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The influence of the reference potential on the operation of the pulse formation system of a 12-pulse controlled rectifier

Streszczenie. *W artykule opisano problem wyboru punktu odniesienia dla napięć fazowych stosowanych w układzie sterowania prostownika 12-impulsowego do załączania mostków tyrystorowych. Jedną z głównych cech prostownika 12-pulsowego jest niska wartość współczynnika THD prądu sieciowego. Proponowany przekształtnik charakteryzuje się lepszymi właściwościami niż typowy prostownik 6-pulsowy. Prostownik wykorzystujący dławiki sprzężone magnetycznie łączy w sobie kilka funkcjonalności. Umożliwia sterowanie napięciem stałym, posiada mniejszą masę i wymiary niż urządzenie energoelektroniczne o podobnej funkcjonalności, ale zbudowane z wykorzystaniem transformatorów dużej mocy.* ***(Wpływ potencjału odniesienia na pracę układu formowania impulsów 12-pulsowego prostownika sterowanego)***

Abstract*. The article describes the problem of selecting a reference point for phase voltages used in the control system of a 12-pulse rectifier for switching thyristor bridges. One of the main features of a 12-pulse rectifier is the low value of the THD factor of the grid current. The proposed converter is characterized by better features than a typical 6-pulse rectifier. The proposed rectifier using magnetically coupled reactors is an interesting solution that combines several functionalities. It allows DC voltage control and has a smaller weight and dimensions than a power electronics device with similar functionality but built with the use of a high-power transformer.*

Słowa kluczowe: prostownik 12-pulsowy, dławiki sprzężone magnetycznie, prostownik sterowany, kondycjonowanie energii.
Keywords: 12-pulse rectifier, magnetically coupled reactors, controlled rectifier, energy conditioning.

Introduction

The main thrust of this paper is the reasonableness of installing multi-pulse rectifiers, which have a lower THD (Total Harmonic Distortion) factor of the grid current as well as a smaller weight and size, for the systems and equipment powered by direct current and used on ships [1,2]. They are distinguished by isolated networks, in which the supplied electrical power is practically equal to the absorbed power. In such systems, the negative effects of converters' operation become even more apparent than in onshore networks, so the use of multipulse rectifiers is justified [3,4].

An additional feature of a multi-pulse controlled rectifier is that it can change the average value of the output voltage. Regarding ships, on which it is expedient to reduce redundant equipment since earning money is realized by carriage goods rather than additional equipment, multifunctionality is a desirable feature. Considering the proposed rectifier, it combines several features. Not only does the rectifier perform the AC/DC conversion but also enables the output voltage control with simultaneous reduction of grid current THD factor value [5]. The use of magnetically coupled reactors, especially in the TDSλ topology, gives the possibility to build a converter whose weight and dimensions are diminished [6,7].

The utilization of magnetically coupled reactors, which are passive and uncontrolled elements, in the construction of the rectifier makes it easier to operate and more resistant to damage. The topology used to connect magnetically coupled reactors reduces their number [8]. Reducing the number of magnetic elements in power electronics devices is now a desirable solution due to the cost of materials and the tendency to minimize the size of devices [7,9]. The combination of reactors with magnetic coupling (MCRs) is called TDSλ (three-phase coupled reactors with lambda connection variant) and is described in more detail in [9,10].

An important disadvantage of the TDSλ system is the lack of galvanic separation, which is present in multi-winding transformers or transformers. The works [11-17] indicate various designs of multi-winding transformers and their advantages and disadvantages. The biggest advantage of this type of transformer is the galvanic separation and the conversion of a certain number of phases into another number of phases. The disadvantages of this type of transformer are the relatively high weight and high cost relative to power. Another disadvantage of this type of transformers is their size. However, it was underlined in [16] that it is still smaller than of traditional transformers, especially when comparing a multi-coil transformer to a corresponding number of single-phase transformers.

The most important advantage of the described solution is the possibility of obtaining three-phase multi-level waveforms by selecting the appropriate number of coils for the adopted topology of reactors connection at the output of the structure with simultaneous simple control of the converters. This results in a relatively low content of harmonics in the input voltages and current waveforms [18].

