

Properties of Twelve-Pulse Rectifier with Short-Circuit Diodes

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Abstract — This paper deals with simulation and experimental efforts verifying influence of short-circuits of semiconductor diodes on subsequent action of twelve-pulse traction rectifier in traction power stations (3kV DC) of the Czech railway. A computer model of a traction power station, results and conclusion of research are described. To verify relevance of results obtained from simulations a measurement on a small laboratory model of twelve-pulse rectifier was performed. These results are part of this paper as well. Short-circuits are always examined using simple and multiple commutation of diodes.

Keywords — primary current, current harmonic, rectifier, transformer, twelve-pulse connection, semiconductor diode

I. INTRODUCTION

Direct-current traction power station can be described in a simplified way by a schema in Fig. 1. Already on the beginning of electrification of DC railways in Czechoslovakia a twelve-pulse scheme of traction rectifier was designed [5]. This had two main reasons. Twelve-pulse rectification is advantageous because output voltage is more smoothed in comparison with six-pulse rectification. A great advantage of twelve-pulse scheme in terms of EMC is generation of the 5., 7., 17. and 19. harmonic frequency of primary current in both sections of rectifier in phase opposition, by which insignificant values on these frequencies in primary current are achieved and the lowest harmonic frequency on the primary side of a transformer is 550 Hz.

A substation 110 kV and a transformer substation 110/22 kV, which are usually property of the railway, are placed in front of most DC power stations. We can say that this part is for every power station carried out very individually. Some exceptions, where a traction power station is supplied directly from public distribution network 22 kV, also exist. However, the other parts of DC power stations can be described in a uniform way.

On the input of the traction substation there is always a vacuum high-speed switch, which as the only one enables to disconnect the transformer and the rectifier from the AC side in case of a failure on the rectifier unit. It is necessary to point out that disconnection of the vacuum high-speed switch takes tens of ms. During this time rectifier still works in an abnormal (faulty) mode and destructive effects can arise in some other semiconductor parts of the rectifier.

The switch is followed by a transformer, which has two secondary windings. One of them is Δ -circuit and the

second one is Y-circuit. An important condition for a rectifier unit working in this way is the same line voltage and leakage inductance of both sections of the transformer. That was also taken into account in the concept of a computer and physical model.

The transformer is followed by a rectifier composed of a couple of six-pulse bridges, which outputs are only through a no-load switch taken out to one point of +3 kV DC and to the ground. An essential part of every rectifier unit is an air choke coil 4 mH. This choke coil restricts the speed of growth of a possible short-circuit current and ensures sufficient amount of time for the high-speed switch to cut off.

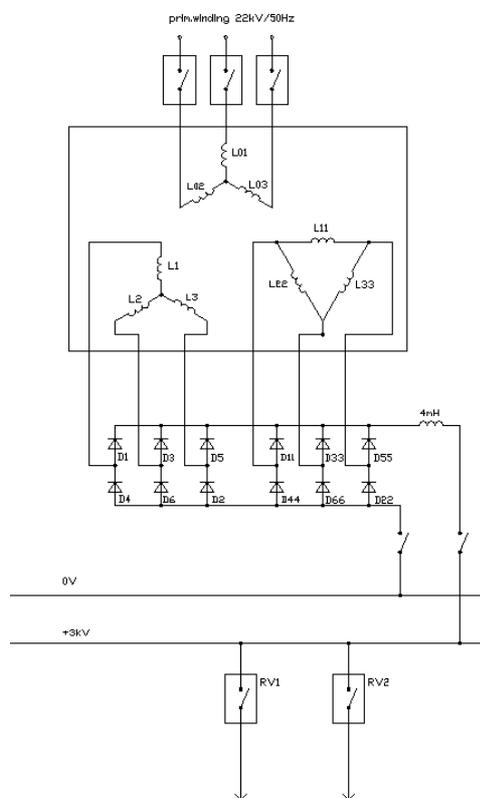


Fig. 1. Schema of the DC traction power station

Output lines are taken out from the mentioned point +3 kV DC into the overhead lines, each of them is in the positive line provided by a DC high-speed switch. Only

with this switch the traction power station can be disconnected from the DC network.

One rectifier unit, supplied by a twelve-pulse transformer 22 kV/3 kV, is outlined in the simplified schema (Fig.1) of the power station. Just two supply lines are given in the schema because of simplicity. Every supply line has to be provided by its own high-speed switch (on the picture marked RV1, RV2), which ensures disconnection in case of a short-circuit or overload of the line.

The main goal of the research presented in this paper is to describe situation in the rectifier during a short-circuit of one or two diodes, with focus on possible threat to other diodes in the rectifier because of an increased current.

