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Features of economical traction 12-phase rectifier transformer

Streszczenie. *W artykule przedstawiono układ połączeń 12-fazowego transformatora o zintegrowanych uzwojeniach wtórnych, przeznaczonego do zasilania trakcji tramwajowej. Układ ten z założenia jest materiałooszczędny. Wykazano, że przy współpracy z układem prostowników niesterowanych napięcie wyjściowe wyprostowane zawsze zawiera największą składową 6- lub 12-pulsową, nie zaś 24-pulsową.*

Abstract. *The paper presents winding arrangement of 12-[hase transformer with integrated secondary windings. Transformer is to used in tram traction substations. It has been shown that this transformer operating with 4 diode rectifier bridges generates dc rectified voltage with major 6th or 12th harmonic instead of 24th harmonic. (* ***Właściwości oszczędnego trakcyjnego 12-fazowego transformatora prostownikowego)***

Słowa kluczowe: transformator wielofazowy, prostownik niesterowany, trakcja elektryczna, komutacja
Keywords: polyphase transformer, diode rectifier, electric traction, commutation

Introduction

Electric tram traction in Poland uses 600 V dc voltage. To obtain this, it is necessary to transform and rectify ac grid voltage (15 or 20 kV). Commonly transformers and diode rectifier bridges are used. Most traction substations are equipped with 3 or 6 phase transformers, with windings arrangements Yd and Yyd. One of transformer's windings is delta-connected in order to eliminate higher harmonics of order $\nu = 3n$ [1]. In traction substations we may meet with e.g. transformers manufactured by Areva Mikołów (now Schneider Electric Energy Poland Sp. z o.o. Zakład Transformatorów) TZM3T-1200/15 (1200 kVA, Yd11y0, 15,75/0,525/0,525 kV or TZE3T 1200/20 (1200 kVA, 21/2x0,525 kV) manufactured by EMIT Żychlin. When transformer's secondary voltages are rectified, dc voltage with some ac components is obtained.

Standard 3-, 6-, 12-phase transformers

Typical 3- and 6-phase transformer winding arrangements are shown in Fig. 1.

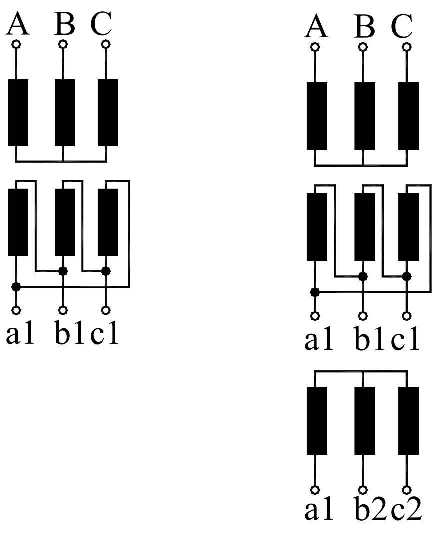


Fig.1. Rectifier 3-phase (Yd) and 6-phase (Yyd) transformer - windings schemes

24-pulse system may be designed on the basis of two (identical) Yyd transformers operating in parallel. In order to generate 24 pulses, secondary voltages must be shifted with respect to each other by 15°, 15°, 75°, 15° etc. (Fig.2). In system under consideration this condition is fulfilled since primary windings are divided and zigzag-connected (Fig.4), so that primary voltages are shifted with respect to each other (Fig. 3) [3].

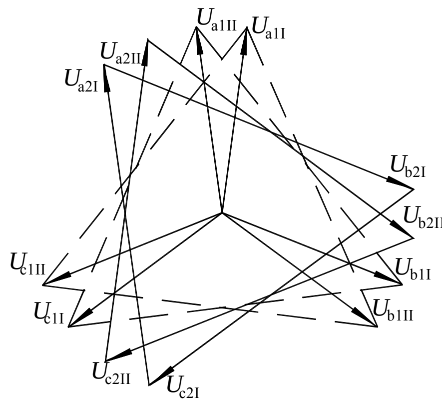


Fig.2. Phasor diagram of secondary voltages of 12-phase transforming circuit consisting of two Yyd transformers; windings marked as in Fig.3; dashed line marks phase-to-phase voltages of wye-connected windings

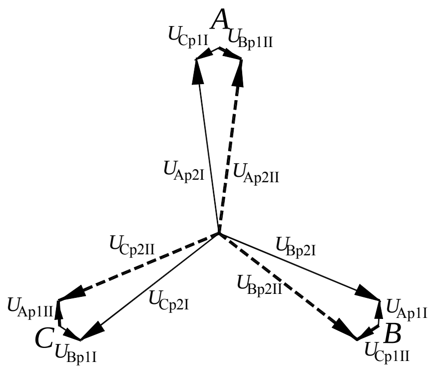


Fig.3. Transformer denoted as 2($Y_Z$yd) - phasor diagram of primary voltages

It must be noted that in this design secondary windings are separated from each other.

