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APPLICATION OF ANT-COLONY ALGORITHM TO THE ISSUE OF IMPROVING RECTIFIED VOLTAGE PARAMETERS IN ELECTRIC TRAM TRACTION

Summary. In this paper, the problem related to transformation of ac voltage into DC voltage used in tram supply is considered. A variable component is always present in rectified voltage. Pulsation of rectified voltage is influenced by different factors. In a 12-pulse system, where two secondary transformer windings are used (one delta-connected and the other star-connected), an additional factor increasing the pulsation is the unbalance of the output voltages at these windings. Tap changer may be used and its setting is optimized here by applying the ant-colony algorithm. Different supply voltage variants have been considered. It is demonstrated that pulsation may be reduced by even 25%.

1. SOLVING OPTIMIZATION PROBLEMS

Demand for numerical optimization of issues from different domains has affected the emergence of new, diversified algorithms, including metaheuristic ones. The heuristic approach is characterized by application of a practical method, which is not necessarily optimal, but it is sufficient, since it speeds up the process of finding a satisfactory-enough solution.

An example of an algorithm belonging to the local search (LS) group is the simplex method (Dantzig 1947 [1]), the first genetic algorithm (GA) that emerged in 1962 (Holland [2]). Afterward, greedy algorithms showed up (GREEDY, Edmonds 1971 [3], GRASP, Feo and Resende [5] 1989) and subsequently tabu search algorithms (TS, Glover 1986 [4]), iteration algorithms (ILS—iterated local search, Martin, Otto, and Felten 1991 [6] and Baum 1986 [7]), genetic programming (GP, Koza 1992 [8]), swarm algorithms (ACO—ant-colony optimization, Dorigo 1992 [9], PSO—particle swamp optimization, Eberhart and Kennedy 1995 [10]), and guided local search algorithms (GLS, Voudouris i Tsang 1995 [11]).

The above algorithms may also be classified as belonging to adaptive memory algorithm group, single-solution algorithms, stochastic or population algorithms, etc. Algorithms based on population may also be classified as EA—evolutionary algorithms (e.g., genetic algorithm GA) and swarm intelligence [12].

Algorithms based on swarm intelligence are inspired by behavior of a large group of individuals belonging to one species. This behavior is coordinated even though central control is absent. An individual belonging to the group (swarm) is called a particle. Each individual is equipped with information on its current state (actions) and what was the previous state (actions) that awarded the best effects. Each individual is also able to inform other individuals (in some way particular to a given species) on what was the optimum way of action (which brought the best possible effects). Each individual is a sender and recipient of information. The system (swarm) evolves dynamically as a whole. Individuals who simulate this particular behavior of other individuals that was the most effective in the past, cause concentration of different individuals in some regions of search areas and in this way a solution of the problem is reached [13].

Two original algorithms based on swarm intelligence were motivated by animal behavior: ant colony (ant-colony optimization [9]) and bird flock (particle swarm optimization [10]). Subsequent algorithms simulated the social structure of bees (communication, task allotment, decision making, beehive localization, choice of partners, mating, and propagation). Here, we may list algorithms such as virtual bee algorithm, bee algorithm, bee ad hoc algorithm, marriage in honeybees, bee system, bee colony optimization, and others. An extensive review of these algorithms may be found in ref. [14]. Apart from bee [15] and ant behavior, scientists also used other mechanisms observed in the animal world. Here, we may cite differential evolution (DE [16]) approach based on bacterial response to chemical stimulants [17], foraging *E. coli* and *M. xanthos* bacteria (BFO—bacterial foraging optimization) [18], glowworm swarm optimization (GSO) [19], echolocation capabilities of bats (BA—bat algorithm) [20], etc. There are at least 40 different algorithms based on natural phenomena not related to animal behavior, such as, e.g., river formation dynamics brain storm optimization, man, and others. An extensive list of these algorithms may be found in, e.g., ref. [21].

2. APPLICATION OF SWARM INTELLIGENCE ALGORITHMS

Algorithms based upon swarm population are widely applied in solving optimization problems in different branches of engineering (civil, process, medical, chemical, electrical engineering, energy transformations, biotechnologies, automatics and robotics, and electronics), such as communication theory, economy, production management, and other sciences. Examples of applying PSO to relatively simple optimization problems with set constraints, such as, e.g., minimization of spring mass, where minimum deflection, allowable stress, natural vibration frequency, external and internal diameters, number of turns, and wire diameter are imposed, may be found in ref. [22]. For engineering purposes, some PSO tools have been designed, adapting PSO algorithms to the demands of programming environment MATLAB (e.g., ref. [23]).

