

## Three-Phase Rectifier Dedicated to DC Traction Substation

**Abstract.** Paper presents modified topology of the Vienna rectifier which has been applied in DC traction substation. Modification consists of replacing a pair of diodes with a pair of thyristors in each single-phase rectifier module. Fully-controlled rectifiers that consist of transistors are becoming more popular, also in traction applications. PWM rectifier, in comparison to the diode- or thyristor-based rectifiers, has higher power losses and its costs are higher. Proposed topology of the rectifier has got less number of transistors so the costs can be reduced. A 1,5 MW modified Vienna rectifier has been tested in computer simulation software.

**Streszczenie.** Artykuł przedstawia zmodyfikowany prostownik Vienna, który został wykorzystany w podstacji sieci trakcyjnej prądu stałego. Modyfikacja polega na zastąpieniu pary diod parą tyrystorów w każdym z jednofazowych modułów prostownika. W pełni sterowane prostowniki są coraz częściej wykorzystywane również w aplikacjach trakcyjnych. W porównaniu do prostowników diodowych lub tyrystorowych, prostownik PWM charakteryzuje się większymi stratami mocy oraz kosztami. Przedstawiona topologia prostownika składa się z mniejszej liczby tranzystorów co umożliwi zmniejszenie kosztów. Zmodyfikowany prostownik Vienna o mocy 1,5 MW został przetestowany z użyciem środowiska symulacyjnego. (Trójfazowy prostownik dedykowany do podstacji trakcyjnej sieci DC).

**Keywords:** Vienna rectifier, traction system, traction substation

**Słowa kluczowe:** prostownik Vienna, system trakcyjny, podstacja trakcyjna

### Introduction

Electric traction system in Poland is supplied with DC voltage. In case of a rail traction system, it is supplied from 3 kV DC voltage [1]–[6]. Typical topology of the 3 kV DC voltage traction system is shown in Fig. 1 (a). Transformation from AC to DC voltage occurs in substation (SUB), that is equipped in step-down transformer TR2 (typically 15 kV / 2,56 kV), rectifier (RE) and output filter (FC). The substation (SUB) is supplied from 15 kV 50 Hz AC voltage. A 15 kV voltage level is obtained by transforming high voltage 110 kV through the 110 kV / 15 kV transformer (TR1) [1, 2].

Electric traction substation is supplied from the three-phase AC voltage. Quality factors, like e.g. voltage distortion, current distortion, DC voltage stabilisation, depends on the rectifier that is applied in the substation. In most cases, substations are equipped in an uncontrolled 6-pulse [4, 7], 12-pulse [1, 2, 4, 8] or even 24-pulse rectifiers [8]. Disadvantages of the uncontrolled rectifiers are voltage distortion on the AC side [9], non-unity power factor (depending on the load), no direct control of the output DC voltage [9, 10]. In electric traction systems there are also used thyristor-based rectifiers [11]. In order to overcome disadvantages of the uncontrolled and thyristor-based rectifiers, transistor-based rectifiers can be used [11, 12, 13]. The main disadvantages of such a solution are higher power losses and higher costs in comparison to the diode- and thyristor-based rectifiers [10].

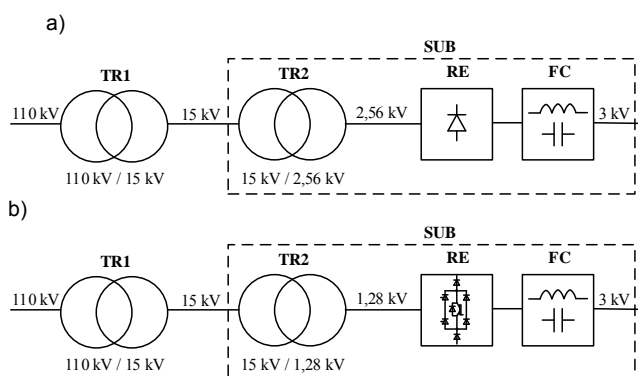


Fig. 1. Topology of the: (a) typical 3 kV DC traction system (b) proposed modified 3 kV DC traction system