II. COMPUTER SIMULATION OF TWELVE-PULSE RECTIFIER UNIT

A. Derivation of the simulated schema [10]

To simulate behaviour of the rectifier and its failure state, the schema of the twelve-pulse rectifier from Fig. 1 was transferred into the computer programme PSpice 10 Demo.

This software, which is a part of a complex software package for projection of electronic circuits OrCad 10.0 [2], enables to show how circuit quantities depend on time and to perform their FFT analysis.

Nevertheless, the schema of the traction rectifier from Fig. 1 needs to be adjusted so that we can perform computer simulations.

First of all the three-phase transformer has to be replaced by a harmonic source which is serial connected with an inductance. This inductance represents leakage inductance of the transformer.

The equivalent circuit of the traction transformer can be for computations up to the 25. harmonic frequency (i.e. 1250 Hz) considerably simplified [1]. Full equivalent circuit of the single-phase transformer is shown in Fig. 2.

Elements RM and LM compensate the influence of magnetizing currents in the transformer. Elements R1 and L1, eventually L2 and R2, represent leakage inductances of the primary (eventually secondary) winding and their resistance. The capacitor C12 represents capacity of the primary and secondary winding, the capacitors C1 and C2 represent capacities between winding and construction parts of the transformer (ground).

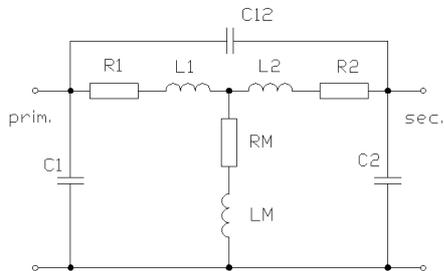


Fig. 2. Full equivalent circuit of the single-phase transformer

For low frequencies it is possible to ignore the influence of individual capacities [1]. The line with elements RM and LM can be neglected, because magnetizing currents and magnetizing dissipation of today's transformers are minimal. After the modification of the equivalent circuit

turns out that current harmonic frequencies in the transformer are influenced only by the turns ratio of its windings and also that their amplification or damping does not occur.

The simplest equivalent circuit of the three-phase transformer is shown in Fig. 3.

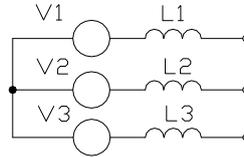


Fig. 3. Equivalent circuit of the three-phase traction transformer

Since simulations of the transformer with couple of secondary windings are needed, a couple of the equivalent circuits from Fig. 2 is used and the equivalent circuit, which simulates Δ -circuit is transfigured into Y-circuit [1]. This has several reasons:

- simplification of the performed simulations,
- ensuring the same leakage inductance of both sections of the "transformer",
- ensuring the same line voltage in the output of the transformer in Δ and Y.

The transfiguration itself consists in a shift of all three sources V11, V22 and V33 in Fig. 5 by 30° in comparison with the sources V1-V3 and also in conversion of the magnitude of the output current while transforming Δ to Y, Fig. 4.

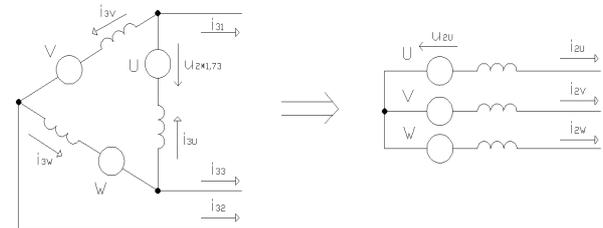


Fig. 4. Transfiguration of the secondary winding from Δ to Y

Then we can get a phase current of one phase of the secondary winding in Y from calculations

$$i_{3U} = \frac{i_{2U}}{\sqrt{3}} \quad (1)$$

-phase current in Y,

$$i_{3V} = \frac{i_{2V}}{\sqrt{3}} \quad (2)$$

$$i_{3W} = \frac{i_{2W}}{\sqrt{3}} \quad (3)$$

$$i_{31} = i_{3U} - i_{3V} = \frac{i_{2U} - i_{2V}}{\sqrt{3}} \quad (4)$$

- line current in the input of the rectifier,

$$i_{32} = i_{3V} - i_{3W} = \frac{i_{2V} - i_{2W}}{\sqrt{3}} \quad (5)$$

$$i_{33} = i_{3W} - i_{3U} = \frac{i_{2W} - i_{2U}}{\sqrt{3}} \quad (6)$$

Calculation of the leakage inductance:

From the results of measuring short-circuit of a real transformer it can be found out [11]:

- line voltage (an average value of the phases)
 $U_s = 1454 \text{ V}$,
- average phase current $I_f = 93,53 \text{ A}$,
- short-circuit losses $P_K = 25598 \text{ W}$.