In electrical engineering, the population-based algorithms may be applied to solving of numerous and very diverse problems—e.g., optimization of energy-storage devices in a system containing wind power stations [24], placing of capacitor banks in distribution systems [25], optimization of charging infrastructure in distribution systems [27], and estimation of three-phase asynchronous motor parameters [28].

The most comprehensive list of publication on application of swarm intelligence algorithms may be found in ref. [29]. An overview of possible applications of different metaheuristic algorithms, including those applied in rail and road transport, may be found in ref. [30], and one of the most complete overviews, including 700 technical publications is given in ref. [31].

A total of 139 papers on rail transport PSO applications have been classified in ref. [32]. The application areas have been roughly divided into scheduling (more than 23% of papers), active control, including compensation of current supply and voltage (c. 13% of papers), network planning, infrastructure design together with stationary energy-storage devices (11.5% of papers), depots, repair shops, ticketing (more than 9% of papers), vehicle and vehicle-element design, design of railroad lines (almost 11% of papers), forecasting of traction loads and passenger loads (c. 10% of papers), train control (more than 9% of papers), diagnostics (c. 8% of papers), parameter determination (c. 3%), and other subjects (c. 2% of papers). This paper may be classified as belonging to the problem area of active supply of rail traction.

3. TRACTION SUBSTATIONS IN POLAND AND TRANSFORMATION OF AC ENERGY

Rail vehicles such as locomotives, EMUs, tram cars, and metro are supplied with DC voltage in Poland. The supply circuit consists of traction substations, traction network (catenaries and contact wires), and return feeders (see Fig. 1). Traction substation consists of high-voltage switching station and devices transforming ac three-phase energy into dc energy and dc switching station. Tram-traction substations are sometimes supplied with 6-kV voltage (Łódź), but mostly with 15 kV or sometimes 20 kV (Katowice). On account of densely populated areas, the supply is mostly provided with cable (underground) lines, and rarely overhead lines are used. Substations are located every few kilometers along the track.

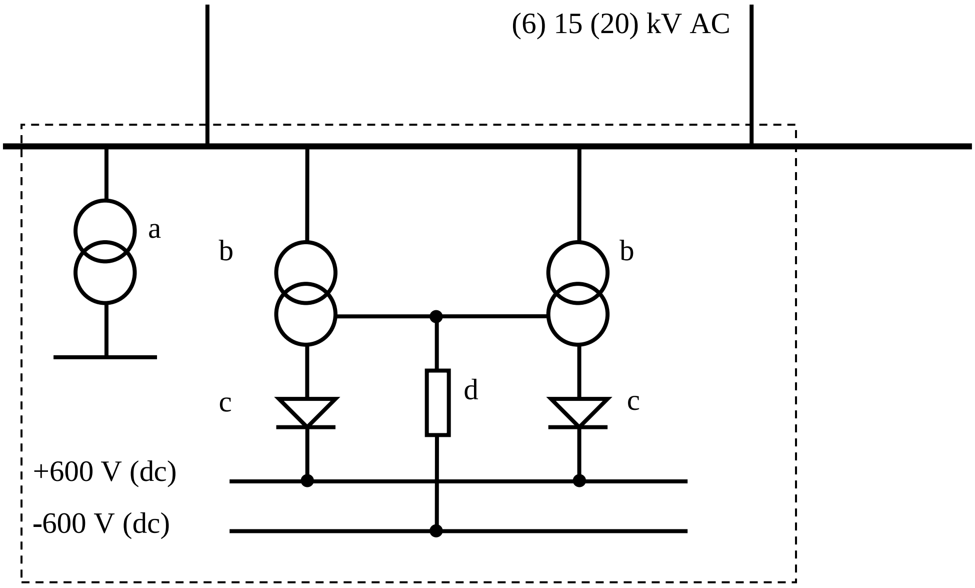

Fig. 1. Simplified scheme of tram-traction substation: a—transformer supplying loads other than traction network, b—rectifier transformer, c—rectifiers, and d—return cables

To transform AC energy into dc energy, rectifier transformers and rectifiers are used. Rectifiers transmit dc voltage to the common buses. Nowadays, simple uncontrolled rectifiers with silicone diodes are used, operating in 6D bridge configuration. Primary and secondary transformer windings are usually connected so that at least one winding is delta-connected while others may be star-connected. This is a standard rule applied in transformer design [34-37].