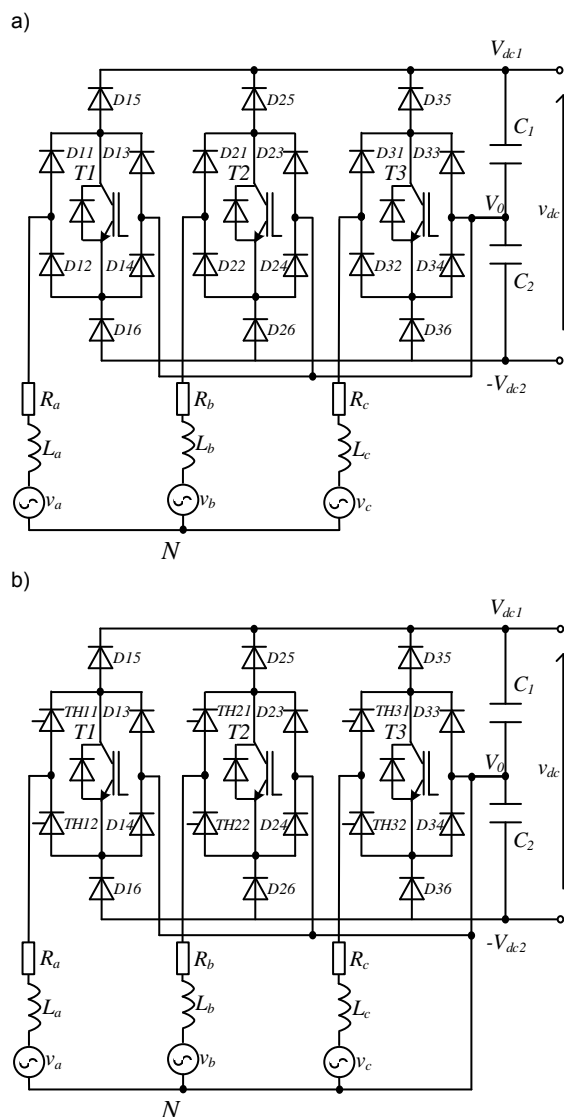


Fig. 2. Topology of the: (a) Vienna rectifier [15] (b) modified (proposed) Vienna rectifier

This paper proposes topology of the rectifier that does not need as many transistors as in [10] and can be applied in electric traction substation. Proposed topology of the

rectifier is a modification of the Vienna rectifier, as it is shown in Fig. 2. Modification of the rectifier consists of replacing pair of diodes (D11, D12 / D21, D22 / D31, D32) with the respective pair of thyristors (TH11, TH12 / TH21, TH22 / TH31, TH32), in each single-phase rectifier module. Rectifier topology change, in addition to the Vienna rectifier, also requires access to the neutral point of the transformer which is connected to the common point of the DC-link capacitors ( $V_0$ ). Different topology of the rectifier used in substation, will also require change in the substation transformer (TR2). Justification of such a modification will be described in the next chapter.