Rectified voltage, transformer rated power and weight

Rectified voltage may be defined as sum of phase voltages:

$$U_A(\alpha) = U_{fm}\sin(\alpha),$$
$$U_B(\alpha) = U_{fm}\sin(\alpha + \frac{2}{3}\pi), \qquad (1)$$
$$U_C(\alpha) = U_{fm}\sin(\alpha + \frac{4}{3}\pi)$$

where U_{fm} – maximum phase supply voltage, $\alpha = \omega t$, $-\alpha_1 \le \alpha \le \alpha_1$, $\alpha_1 = \pi/2m$ and m – number of phases.
Average rectified voltage

$$(2) \quad U_0 = \frac{m}{\pi}\int_{-\alpha_1}^{\alpha_1}\left[U_A(\alpha) - U_B(\alpha)\right]d\alpha = \frac{2m}{\pi}U_m \sin\left(\frac{\pi}{2m}\right)$$

where U_m – maximum phase-to-phase secondary voltage value.

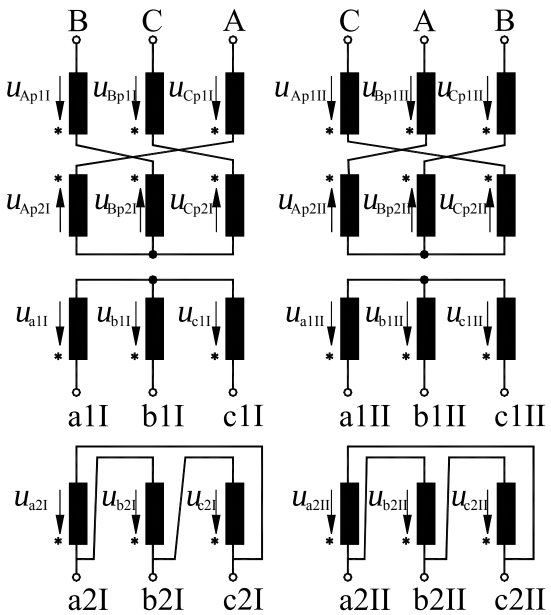


Fig.4. Transformer denoted as 2($Y_Z$yd) - windings scheme

Secondary current RMS-value (current flowing from transformer to rectifier):

$$(3) \quad I_s = \sqrt{\frac{1}{6\alpha_1}\int_{-\alpha_1}^{3\alpha} I_0^2 d\alpha}, \quad I_s = \sqrt{\frac{2}{3}}I_0,$$

where I_0 – average rectified current.
Power rating of secondary winding may be calculated from relationships cited above as:

$$(4) \quad S_{sN} = \frac{\pi P_0}{2m\sin\left(\frac{\pi}{2m}\right)},$$

where $P_0 = U_0\ I_0$ is dc power. Power rating of secondary windings is always higher than dc power [6]. In case of 3-phase transformer secondary power rating is equal to primary power rating and overall power rating of the transformer [2]. Results of similar discussion carried out for 6- and 12-phase transformers are set out in Table 1.

Table 1. Power rating of rectifier transformers

Windings scheme	No. of phases m	Ratio of power rating to dc power S_N/P_0
Yd	3	1,047
Yyd	6	1,22
2($Y_Z$yd)	12	1,76

Increase of power rating causes increase in consumption of constructing materials (copper, laminations). Detailed analysis of these issues may be found in [10,11,12], and partial (relevant) results are quoted in Table 2.

