The Effect of Fault States of the Twelve-pulse Rectifier During the Recuperation

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Abstract — The paper deals with analysis of states from the viewpoint of the rectifier DC side. In the case of diode breakdown the interphase short-circuit occurs and the transformer is disconnected from the primary side by a high-speed switch. After disconnecting the DC current of a recuperative traction vehicle influences the circuit. The fault states of the twelve-pulse rectifier in a substation of 3 kV DC traction system used at railways in the Czech Republic are analyzed. The situation at the rectifier diode breakdown and at the same time recuperative vehicles in power supply section is examined. The vehicle with recuperation can increase strain of elements in power supply system under certain conditions during fault states of the rectifier. The simulation computer model was created for analysis of current waveforms in trolley line at this situation. All simulations were created by the program PSpice. The main goal is to analyze the endanger of power supply system elements and to present the recommendation for increasing the reliability of this mentioned power supply system.

Keywords — component; twelve-pulse rectifier; diode breakdown; recuperation; traction substation; transformer

I. INTRODUCTION

The operation of electrified railway lines depends on the stability and reliability of the electric energy distribution at the traction power supply system. Every fault in this traction system leads to a reduction of electrical transport with following significant decreasing of railway line capacity. These faults can be represented by a damage of the catenary due to weather conditions or defective co-operation between the pantograph and contact wire and also faults in the traction substation. The switch off overcurrent or undervoltage protections of the 3 kV DC traction substation is easily soluble by the remote control and the electrified railway lines can be operated in short time again.

A bigger problem can occur at the faults of the power rectifier units located in the traction substation where the number of these units can be limited due to the previous faults. This situation can bring the effect to decrease the railway line capacity or in the extreme case stopping of the railway transport.

II. VEHICLE WITH RECUPERATION

The condition at the 3 kV DC traction system is that electric energy got by the recuperation must be consumed at the same time by other electric traction vehicle or vehicles in the feeding connected section of the traction system and it cannot be returned back through the traction substation to the main network [1-2]. A different situation can arise in the case of two diode breakdowns with opposite polarity in one of the bridges (six-pulse rectifier). In this situation of the catenary short-circuit and thus also the short-circuit of the vehicle with recuperation occurs. This short-circuit represents the consumption for this vehicle.

Figure 1 shows an example in such conditions. There took place the diode breakdown (D5 and D2) creating the short-circuit source, which is represented in the circuit DC link by capacitor Cv of the vehicle with recuperation (the flowing current is shown by red color). The current is reduced by the substation inductance Ls, catenary resistance Rc and catenary inductance Lc.

![Fig.1: The recuperative current flow direction through the rectifier](image)

The switch before the primary winding of the rectifier transformer in Fig. 1 disconnects rectifier unit from the AC side in the case of diode breakdown.

The DC high-speed switches are placed in output of the substation and they separate each outlet of the catenary from the DC bus 3 kV. A rectifier unit can have at its output a few high-speed switches for several sections. The isolator switch enables to disconnect the rectifier from the DC bus placed between the DC bus and rectifier.

III. EQUIVALENT CIRCUIT

The equivalent circuit of the traction system has been derived for the necessary simulations. The simulations of the effect of the vehicle with recuperation on the power rectifier with the diode breakdowns and the traction substation transformer were researched for the reason of the current situation at the Czech Railways at the 3 kV DC traction system.
A. Equivalent circuit for recuperation

The equivalent circuit for the recuperation allows the simulation of diode breakdowns in the rectifier and is depicted in Fig. 2. The middle part of the equivalent circuit represents vehicle with recuperation by capacitor C₁ in the DC link. If the voltage of this capacitor overpasses the actual values of catenary voltage then the vehicle current flows to the catenary (recuperation). In the circuit this current with the value \( P_{\text{rek}}/U_{\text{c}} \) [A] is supplied by the voltage dependent current source G. The Zener diode D₂ has set the Zener voltage value of 3 600 V and it represents the ability of the vehicle to control the voltage at the pantograph (just at this value). The left part of the equivalent circuit represents the model of the traction substation at the fault.

The first stage of the simulation of the left traction substation has the same function as the right traction substation in the circuit. The simulation of a short-circuit of the vehicle with recuperation at the diode breakdown is done by the circuit switch S₁+S₂ [3-6].