Rectifier transformers operating in Poland may be equipped with three-phase, six-phase, nine-phase (rarely), or 12-phase secondary winding. When a rectifier is connected, then six-, 12-, 18-, or 24-pulse rectified voltage is obtained. Transformer ratings usually range from 1200 to 1900 kV·A. The rectifier circuits built until the last decade of the 20th century were mostly three-phase and six-pulse ones. Nowadays, 12-pulse systems are installed as a rule. For instance, out of 43 substations working in Warsaw, only four still operate as six-pulse systems. A total of 12-pulse rectifier circuits may be connected in series or in parallel. Parallel circuits are used in tram-traction substations (dc voltage 600 V), trolley bus substations (600 V), and metro substations (750 V).

At the dc side, the three-phase rectifier system outputs rectified voltage with a variable component of fundamental frequency equal to 6*f*, where *f* is frequency of the AC supply network (power grid). In six-phase systems, two two-winding transformers may be used; more often, a three-winding transformer is applied. These transformers are usually connected to Yyd configuration; these are oil-filled transformers or—in newer substations—dry transformers are used. Some connections of three-, six-, and 12-phase transformers are shown in Fig. 2.

When energy-transformation circuits are considered, one of many technical problems is the “quality” of dc electrical energy at a given load type (and investigated for a given load range). This may be discussed, as e.g., quantity and frequency of dc voltage ripple. Other issues may of course also be contemplated, such as the impact on AC power grid supply network, electromagnetic compatibility, etc.

Six-pulse systems are characterized by a simple design, but the variable component in dc voltage is high. It may be limited by increasing the number of pulses, e.g., 12, 18, and 24 (Table 1).

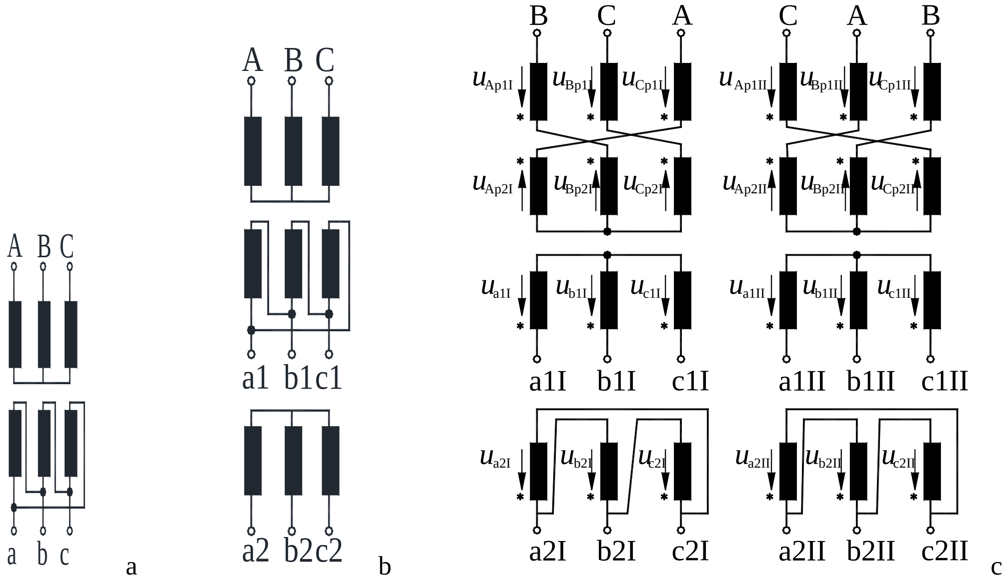

Fig. 2. Transformer-winding configurations: a) three-phase (Yd), b) six-phase (Yyd), and c) 12-phase ($2Y_Zyd$)

Table 1

Comparison of THD coefficient in rectified voltage depending on transformation circuit. Sinusoidal supply

	Transformer-winding configuration		
	Yd	Yyd	$2(Y_Zyd)$
Number of pulses	6	12	24
THD in %	5,50	1,89	0,35

The design of a 12-pulse system is possible, when rectified voltages (i.e., six voltages at transformer's secondary side) are shifted in relation to each other by 30° (el). This condition may be achieved by different means; a common solution is to use a three-winding transformer with two secondary windings, where one winding is delta-connected and the other is star-connected (Fig. 2b). The design of such transformer is relatively simple and it is practically batch-manufactured. If two full rectifier bridges (6D) are used, then these bridges may be connected either in series or in parallel. Circuit connections influence power losses in the transformer, harmonic spectrum in rectified voltage, and other issues (these matters were discussed in detail in ref. [38]).

When operation of rectifiers supplied by a three-winding transformer is investigated, the possible unbalance of phase-to-phase voltages of secondary windings (delta and star) must be taken into account. Identical voltages should be induced in these windings, which means that the number of turns of delta-connected winding should be equal to precisely $\sqrt{3}$ multiplied by the number of turns of star-connected winding. Since numbers of turns are integer numbers, if secondary side voltages are low (small numbers of turns), then the voltage unbalance will always be present.