Table 2. Increase in transformer weight related to reference transformer (Yd)

Windings scheme	No. of phases m	Ratio of transformer weight to Yd transformer weight m_{Tr}/m_{TrYd}
Yd	3	1
Yyd	6	1,12
2($Y_Z$yd)	12	1,76

Harmonic content in rectified voltage and supply current

Installation of transforming systems with increased number of pulses (12, 24) is justified by attenuation of pulsations in rectified voltage and, what is more important, lessening of adverse impact of transformer-rectifier set on the power grid [5]. Rectified voltage and supply current waveforms and harmonic spectra may be calculated and compared for different types of rectifier circuits, assuming identical supply conditions. Assumptions and detailed analysis may be found in [7,8,12], summarized results for symmetrical and sinusoidal supply are set out in Table 3 for transformers loaded with rated load. They have been obtained by computer simulations run in TCAD for 10 kV·A transformers, with parameters directly measured in lab models.

Table 3. THD coefficients for rectified voltage (THD_0) and supply current (THD_I); different transformers and rectifiers connected in parallel (R) and in series-parallel (SR)

Windings scheme	No. of phases m	THD_0 in %		THD_I in %	
		R	SR	R	SR
Yd	3	5.74	-	22.23	-
Yyd	6	1.89	2.08	6.37	4.19
2($Y_Z$yd)	12	0.34	0.71	3.89	1.55

Novel design of rectifier transformer

A question can be raised whether it is possible to lower the investment cost of 12-phase transformer, keeping THD_0 and THD_I coefficients at the level of standard 2($Y_Z$yd) system (see Table 3). A novel 12-phase transformer with non-standard windings connections was patented in 2002 [4]. Windings scheme of this transformer is shown in Fig.5 and phasor diagrams for secondary voltages are given in Fig.6. Transformer has a single core. Standard wye-connection has been extended by adding two groups of windings (with small and equal numbers of turns) at appropriate transformer legs so that instead of one three-phase system two systems are obtained, shifted with regard to each other by 15° (phase-to-phase). These two systems are inter-connected, since there is a common node for each phase (and so, a common potential). This arrangement shall be henceforth be called “modified wye” winding. Delta winding has been likewise modified by adding additional windings with numbers of turns much lower than those of main delta winding. In this way a voltage hexagon has been obtained, with three longer and three shorter edges. arrangement shall be henceforth be called “modified delta” winding. This modified delta winding generates two three-phase systems, which however are not separated since there are nodes common to both systems. This design has been denoted as Yd_6y_6.

Demand for phase shifts (15°, 75°) between secondary side voltages has been fulfilled. It must be stressed yet again (see Fig.5) that secondary windings are not completely separated from each other, i.e. every two three-phase systems from modified wye and modified delta connection (Fig.6) have some nodes in common (with identical potentials).