From the obtained data the leakage inductance and the value of resistance in the equivalent circuit were computed [4]

$$\cos \varphi = \frac{P_K}{\frac{U_s * I_f}{\sqrt{3}}} \quad (7)$$

$$\cos \varphi = \frac{25598}{\frac{1454 * 93,53}{\sqrt{3}}} = 0,326 \quad (8)$$

$$\arccos 0,326 = 70,97 \quad [^\circ] \quad (9)$$

$$Z = \frac{U_s}{\sqrt{3} * I_f} \quad [\Omega] \quad (10)$$

$$Z = \frac{1454}{\sqrt{3} * 93,53} = 8,97 \quad [\Omega] \quad (11)$$

$$X_L = Z * \sin 70,97 \quad [\Omega] \quad (12)$$

$$X_L = 8,97 * \sin 70,97 = 8,48 \quad [\Omega] \quad (13)$$

$$X_L = \omega L^* \Rightarrow L^* = \frac{8,48}{2 * 50 * \pi} = 27 \quad [mH] \quad (14)$$

$$R^* = Z * \cos 70,97 \quad [\Omega] \quad (15)$$

$$R^* = 8,97 * \cos 70,97 = 2,92 \quad [\Omega] \quad (16)$$

After conversion of the computed values to the secondary side we get parameters of the equivalent circuit

$$p = \frac{23000}{2500} = 9,2 \quad (17)$$

$$L = \frac{L^*}{p^2} = \frac{27m}{84,64} = 318 \quad [\mu H] \quad (18)$$

$$R = \frac{R^*}{p^2} = \frac{2,92}{84,64} = 0,0345 \quad [\Omega] \quad (19)$$

where p is the turns ratio of the transformer (stated in record of measuring).

The same leakage inductance is used for both sections of the transformer winding (Y, Δ).

Equivalent circuit of the rectifier unit

Equivalent circuit of the twelve-pulse unit used for all the following simulations is shown in Fig.5.

The transformer with a couple of secondary windings is replaced by a harmonic source V1, V2 and V3 (Y-circuit), V11, V22 and V33 (simulation of Δ -circuit). The voltage of these sources results from the line voltage, which is provided by a real transformer, i. e. 2500 V.

$$\frac{2500}{\sqrt{3}} = 1443,4 \quad [V] \quad (20)$$

- effective phase voltage,

$$1443,4 \sqrt{2} = 2041 \quad [V] \quad (21)$$

- amplitude of the phase voltage.

Sources V1, V2 and V3 are respectively shifted by 120° , sources V11, V22 and V33 are shifted by 30° compared with the sources V1, V2 and V3.

The used leakage inductance and resistance values were computed earlier.

A model of a modified diode from PSpice library was used for rectification [2].

A choke coil 4 mH restricting the growth of the short-circuit current is essential to be on the output of the rectifier. Then the load itself follows, represented by parameters RL.

Load

Specific inductance of the overhead lines is about 1 mH/km. Use of a substitutive inductance of about 10 mH seems to be realistic consideration for half of the section length between two traction power stations. The inductance of the LC filter in the input of modern traction vehicles reaches up to only tens of μH . In comparison with the inductance of the overhead lines it is insignificant and thus the total substitutive inductance depends only on the length of the overhead line under consideration.

Value of the substitutive resistance is chosen considering required load of the rectifier unit.

Load current was varied by setting the RL load.

Simulations were performed using two different loads with regard to the commutation time of the diodes. When the load current is 170 A (load 20 Ω /10 mH), only two diodes commutate, which is consistent with theory. When the load is 3,2 Ω /10 mH (load current 1020 A), multiple commutation already occurs. The difference in commutation during short-circuit of diodes was also one part of the research.

B. Results of simulations with multiple commutation of diodes (load 3,2 Ω /10 mH)

Multiple commutation of diodes means a state, when the current flows in more than two diodes at the same time. From the simulations turns out that this state is quite common for a loaded twelve-pulse rectifier.

