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DISTURBANCE IN THE POWER SYSTEM CAUSED BY AUXILIARY DC INSTALLATION FAILURE OF SWITCHYARD

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ABSTRACT
Due to failures of auxiliary DC installations outages of power plants and substations and degradation of reliability and security of power system in the past occurred.
The auxiliary DC installation in switchyard has been calculated based simplified stationary model.
New standard 61660-1 had been published 1997 and it was significant improvement of conditions related to dimensioning and analyzing auxiliary DC installation. That standard related to calculation of short circuit current took into account not only resistances, but inductances and capacities of all auxiliary DC installation components as well as the active alternative current network in front of the rectifier.
In the past it was recorded numerous failures of auxiliary DC installation and it was reason for reconstruction of the most jeopardized DC subsystems.
After reconstructions old and nonselective existing auxiliary DC installations and construction of DC subsystems in new switchyards respected of new criteria and IEC 61660-1 reliability and security of these switchyards and whole power system had been improved. However standard IEC 61660-1 should be changed from the reasons of new technology of components and new input data relevant for correct dimensioning and analyzing of auxiliary DC installation.

KEY WORDS
Auxiliary DC installation, failure, reliability and security

1. Introduction

The auxiliary DC installations as autonomy DC electricity supply subsystems in power plants and substations are extremely important because they enable reliable operation in normal operating mode as well as in the case of operating mode failure.
The auxiliary DC installation consists of three basic modules: source (battery and rectifier) DC distribution subsystem, and consumers.
Some vital parts of switchyard should have continuous and reliable DC power supply because that equipment must be in function in all operating modes. Accordingly, auxiliary DC installations are expected to be the most secure and the most reliable subsystem in the switchyard.
Nevertheless, in the past thirty years there have been numerous failures in switchyards and consequences disturbances in some part of power system including local interruptions power supply due to malfunction of auxiliary DC installation operation. In the most cases, malfunction was caused by wrong selectivity of protection devices and failures of particulary components.
In the Croatia it was recorded two regional disturbances in the power system operation caused by failure of protection devices (wrong selectivity) in auxiliary DC installation in substations:

- 1981. Substation Jarun (Zagreb region) 110/30/10 kV, destroyed switchyard 30 kV – capital Zagreb was partly without electricity,
- 1996. Substation Koprivnica 110/35 kV, destroyed switchyard 35 kV – town Koprivnica was partly without electricity as described in [3] and [4].

After some smaller and those huge incidents in the mentioned substations which caused interruptions of power supply, damages of equipment and significant appropriate costs and needs to replacement old components in auxiliary DC installation too, Croatian inspectorate for energetic and Croatian Power System Commission gave recommendation for changing the existing way of analyzing and dimensioning DC power supply subsystems.
Similar process of changing the existing approach of analyzing and dimensioning of auxiliary DC installations in switchyards happened under the supervision of IEC and IEEE.
1996. Draft International Standard IEC 1660-1: “Short circuit currents in DC auxiliary installations in power plants and substations” and 1997 IEC 1660-1: “Short circuit currents in DC auxiliary installations in power plants and substations” had been published, and set the new criteria of auxiliary DC installation dimensioning and analysis.

By setting of new IEC standard conditions for short circuit current calculation and dimensioning of auxiliary DC installations and especially selectivity calculation had been facilitated and improved.
However some parts of that IEC standard with new numeration 61660-1 should be changed from the reasons of new technology used in auxiliary DC installation and new conditions related to different treatment of active network and needs for limitation of short circuit current by rectifier.
This paper describes the main features of new approach of auxiliary DC installation dimensioning and analyzing and underlines changes those should be made in IEC 61660-1.
Correct design, construction, operates and maintenance of auxiliary DC installations especially are important in prevention of future outages of switchyards and consequently disturbances in the power system operation due to failures auxiliary DC installations.