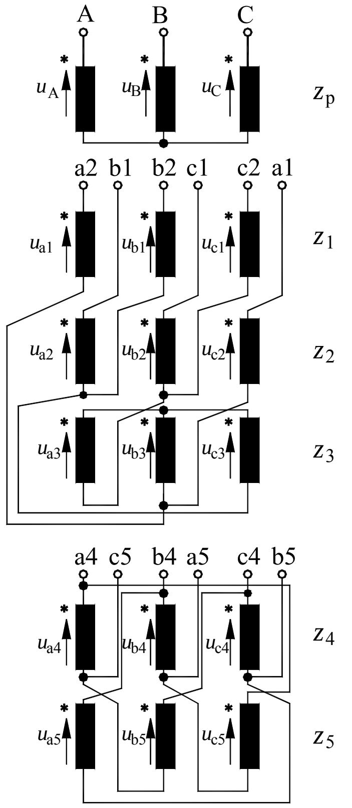


Fig.5. Transformer designated as Yd_6y_6 - windings scheme

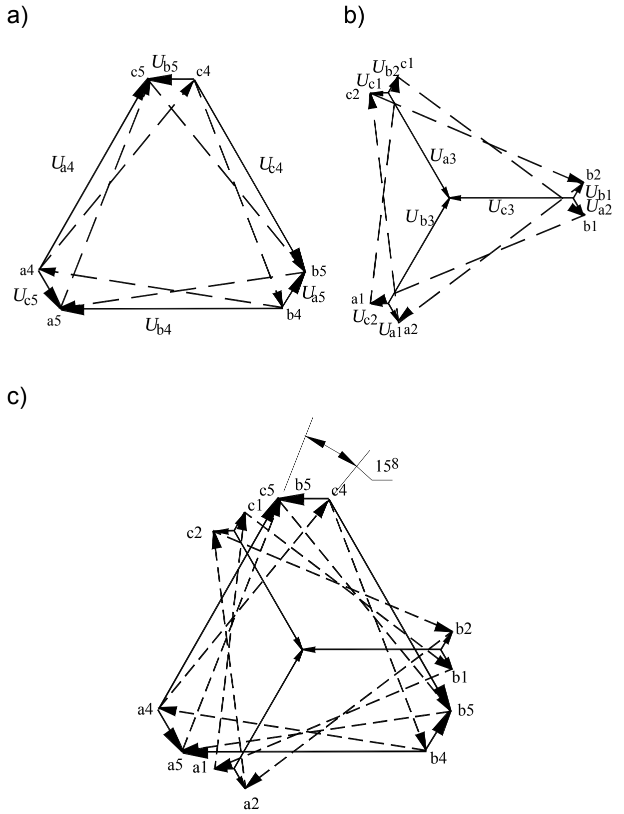


Fig.6. Phasor diagram of secondary voltages, Yd_6y_6 transformer; a) modified delta winding, b) modified wye winding, c) all phase and phase-to-phase voltages. Phase-to-phase voltages marked with dashed lines. Voltage designations as in Fig.5

This transformer is characterized by ratio of power rating to dc power equal to 1.3 (in case of 2(YZyd) transformer it was 1.76) and relative weight equal to 1.18 (in case of 2($Y_Z$yd) transformer it was 1.76). Transformer design is thus economical.

Rectifier transformer operation

If transformer-rectifier set is to operate correctly, then apart from appropriate phase shifts between voltages connected directly to rectifier input, proper voltage level must also be ensured. Phase-to-phase voltages RMS-values must be identical for modified wye and modified delta windings (e.g. wye voltage U_{a2c2} and delta voltage U_{a4c4} – *cf*. Fig.6). Voltages magnitudes and phase angles result from execution of the windings. In case of circuit shown in Fig.5, the following relationships may be derived (basing on phasor diagrams and assuming that flux density is constant):

(5)
$$U_Y = \frac{\sin 120^\circ}{\sin 30^\circ} \cdot \frac{\sin 120^\circ}{\sin 52.5^\circ} \cdot U_{x3} = 1.89 U_{x3}$$
$$U_\Delta = \frac{\sin 120^\circ}{\sin 52.5^\circ} \cdot U_{x4} = 1.09 U_{x4}$$

where U_Y – phase-to-phase output voltage (rms) for windings connected into modified wye (windings z_1, z_2, z_3, voltages U_{c2a2}, U_{a2b2}, U_{b2c2}, U_{c1a1}, U_{a1b1}), $U_{x3,}U_{x1}$ – phase voltages of same windings (e.g. voltages U_{c3}, U_{c1}, U_{a3}, U_{a1}, U_{b3}, U_{b1}), U_Δ – phase-to-phase output voltage (rms) for windings connected into modified delta (windings *z4*, *z5*, voltages U_{c4a4}, U_{a4b4}, U_{b4c4}, U_{c5a5}, U_{a5b5}, U_{b5c5}), $U_{x5,}U_{x4}$ – phase voltages of same windings (e.g. voltages U_{a4}, U_{b4}, U_{c4}, U_{a5}, U_{b5}, U_{c5}). Voltages and windings designations are in accordance with Figs. 5 and 6.

Diode commutation in the rectifier takes place if difference in voltages between its anode and cathode is appropriate (other parts of the circuit must also be suitably configured). When phasor diagrams are analyzed, we can observe that apart form "desirable" three-phase voltage systems (e.g. two three-phase voltage systems generated by modified delta windings z_4, z_5), potential differences may arise between diodes due to particular connections of transformer windings. These voltages are different from those which should act upon the rectifier diodes according to the brief foredesign. Examples of these voltages are shown in Fig.7.