The meaning of other elements and symbols in Fig. 2 is: \( P_{\text{rek}} \) is recuperation power coming to the catenary, \( D_{\text{h}}, V_{\text{h}} \) and \( R_{\text{h}} \) represent one of the substations which works against the substation represented by \( L_{\text{h}2}+D_{\text{h}}+V_{\text{h}} \) (two-way feeding). The resistor \( R_{\text{h}} \) (its value approximates infinity) is only for simulation, the inductances \( L_{\text{h}1} \) and \( L_{\text{h}2} \) are air chokes with 4 mH added at the output of each substation from the reason of increase of the speed of short-circuit current rise. The \( L_{\text{h}1} + R_{\text{h}} \) simulate the consumption of the recuperative power and represent the vehicle with fixed speed. The S₃ switches on the recuperation by current source G. The S₄ and \( R_{\text{h}} \) are only auxiliaries elements for simulation. The \( L_{\text{h}} \) and \( C_{\text{h}} \) represent input filter of a modern recuperative vehicle.

\[ \text{Fig. 2: The equivalent circuit for simulation of faults at recuperation} \]

B. Model transformer

The three-phase transformer with two secondary windings and the nominal power of 5 000 VA was used for measurement of characteristics of the DC current flowing through the secondary windings of the transformer.

The primary winding has the Y-connection, transformer ratio is 1:1 and the transformer phase angle corresponds to the real transformer with two secondary windings of the type RESIBLOC Yyn0d1. The same leakage inductances of two secondary windings of the transformer and also the same phase-to-phase voltages of output of both secondary windings are necessary conditions for transformer feeding the twelve-pulse power rectifier at the 3 kV DC traction system.

The same phase-to-phase voltages and a little bit different inductances of both secondary windings of the transformer at no-load mode were found out by experimental measurements. The short-circuit current does not pass through the secondary winding of the transformer in Fig. 1.

IV. ANALYSIS OF SITUATION AT FAULT RECTIFIER AT RECUPERATION

The short-circuit of the rectifier happens due to the diode breakdown as it was mentioned at the situation in Fig. 1. At the situation when the vehicle with recuperation is located in the feeding section of the catenary, this source will be short-circuited and its current increases the load of parts of the traction system.

A. Estimation of current waveforms flowing back to traction substation

The current waveforms which can flow back to the traction substation, were analyzed by simulation using the equivalent circuit from Fig. 2. The example of the simulations is the situation with two passing vehicles in half of the section between traction substations (20 km), Fig. 3. One vehicle is breaking (i.e. recuperation with power 6 MW) and the second vehicle is starting. At the first stage of the simulation the second vehicle is fed only by traction substations (each of the traction substation supplies the half current for the vehicle). The first vehicle starts to recuperate in time of 100 ms and the voltage of the catenary reaches the voltage value of 3600 V [7-8]. The recuperative current of the first vehicle covers all other consumptions and therefore the current of the traction substations is zero.

\[ \text{Fig. 3: The situation with two passing vehicles} \]
V. ANALYSIS OF THE TRANSFORMER INDUCTANCE

In the case of recuperative current flowing through the transformer secondary windings, it is obvious that the inductance between two phases will slow down the current rise to the traction substation with the faulty rectifier. The theoretical analysis of the relations between the inductances of the traction transformer each winding was done to verify the recuperative current waveforms flowing through the transformer secondary winding. The analysis of failure modes without detailed knowledge of these transformer parameters is not possible to complete. Therefore the passing of this recuperative current was analyzed experimentally in the laboratory. The speed of the short-circuit current rise and the value of inductance between two phases at the real traction transformer during the fault of the rectifier and energy from the vehicle with recuperation at the rectifier fault is deduced from the results. The inductance of 5.27 H at the Y-connection winding and 5.79 H at the Δ-connection winding were found out by measurements at no-load mode.

The measurements of the current flow time response through the pairs of the transformer secondary windings to the voltage jump was done for verification of the values of this inductance obtained from laboratory measurements. During the measurements it was monitored the time (a period) when the DC current reached 63 % of its steady value. This time was 0.5 s. In the case of the first system order, it would be possible to evaluate the value of the inductance in the circuit on the basis of the L / R ratio. Similar measurements were done at the secondary winding at the Δ-connection and the obtained value was 0.7 s.

From the time response measurements of the current flows through the pair of the transformer secondary windings to the voltage jump the value of the inductance of 0.60 H at the Y-connection and 0.91 H at the Δ-connection was determined.

VI. THE ANALYSIS OF TRANSFORMER CURRENT IN THE CASE OF DC POWER SUPPLY

Theoretically it is possible to describe this situation by the equivalent circuit in Fig. 6. This circuit describes the real transformer fed by DC voltage. The secondary circuit is created by the elements $L_2$ and $R_2$ representing the magnetic losses of the transformer. The difference of the inductance values found out by the AC measuring at no-load mode and by the current response to the voltage jump comes out at the loaded transformer when the mutual magnetic coupling of the primary and the secondary circuit becomes evident.

