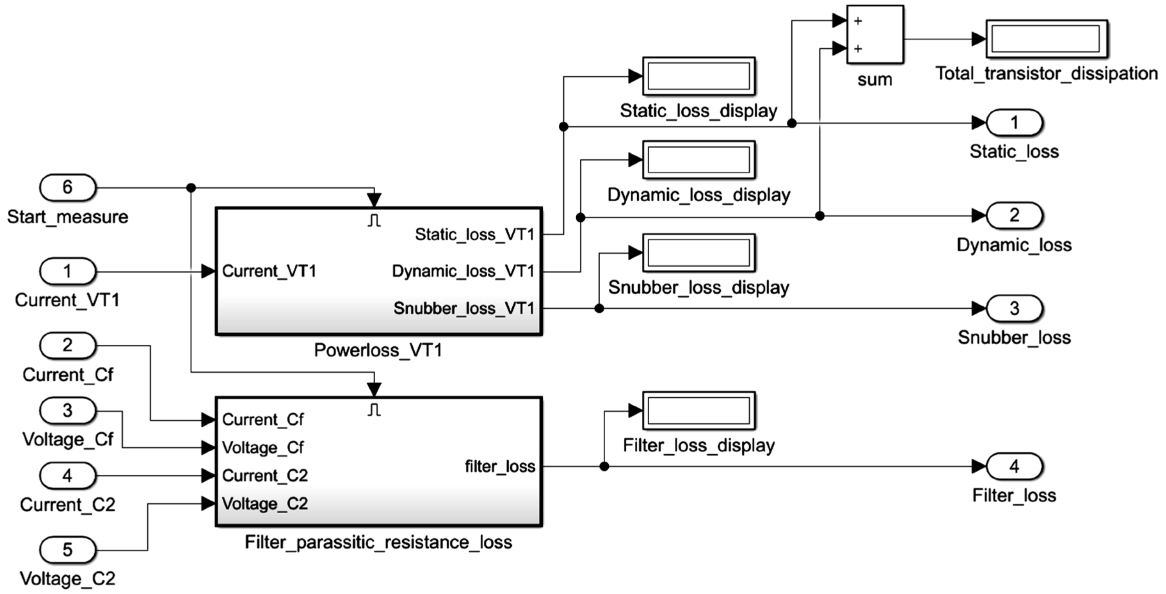


Fig. 7. Block of determination of power loss in the transducer elements

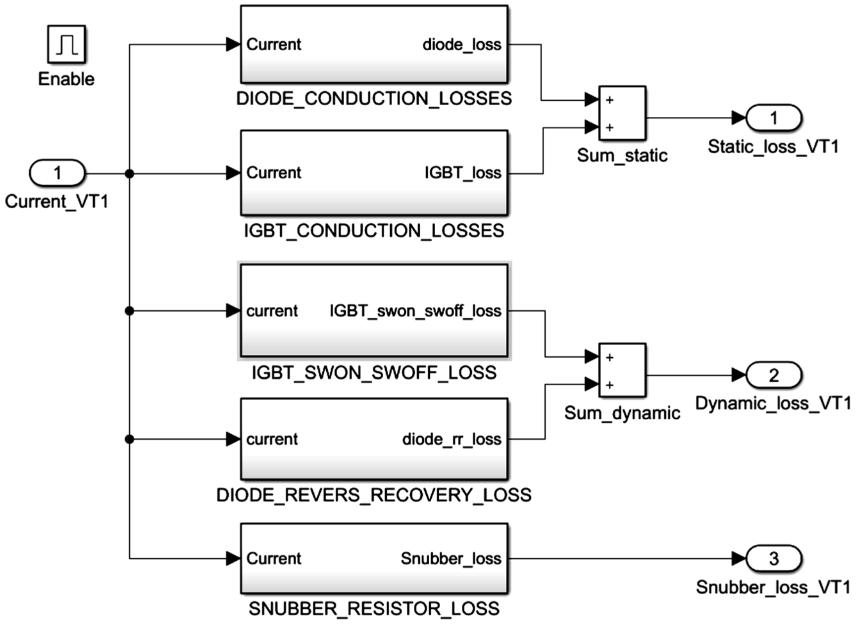


Fig. 8. Block of determination of the IGBT transistor loss

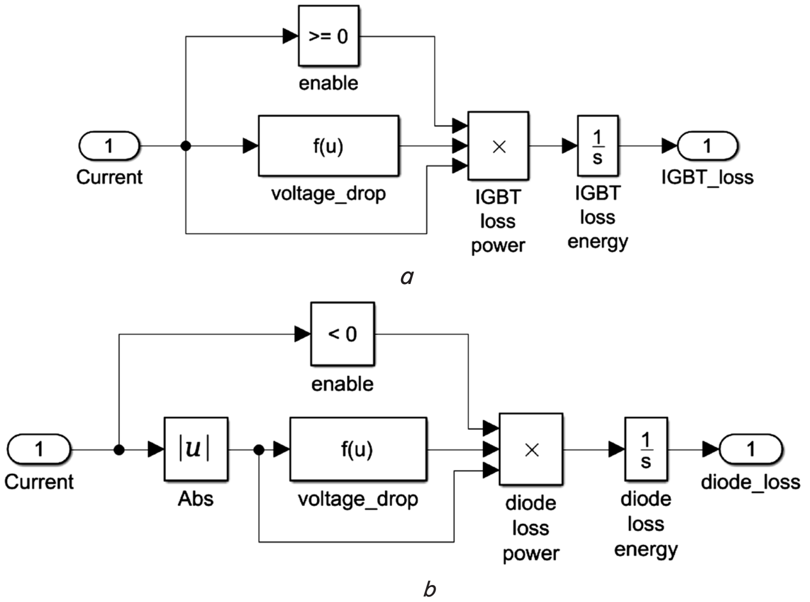


Fig. 9. Blocks of determination of conduction loss: *a* – transistor; *b* – a diode

Reference dependences of the energies of switching on and off the current transistor are given in the Eswon, Eswoff blocks, the dependence of the reverse recovery energy of the diode on the current through it is given in the Err block.

Fig. 12 shows the SNUBBER_RESISTOR_LOSS block, which implements the calculation of loss on the snubber resistor of the fixing dissipative snubber, the parameters and loss calculation method of which are chosen according to [19].

For the calculation of the filter parasitic resistance loss, the Filter_parasitic_resistance_loss block, shown in Fig. 13 is used. Due to the fact that the filters are connected directly to the DC link, the loss in them is determined by simple multiplication of voltage by the current through them.