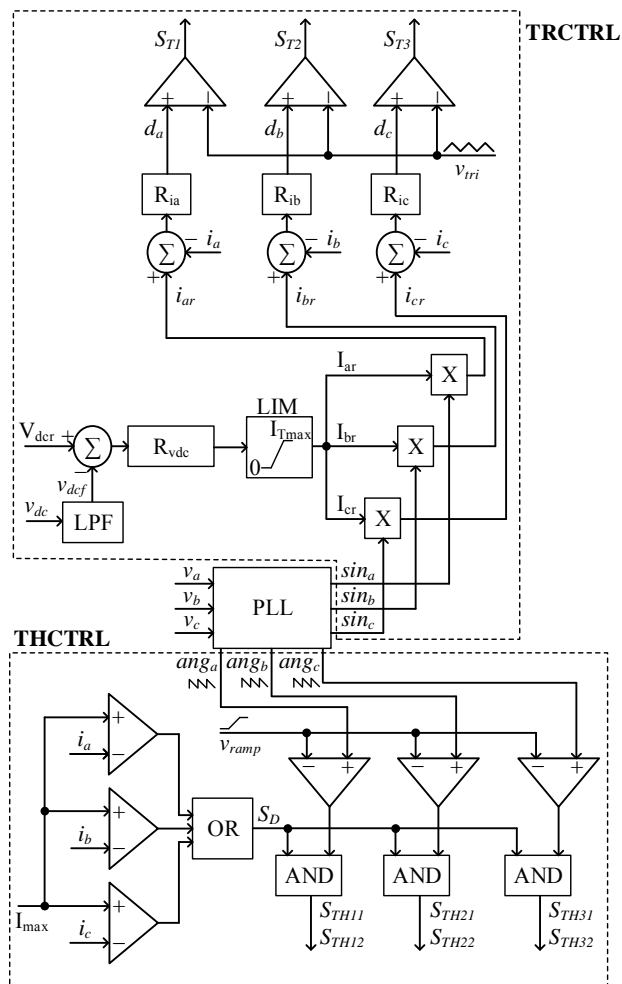


Fig. 3. Control system of the modified Vienna rectifier

### Properties of the modified Vienna rectifier

Modified Vienna rectifier is a boost-type rectifier – it means that the output voltage is higher than the input voltage, which for diode or thyristor rectifier is not available. Diode or thyristor rectifier is supplied from three-phase three-wire system, thus the maximum DC output voltage depends on the amplitude of the AC line-to-line voltage. Assuming symmetrical, three-phase AC voltage, the maximum DC output voltage for diode or thyristor rectifier can be described as:

$$(1) \quad v_{dc} \leq V_{l-l} \cdot \sqrt{2} \cong 1,41 \cdot V_{l-l}$$

where:  $V_{l-l}$  – line-to-line RMS voltage,  $V_m$  – phase voltage amplitude.

On the other hand, proposed rectifier (boost-type rectifier) is supplied from the three-phase four-wire system (Fig. 2 (b)) and it operates as a three, independent, single-phase rectifiers, with minimum DC voltage:

$$(2) \quad v_{dc} \geq 2 \cdot V_m = 2 \cdot V_{l-l} \cdot \sqrt{\frac{2}{3}} \cong 1,63 \cdot V_{l-l}$$

Voltage across the primary and secondary windings of the substation transformer TR2 that are shown in Fig. 1 are a line-to-line RMS values. Proposed rectifier operates as a boost-type converter, thus the output DC voltage should be higher than the AC input phase voltage amplitude. If the secondary winding line-to-line RMS voltage was 2,56 kV (Fig. 1(a)), boost operation would not be possible (3).

$$(3) \quad v_{dc} = 3kV \not\geq 1,63 \cdot V_{l-l} = 1,63 \cdot 2,56kV = 4,17kV$$

On the other hand, if the secondary winding line-to-line RMS voltage was two times lower (1,28 kV; Fig. 1(b)), boost operation would be available (4).

$$(4) \quad v_{dc} = 3kV \geq 1,63 \cdot V_{l-l} = 1,63 \cdot 1,28kV = 2,09kV$$

Consequently, the change of the turns ratio (voltage ratio) is needed so the boosting voltage operation could be realised by the modified Vienna rectifier. Consequently, voltage ratio of the substation transformer (TR2), shown in Fig. 1(b), has been multiplied by two, in comparison to the voltage ratio shown in Fig. 1(a).

Both Vienna and modified Vienna rectifier are three-level converters – they produce DC three voltage levels  $V_{dc1}$ ,  $V_0$  and  $-V_{dc2}$ . In case of DC traction system, two-wire output is used – from  $V_{dc1}$  and  $-V_{dc2}$  voltage level. Consequently, the DC output voltage ( $v_{dc}$ ) is a sum of voltages across capacitors  $C_1$  and  $C_2$ . For modified Vienna rectifier, a boost factor can be defined as a ratio between rectifier's output and input voltages, and its minimum value (MBF) can be calculated as:

$$(5) \quad MBF = \frac{v_{dc}}{1,63 \cdot V_{l-l}} = \frac{3kV}{2,09kV} = 1,44$$

From control point of view, modified Vienna rectifier should provide:

- stable output DC voltage at the reference level,
- sinusoidal input phase currents,
- unity power factor,
- protection against overload (current limit) and short-circuit,
- pre-charge operation.

In order to assure above requirements, the control system has been proposed (Fig. 3).