Different design variants of rectifier transformer circuits were previously evaluated [39,40] from the viewpoints of the cost corresponding to improvement of dc voltage parameters (complexity of the transformation circuit, increase in the number of elements, and price). We also discussed whether the intended improvement would be persistent and independent of varying supply conditions. For instance, if we calculate transformer-rated power for 12-pulse and 24-pulse systems, assuming that dc power P_0 is constant, the $2(Y_Zyd)$ transformer's weight (24-pulse circuit) is increased in relation to Yyd transformer's weight (12-pulse circuit) by c. 54% [38].

Rectifier transformers are supplied with theoretically sine voltage. In practice, distortion of supply voltage brings about very serious effects. Detailed discussion of this issue may be found in refs. [38, 41]. For instance, in 24-pulse system, the 24th harmonic prevails in rectified voltage only if supply voltage is purely sinusoidal; the ripple in dc voltage is low (THD coefficient is <1%). Distortion of supply voltage may lead to an increase in the 6th harmonic, it may be even several tens of times higher than the 24th harmonic; in other words, a 24-pulse system turns into a six-pulse system.

These effects may be to some degree reduced using cathode reactors [41].

The other result of distortion in supply voltage is uneven loading of diode rectifiers and increase in power losses (which leads to excessive heating in a transformer) [38]. After analyzing different pros and cons, the authors have arrived at the conclusion that from both the economic and technical point of view, the most favorable transformation circuit is the one using a six-phase transformer (i.e., a 12-pulse rectifier circuit).

4. PULSATIONS OF RECTIFIED VOLTAGE IN A 12-PULSE SYSTEM

During previous research [42], we considered the operation of a six-phase transformer supplied by different voltages (three-phase symmetrical sinusoidal voltage and distorted three-phase symmetrical voltage, containing 5th and 7th harmonic and with THD coefficient equal to 7.81%). We also assumed different phase angles of supply voltage higher harmonics (i.e., different voltage waveform shapes).

If the transformer's secondary side voltages are identical as to the value and shifted in phase by 30° (Fig. 3b), then we obtain the correct operation of rectifier circuits and pulses in output voltage will be identical (Fig. 3a). However, if these voltages will differ as to a value (Fig. 3d), even though the distribution of voltages remains correct (this depends on spatial distribution of windings in the transformer), then the output voltage waveform will show increased pulsations – see Fig. 3c.

A simple calculation of secondary voltages for a transformer rated at S_N=10000 kV·A and secondary phase-to-phase voltages equal to 230 V is given in Table 2. It has been assumed that flux density in the transformer's core is equal to 1.44 T, and voltage per one turn is 1.35 V. Calculations were done for numbers of turns differing by one turn and taking into account the fact that the number of turns of delta-connected winding should be equal to $\sqrt{3}$ multiplied by the number of turns of star-connected winding.

If the transformer's supply voltage is additionally distorted, then the increased pulsations in the rectified voltage will be further enhanced by the secondary side voltage unbalance. The pulsation magnitude will depend on supply voltage waveform shape.

Pulsation has been defined as $p = \frac{U_{\max} - U_{\min}}{2U_{sr}}$ and expressed in percentage values. The results of calculations for two supply variants are shown in Fig. 4 (for comparison purposes, pulsations for other transformation circuits are also given).

Table 2

Phase-to-phase voltages, transformer's secondary side, and connections as in Fig. 2b

Winding configuration	Number of turns	Phase-to-phase voltage in V	Voltage difference—most favorable case
Delta (1)	169	228.15	231.21–230.85=0.36 V
	170	229.5	
	171	230.85	
	172	232.2	
Star (2)	98	228.88	
	99	231.21	
	100	233.55	

To extend the calculation range, we considered identical RMS values of 5th and 7th harmonic and the same THD value, but the phase angles of higher harmonics (ν=5 and ν=7) were changed continuously in the range of 0°– 360°.