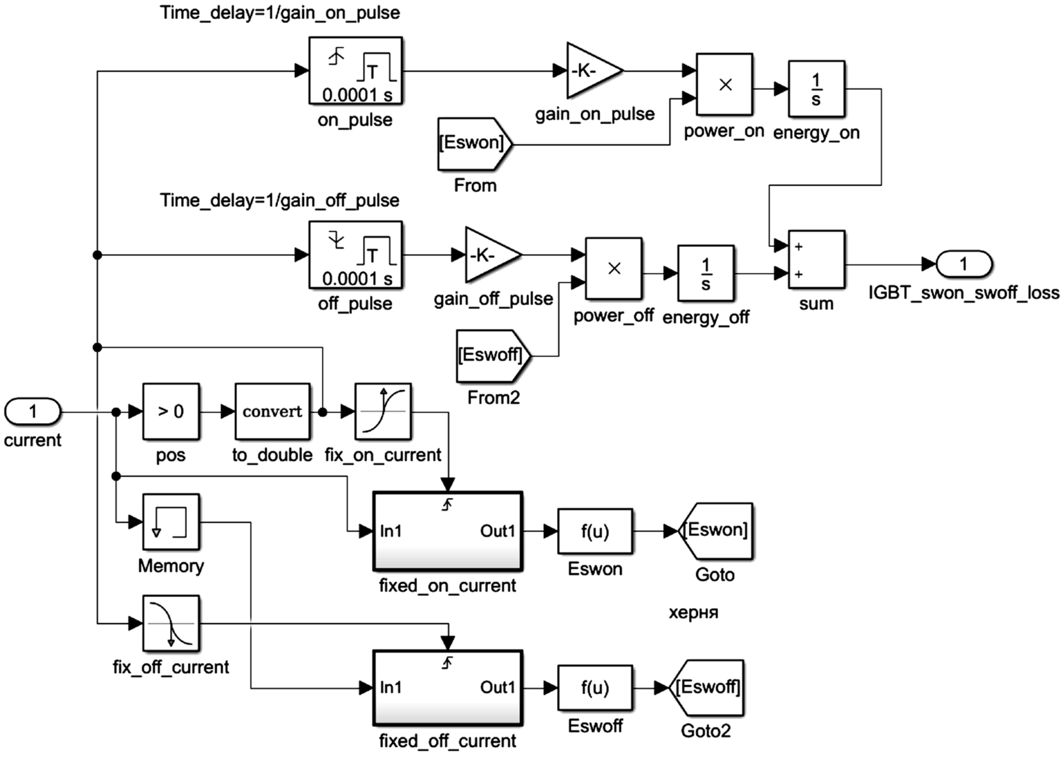


Fig. 10. Block of determination of the transistor dynamic loss

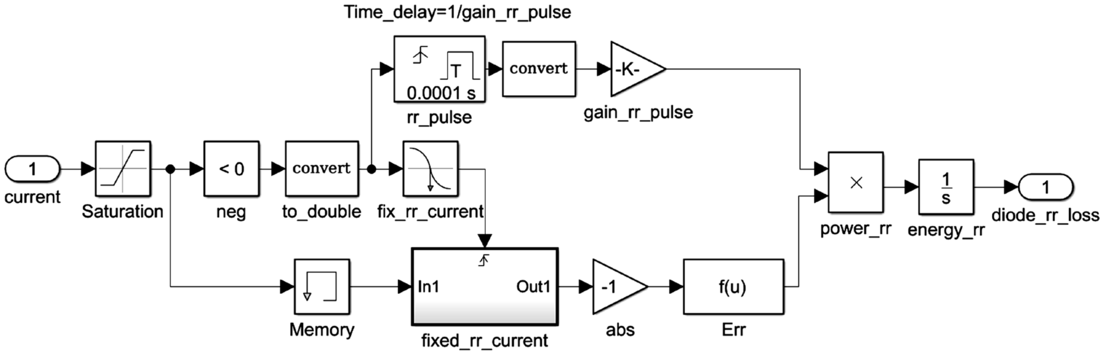


Fig. 11. Block of determination of the freewheeling diode dynamic loss

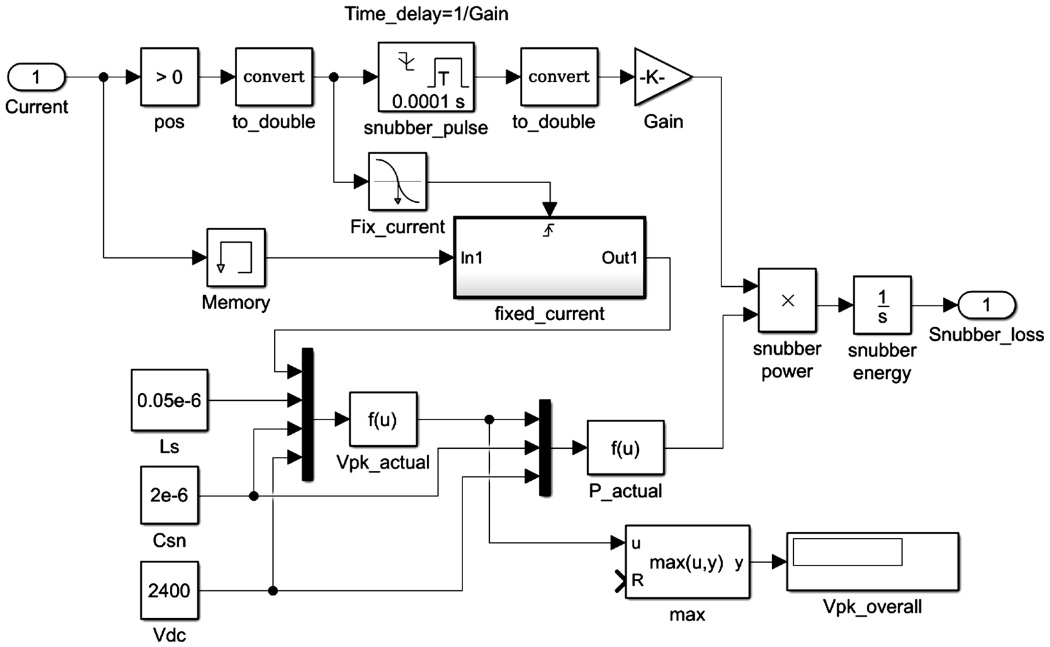


Fig. 12. Block of calculation of the snubber resistor loss

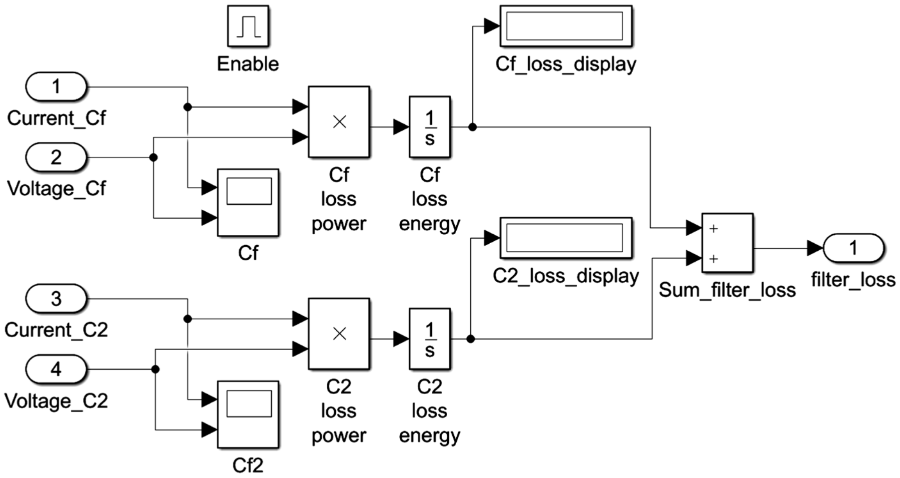


Fig. 13. Block of calculation of the filter parasitic resistance loss

6. Identification of optimum values of the PWM parameters for the test problem

To determine the PWM parameters for the optimum power factor in terms of minimizing the reactive power in the "locomotive – traction network" system, test simulation of the 4qs transducer is carried out according to the above-mentioned method. Basic parameters of the power circuit of the AC passenger electric locomotive, used in solving the test problem, are given in Table 1.