Firstly, control of the thyristors will be described THCTRL (Fig. 3). When the DC output voltage is low, the pre-charge procedure is applied. It can be achieved simply by providing two signals to the comparator – ramp signal ( $V_{ramp}$ ) and phase voltage angle ( $ang_a$ ,  $ang_b$ ,  $ang_c$ ). Ramp signal  $V_{ramp}$  determines the speed of charging output capacitors ( $C_1$ ,  $C_2$ ). Charging of the output capacitors should not be done rapidly because of higher inrush current. Phase voltage angles are synchronised with the respective phase voltages ( $v_a$ ,  $v_b$ ,  $v_c$ ) in the phase-locked loop block (PLL), so the appropriate thyristors would be fired ( $S_{TH11}$ ,  $S_{TH12}$  /  $S_{TH21}$ ,  $S_{TH22}$  /  $S_{TH31}$ ,  $S_{TH32}$ ). What is more, firing signals of the thyristors can be reseted because of fault condition, like e.g. short-circuit. Additional AND gate has been applied to the thyristor control system (THCTRL), so in case of fault condition, disconnection of the supplying AC voltage (grid) will occur. Information about abnormal operation is provided by logic signal  $S_D$ . This signal ( $S_D$ ) can disable operation of thyristors if one of the phase currents ( $i_a$ ,  $i_b$ ,  $i_c$ ) is higher than the maximum rectifier current ( $I_{max}$ ). During pre-charge operation, the firing angle rises with time and finally each thyristor becomes fully-latched – thyristor operates like a diode. Then, the transistor control system

(TRCTRL) that stabilises DC output voltage ( $v_{dc}$ ) and controls the phase currents ( $i_a, i_b, i_c$ ) can be applied.

Control of the DC output voltage ( $v_{dc}$ ) and phase currents ( $i_a, i_b, i_c$ ) is shown in Fig. 3. Control system of the modified Vienna rectifier consists of outer loop control that controls DC voltage and inner control loop that controls phase currents. Firstly, measured DC voltage ( $v_{dc}$ ) is filtered through the low-pass filter (LPF) to obtain only average value of the DC voltage ( $v_{dcf}$ ). Measured and filtered DC voltage ( $v_{dcf}$ ) is compared with the reference value of the DC voltage ( $V_{dcr}$ ). Voltage controller  $R_{vdc}$  assures zero steady-state error between the measured ( $v_{dcf}$ ) and reference ( $V_{dcr}$ ) value. Output signal of the voltage controller is the reference amplitude of the phase current which might be limited by the block LIM if the signal exceeds maximum transistor current ( $I_{Tmax}$ ). Reference amplitude of the phase current ( $I_{rm}$ ) is multiplied to by the unity sinusoidal signals ( $sin_a, sin_b, sin_c$ ) which are synchronised with the respective phase voltages ( $v_a, v_b, v_c$ ) to obtain unity power factor. Afterwards, reference phase currents ( $i_{ar}, i_{br}, i_{cr}$ ) are compared with the measured phase currents ( $i_a, i_b, i_c$ ) and the respective phase current controllers ( $R_{ia}, R_{ib}, R_{ic}$ ) ensures good reference signal tracking. Output signals of the phase current controllers ( $R_{ia}, R_{ib}, R_{ic}$ ) are the duty cycle values ( $d_a, d_b, d_c$ ) which are compared with triangular signal ( $v_{tri}$ ) in the pulse width modulator.

### Simulation results

Performance of the modified Vienna rectifier has been tested under various conditions which are presented in Fig.4. Basic simulation parameters, that were applied in PSIM® software, are listed in Table 1. Operation of the modified Vienna rectifier, shown in Fig. 4 can be divided into several parts:

- precharge operation (Fig. 5)
- applying previously presented control idea (Fig. 3)
- performance of the rectifier during step load change (Fig.6)

- performance of the rectifier when a single transistor is faulted (Fig. 7)
- performance of the rectifier under short-circuit fault condition (Fig. 8).