Transportation uses 12-pulse rectifiers, which are not controlled and use large and heavy oil or dry transformers [19]. An alternative solution would be a chopper, however, a system that utilizes high-power passive reactors and thyristors in marine conditions is a more favorable solution due to its operation reliability in harsh environments [20].

The article describes the problem of selecting a reference point for the phase voltages used by the control system to trigger pulses in the thyristor bridges of a 12-pulse rectifier with magnetically coupled chokes. The work examines two models of thyristor bridge synchronization, presents simulation studies and experimental studies. In the tested system, thyristor bridges are connected in parallel to the load.

Topology and principle of operation of 12-pulse controlled rectifier

The three-phase coupled reactor (Harmonic Canceling Reactor, Harmonic Blocking Current Transformer) was patented in 1974 by U. Meier [8]. Between 1989 and 1990, M. Depenbrock and C. Niermann published a 12-pulse rectifier circuit using three-phase coupled reactors for parallel operation of two three-phase bridge circuits [8,9]. The circuit using TDSλ-type magnetically coupled reactors was also used to develop 12-, 18- and 36-plus-pulse rectifiers operating as stable voltage sources for multilevel inverters in works [19,20].

What is more, it should be mentioned that a three-phase coupled reactor, thanks to appropriate design, blocks certain higher harmonics. Among them, there are harmonics of the following orders: 5, 7, 17, 19, etc.

Reactors (MCR) are built from three separate magnetic cores with a properly selected number of windings (N_x, N_y, $N_z=N_x+N_y$). Thanks to the appropriately selected ratio of the reactors' windings, two three-phase symmetrical voltage systems mutually shifted in phase by an angle equal to π/6 are obtained at the reactors' output. Such a value of angle is required by the described system, but in general, the mutual phase shift can be modified by changing the number of windings within a relatively wide range.
The value of the phase angle between the space vectors of the output voltages of the TDSλ system (Figure 1) depends directly on the ratio of the number of windings (N_y/N_x) of the corresponding windings. According to [19], the dependence of the ratio p of the reactors in the TDSλ system on the angle α of the offset of the three-phase supply voltage systems is obtained. The ratio of the number of windings satisfying the above condition, for the corresponding reactors of the TDSλ system, is as follows:

Magnetically coupled reactors play a similar role as converter transformers in this system. However, in comparison to converter transformers, they are characterized by several times less power, but a more complex arrangement of secondary windings.

Figure 1 shows a diagram of the 12-pulse controlled rectifier. Such a rectifier can be also implemented with the use of a transformer system. In this case, rectifiers are connected in a transformer system with three windings of the Yyd type. For powering uncontrollable rectifiers with 12-pulse output voltages, maintenance-free dry-type transformers suitable for increased thermal losses are usually used, while traditional traction substations use power oil transformers. However, the system shown in Figure 1 uses TDSλ magnetically coupled reactors because of their properties mentioned earlier in the text. 12-pulse rectifiers are usually constructed using uncontrolled power electronics elements such as diodes, which means that those rectifiers cannot change the average value of the output voltage.

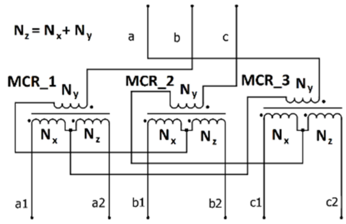


Fig. 1. Circuit configuration of magnetically coupled reactors in TDSλ system

The power supply in the presented controlled rectifier system is a three-phase line-to-line voltage, whilst the resistors $R_{a,b,c}$ and inductances $L_{a,b,c}$ represent the equivalent impedance of the grid. The reactor system $MCR_{1,2,3}$ consists of two three-phase systems shifted by an angle of π/6. Phase voltages between the reactors and rectifiers are measured in relation to the apparent zero point. These voltages are then used by the control systems to synchronize the triggering pulses of the thyristors in the rectifier. The presented rectifier uses two independent bridges made of thyristors. The control of the rectifiers is performed in the range of π/6 to π/2. Due to the phase shift between the voltages u_{a1}, u_{b1}, u_{c1} and the voltages u_{a2}, u_{b2}, u_{c2} by an angle of π/6, the considered 12-pulse rectifier shall use two independently synchronized thyristor bridge control systems.