The simulation results are shown in Fig. 14. The value of the power factor for the regenerative braking mode and the shift coefficient for the traction mode are given for illustrative purposes.

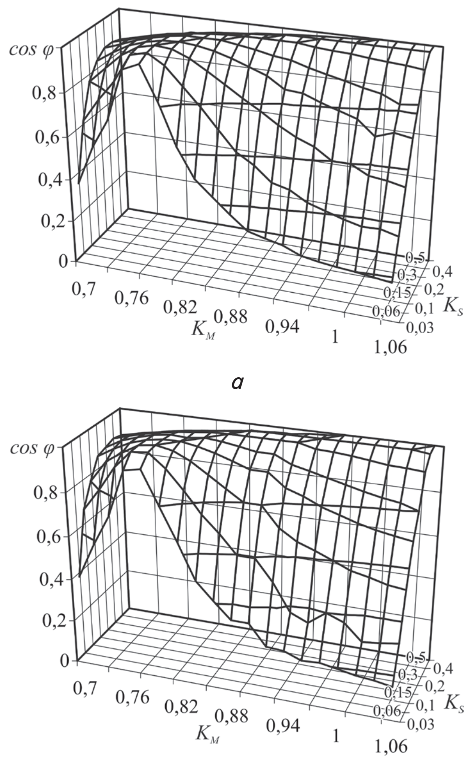
Using the obtained data, the pair of values (K_M, K_S), in which the power factor is maximum for the traction mode and minimum for the regenerative braking mode at different currents of the DC link was chosen, the obtained dependences are shown in Fig. 15. The figures are: 1 – shift between the network current and the reference sine-wave signal, 2 – modulation coefficient, and 3 – power factor (cos φ) of the traction network.