The derived equation for the current waveform was solved numerically by substitution of the values corresponding to parameters of the laboratory transformer. For the circuit in Fig. 6, the magnetic coupling simulation of the transformer primary and secondary windings (respectively the magnetic coupling between the primary winding and fictive secondary winding simulated the influence of eddy currents in the magnetic circuit) is valid

$$u_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}, \quad (1)$$

$$0 = R_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}, \quad (2)$$

where

$$L_2 = L_0 + L_{22σ}. \quad (3)$$
After differentiation of equations 1 and 2 we get

$$0 = R_1 \frac{d_1}{dt} + L_1 \frac{d^2 i_1}{dt^2} + M \frac{d^2 i_2}{dt^2},$$

$$0 = R_2 \frac{d_2}{dt} + L_2 \frac{d^2 i_2}{dt^2} + M \frac{d^2 i_1}{dt^2}.$$  (4)

(5)

The linear differential equation of the second order with constant coefficients has the form

$$u_1 = R_1 i_1 + \left( L_1 + \frac{L_2 R_1}{R_2} \right) \frac{di_1}{dt} + \left( \frac{L_1}{R_2} M^2 + \frac{L_2}{R_2} \right) \frac{d^2 i_1}{dt^2}.$$  (6)

We get for the laboratory transformer numerical values of the characteristic equation solution \( \lambda_1 = 0.095 \) and \( \lambda_2 = -14.34 \). Supposing real different solutions of the characteristic equation we get a general solution of the differential equation in form

$$i_{10} = K_1 e^{\lambda_1 t} + K_2 e^{\lambda_2 t}.$$  (7)

After determining of the coefficients \( K_1 \) and \( K_2 \) we obtain the equation for the current waveform

$$i_1(t) = -0.149 e^{-0.095 t} - 0.151 e^{-14.34 t} + 0.3.$$  (8)

The coefficients in the equation 8 were obtained by substituting of the actual transformer parameters to the equation 7. The current response time waveform to voltage jump is obtained by representation of the solved equation 8, Fig. 7, where \( t \) is the instantaneous value of the current.

The dependence of this time response on the value of the resistor \( R_2 \) (in Fig. 6) is evident from the derived equations. This resistance represents at the real transformer no-load mode the effect of losses, especially eddy currents in the magnetic circuit of the transformer. The above mentioned calculations were further verified by measuring of the time response of the current to the voltage jump on the laboratory transformer and by the simulation of the equivalent circuit using the connection in Fig. 6.

The main inductance between two phases is not indicative exactly for the speed of the DC short-circuits current rise in the transformer secondary winding as it was proved by previous calculations. They do not contain the losses in the magnetic circuit of the transformer. The speed of the rise of the DC short-circuit current will be higher in the case of the recuperation. The waveform of the short-circuit current rise at the time of the recuperation will rather correspond to the curve in Fig. 7, because the real transformer is loaded by the losses in the magnetic circuit (cos \( \varphi \) at no-load mode is 0.73). At the first stage it will be a very quick process practically limited only by the transformer leakage inductance and the recuperating current will increase the current strain of the transformer in the traction substation.

VII. CONCLUSION

In the first part of this paper, the values of short-circuit currents flowing through 3 kV DC traction system were numerically simulated. Independently the situation, when the short-circuit DC current flowing through the transformer secondary winding was analyzed. The inductances of this transformer slow down the rise of the DC short-circuit current. However, in the first stage of this DC short-circuit current rise, the transformer leakage inductances which allow a rapid rise of this current, become evident.

The whole interval of the short-circuit current rise at the real transformer is further reduced by the effect of oversaturation of the magnetic circuit at connection to the DC source. It is possible to conclude by the circuit theory that the worst situation is in the case of vehicle with recuperation very close to the traction substation when the short-circuit current is not limited by the traction line resistors.

The simulations show, the voltage drop on the pantograph below 2 kV occurs by this close short-circuit. The vehicle has a good opportunity to recognize this non-standard situation and stop the recuperation. Potentially the most hazard situations can be considered, when a vehicle with recuperation is close enough to pass through the catenary the high current, but far enough that the voltage on the pantograph does not fall below 2 kV. If the DC source in the contact line passes through a higher current to the traction substation than the set of the high-speed circuit breaker, this circuit breaker will be turned off.

The current values by the effect of the inductances in the circuit reach their steady maximum. This situation is dangerous especially for the machine isolator (circuit breaker) located between the 3 kV DC bus and damaged rectifier. The circuit breaker starts to disconnect immediately after the switch off of the transformer primary switch (responding to diode breakdown in the rectifier). Therefore, it is always appropriate to add the protection to the rectifier evaluating the direction of the DC current flow. This protection is already installed in some built traction substations. Usage of this protection makes sure disconnection of the damaged rectifier unit from the catenary.

The only vehicle, that would recuperative even if very low value of voltage at the pantograph, could complicate this situation (i.e. the situation of recuperation close to the traction substation when the current flowing back to the traction substation could be up to tens of milliseconds with very high values). The recuperation at the low catenary voltage is always suitable to interrupt from
viewpoint of the traction substation protection from dangerous current flow back to this traction substation.

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**REFERENCES**