The control system of a single rectifier bridge (Figure 2 - control1 and control2 blocks) includes a PLL (phase-locked loop) and a system for thyristors pulse generation, which was taken from the PLECS program library.

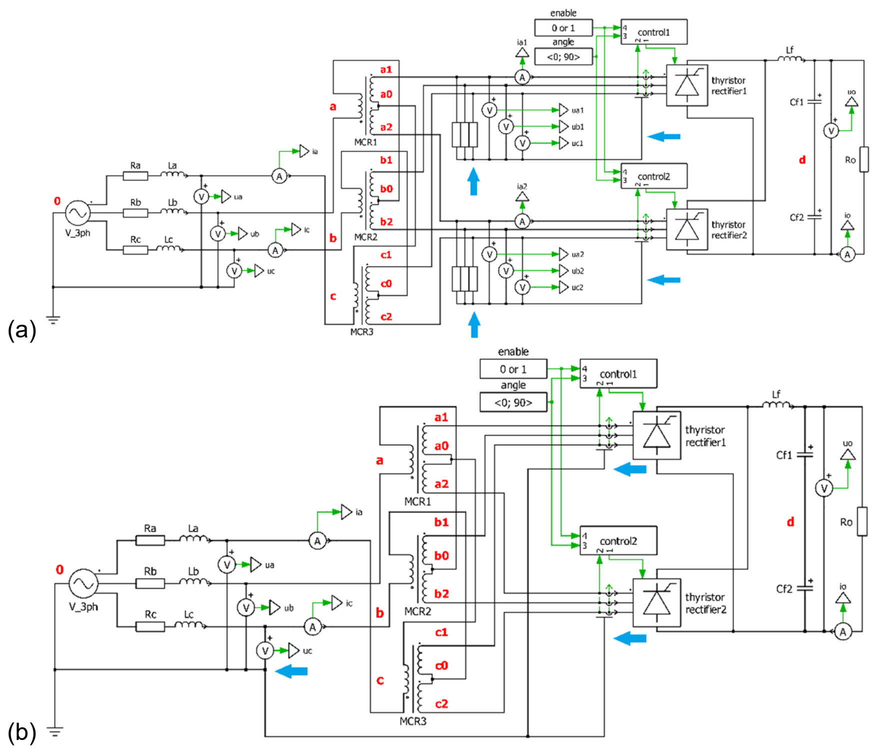


Fig.2. Schemat of a controlled 12-pulse rectifier, where the reference potential of the phase voltages is: (a) generated by the connected resistances and (b) connected to the ground point of the power supply

The voltages occurring between points "a", "b", "c" and "d" result from the following equations:

$$\begin{aligned} u_{ad} &= u_{a1d} + [N_{xy1}]u_{a1a2} + [N_{xy2}]u_{c1c2} \\ u_{bd} &= u_{b1d} + [N_{xy1}]u_{b1b2} + [N_{xy2}]u_{a1a2} \\ u_{cd} &= u_{c1d} + [N_{xy1}]u_{c1c2} + [N_{xy2}]u_{b1b2} \end{aligned} \tag{1}$$

where: $N_{xy1} = (N_x+N_y)/(2N_x+N_y)$, $N_{xy2} = N_y/(2N_x+N_y)$.

To determine the voltage between points "a", "b", "c" and "0", the voltage of the zero component, u_{0d}, between points "0" and "d" has to be calculated in accordance to:

$$u_{0d}=(1/3)(u_{ad} + u_{bd} + u_{cd}) \tag{2}$$

Thus, the voltage measured between points "a", "b", "c" and "0" is equal to:

$$\begin{aligned} u_a &= u_{0d} - u_{ad} \\ u_b &= u_{0d} - u_{bd} \\ u_c &= u_{0d} - u_{cd} \end{aligned} \tag{3}$$

The design of the TDSλ system is related to its overall power. It is defined as the arithmetic average of the power of windings of an equivalent transformer (with two windings). It can be determined assuming that the associated magnetic flux of the reactor is produced by a sinusoidal alternating voltage with a grid pulsation ω. Nevertheless, the determination of the overall power is not the subject of this paper.

