

# A 12-pulse rectifier using coupled reactors for supplying three-inverters

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**Abstract.** The paper presents a proposal of an auspicious multi-pulse rectifier convenient for supplying three-level inverters. The rectifier consists of two three-phase bridges. Their outputs are connected in parallel while inputs are connected to the line by use of coupled reactors. These reactors are connected and work in an exceptional variant 3CRλ. The application of 3CRλ makes that the diodes conduction angle in rectifiers achieves 180°. Simulation and experimental works prove that multi-pulse rectifier gives a worthy performance and has some respectable properties.

## Key words

Multi-pulse rectifier, 12 pulse rectifier, coupled reactors, 3-level inverter

## 1. Introduction

Providing supply for electrical energy conversion systems in which multilevel inverters are used brings serious problems related with the load of the supply network. On the one hand, contemporary converters are designed using very fast switching semiconductor connectors, which reduces their electromagnetic compatibility. On the other hand, those systems are used in situations when large power is required at the reception side [1, 2, 3]. A multilevel voltage inverter requires a multipolar DC voltage supply in which the number of poles corresponds to the number of levels in the inverter. For instance, in the three-level voltage inverter of NPC type, the internal inverter system should be capable of being connected to three poles of the supply network. In standard NPC inverters, a common procedure is to use for this purpose an intermediate circuit with divided voltage  $U_D$ , the three poles of which correspond to potentials 0,  $U_D/2$ , and  $U_D$ . The voltage to the intermediate circuit is usually delivered by the rectifiers, which are AC/DC voltage converters. The rectifiers, along with the intermediate circuit and the inverter working, for instance, in drives with AC motors, are nonlinear receivers of electrical energy which generate higher harmonics in the supply network. These harmonics are highly undesirable, since they are a source of additional power losses in the supply line, deform the

supply voltage, and emit electromagnetic signals which disturb the operation of IT and control systems. The international standards, IEEE for instance, define very severe requirements concerning the presence of higher harmonics in the currents taken from the supply sources and the permissible voltage distortion [4]. The main current and voltage distortion coefficients are defined as follows:

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \cdot 100\% = \frac{\sqrt{I^2 - I_1^2}}{I_1} \cdot 100\% \quad (1)$$

where  $h$  is the order of the harmonic,  $I_h$  is the RMS value of the current harmonic,  $I_1$  is the RMS value of the fundamental current harmonic and  $I$  is the RMS value of the current taken from the supply source. Similarly, the Total Harmonic Distortion of the voltage,  $THD_U$ , is defined as:

$$THD_U = \frac{\sqrt{\sum_{h=2}^{\infty} U_h^2}}{U_1} \cdot 100\% = \frac{X_Z}{U_1} \sqrt{\sum_{h=2}^{\infty} (h \cdot I_h)^2} \cdot 100\% \quad (2)$$

because  $U_h = hX_Z I_h$ . Here,  $X_Z$  is the supply source reactance, which is determined from the short-circuit test. Once the short-circuit current  $I_Z$  is known, the reactance can be calculated as  $X_Z = U_1 / I_Z$ .

The permissible voltage distortion coefficient for receivers supplied from the LV network is equal to 3% in the case of special objects, such as hospitals or airports for instance, and to 5% for general objects, industrial plants for instance. It results that, in general, the permissible current distortion coefficient should not exceed several percent (2% ÷ 10%). It is also noteworthy here that the requirements referring to permissible amplitudes of individual current harmonics are also standardised.

A multi-pulse AC/DC converter generates current harmonics, the order of which depends on  $q$  where  $q$  is the number of pulses in one period of the current

$$h = kq \pm 1 \quad k \in \mathbb{N} \quad (3)$$

An obvious conclusion resulting from it is that we should use converter systems with large  $q$  values (multi-pulse

systems) to meet the requirements defined by the standards. In practice, 6-, 12-, and 18-pulse systems are frequently used for electric drive purposes. The following approximate THD<sub>I</sub> values representing the contents of higher current harmonics are obtained: 31% for q= 6; 15% for q=12, and 9,6 % for q=18. Certainly, increasing the supply source reactance by using reactors leads to considerable reduction of THD<sub>I</sub>.