2. Description and importance of auxiliary DC installation

The main role of auxiliary DC installation in power plants and substations is enables reliable operation and control in normal operating mode and especially after blackout, or forced outages of switchyard.
Auxiliary DC installation as mentioned before consists of battery, rectifier and appropriate distribution DC subsystem with corresponding consumers which are integrated in primary and secondary equipment due to carrying out of control functions.
Some vital components of switchyards such as power transformer, circuit breakers, disconnectors, protection and control devices should have uninterruptible and reliable DC power supply because these components should be continues in operate in all operating modes, especially during the restoration of the power system after blackout or outages of switchyards.
Accordingly auxiliary DC installation must be one of the most secure and the most reliable subsystems of switchyard.
Auxiliary DC installation should satisfy:

- dimensioning and selection of battery,
- check of conductor squares in case of short-circuit heating (calculation of conductor heating in cases of protection operating selectively and nonselectively),
- voltage drop calculation,
- check of conductor squares considering permanent current,
- voltage drop calculation (on battery and on conductors) and
- selectivity check of protection elements.

These criteria correspond with IEEE 946-1992 standard "Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations" as described [5] and [6].

Typical and simplified auxiliary DC installation applied in the power plants and substations showed Fig. 1.

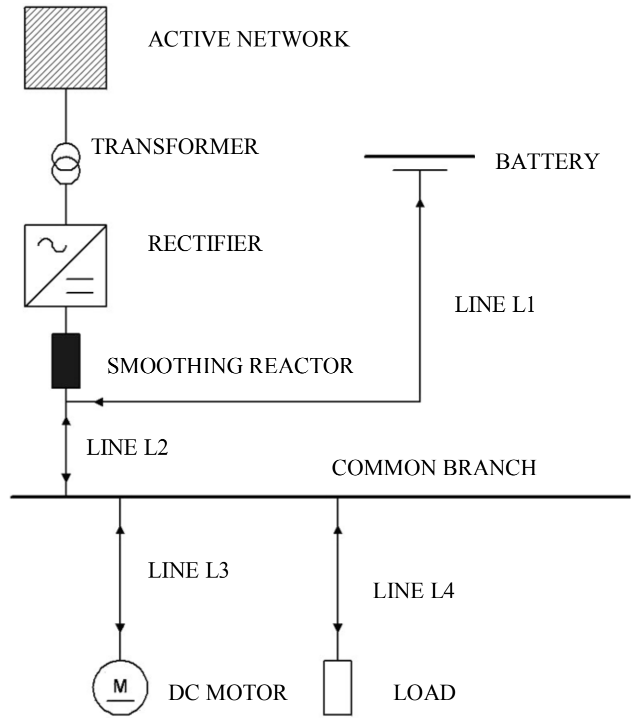

Fig. 1 Simplified auxiliary DC installation

Battery is the vital part and often the most expensive part of auxiliary DC installation. The process of battery dimensioning and selection considers the following criteria:

- the battery must meet the requirement of safe supply of priority consumers during 1,3 or 5-hours in the failure operating mode,
- the battery voltage drop after 1,3, or 5-hour discharge mode under repeated maximum load must not exceed 10 % of the rated voltage, i.e.:

$$U_{b5h} - (i_{\max} - I_{ht}) \cdot R_{b5h} \geq 0.9 \cdot U_n \qquad (1)$$

where:

U_{b5h} is the battery voltage after 5 hours of discharge (taken from the battery discharge characteristic) [V],
i_{max} is the maximal load current [A],
I_{ht} permanent discharge current [A],
R_{b5h} is the battery resistance after the permanent current discharge (taken from the characteristic of resistance rise during discharge) [Ω] and
U_n is the rated voltage [V].

- the battery must meet the above mentioned criteria at the reduced temperature of 5°C and at the end of its lifetime (80 % of the rated capacity).

Among these criteria very significant is the second one, whose incorporation in the battery selection increases the battery capacity (up to 50%), but also the price. It is commonly understood that the battery must satisfy that criterion as well, because it significantly increases the reliability and security of auxiliary DC installations, while the ratio of the price of the battery selected in this way and the price of a possible outages in the power plant or substation due to failure of auxiliary DC installation is very small.
In the process of voltage drop calculation on the battery and every single outlet we consider the fact that consumers do not necessary have to work continuously during the failure operating mode, but work in a particular time interval which is placed in the interval of total failure operating mode duration. It should be calculated the shortest time interval in which there is a change of consumer's activity (the consumer works or doesn't work) and divides the interval of total failure operating mode duration into belonging subintervals. Voltage drop is calculated separately for each subinterval, because the lead currents change from one interval to another. Finally, the maximum voltage drop calculated through the whole fault operating mode duration interval by subintervals is taken for every outlet. Protection devices selectivity is one of the principal criteria for correct function of auxiliary DC installation and consequently secure and reliable operation and control of power plants and substations in all operates modes. Protection devices selectivity means isolation only of faulted part of DC subsystem while the rest of the subsystem has to properly work without other disturbance and noise too. For higher short circuit currents in the auxiliary DC installation, usually number of DC protection levels, depend of number and installed power of consumers, should not exceed three or four.