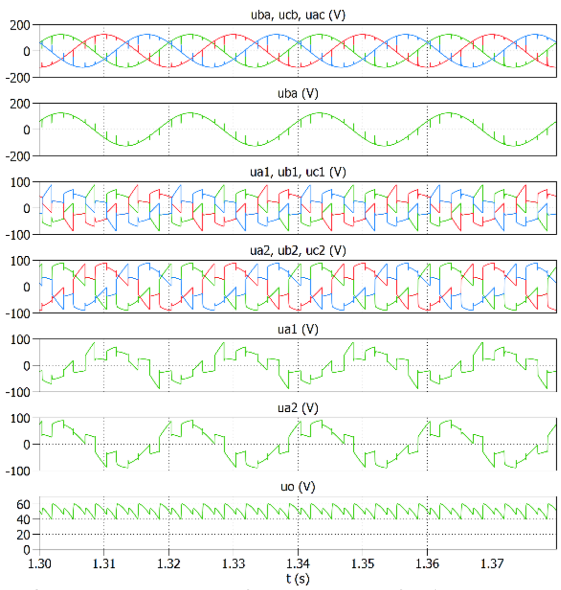


Fig.3. Selected voltage waveforms at angle of 30˚

Rectifier models

For synchronization of the rectifier control system 12-pulse, the voltages recorded between the choke system (terminals: a1, a2, b1, b2, c1, c2) and the thyristor bridges should be used. These may be phase or interphase voltages. Using interphase voltages seems to be a simpler solution because it does not require a reference potential. In the case of phase voltages, it is strategic to adopt the appropriate reference potential. The article focuses on examining the impact of the synchronization of the phase voltage control system, because the laboratory system is synchronized in this way. Figure 2 shows two circuit diagrams according to the reference potential selection method. In the circuit shown in Figure 2a, an apparent reference potential was created using a high-value resistance.

Simulation tests showed that the resistances should be much more than 15 kΩ. In the second case (Fig. 2b), the reference potential of the network was taken as the reference potential.

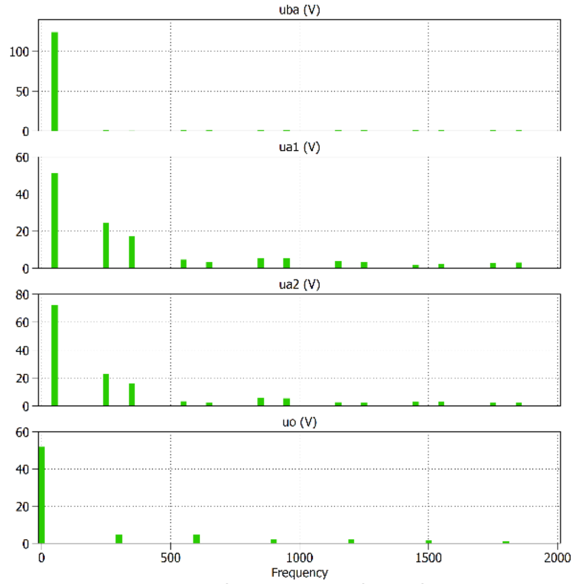


Fig.4. Amplitude spectra of voltage waveforms from Figure 3 at angle of 30˚

Simulation tests have shown that both models ensure correct operation of the control system and allow for obtaining similar results, which are presented in one version in Figure 3.

Simulation studies

Simulation tests of a 12-pulse controlled rectifier using magnetically coupled reactors have been performed in PLECS software. Simulation tests were carried out for similar power supply and load conditions as in the laboratory system, in which the operation of the system was verified. The supply voltage was reduced to a phase-to-phase voltage of 3 x 110 V and the load was set to 25 Ω. These are the settings at which excellent results were obtained for the uncontrolled version of the 12-pulse rectifier - so they were considered the reference set.

Due to the correct operation of the synchronization system, the voltage waveforms u_{a1}, u_{b1}, u_{c1} and the voltages u_{a2}, u_{b2}, u_{c2} are important, which, as shown by the simulation, are significantly distorted and their THD is over 43%. This fact is also confirmed by the amplitude spectra presented in Figure 4.