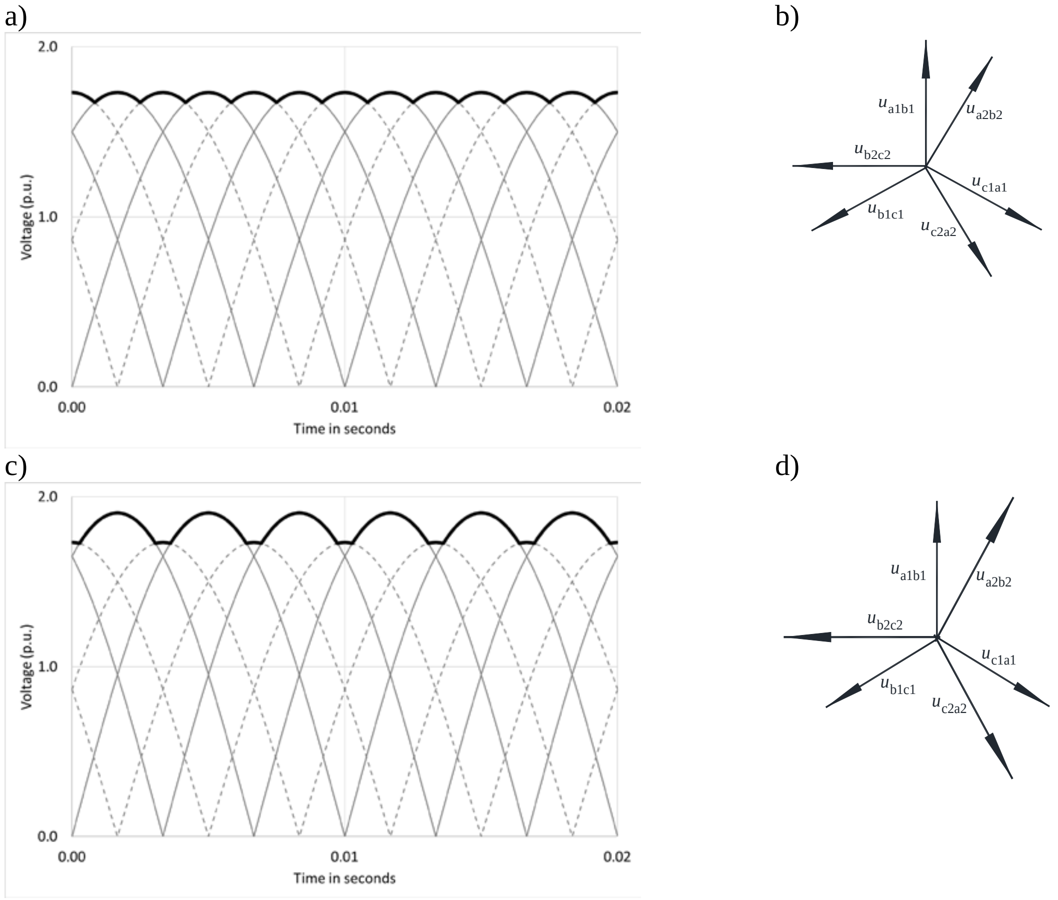

Fig. 3. a) Transformer voltage waveforms, secondary sides, rectified voltage marked (commutation impact has been neglected) - star, and delta voltages are equal; b) vector diagrams of secondary side voltages - star and delta voltages are equal; c) transformer voltage waveforms, secondary sides, rectified voltage marked (commutation impact has been neglected) - star, and delta voltages are not equal; b) vector diagrams of secondary side voltages—star and delta voltages are not equal. Voltage denotations are indicated as in Fig. 2

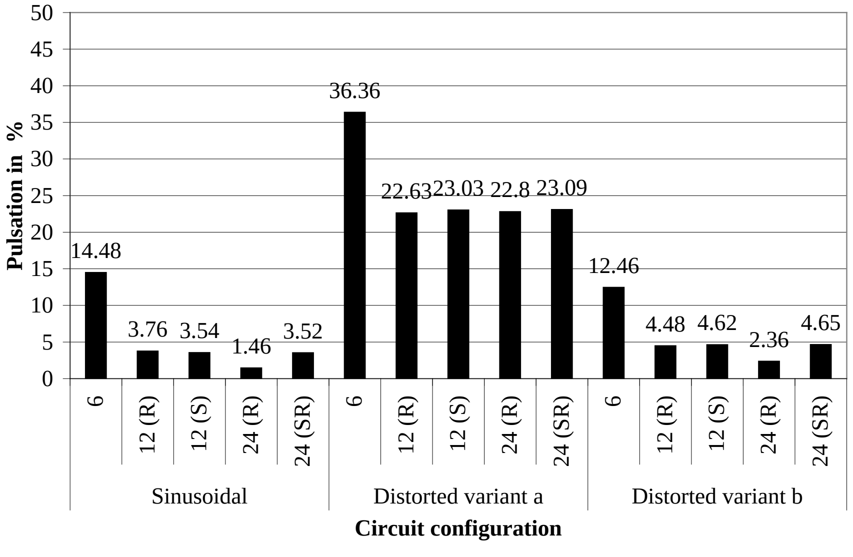

Fig. 4. Pulsations in different rectifier circuits (six-pulse, 12-pulse with rectifiers connected in parallel /R/ and in series /S/, 24-pulse with rectifiers connected in parallel /R/ or in mixed fashion /SR/). Variant a: $\mathrm{THD}_U = 7.81\%$, $u_{5\%} = 6\%$, $u_{7\%} = 5\%$ (values related to the fundamental harmonic), $\varphi_5 = 0^{\circ}$, and $\varphi_7 = 180^{\circ}$ (phase shifts); Variant b: $\varphi_5 = 180^{\circ}$, $\varphi_7 = 180^{\circ}$