Table 1. Simulation parameters of the modified Vienna rectifier

Parameter	Value
$P_N$	1,5 MW
$V_{ll}$	1280 V
$f_{ac}$	50 Hz
$V_{dcr}$	3000 V
$R_a, R_b, R_c$	0,5 $\Omega$
$L_a, L_b, L_c$	0,5 mH
$C_1, C_2$	5 mF
$f_{PWM}$	2 kHz

where:  $P_N$  – nominal power;  $V_{ll}$  – line-to-line RMS voltage;  $f_{ac}$  – voltage frequency  $V_{dcr}$  – reference value of the output DC voltage;  $R_a, R_b, R_c$  – phase resistances;  $L_a, L_b, L_c$  – phase inductances;  $C_1, C_2$  – output filter capacitances;  $f_{PWM}$  – switching frequency

Table 2. Performance of the modified Vienna rectifier – quality factors

Quality factor	Input power $P_{ac}$	
	1,5 MW	2 MW
THDI	4,7 %	5,2 %
PF	0,99	0,99

where: THDI – current total harmonic distortion; PF – power factor

Firstly ( $0 s < t < 0,1 s$ ), modified Vienna rectifier applies pre-charge procedure (Fig. 5). Such an operating state is desired when the output DC voltage is low, so the inrush current caused by the charged capacitors ( $C_1, C_2$ ) is limited. It is achieved by a change of the thyristor's firing angle.

Secondly (at the time  $t = 0,1 s$ ), the control idea of the modified Vienna rectifier is applied. Control system assures sinusoidally shaped current with low total harmonic distortions (THDI), unity power factor (PF) and stable output DC voltage ( $v_{dc}$ ). Aforementioned values are listed in table 2.

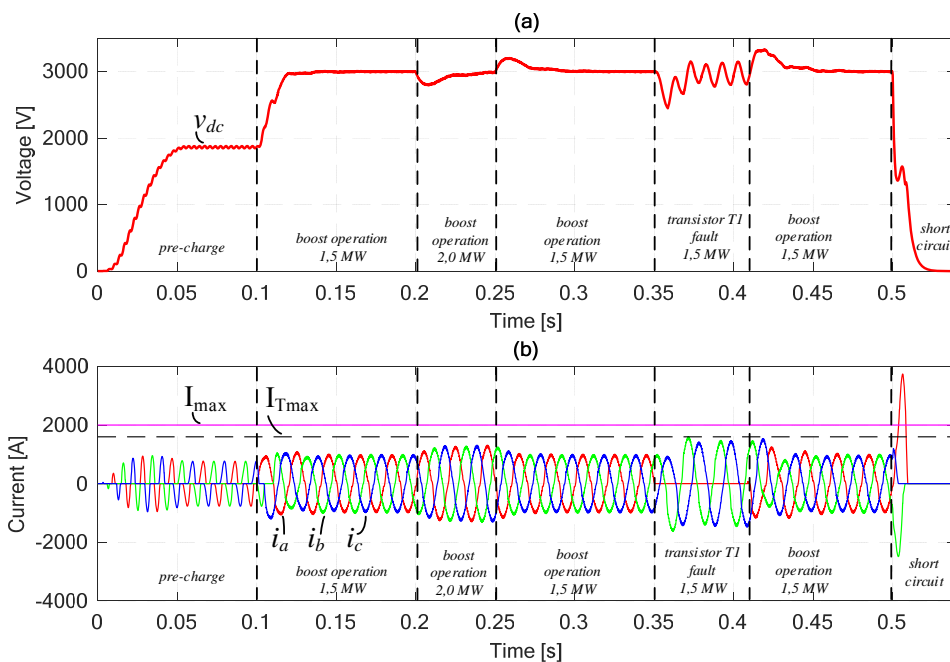


Fig. 4. Analysed operating states of the modified Vienna rectifier: (a) rectifier's output DC voltage  $v_{dc}$  (b) phase currents drawn from the AC grid  $i_a, i_b, i_c$