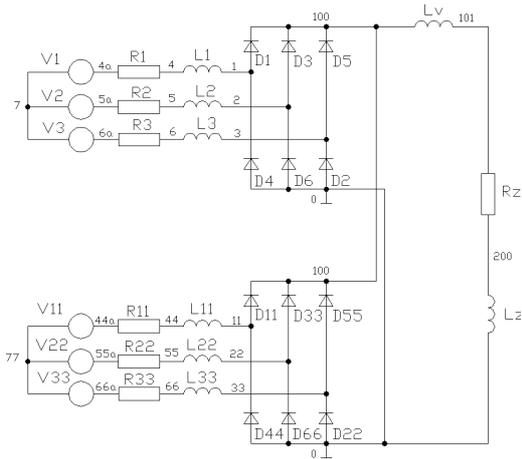


Fig. 5. Equivalent circuit of the rectifier unit

Short-circuit of diode D1

During the short-circuit simulations all the diodes were short-circuited successively. In Fig. 6 there is shown the load current when the diode D1 is short-circuited. From Fig. 7 and 8 the degree of the load current of all other diodes in twelve-pulse rectifier can be judged.

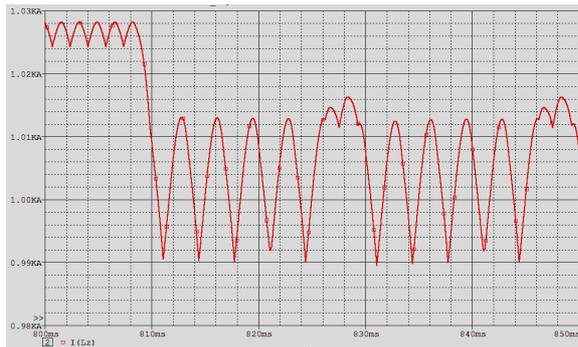


Fig. 6. The load current t when the diode D1 is short-circuited

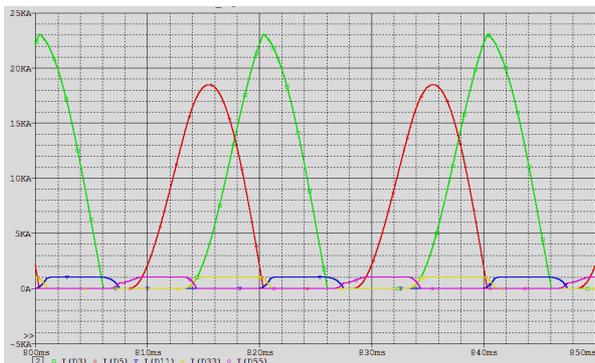


Fig. 7. The diodes D3, D5, D11, D13 and D15 current when short-circuit the diode D1 is short-circuited

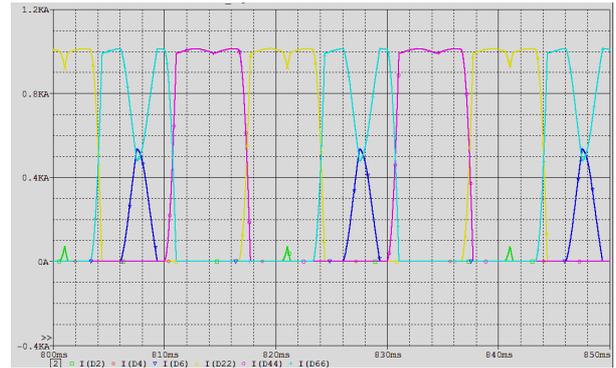


Fig. 8. The diodes D2, D4, D6, D22, D44 and D66 current when the diode D1 is short-circuited

Short-circuit of more diodes with the same polarity at the same time (D1 and D3)

When considering short-circuit of one diode and the following measured load of the other ones (according to the previous paragraph), we can expect short-circuit of these more current loaded diodes as well. Load current of the rest of the diodes when simultaneous short-circuit of D1 and D3 occurs is shown in Fig. 9 and 10.

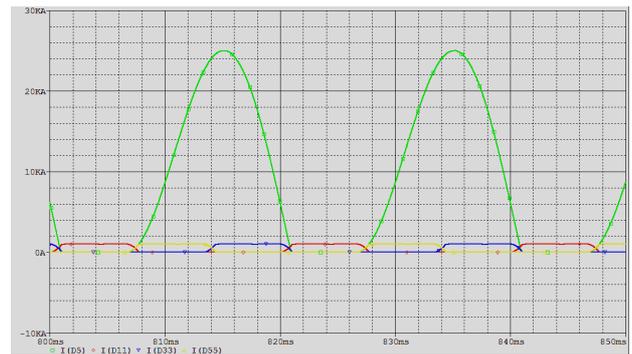


Fig. 9. The diode D5, D11, D13 and D15 current when the diodes D1 and D3 are short-circuited at the same time