Results for calculations (for a 12-pulse system and rectifiers connected in parallel) are shown in Fig. 5. The actual pulsation value is given here, for two different phase angles of 5th harmonic. The averaged pulsation value is given in the subsequent section ("Averaged pulsation value" is defined as $p_{sr} = \frac{1}{n}\sum_{i=1}^{n} p_i$, where n—number of all phase angles of 7th harmonic, range (0°–360°), for which pulsation calculations have been done; p_i—pulsation value for a given angle).

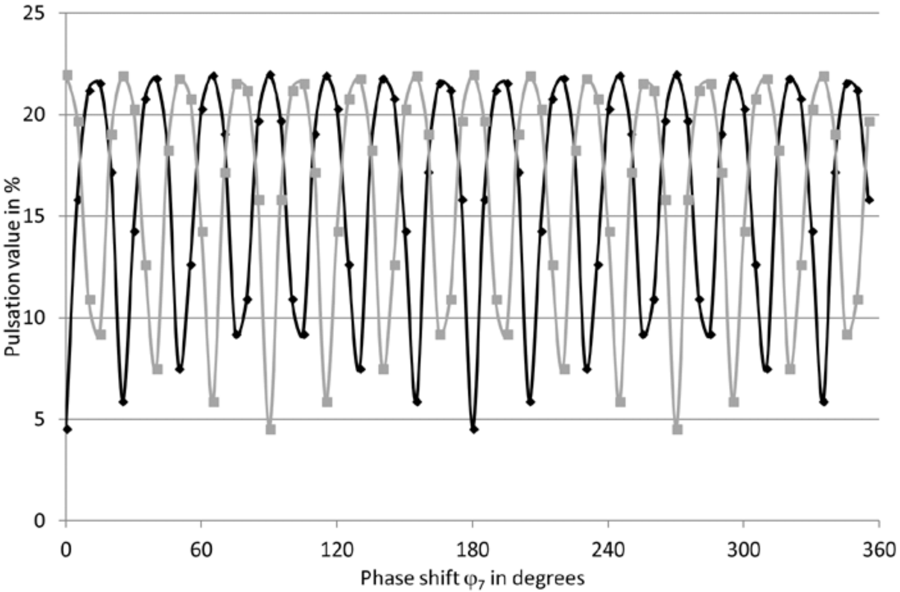

Fig. 5. Pulsation of rectified voltage as a function of phase angle of 7th harmonic of supply voltage; phase angle of 5th harmonic is equal to 0° (dark line) and 90° (light line)

There are different possibilities of reducing pulsation in rectified voltage, e.g., use of output voltage filters, active filtration of supply voltage [43, 44], or use of cathode reactors. An on-load tap changer may also be used, such as a switch that is connected to one selected secondary side winding. This tap changer has to precisely adjust the voltage at this winding in order to reduce pulsation in rectified voltage. An attempt at optimization of voltage ripple has been undertaken using the ACO algorithm (ant colony optimization). It must be noted that the authors propound just the concept of using the on-load tap changer. We do not, at this stage, consider the actual mechanism of device's operation—this might constitute an interesting subject for further research.

5. ANT-COLONY ALGORITHM AND ITS APPLICATION IN VOLTAGE CONTROL

For the first time, the behavior of the ant colony as a population was used in the optimization process by Marco Dorigo [9]. Dorigo noted several ant-behavior patterns and he transferred these to algorithm-solving traveling-salesman problem. This approach inspired other uses of ant-colony behavior, for instance in the process of functional minimization; the algorithm used here was first proposed by Toksari and used to minimize a function [45]. The task is to minimize a function, but we do not have any information on function properties; we can only determine values of this function at selected domain points:

$$f(x_1, x_2, ..., x_m) \to \min, \text{ where } (x_1, x_2, ..., x_m) \in \mathrm{D} \subset \mathrm{R}^m \tag{1}$$

An introductory stage, i.e., initialization of the algorithm, starts with determining algorithm parameters:

- N—population density
- Maximum number of iterations I

- Neighborhood parameter should be “large enough” at first, c. 60% of the variable range length.