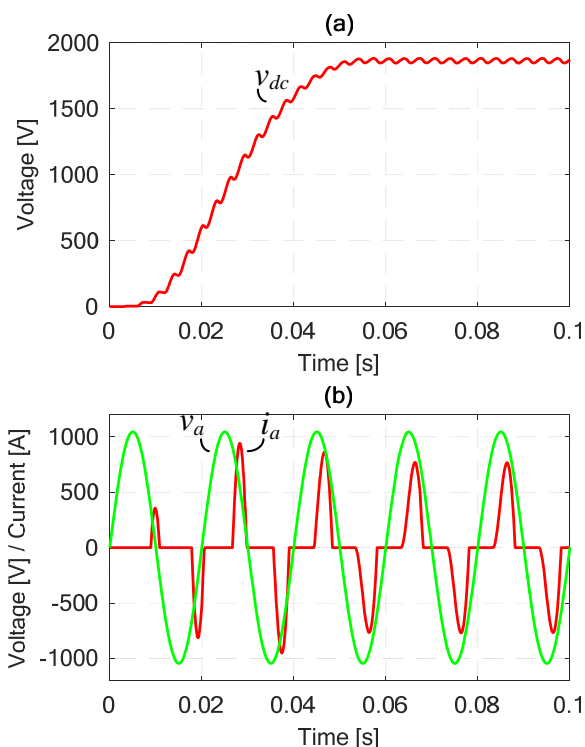


Fig. 5. Pre-charge operation of the modified Vienna rectifier: (a) rectifier's output DC voltage  $v_{dc}$  (b) phase voltage  $v_a$  and current  $i_a$  drawn from the AC grid

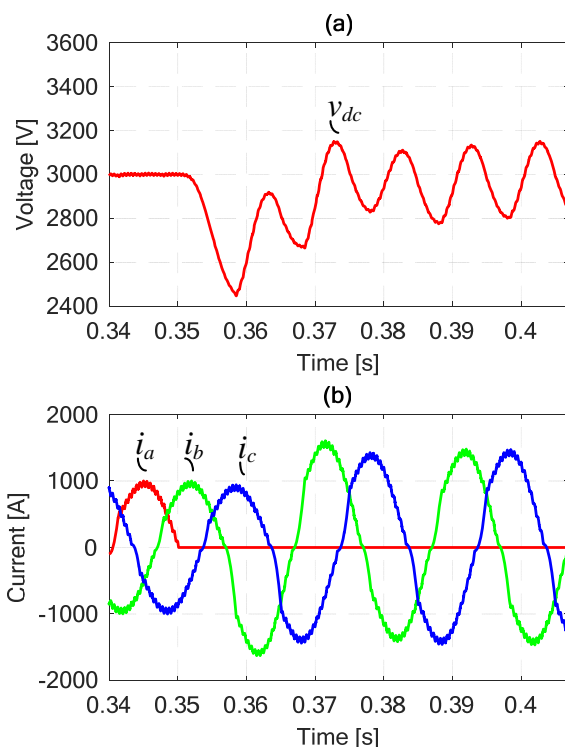


Fig. 7. Operation of the modified Vienna rectifier under transistor T1 fault condition: (a) rectifier's output DC voltage  $v_{dc}$  (b) phase currents drawn from the AC grid  $i_a, i_b, i_c$

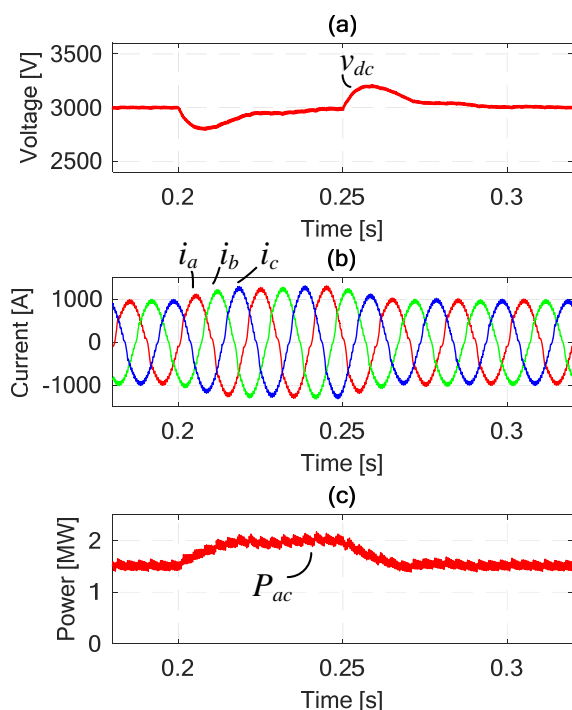


Fig. 6. Performance of the modified Vienna rectifier during step load change from 1,5 MW to 2 MW: (a) rectifier's output DC voltage  $v_{dc}$  (b) phase currents drawn from the AC grid  $i_a, i_b, i_c$  (c) power taken from the AC grid  $P_{ac}$