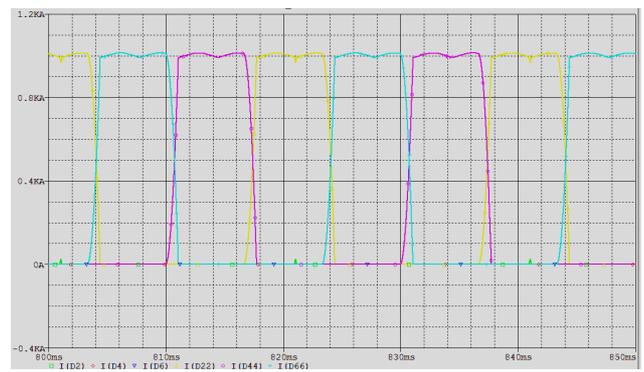


Fig. 10. The diodes D2, D4, D6, D22, D44 and D66 currents when the diodes D1 and D3 are short-circuited at the same time

It can be observed that a higher load current of the same diodes occurs for a short-circuit of two diodes with the same polarity just as for separate short-circuit of these diodes.

Short-circuit of more diodes with opposite polarity at the same time (D1 and D44)

Different situation in comparison with the short-circuit of diodes with the same polarity arises for short-circuit of diodes with the opposite polarity (one is in the positive line and one in the negative line). In this case higher load current of all other elements in the rectifier turns up, as it is illustrated in Fig. 11 and 12.

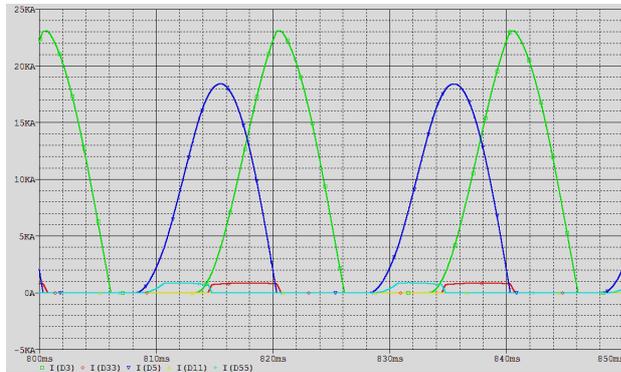


Fig. 11. The diode D3, D5, D11, D33 and D55 current when the diodes D1 and D44 are short-circuited at the same time

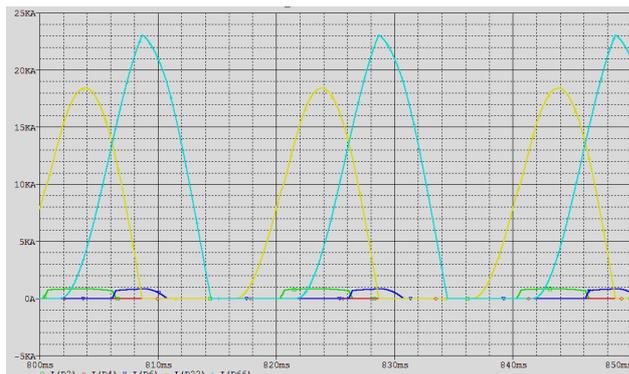


Fig. 12. The diodes D2, D4, D6, D22 and D66 current when the diodes D1 and D44 are short-circuited

C. Results of simulations with simple commutation of diodes (load 20 Ω/10 mH)

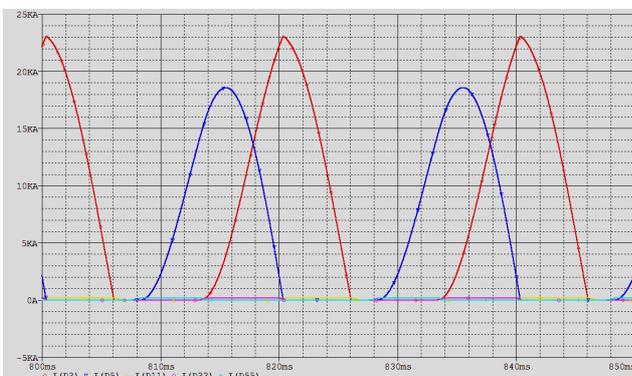


Fig. 13. The diodes D3, D5, D11, D33 and D55 current when the diode D1 is short-circuited, load is 20 Ω/10 mH

Performing similar simulations as in the case of multiple commutation we get the same conclusions for the degree of threat to the surrounding diodes. For comparison there are in Fig. 13 and Fig. 14 shown the other diodes currents when the diode D1 is short-circuited.