Experimental research

Experimental tests have been conducted on a laboratory stand using magnetically coupled reactors and two thyristor bridges adapted for the study. The system includes three single-phase magnetically coupled reactors with the following number of turns: on the primary side - 29 turns, and the on secondary side - 79 and 108 turns. Two controlled rectifiers are built from thyristors controlled by the pulse-generating system used in the laboratory. The thyristor triggering system is synchronized by the phase voltages measured for each of the six phases formed at the output of the reactors. The rectifier is powered by a laboratory transformer, in which the line-to-line voltage is equal to 110 V. The rectifier circuit has been started at the reduced voltage to ensure safe operating conditions and, at the same time, to check the operation of the circuit at low voltage. An uncontrolled rectifier, let alone a controlled one, requires a suitable load for proper operation. In this case, the load consists of four high-power resistors connected in parallel with a nominal value of 100 Ω each. Unlike the simulation studies presented earlier in the text, no capacitive or inductive filter has been applied to the output (before the load) in the experimental studies.

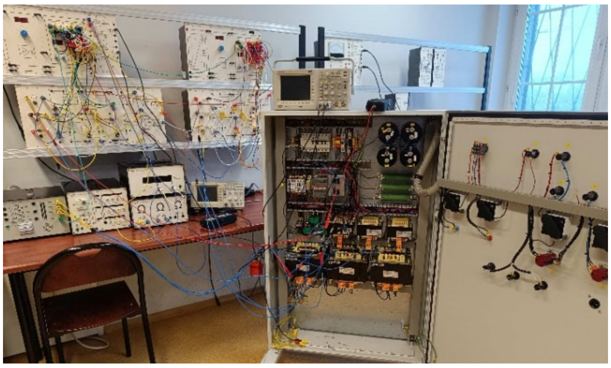
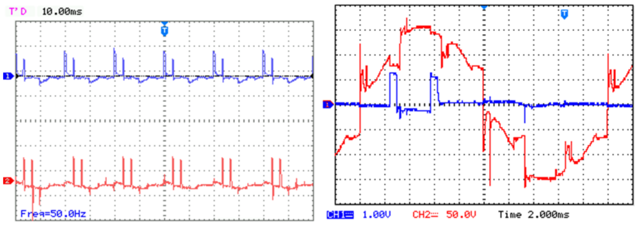
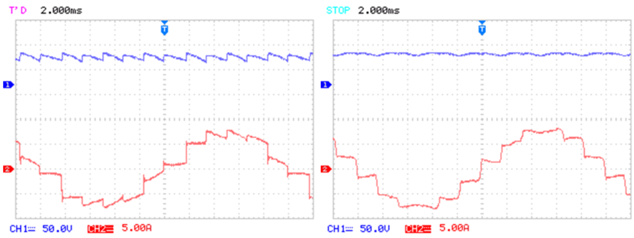


Fig. 5. View of the laboratory bench with thyristor bridges, coupled reactors, and electrical apparatuses



(a) (b)

Fig. 6. Pulses triggering thyristors phase 2 (p) and phase 1 (n) (a) and oscillogram of voltage u_{a1} (red) used to synchronize the thyristor pulses triggering system and exemplary pulses of one thyristor (blue) (b)



(a) (b)

Fig. 7. Oscillograms with selected output voltages u_o (blue) and input currents i_a (red), which were measured for two angles equal to 30˚ (a) and 10˚ (b)

Conclusion

The 12-pulse controlled rectifier using magnetically coupled reactors proposed in the paper is a further development of the uncontrolled rectifiers presented in [9,10]. The 12-pulse controlled rectifier is characterized, like the uncontrolled rectifier, by good power-conditioning properties such as an input current shape with a low content of higher harmonics, and a small weight and dimensions. Moreover, the angle value changes in the range from 30˚ to 90˚ enables a wide range of output voltage values.

For the correct operation of the system, it is necessary to provide appropriate signals to synchronize the control system. As shown by simulation and experimental studies, the obtained results show that the voltages used for synchronization are significantly distorted. Due to the use of phase voltage synchronization in the control system, an appropriate reference point is required. The tested variants of connecting the reference point to the control system showed that both solutions ensure proper operation despite distorted phase voltages.

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