Before the iteration process starts, it is necessary to

- generate randomly initial population of N ants x^i, $i = 1, 2, \dots N$, which are located in the region of the discussed problem $\mathrm{D} \subset \mathrm{R}^m$
- determine the value of the objective function (intensity of pheromone trail) for all N ants: $f(x_1^i, x_2^i, \dots, x_m^i)$, for $i = 1, 2, \dots, N$.
- from the ant population, the one with the best location must be selected (with the smallest value of objective function x^{best}).

Basic part of the algorithm:

1. Starting with the best-located ant (x^{best}), we generate a new ant population; these ants are randomly placed in the neighborhood of the best-located ant, i.e., with the most intensive pheromone trail:

$$x^i = x^{\text{best}} + \mathrm{d}x, \quad i = 1, 2, \dots N \tag{2}$$

where $-\alpha \le \mathrm{d}x_j \le \alpha,\ j = 1, 2, \dots m$ is a value chosen at random.

2. We choose a best-located ant in this new population—i.e., we update x^{best}.
3. Points 1–2 must be repeated I^2 times.
4. We constrain the neighborhood parameter $\alpha = 0.1 \cdot \alpha$
5. Points 1–4 must be repeated I times.

The x^{best} obtained in this way is treated as the solution of the problem. It must be pointed out that the algorithm is metaheuristic, and therefore it should be run several more times (with identical input data) and the best result should be selected as the final solution.

In the problem considered here, the objective function is the DC voltage pulsation; it depends on the gain coefficients. These should be selected in such a way that the smallest possible pulsation is obtained. It must be noted that in this particular case, the solution may be verified by a simple calculation.

In order to define an objective function (pulsation), let us first define the phase voltages of the fundamental harmonic of the transformer’s secondary voltage at one winding (see Fig. 2b):

$$\begin{aligned} u_{a1\_1}(t) &= A_{ph\_1}\sin(\omega t) \\ u_{b1\_1}(t) &= A_{ph\_1}\sin(\omega t + \tfrac{2}{3}\pi) \\ u_{c1\_1}(t) &= A_{ph\_1}\sin(\omega t + \tfrac{4}{3}\pi) \end{aligned} \tag{3}$$

where A_{ph_1}, $ph = a1$, $b1$, or $c1$ is the maximum value of phase voltage, which is the fundamental harmonic.

Phase voltages of 5th harmonic are expressed as

$$\begin{aligned} u_{a1\_5}(t) &= A_{ph\_5}\sin\left(5(\omega t + \beta)\right) \\ u_{b1\_5}(t) &= A_{ph\_5}\sin\left(5(\omega t + \frac{2}{3}\pi + \beta)\right) \\ u_{c1\_5}(t) &= A_{ph\_5}\sin\left(5(\omega t + \frac{4}{3}\pi + \beta)\right) \end{aligned} \tag{4}$$

where A_{ph_5} is the maximum value of phase voltage harmonic $\nu = 5$.

Phase voltages of 7th harmonic are expressed as

$$\begin{aligned} u_{a1\_7}(t) &= A_{ph\_7}\sin\left(7(\omega t+\gamma)\right) \\ u_{b1\_7}(t) &= A_{ph\_7}\sin\left(7(\omega t+\frac{2}{3}\pi+\gamma)\right) \\ u_{c1\_7}(t) &= A_{ph\_7}\sin\left(7(\omega t+\frac{4}{3}\pi+\gamma)\right) \end{aligned} \tag{5}$$

where A_{ph_7} is the maximum value of phase voltage harmonic $\nu = 7$.

Total phase voltages are expressed as

$$\begin{aligned} u_{a1}(t) &= u_{a1\_1}(t)+u_{a1\_5}(t)+u_{a1\_7}(t) \\ u_{b1}(t) &= u_{b1\_5}(t)+u_{b1\_5}(t)+u_{b1\_7}(t) \\ u_{c1}(t) &= u_{c1\_1}(t)+u_{c1\_5}(t)+u_{c1\_7}(t) \end{aligned} \tag{6}$$

Other three phase voltages (i.e., voltages at the other secondary winding) are obtained based on phase voltages of the first winding:

$$\begin{aligned} u_{a2}(t) &= k_a\left(u_{a1}(t)-u_{b1}(t)\right)/\sqrt{3} \\ u_{b2}(t) &= k_b\left(u_{b1}(t)-u_{c1}(t)\right)/\sqrt{3}\ . \\ u_{c2}(t) &= k_c\left(u_{c1}(t)-u_{a1}(t)\right)/\sqrt{3} \end{aligned} \tag{7}$$

Parameters k_a, k_b, and k_c are directly related to correction of used number of turns of the second secondary winding. In other words, they describe the adjustment of taps.