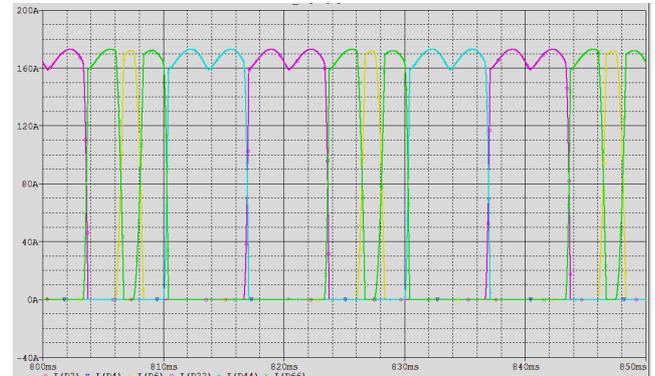


Fig. 14. The diodes D2, D4, D6, D22 and D44 current when the diode D1 is short-circuited, load is 20 Ω/10 mH

III. MEASURING ON THE LABORATORY MODEL

A. Description of the laboratory model

To verify results we get from simulations described in the previous paragraphs, a laboratory model of twelve-pulse rectifier unit with nominal power 5 kW was created, Fig. 15.

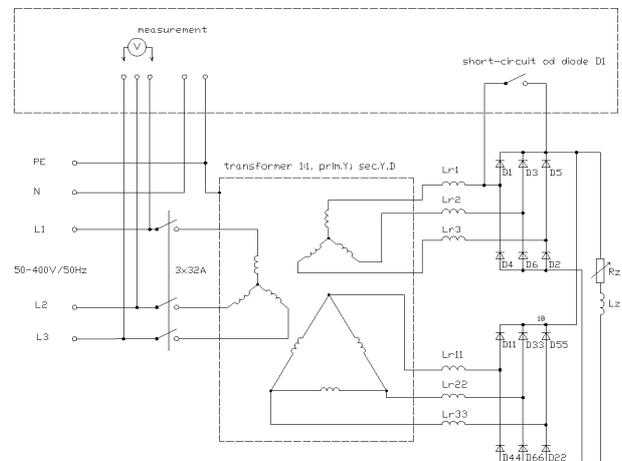


Fig. 15. Full schema of laboratory workplace

The model is power supplied from the autotransformer 3x400 V, which enables to supply the whole system with lowered voltage during the time of measured short-circuits of the diodes or short-circuit of the load.

Transformer

We assume a three-phase transformer with a couple of secondary windings. All windings are taken out into the connector, where they are connected in Δ and Y. Line voltage of both secondary windings is 3x400 V, from which results the transformer turns ration 1:1. Primary winding is connected in Y.

Electric power of the transformer and thus of the whole workplace was selected 5000 VA. This value is a compromise which takes into account weight and price of the transformer. Another advantage of the used electric power is a possibility to supply the workplace from a socket protected for 3x10 A.

The transformer is produced in the heat class F because of a possible rise of temperature of the winding during short-circuits.

Choke coils 2 mH are serial connected with the outputs of the transformer secondary windings. The purpose is to get near to the conditions of the simulated transformer with regard to the magnitude of the short-circuit reactance in context with the other parameters of the circuit [7], [8].

Semiconductor diode

Twelve-pulse rectifier was created from rectifier modules SEMIKRON SKKD 100/16. These modules contain always two independent serial connected diodes, from which a three-phase bridge can be easily set up. The mentioned modules with nominal current 100 A were chosen mainly because it is easy to attach them to the cooler, which serves at the same time as a support for the rectifiers.

Load

Just like in the previous simulations, the measuring was performed with a simple and multiple commutation of the diodes.

The time constant L/R was kept the same during the simulations and measuring to enable good comparison between them.

In case that the simulated circuit is loaded with 3,2 Ω/10 mH, a multiple commutation occurs and commutation angle is about 39°. Setting of the commutation angle on the laboratory model was done experimentally. Load of 17,5 Ω/52 mH satisfies stated conditions.

Choice of the load was done during failure-free work of the rectifier and full supply voltage (3x400 V).

Setting of the load for measuring of failure states with simple commutation ran according the same principles. The same commutation angle (15°) was used in simulations and in the laboratory. Nevertheless, the time constant (during simulations 10 mH/20 Ω) couldn't be kept in the laboratory (load 315 Ω). It would require a choke coil 157 mH, which couldn't be provided in laboratories of KEEZ. The circuit was thus loaded by 315 Ω/51 mH.

B. Results of measuring with multiple commutation of diodes (load 17,5 Ω/51 mH)

Results of measuring are organized in a similar way as in the previous paragraphs to enable comparison with the results of simulations. The current in the diodes is influenced by the supply line voltage, which was lowered to 50 V to protect the transformer and the rectifier against the overload.