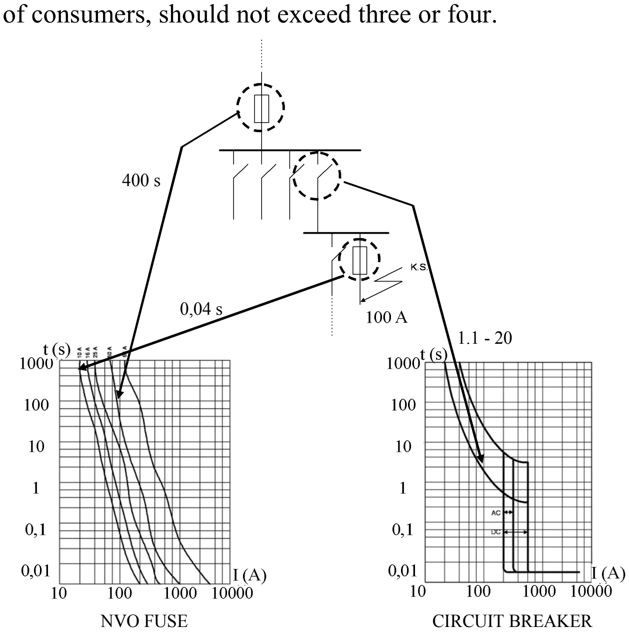

Fig. 2 Example of achieved selectivity

Selectivity of protection devices is achieved if difference of time between two protection devices is higher than 100 ms.
Fig. 2 represents simple example of achieved selectivity in three protection levels of DC subsystem, with one circuit breaker and two fuses. Correct selectivity in this case has been achieved because failure of one outlet on third level eliminated by appropriate fuse and only this outlet has been out operation. Wrong selectivity could be cause of reaction circuit breaker for protection of all third level and switch of out operation all consumers connected on third level.

3. Failures in the auxiliary DC installations

Old and unreliable batteries and rectifiers in power plants and substations, old and damaged isolation of conductors and improprieties of protections switchers and fuses as well as nonselectivity can be causes of failures of auxiliary DC installation.
But failure can be occurred even in a new auxiliary DC installation, because of fact that DC subsystem is not correct dimensioned and calculated. Inappropriate mathematical model for short-circuit calculation can be cause of wrong selectivity calculation and consequently it can provoke nonselectivity outage of auxiliary DC installation due to failure in the DC subsystem.
Unavailability auxiliary DC installation in power plant and substation due to failure in the DC subsystem means loss of control functions in switchyards, possible forced outages those points of power system supply and significant jeopardy of power system reliability. The worst consequences of outage of substation due to failure in DC subsystem are interruption electricity supply all connected customers, damages of equipment and operations risk during repairs and replacement of equipment.
After mentioned incidents in substations in the north-west part of Croatian power system caused by failures in auxiliary DC installations, and probability of possible outages DC subsystems due to old and unreliable DC equipment Transmission Division of Croatian Power System company concerning to order of Croatian inspectorate for energetic and recommendation of their own Commission decided to replace the most jeopardized auxiliary DC installations in substations of transmission network.
According to review and analysis of existing auxiliary DC installations and implementing of new criteria has been carried out the specific list of priority related to reconstruction of DC subsystems as described in [8]. In the period 1997-2002 the most critical auxiliary DC installations replaced by new DC subsystems and after that are not recorded outages of substations and disturbances in the power system operation due to failures of auxiliary DC installations. It was significant contribution to increasing reliability and security of those substations as well as whole power system.

4. The changes of IEC standard 61660-1

The previosly practice of dimensioning and analysing of auxiliary DC installations has been based on model which included resistences of elements of auxiliary DC installations. This model neglects impact of active network in front of rectifier.

Such model often be called stationary model and it did not reflect real situation in auxiliary DC installations.