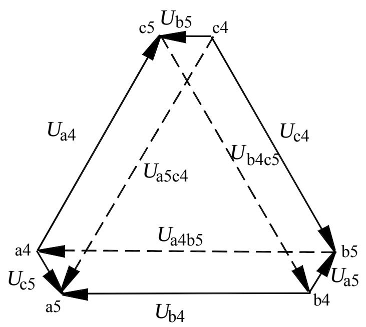
These potential differences are always greater than phase-to-phase voltages shown in Fig.6. They may be calculated as:

(6)
$$U_{Ych} = \frac{\sin 120^\circ \cdot \sin 135^\circ}{\sin 52.5^\circ \cdot \sin 22.5^\circ} U_{a3} = 2.02 U_{a3}$$
$$U_{\Delta ch} = U_{a4} + 2U_{b5} \cdot \sin 30^\circ$$

where U_{Ych} denotes undesirable potential difference caused by voltages of modified wye connection, and $U_{\Delta ch}$ is the undesirable potential difference caused by voltages of modified delta connection. For instance, these are voltages U_{c1a2} and U_{a5c4} in Fig.7.

In case of model transformer which was tested in laboratory and whose operation was computer simulated, the respective voltages are equal to: modified wye, phase voltages U_{a3} = 108,9 V and U_{a2} = U_{a1} = 17,8 V, phase-to-phase "correct" voltage U_Y = 205,8 V, "incorrect" voltage U_{Ych} = 219,65 V; modified delta, phase voltages U_{a4} = 191 V and U_{a5} = 26,7 V, phase-to-phase "correct" voltage U_Δ = 208,5 V, "incorrect" voltage $U_{\Delta ch}$ = 217,7 V. Small discrepancy in phase-to-phase voltages of modified wye and modified delta windings is due to slight inaccuracies occurring during winding processes.

a)



b)

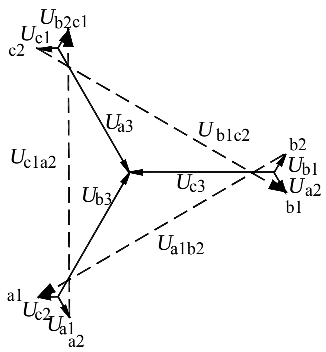
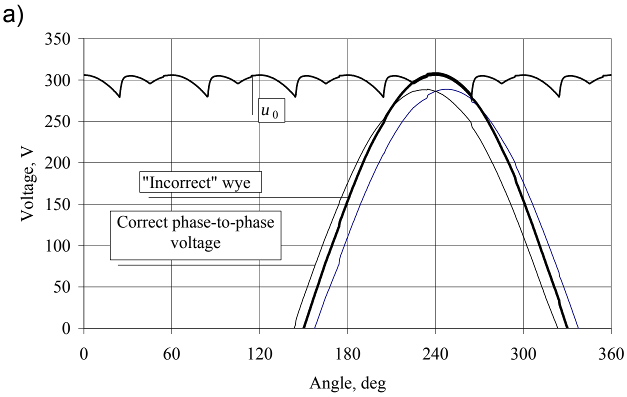


Fig.7. Phasor diagrams of Yd_6y_6 transformer secondary voltages; a) modified delta winding voltages, b) modified wye winding voltages. Phase voltages are marked with continuous lines; dashed lines denote maximum potential differences between individual phase terminals ("undesirable" or "incorrect" voltages)

a)



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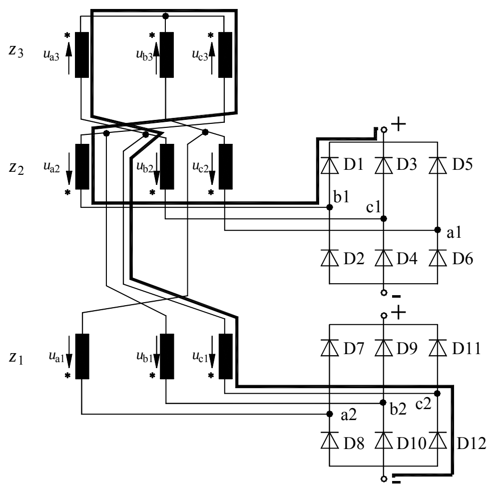

c)

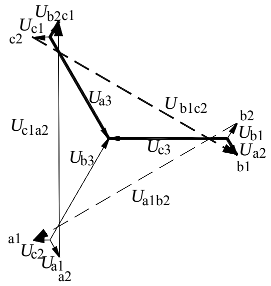

Fig.8. Transformer-rectifier operation, very small load, rectifiers connected in parallel; a) modified wye winding voltage waveforms, b) current path, modified wye winding and corresponding bridges shown only, c) voltage acting in this circuit U_{b1c2} (marked with dashed line on modified wye phasor diagram)