In classical solutions, the q value can be multiplied, for instance, by serial or parallel connection of three-phase bridge systems and relevant phase shift in the transformers supplying the converters [5, 6].

This article presents a proposal of a system supplying three-level inverters where DC voltage is obtained from the AC/DC converter in which multi-pulse diode rectifiers with coupled reactors were applied to block higher current harmonics. The converter system ensures considerable reduction of the distortion factor of the current taken from the supply source [7, 8, 9, 10].

## 2. Multi-pulse AC/DC converter using coupled reactors

The schematic diagram of the 12-pulse diode rectifier in which magnetically coupled reactors were used in the variant 3CRλ is shown in Fig. 1. The rectifier consists of two three-phase bridges (P1, P2) connected in parallel, and delivers the voltage 2E<sub>d</sub> to the R-C load. The capacitance C resulting from serial connection of two capacitances 2C makes the system act as a voltage source. Figure 1 presents too the schematic diagram of the considered rectifier supplying a 3-level NPC inverter. The operation of the system, the way of determining current and voltage waveforms, as well as the design and results of simulation and experimental tests have been presented and discussed in [5, 6, 7, 8].

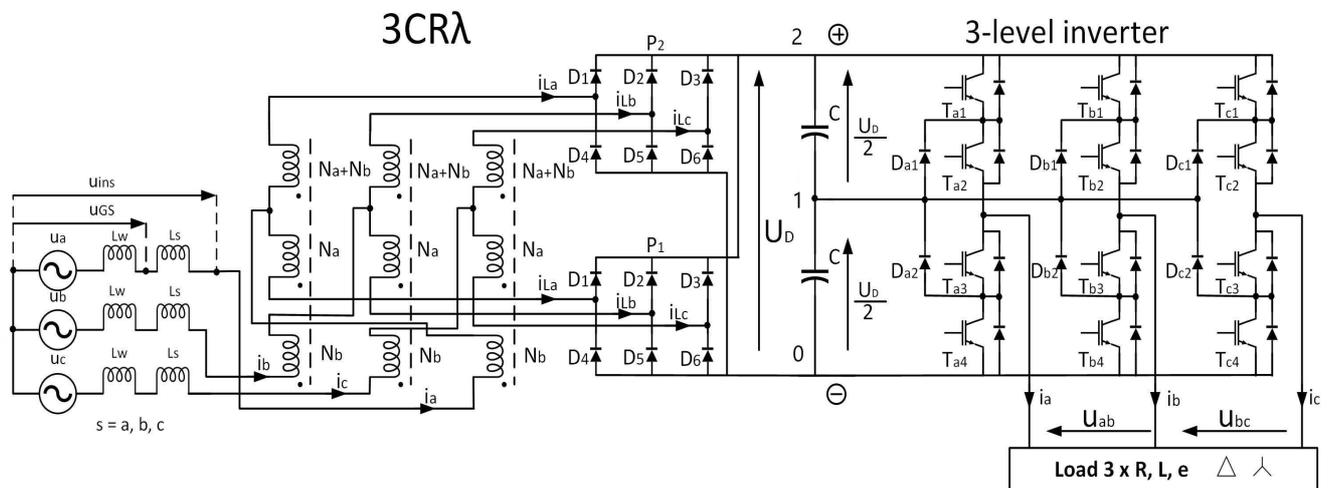


Fig. 1. Schematic diagram of the considered rectifier supplying a 3-level inverter.

The essence of operation of coupled reactors consists in blocking (eliminating) higher harmonics, of the order of  $6k \pm 1$ , in the output voltage. The application of 3CRλ reactors makes that the diode conduction angle in bridge rectifiers is  $180^\circ (\pi)$ , against  $2\pi/3$  in conventional receivers acting as current sources. The reactors are constructed of three separate magnetic cores with selected numbers of turns ( $N_a, N_b, N_a+N_b$ ). When the turns ratio is selected properly, two symmetric three-phase voltage systems, phase shifted by  $\pi/6$ , are obtained at reactor output. Since the diode conduction angle in the rectifier is equal to  $\pi$ , the voltage at output terminals of the reactors has the 12-pulse waveform at nominal load. The rectifier with a system of coupled reactors is supplied from the three-phase network having the internal inductance  $L_w$  in each phase. Network reactors of inductance  $L_s$ , much higher than the internal inductance of the source,  $L_s \gg L_w$ , were installed between the phase voltage and the rectifier input.