The existing standard IEC 61660-1 “Short circuit currents in DC auxiliary installations in power plants and substations” includes transient state of short-circuit currents and it also deals with additional parameters of auxiliary DC installations (inductivity and capacity of conductors and the battery), as well as basic specifications of DC engines and it was big progress of treatment of DC subsystems.

But there is one major constrain in IEC 61660-1 – the influence of active network in front of rectifier is enormous.

Briefly it can be explained on simple auxiliary DC network from Fig. 1.

Input parameters for short-circuit calculation are shown in table I and results of calculation are presented in table II and Fig. 3.

TABLE I
PARAMETERS OF ELEMENTS SHOWED IN FIG. 1.

BATTERY	MOTOR	LINES	TRANSFO.
n=107	U_M=220V	L1 0.44mΩ 6.5µH	U_1/U_2=660/244
U_{nb}=2V/cell	P_M=100kW	L2 0.23mΩ 3.78µH	S=364kVA
U_b=225V	I_M=497A	L3 1.39mΩ 15.6µH	P_{Cu}=4.01kW
C_{10}=1000 Ah	n_M=25s^{-1}	L4 0.94mΩ 15.1µH	u_k=3.2%
R'_b=0.13mΩ/cell	n_{mM}=1.08 n_M	SMOOTHING REACTOR	ACTIVE NETWORK
L'_b=0.2µH/cell	R_M=42.2mΩ	R_p=0.88mΩ	U_n=660V
RECTIFIER	L_M=0.4mH	L_p=30µH	I''_k=30kA
I=1kA	R_F=10Ω		R_Q/X_Q=0.3
	L_F=10H		C_{max}=1.05
	J=6.6kgm^2		

TABLE II
SHORT CIRCUIT CALCULATION RESULTS

		i_p [kA]	I_k [kA]	t_p [ms]	τ_1 [ms]	τ_2 [ms]
IEC 61660	Rectifier	30.10	26.87	11.73	5.70	5.57
	Battery	16.58	14.24	13.00	2.50	100.00
	Motor	4.06	0,00	30.00	8.10	168.00
	Final result	**49.80**	**44.80**	**11.73**	**3.91**	**35.80**

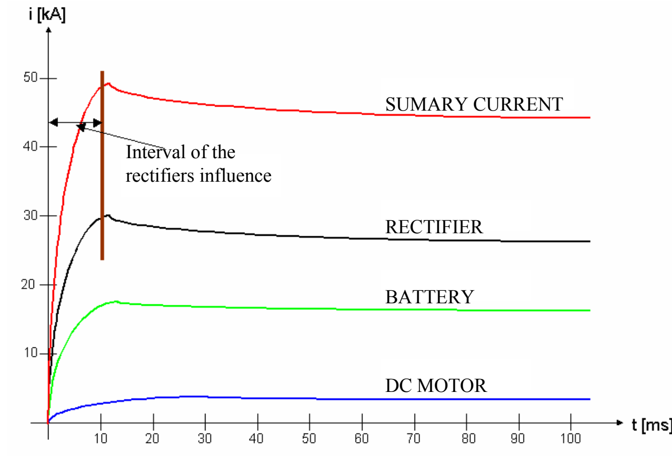

Fig. 3 Contribution of each element in the short circuit current

It can be marked that summary short circuit current is 44,80 kA. The contribution of the active network in front of the rectifier of 26,87 kA can not be accepted as a fact.

The calculation corresponding to previously methodology has been resulted by summary short circuit current of 15,21 kA.

The calcuation of short circuit current in auxiliary DC installation according to standard IEC 61660-1 does not take into account limitation of short circuit current by thiristors rectifier.

Therefore the summary short circuit current calculation in accordance to standard IEC 61660-1 does not correspond to real situation in auxiliary DC installation.

Respected fact of limitation the contribution of the active network through those rectifiers will be effective only in the first half cycle or less (5-10 ms) and after that it will drop to nominal rectifiers current as showed in Fig. 4.