"Incorrect" voltages present in the system cause unexpected (i.e. not foreseen) sequence of diode commutation in different rectifier bridges. Therefore during some time intervals rectified voltage does not result from diode commutation induced by correct phase-to-phase voltages. As a consequence rectified voltage shows segments of voltages too high or too low with respect to those expected. This fact may be substantiated in a different way, if we observe that individual rectifiers do not operate separately, and are not supplied by voltages independent of each other. On the contrary, voltage induced in one three-phase system of windings goes over (instantaneously) to the rectifier, which should theoretically cooperate solely with other three-phase system. Original cause of this state of things is due to existence of electrical connections between transformer windings output to different rectifiers, and this in turn is caused by integrated windings arrangement. Graphic illustration of this effect is shown in Fig.8.

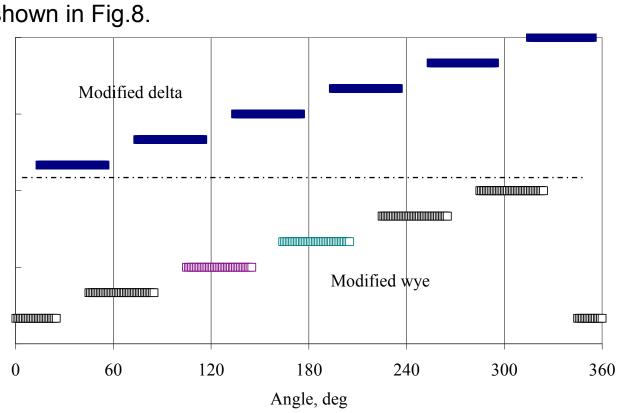

Fig. 9. Changeover of voltages in the circuit (unloaded): lower half of drawing relates to "incorrect" voltages from modified wye system, upper half relates to "incorrect" voltages from modified delta system (cf. Fig.7)

Voltage waveforms shown in Fig.8 relate to transformer-rectifier circuit operating at very small load (current equal to *c.* 10% of rated current). For each subsequent commutation interval, of 40° duration, operation alternates between two rectifiers ("incorrect voltages", wye or delta winding) or four rectifiers ("incorrect voltages", wye and delta winding at the same time). Twenty four different configurations of transformer voltages generating rectified voltage are present; however, due to the fact that these are only "incorrect" modified delta or wye voltages (see Fig.7), the principal harmonics in rectified voltage will be of $\nu = 12$ and $\nu = 6$ order. We may draw the conclusion that with transformer's operating practically with no load and uncontrolled rectifiers connected to transformer windings, the required 24-pulse voltage at dc output will not be achieved.

When transformer is loaded, commutation voltage drops proportional to product of transformer's appropriate reactance and dc current appear in the system. Diode total conducting times increase and instantaneous potentials in bridge nodes change. In case of discussed Yd_6y_6 transformer, change of bridge potentials due to load increase is equivalent to changes of potential distribution in all four bridges taking part in commutation. Instantaneous values (and resultant average values) fall down and phase-to-phase ("correct") voltages start to participate in operation. In this case rectified voltage is influenced by maximum phase-to-phase "incorrect" voltages as well as phase-to-phase voltages shown in Fig.6.

Graphical illustration of this effect is shown in Fig.10.

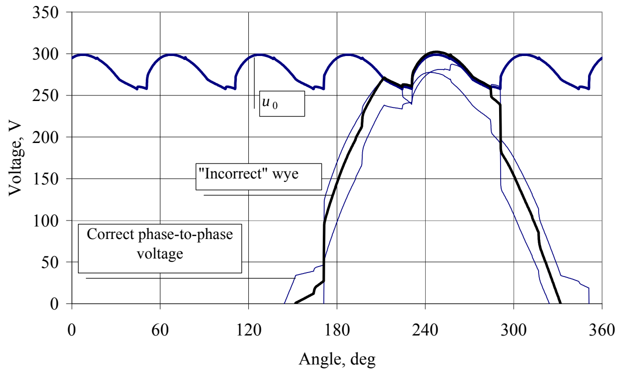

Fig. 10. Transformer-rectifier operation, system loaded, rectifiers connected in parallel; modified wye winding voltage waveform, thick black line marks voltage between potentials belonging to different phases, thinner lines show correct phase-to-phase voltages; rectified voltage waveform u_0 is also shown