## 3. Simulation Tests

The simulation tests of system operation were performed for different network reactor inductances, assuming that the load power was constant and equal to 2 kVA.

The percentage relation between  $L_s$  and the short-circuit voltage of the supply source is given by the formula  $u_{z\%} = (\omega L_s I_s / \sqrt{3} U_s) \cdot 100\%$ . Basic parameters of the simulation model of the rectifier system are collated in Table 1.

Table I. - Parameters of simulation and laboratory models of 2 kVA 12-pulse rectifier

Nominal line-to-line voltage	$U_s = 400V$
Short-circuit voltage of supply source ( $L_w+L_s$ )	$u_{z\%} = 10\%$
Maximal inductance in magnetic cores	$B_m = 1,0T$
Number of turns $N_a$ in winding	204
Number of turns $N_b$ in winding	75
Inductance of network reactor	$L_s = 22 \text{ mH}$
Capacitance of load circuit capacitor	$C = 10 \text{ mF}$
Resistance of load	$R = 102 \Omega$
Current density in coupled reactor windings	$J = 2,5A/mm^2$
Cross section area of TDSλ core column	$S_{Fe} = 8 \text{ cm}^2$
Shift angle of diode bridge input current vectors	$2\alpha = 30^\circ$
Internal inductance of supply line	$L_w = 0,1 \text{ mH}$
Coefficient of core filling with iron	$k_{Fe} = 0,9$

Figure 2 shows the results of simulation tests in the form of the waveforms of phase currents taken from the network for different values of inductance  $L_s$ .

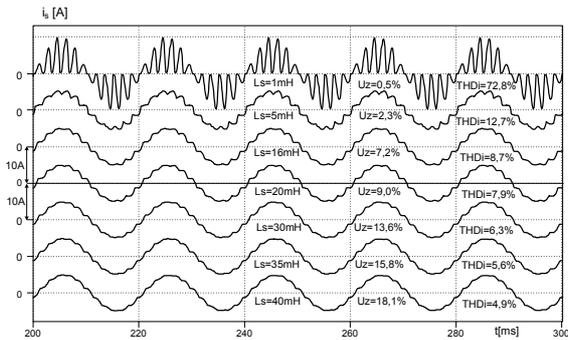


Fig. 2. Source current waveforms as functions of  $L_s$  in the rectifier arrangement from Fig. 1.

The next figure, Fig. 3, presents the  $THD_i$  values as functions of the short-circuit voltage and the reactor inductance  $L_s$ .

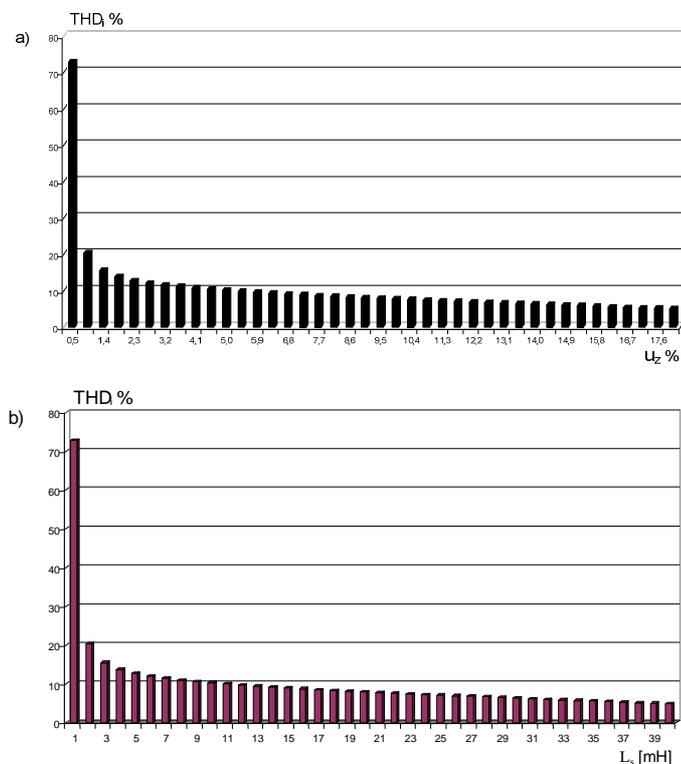


Fig. 3.  $THD_i$  factor as function of: a) short-circuit voltage, b) reactor inductance  $L_s$ .