Short-circuit of diode D1

All diodes were again short-circuited successively in the laboratory. From Fig. 16 and 17 we can judge the

degree of the current load of all the other diodes in the twelve-pulse rectifier.

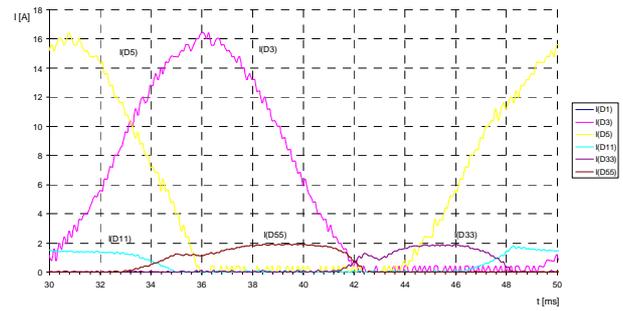


Fig. 16. The measured currents in the diodes D3, D5, D11, D33 and D55 when the diode D1 is short-circuited

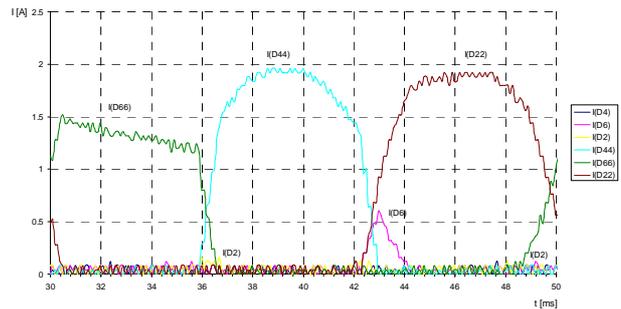


Fig. 17. The measured currents in the diodes D2, D4, D6, D22, D44 and D66 when the diode D1 is short-circuited

Short-circuit of more diodes with the opposite polarity at the same time (D1 and D22)

Because of the short-circuit of two diodes with the opposite polarity higher current load of all the other elements in the rectifier arises, which can be seen in Fig. 18 and 19.

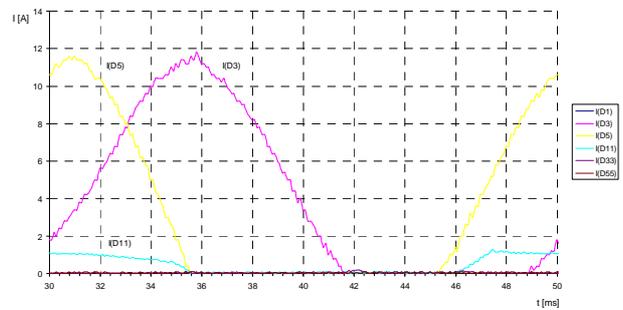


Fig. 18. The measured currents in the diodes D3, D5, D11, D33 and D55 when the diodes D1 and D22 are short-circuited at the same time

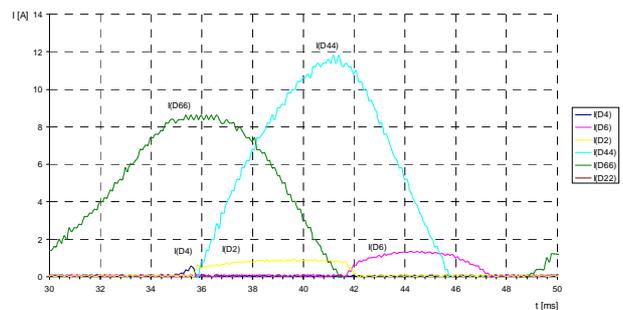


Fig. 19. The measured currents in the diodes D2, D4, D6, D44 and D66 when the diodes D1 and D22 are short-circuited at the same time

C. Results of measuring with simple commutation of diodes (load 315 Ω/51 mH)

The Figs. 20 is for comparison presented the diodes in danger for simple and multiple commutation. It is shown the diodes D3, D5, D11, D33 and D55 current when the diode D1 is short-circuited with a minimum loaded rectifier. The D22, D44 and D66 current is defined only by load value in this case.