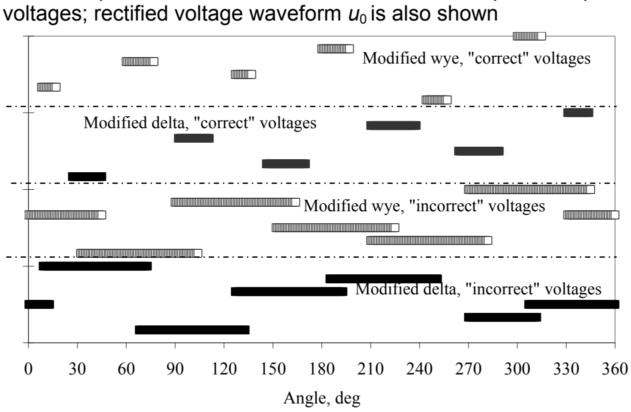

Fig. 11. Changeover of voltages in loaded circuit

If one or more phase-to-phase voltage systems affect rectified voltage simultaneously with maximum "incorrect" voltage (see angle interval 10°-20°, Fig. 11), then these "incorrect" voltages play main role in system operation. Rectified voltage exhibits a 24-pulse component due to operation of 4 phase-to-phase "correct" voltages, but its value is minimum and the circuit will operate as 12-pulse or 6-pulse system.

Harmonic analysis of rectified voltage was run and results are set out in Table 4.

Table 4. Harmonic content in rectified voltage

		THD_0 in %	ν = 6	ν = 12	ν = 18	ν=24
R*	No load	2.10	1.14%	**1.44%**	0.77%	0.36%
	0.03 rated	4.09	**3.60%**	1.41%	0.98%	0.74%
	0.2 rated	5.33	**5.09%**	1.42%	0.50%	0.30%
	Rated	3.65	**3.20%**	1.38%	0.56%	0.63%
SR*	No load	1.70	0.30%	**1.60%**	0.20%	0.40%
	0.03 rated	1.84	**1.55%**	0.62%	0.67%	0.34%
	0.2 rated	3.97	**3.87%**	0.74%	0.38%	0.21%
	0.4 rated	11.3	**9.50%**	4.30%	2.60%	2.10%

*R – rectifiers connected in parallel,
SR – rectifiers connected in series-parallel

With diode bridges connected in parallel, dc voltage exhibits a dominant 12-pulse component for no-load operation only. When the system is loaded with even small load, it switches over to 6-pulse operation.

The same is true for system operating with rectifiers connected in mixed fashion, i.e. series-parallel. The harmonic content in rectified voltage is lower than in case of parallel operation: transformer windings are connected in series, and this causes attenuation of all harmonics and overall *THD* coefficient. *THD* coefficient in supply current behaves in a similar way.

Operation of transformer different windings and rectifier bridges was also considered. When both systems are loaded with comparable load, the windings and bridges operate similarly for parallel and series-parallel loads. Bridges connected to modified wye windings are loaded almost evenly, bridges connected to modified delta windings operate differently. This is caused by the fact, that the brunt of load in case of delta windings is due to current commutating between the bridges (periods of commutation are several times higher than conduction periods). Bridge #3 (connected to modified delta winding) picks up voltage which is too low for this bridge to operate for longer periods of time. The output voltage pulse which should theoretically arise from this bridge's operation is therefore almost non-existent. Same principle applies, to a lesser degree, to the other bridge connected to modified delta winding.

Majority of the load is carried by "principal" windings of modified wye and delta systems (U_{x3} and U_{x4}, see Fig.7)

Example of rectified voltage waveform for both rectifier connections is given in Fig. 12.

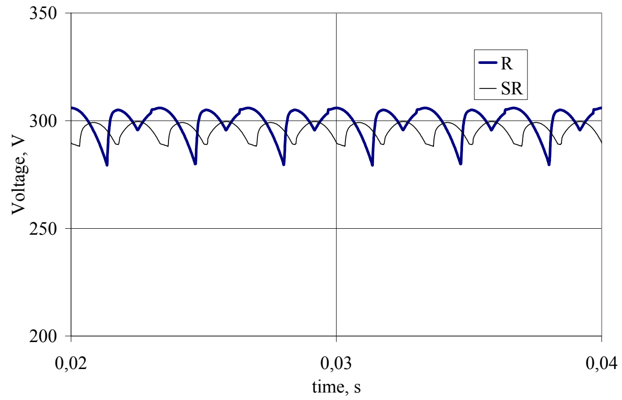

Fig. 12. Rectified voltage waveform, no-load operation, rectifiers connected in parallel (R) and series-parallel (SR)