It was assumed that the network is symmetrical, and the phase voltage waveforms have the shape of a mathematical sine curve. For a small value of  $L_s$  (1 mH,  $u_z\% = 0,5\%$ ), the current waveform is discontinuous and the total harmonic distortion coefficient,  $THD_i$ , reaches 72,7%. Increasing the inductance improves the shape of the supply current waveform. For the inductance  $L_s = 20$  mH and the assumed load of 2 kW, the  $THD_i$  value is below 8%. Certainly, increasing the inductance  $L_s$  leads to the increase of the commutation angle.  $THD_i$  decreases to about 10% when the short-circuit voltage increases to 5% ( $L_s \approx 10$  mH), which is the value typical for transformers of several hundred kVA in power. Reaching this  $THD_i$  value in the 12-pulse system can be considered a good result, as the  $THD_i$  value of the 12-pulse rectifier loaded with the

current source is 15,2% when neglecting the current source inductance. Figure 4 presents the amplitudes of the selected higher harmonics ( $n = 11, 13, 23, 25, 35, 37$ ) as a function of the current source inductance.

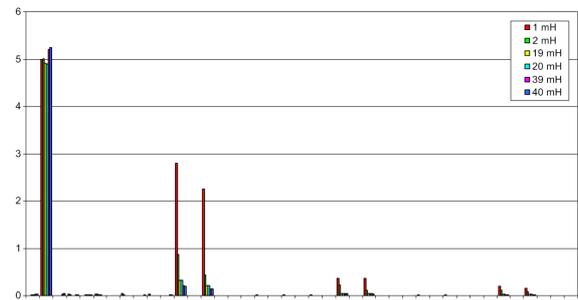


Fig. 4. Amplitudes of selected harmonics for different values of inductance  $L_s$  and constant load power 2kVA.

The obtained results have revealed that in the assumed short circuit voltage interval, the increase of inductance  $L_s$  did not practically affect the amplitude of the fundamental current harmonic, but led to a considerable decrease in amplitudes of higher harmonics existing in the 12-pulse rectifier system.

#### 4. Experimental Results

Should clearly indicate advantages, limitations and possible applications. Experimental tests have been executed on assumption that 3-level inverter introduced to the system the load equal to 2 kW. It was assumed that the state of the inverter was described by a voltage vector  $V_{210}$  what means that phase A has been connected to point 2 ( $U_D$ ), phase B to point 1 ( $U_D/2$ ) and phase C to point 0. Next figures, Figures 5-9 illustrate results of the experimental tests done at 2 kW load. These tests included measurements of waveforms of the following quantities: input voltage for the 3CR $\lambda$  system (Fig. 1); current taken from the supply source, and winding currents in the 3CR $\lambda$  system (Fig. 2); current taken from the supply source and the voltage measured on terminals  $K_1 K_2$  (Fig. 8).

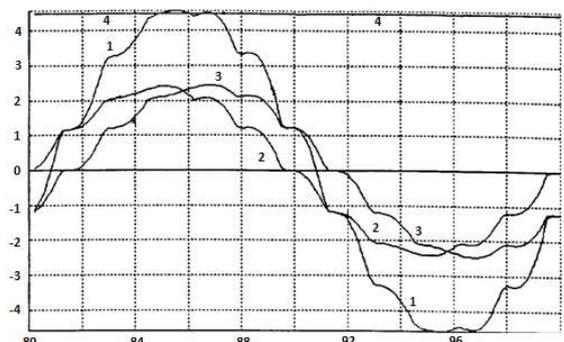


Fig. 5. Waveforms of network current  $i_{R/1/}$ , stabilised current  $i_{d/4/}$  and 3CR $\lambda$  winding currents  $i_{1R/2/}$ ,  $i_{2R/3/}$  for the 2kW rectifier.