Later, the modified Vienna rectifier was tested during step load change. Average power taken from the grid changes from 1,5 MW to 2 MW (at  $t = 0,2$  s), and then (at  $t = 0,25$  s) it comes back to the 1,5 MW. For both power

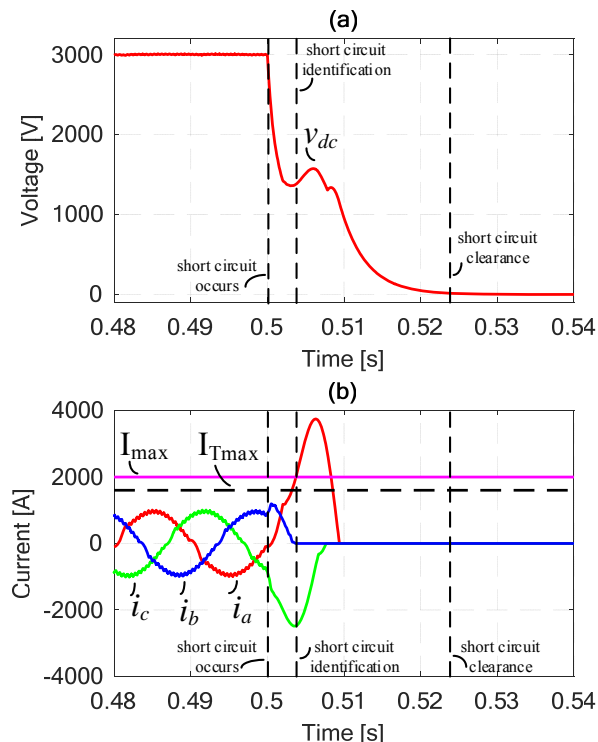


Fig. 8. Operation of the modified Vienna rectifier under short-circuit condition: (a) rectifier's output DC voltage  $v_{dc}$  (b) phase currents drawn from the AC grid  $i_a, i_b, i_c$

values, phase currents are sinusoidal (Fig. 6 (b)) and their total harmonic distortions (THDI) are at acceptable levels (Table 2). Small power fluctuations are caused by the switching frequency harmonics.

Operation of the modified Vienna rectifier was also tested when one of the transistors, i.e. T1, was faulted (Fig. 7). Output voltage across one of the capacitors (C1, C2), during this fault condition, was higher than the rectifier's input voltage, thus the affected phase current  $i_a$  was not flowing – thyristors and diodes were blocked. Total power that was needed to supply the load, was delivered by the two, not affected phases. Periodic oscillation (100 Hz) of the output DC voltage occurs but its amplitude does not exceed 6 % of the reference value  $V_{dcr}$ .

Finally, modified Vienna rectifier was tested under short-circuit fault condition (Fig. 8). During short-circuit, the phase current value, at some point, exceeded transistors current limitation ( $I_{Tmax}$ ) and they are immediately turned-off. Consequently, current was flowing through the thyristors and diodes, which can withstand higher currents. Rising phase currents has also exceeded maximum current level ( $I_{max}$ ), thus the thyristors' firing signals were turned-off. As soon as the instantaneous phase currents values reached zero, the thyristors were not conducting. Output capacitors (C1, C2) were discharging through the load.

### Conclusions

The paper presented modification of the Vienna rectifier which provides new functionalities – pre-charge and circuit disconnection. The first one is useful when voltage across capacitors on the DC side is low, so controlled charging is available and results in reduction of inrush current. The second functionality – circuit disconnection on the AC side, can be used e.g. in case of short-circuit. Proposed topology of the three-phase modified Vienna rectifier consists of three transistors, whereas PWM rectifier consists of six transistors, thus the costs of the converter can be reduced. Applying presented topology of the rectifier in DC traction substation should also require slight modification in the substation transformer – change of turns ratio. Simulation results shows that proposed control system can be applied to the rectifier and resulted in stable output voltage, phase current with low total harmonic distortion and unity power factor.

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