Verification of simulations

Computer simulations have been verified by lab tests. Rectified voltage waveforms (measured) are shown in Fig. 13. Transformer was supplied with distorted voltage (*THD* = 3.5%), since purely sinusoidal voltage was not available under lab conditions; it was loaded with 5 kV·A of dc power (dc motor acting as load).

The harmonic content was analyzed and the results are shown in Table 5.

For parallel connection of rectifiers the participation of harmonics ν = 6 % and ν=12 % is almost identical, while harmonic ν = 24 % is almost three times lower. For series-parallel connection pulsation is suppressed, participation of 6th and 12th harmonics drops down to *c.* 0.5% and 24th harmonic to *c.* 0.2%. In each case system operates as 6-pulse circuit; this adequately confirms results of simulations.

Table 5. Harmonic content in rectified voltage-lab tests results

		THD$_0$ in %	ν = 6	ν = 12	ν = 18	ν = 24
R*	Rated	1.89	**1.4**	1.3	0.2	0.5
SR*	0.2 rated	0.74	**0.5**	0.45	0.1	0.2

*R – rectifiers connected in parallel,
SR – rectifiers connected in series-parallel

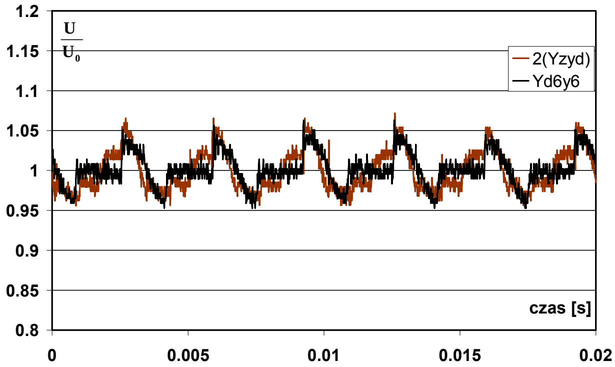

Fig.13. Rectified voltage waveforms (additional waveforms given for $2(Y_Zyd)$ transformer) - rectifiers connected in parallel

Table 5. Harmonic content in rectified voltage-lab tests results

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SR*	0.2 rated	0.74	**0.5**	0.45	0.1	0.2

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SR – rectifiers connected in series-parallel

Conclusions

Transformer with windings scheme designated as Yd_6y_6, with partially integrated secondary side windings, is intended to operate as part of transformer-rectifier set in tram traction substations. Diode bridges are used as rectifiers. It was assumed that this system would operate with 24 pulse content in rectified voltage. Special design of the transformer resulted in decrease of its power rating and materials consumption in comparison to well known standard 24-pulse systems, built of two Yyd transformers wound on separate cores.

It has been proved that under ideal supply conditions, i.e. non-varying sinusoidal symmetrical voltage, this transformer will not generate 24-pulse rectified voltage; output dc voltage will contain mostly 6 pulses. Therefore we feel justified in comparing this transformer's operational parameters with standard Yyd transformer (instead of $2(Y_Zyd)$ 12-phase transformer). Relative weight of Yd_6y_6 is equal to 1.18 with Yyd equalling 1.12 (reference value used in both cases is Yd transformer weight), power ratings are equal to, respectively, 1.3 and 1.22 (again, Yd transformer power rating is used as reference). Rectified voltage *THD* coefficient for Yyd system and rectifiers connected in parallel is equal to 1.89%, for Yd_6y_6 3.65% (system fully loaded). *THD* coefficient in supply current [12] equals 6.37% for Yyd and 7.15% for Yd_6y_6 (rectifiers connected in parallel). From the viewpoint of impact of those systems on the supply network and quality of rectified voltage it seems that these two systems are comparable; differences in cited parameters are not overwhelming.

It must however be stressed that investigation was carried out for ideal supply conditions. In order to obtain full picture of Yd_6y_6 possibilities, behaviour of this transformer under all possible supply conditions such as asymmetry and distortion should be investigated.

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