The rectified voltage is defined as

$$U_0(t) = \max\left\{|u_{a1}(t)|,|u_{b1}(t)|,|u_{c1}(t)|,|u_{a2}(t)|,|u_{b2}(t)|,|u_{c2}(t)|\right\}\ . \tag{8}$$

and pulsation as

$$p(k_a,k_b,k_c) = 100\frac{\max\limits_{t\in[0,2\pi]}U_0(t)-\min\limits_{t\in[0,2\pi]}U_0(t)}{\left(\dfrac{\max\limits_{t\in[0,2\pi]}U_0(t)+\min\limits_{t\in[0,2\pi]}U_0(t)}{2}\right)}\ \%\ . \tag{9}$$

In the discussed case, we have adopted the following parameters of the ant-colony algorithm: $N = 5$, $I = 6$, gain coefficient range [0.85–1.15], and neighborhood parameter ▱= 0.2.

The results of applying the algorithm are shown in Fig. 6 and Table 3.

6. CONCLUSION

Population algorithms (swarm intelligence algorithms) have been lately used for solving more or less-complex technical problems. In this paper, we have considered a problem related to transformation of ac voltage into DC voltage used in tram supply. On account of transformation circuit configuration (use of uncontrolled rectifiers and transformers with different winding connections), a variable component is always present in rectified voltage. The magnitude of this variable, i.e., pulsation of the rectified voltage, is influenced by different factors such as configuration of the rectifier circuit, shape of supply voltage waveform, and load. In a 12-pulse system, where two secondary transformer windings are used (one delta-connected, the other star-connected), an additional factor increasing the pulsation is the unbalance of the output voltages at these windings. We have demonstrated that in steady state, pulsation may be reduced by adjustment of voltage at one of these windings with the help of on-load tap changer. We investigated the case when the transformation circuit is supplied with distorted voltage, characterized by the THD coefficient, it is confined within limits set by appropriate legal regulations. Optimizing voltage regulation (adjustment) by applying the ant-colony algorithm to different variants of supply voltage (different phase angles of 5th and 7th voltage harmonic), we have demonstrated that pulsation may be reduced by several percentage points (in absolute values by even 25%). Reduction in pulsation corresponds to a change in DC voltage total harmonic content (THD coefficient). This is voltage supplying different tram circuits, in particular the drive motors. In modern trams, motors are used in conjunction with power electronic converters (DC motors and choppers, induction motors, and inverters). These power electronic circuits usually tend to filter the supply voltage to some degree, and actual performance depends on the devices used. To assess the impact of the solution proposed by the authors, which leads to reduction of DC voltage ripple, a particular solution of the drive system should be considered. This, however, has not been the aim of this paper.

Table 3

Pulsation of rectified voltage, averaged in relation to phase angle of 7th harmonic φ_7; average, minimum, and maximum values

	Without adjustment	With adjustment
Average value	15.31	11.33
Minimum value	14.28	9.65
Maximum value	16.20	12.86

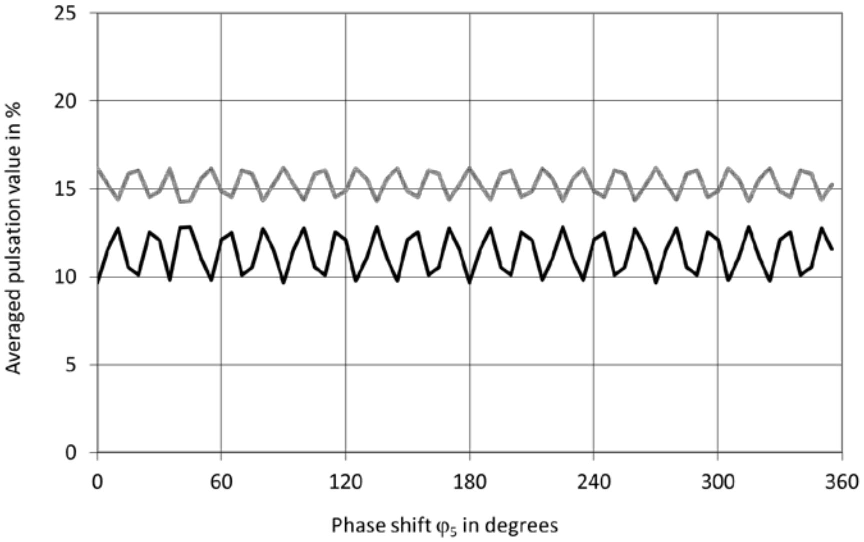

Fig. 6. Pulsation of rectified voltage vs. phase shift of 5th harmonic—averaged in relation to phase angle of 7th harmonic of rectified voltage; before optimization (light-colored line) and after optimization (dark-colored line)

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