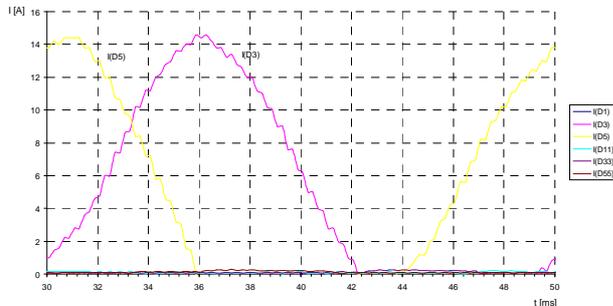


Fig. 20. The measured currents through diodes D3, D5, D11, D33 and D55 when the diode D1 is short-circuited, load is 315 Ω/51 mH

IV. SUMMARY OF THE RESULTS

From the simulated and measured currents it can be easily deduced which diodes will be endangered when one of the twelve diodes of the rectifier is short-circuited. Simulations of all these twelve short-circuits were performed and verified with the laboratory measuring. From the obtained data a chart (TABLE I) was created, summarizing which diodes are endangered because of the overcurrent when any of elements is short-circuited.

TABLE I. SUMMARY OF ENDANGERED DIODES FOR SHORT-CIRCUIT OF ONLY ONE DIODE

	At the time of short-circuit diodes:											
	D1	D3	D5	D11	D33	D55	D2	D4	D6	D22	D44	D66
D1		X	X									
D3	X		X									
D5	X	X										
D11					X	X						
D33				X	X							
D55			X	X								
D2								X	X			
D4							X		X			
D6							X	X				
D22										X	X	
D44										X		X
D66									X	X		

To complete results of the investigated phenomenon it is necessary to check up situation for short-circuit of more semiconductor elements at the same time.

This task can be divided into the short-circuit of more diodes with the same polarity (in positive or negative line) at the same time and into the short-circuit of elements with the opposite polarity.

After analysing the shown currents the following conclusions can be stated:

- At the short-circuit of adjacent diodes (same polarity) in one bridge the third adjacent diode is always endangered (as in the case of short-circuit of just one diode, TABLE I);
- At the short-circuit of two diodes with the same polarity in one bridge the third diode with the same polarity is endangered (Fig. 9 and 10);
- At the short-circuit of two diodes with the same polarity when one is from the bridge Δ and the other one from Y, all the other diodes with the same polarity are endangered (TABLE I);
- At the short-circuit of diodes of both polarities (one from Δ and one from Y) all the other diodes with the same polarity in the same bridge are endangered (Fig. 11, 12, 18, 19);
- At the short-circuit of diodes of both polarities in the same bridge a significant growth of current in all the other diodes arises; rate of their risk received from the simulations is expressed in TABLE II.

TABLE II. RATE OF RISK OF THE OTHER DIODES FOR SHORT-CIRCUIT OF TWO DIODES WITH THE OPPOSITE POLARITY AT THE SAME TIME

	At the time of short-circuited diodes:			
	D1 +D6	D1+ D44	D33+ D22	D2+ D33
D1			87%	
D3		100%	22%	
D5	80%	100%	100%	
D11	37%		80%	100%
D33	100%			
D55	31%			100%
D2			32%	
D4			35%	100%
D6			100%	100%
D22	100%	100%		
D44	100%		71%	
D66		100%		

In the TABLE II it can be seen, that for the short-circuit of the diodes with the opposite polarities from different bridges, just adjacent diodes are endangered (for example

D1+ D44; D2 + D33), it is similar as in the case of the short-circuit of only one diode (see TABLE I).

Different situation occurs for a short-circuit of the diodes with the opposite polarities in one bridge (for example D1+ D6; D33 + D22). In these cases an increase of current arises nearly in all neighbouring diodes, according the TABLE II.

This table shows only some of the possible combinations. In the same way all the other combinations were simulated and measured.

Methodology used for determination of the rate of risk of the diodes in TABLE II

Risk of the other diodes in the rectifier is considered based on value of mean forward current of commonly used diode DV808-1360-60 in traction rectifiers. This diode has the mean forward current 1360 A and unrepeatable peak forward current 17,5 kA.

The diodes which overcome this temporary peak forward current are indicated as 100 % endangered.

For the other ones an average current load is determined. Value of the average current load 1360 A corresponds to 0 %, average current load 9 kA (corresponds to the peaks 17,5 kA two times in a period) is indicated as 100 % load current. The scale between these values is linear.

V. CONCLUSIONS

The submitted work investigates the influence of short-circuit of one or more semiconductor diodes on the load current and thus also on the risk of all the other diodes in twelve-pulse rectifier during the time between failure and cut off of the high-speed switch in the input.

Practical conclusions of the research are best shown in TABLES I and II. If a short-circuit of one or more diodes in a traction power station occurs, these charts can be used as a background for revision of the rectifier. The charts refer to all elements which are endangered with high probability.

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