Table 1

Basic parameters of the power circuit of the 4-qs electric locomotive transducer

Parameter	Value
Secondary voltage of the traction transformer, V	1,310
Reduced inductive resistance of the traction transformer, H	$4 \cdot 10^{-3}$
Reduced active resistance of the traction transformer, Ohm	0.01
Filter condenser capacity, F	0.01
Filter capacitor parasitic resistance, Ohm	$1 \cdot 10^{-3}$
Second harmonic filter condenser capacity, F	$6.6 \cdot 10^{-3}$
Second harmonic filter inductance, H	$0.38 \cdot 10^{-3}$
Second harmonic filter parasitic resistance, Ohm	$2 \cdot 10^{-3}$
Reduced EMF of the traction motor, V	2,400
Reduced inductance of the traction motor, H	$1 \cdot 10^{-3}$
Reduced resistance of the traction motor, Ohm	0.05

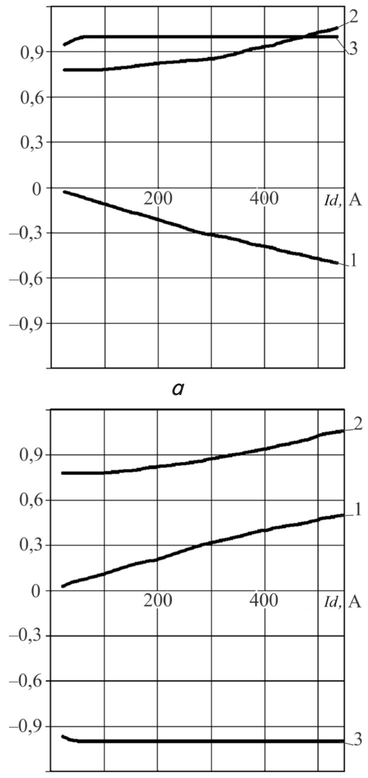
The obtained dependences were the basis of the system of generation of control signals of transistors, thus the modified model realizes the optimum power factor over the entire range of operating currents.



a

b

Fig. 14. Transducer simulation results, K_M – modulation coefficient, K_S – shift between the network current and the reference sine-wave signal: *a* – in the traction mode, *b* – in the regenerative braking mode

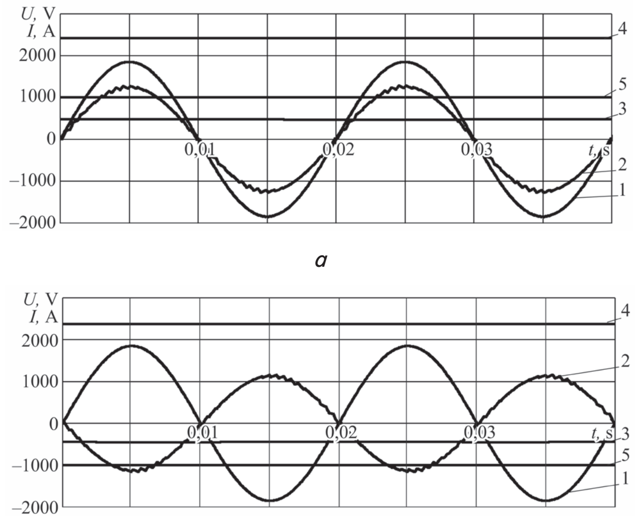


a

b

Fig. 15. Dependence of the PWM parameters on the DC link current: *a* – in the traction mode; *b* – in the regenerative braking mode

Fig. 16 shows graphs of currents, voltages and power factor of the traction network obtained during the operation of the modified transducer with the load of 80 % in the traction and regenerative braking modes. The figures are: 1 – voltage of the traction network, 2 – current of the traction network, 3 – DC link current, 4 – DC link voltage, 5 – power factor multiplied by 1,000.