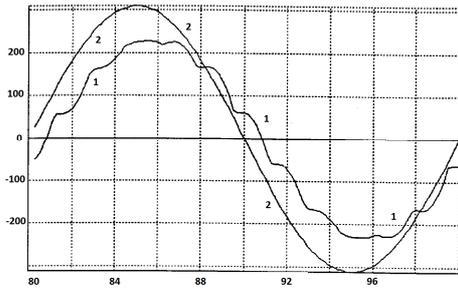


Fig. 6. Waveforms of voltage  $u_{p/2l}$  and current  $i_{R/1l}$  of the supply line, at nominal load of the 2 kW rectifier.

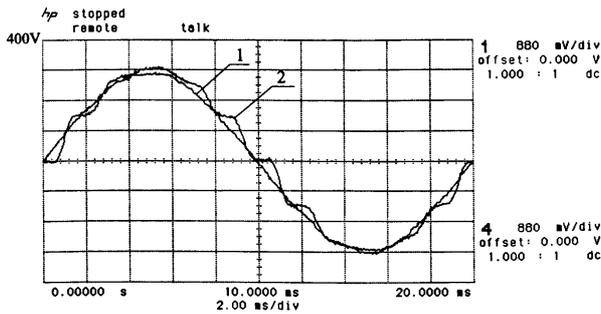


Fig. 7. Oscillograms of undistorted phase voltage  $u_{R-1}$  in the supply network, and voltage  $u_{GR0-2}$  at input terminals of the 3CR $\lambda$  system at nominal converter load.

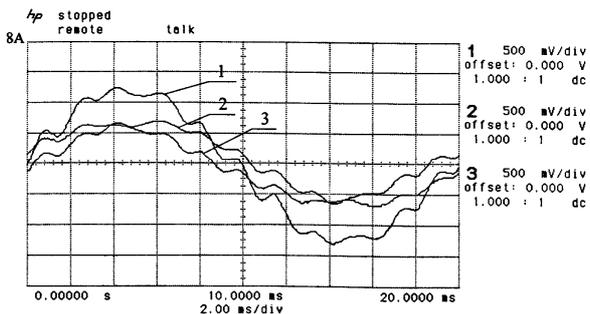


Fig. 8. Oscillograms of network current  $i_{R-1}$  and 3CR $\lambda$  winding currents  $i_{1R-2}$ ,  $i_{2R-3}$  at nominal converter load.

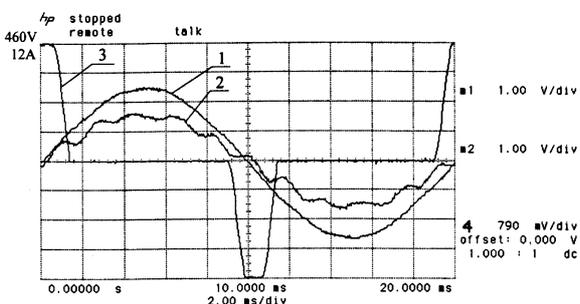


Fig. 9. Oscillograms of voltage  $u_{R-1}$  and current  $i_{R-2}$  in the supply line, and voltage  $u_{K1RK2R-3}$  on main 3CR $\lambda$  windings, at rated converter load.

The presented results of the simulation and experimental tests comply to a sufficient degree with the theoretical results.

## 5. Conclusion

The presented research work based on simulation and experimental tests proved a significant usefulness of multi-pulse rectifiers for supplying multilevel inverters. The paper presents the 12-pulse rectifier connected to the line by use of three-phase coupled reactors. The 12-pulse rectifier consists of two classic bridge rectifiers and the reactors are connected and work in a special variant 3CR $\lambda$  described in cited contributions. The application of such a solution makes that the diodes conduction angle in rectifiers achieves 180°. Certainly increasing the inductance improves the shape of the supply current waveform but it leads to the increase of the commutation angle. For the inductance  $L_s = 20$  mH and the assumed load of 2 kW, the THD<sub>i</sub> value is below 8%. Although the experimental tests have been done on low power level but these works proved that multi-pulse rectifier gives a worthy performance and has some respectable properties.

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