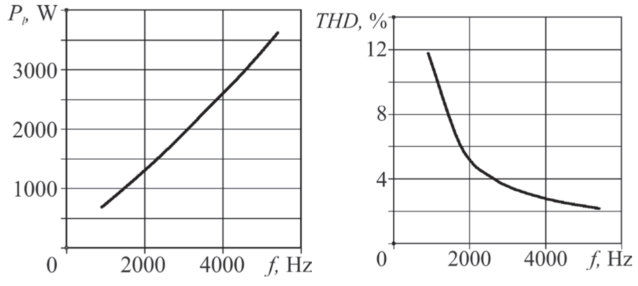
a

b

Fig. 16. Currents, voltages and power factor obtained during the transducer simulation: *a* – in the traction mode; *b* – in the regenerative braking mode

7. Determination of the dependence of transducer power loss and total harmonic distortion on the transducer clock frequency

As a result of the simulation, the dependences of the loss and total harmonic distortion on the transducer clock frequency are obtained. Fig. 17 presents the specified dependences in the traction and regenerative braking modes at the rated power of the transducer.



a *b*

Fig. 17. Parameters of the transducer at the rated power: *a* – transducer power loss; *b* – total harmonic distortion

In the simulation of the transducer with the clock frequency of 900 Hz, the dependences of efficiency on the DC link current (Fig. 18) and the distribution of power loss in the elements are obtained (Fig. 19).

The dependence of the transducer power loss on the type of IGBT transistors used and clock frequency is determined. The dependence of the total harmonic phase current distortion on clock frequency is determined. It is found that the rational clock frequency lies within 900…2,000 Hz. At such clock speed, the transducer efficiency is 98…95 %, total harmonic distortion is 12…5 % in the load range of 10…100 % of the rated one. With the load of less than 10 %, the efficiency decreases due to the occurrence of the reactive component of the network current and the relative loss increase in power switches. It is determined that for such a transducer, the exclusion of the snubber from the design can significantly reduce power loss. It is found that the filter parasitic resistance loss is insignificant, so they can be ignored in the simulation of such transducers.

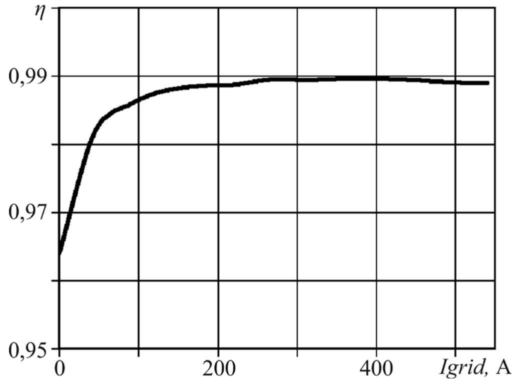


Fig. 18. Efficiency of the transducer at the clock frequency of 900 Hz

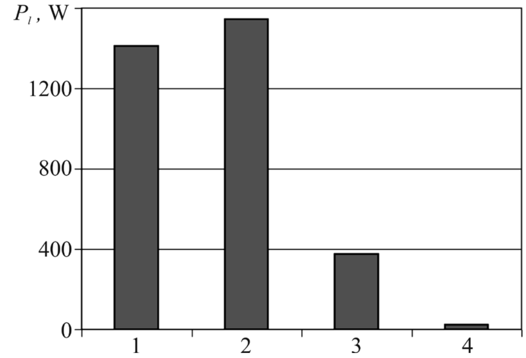


Fig. 19. Loss distribution at the rated power: 1 — static loss of the IGBT transistor and freewheeling diode, 2 — dynamic loss of the IGBT transistor and freewheeling diode, 3 — snubber resistor loss, 4 — filter parasitic resistance loss

8. Discussion of the results of the study of the 4qs transducer

The developed method of identification of the PWM parameters of the 4qs- transducer has the following features:

– maintenance of the maximum possible power factor of the traction network throughout the range of electric locomotive currents in both traction and regenerative braking modes;

– determination of the influence of clock frequency on the transducer efficiency and total harmonic distortion;

– accounting of nonlinear characteristics of the IGBT transistors of the transducer.

As can be seen from Fig. 15, 18, a sharp decrease in the transducer power factor and efficiency occurs at the load of 0…10 %. The effect of deterioration of power parameters at small currents on the integrated value is insignificant, so it is considered inappropriate to use additional systems that improve the power performance of these modes, such as active filters or bootstraps.

As can be seen from Fig. 14, a rather high power factor is maintained under a small variation of the PWM parameters K_M and K_S in the zone of near optimum values. This can be explained by a rather small deviation of the power factor in the vicinity of the optimum point, that is, with a small discrepancy between the current PWM parameters with the optimum ones.

Thus, the transducer with the table system of setting the PWM parameters can provide a relatively small value of the reactive power component in the traction network.

Features of the proposed transducer require a traction transformer with a significant value of leakage inductance used as the operating inductance of the transducer. Such an approach can limit the use of traction transformers of the AC rolling stock with the zone-phase control method.

The given model of the traction transducer does not consider possible variations of frequency and voltage in the traction network, as well as variation of the specified parameters of the traction motor when the load is changed. The development of the control system that implements the optimum PWM parameters obtained by the proposed method and takes into account the above-mentioned factors is considered the subject for further research.

9. Conclusions

1. The method of identification of the PWM parameters of the 4qs transducer, which ensures high power efficiency in the traction and regenerative braking modes in the whole range of operating currents is developed. The method consists of the following steps:

– simulation of the transducer at various values of the modulation coefficient and coefficient of shift between the network current and the reference sine-wave signal;

– according to the results of stage 1, determination of modulation and shift coefficients, providing the maximum power factor in the traction network; entering the obtained values in the table of the control system of the electric locomotive transducer;

– determination of power loss in the transducer elements and the value of total harmonic distortion of the network current at different values of clock frequency; selection of the rational value of clock frequency.

The feature of the method is the calculation of the dependences of the power factor of the traction network on the PWM parameters, carried out in the first step, only once and with a rather large sampling step. Due to this approach and rather small influence of variation of the PWM parameters near the optimum values on the power factor of the 4qs transducer, it is possible to obtain a well-working table control system over a short period of time.

According to the proposed method, the identification of the optimum values of the PWM parameters of the AC electric locomotive transducer for the test problem is carried out.

2. The simulation model of the 4qs transducer in the AC electric locomotive is created. The peculiarity of the model is the determination of the power factors of the traction network and current in the DC link at all values of the input PWM parameters on the first step, after which the optimum vectors of the input PWM parameters in terms of the minimum reactive power of the traction network are entered in the table of

the control system of the IGBT transistors of the transducer. In the second step, power loss in the optimized transducer is determined using the parameters of real IGBT transistors and taking into account the variation of parameters depending on the current and voltage on them. The process of determining the PIM parameters is divided into 2 steps, which allows removing unnecessary blocks from the simulation model. Also, due to division, simplification of the model and reduction of the simulation time of each of them are achieved.

3. For the given example, the dependence of the coefficients of modulation and shift between the network current and the reference sine-wave signal on the DC link current, which provide the maximum power factor for the entire range of currents in the traction and regenerative braking modes of the electric locomotive is found. It is determined that the developed system is able to provide the maximum power factor in the load range of 10...100 % of the rated one. In the load range of 0...10 % of the rated one, the power factor is reduced, which is due to the features of the 4qs transducer. It is determined that provision of the near optimum power factor of the "electric locomotive network" system is possible with the help of a simple table system of setting the PWM parameters. It is considered promising to use a simple PWM controller, in which rather large errors will be compensated by a predetermined operating range of output values.

4. It is determined that for the given example, the rational clock frequency of the transducer lies within 900...2,000 Hz. At such clock speed, the transducer efficiency is 98...95 %, total harmonic distortion is 12...5 % in the load range of 10...100 % of the rated one.

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