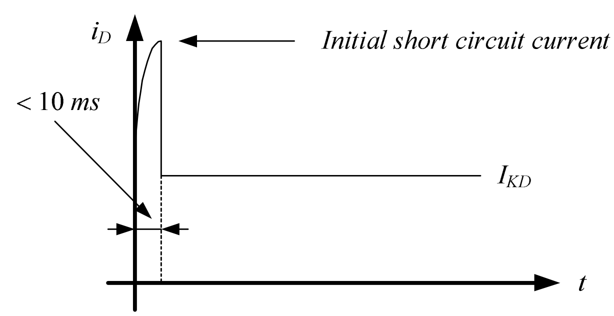

Fig. 4 Form of short circuit current of rectifier

The stationary current of rectifier is

$$I_{kD} = I_{ID} - U_{iN} \cdot R_{DL} \tag{2}$$

where:

I_{kD} is stationary current of rectifier

I_{lD} is current of limitation of rectifier

U_{iN} is voltage of rectifier

R_{DL} is resistance of line between rectifier and buses

It is the first reason that standard IEC 61660-1 has to be modified.

In auxiliary DC installation nowdays implements new tehnology of high frequency rectifiers which has different input data related to short circuit current calculation.

It is the second reason for change of standard IEC 61660-1.

The summary short circuit current and consequently all conditions for dimensioning of components and whole auxiliary DC installation and selectivity calculation due to implementation of new technology of rectifier will be more favorable.

Due to comparison of results of short circuit current calculations according IEC 61660-1 and results of measurement of short circuit current in defined auxiliary DC installation has been realized laboratory test as described in [9]. Fig. 5 shows principal schema for the performed test. Table III represents input parameters for short circuit calculation.

The results of measurements short circuit current given by laboratory test and comparison with results given by calculation according to IEC 61660-1 as well as contribution of each components of the auxiliary DC installation are presented in Table IV.

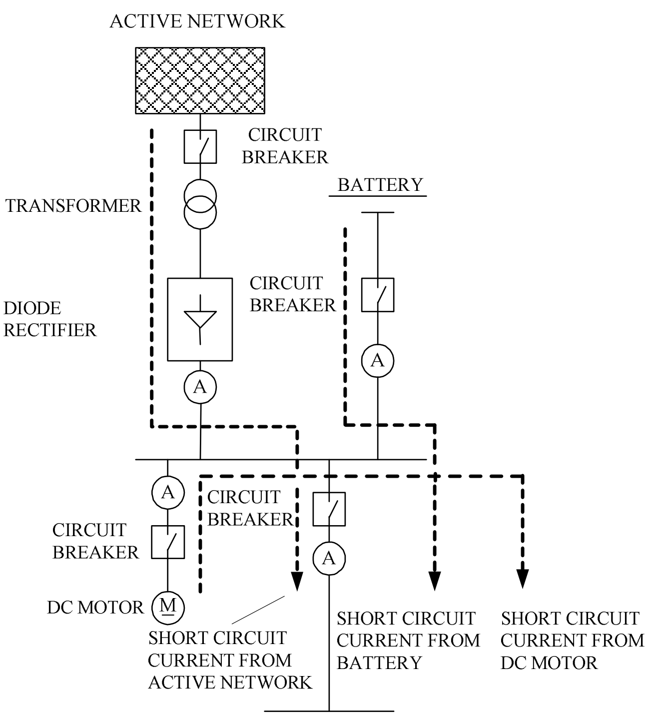

Fig. 5 Principal schema for the laboratory test

TABLE III
PARAMETERS OF ELEMENTS SHOWED IN FIG. 4.

ELEMENT	PARAMETERS
Active network	U_n = 380 V, I_k = 30 kA, c_{max} = 1.05, R_q/X_q = 0.3
Transformer	S=50 kVA, u_k = 4 %
Rectifier	In=300A
DC motor	P=40kW n_M = 25 s^{-1}, J = 3 kgm^2, U = 220 V
Battery	C = 400 Ah, U = 220 V, R = 57 mΩ

TABLE IV
RESULTS OF SHORT CIRCUIT CURRENT LABORATORY TEST

ELEMENT	SHORT-CIRCUIT CURRENT (A)	
	Calculation	Measurement
Rectifier	1848	250
Battery	4400	2500
DC motor	0	0

The results of mentioned laboratory test has been proved that influence of active network and rectifier on summary short circuit current of auxiliary DC installation were significant less than showed the calculation according to actual standard.

In this way conditions and circumstances for dimensioning and analyzing of auxiliary DC installation are more favorable than in a case of full implementing of actual standard.

Therefore IEC standard 61660-1 has to be changed in the parts related to impacts of rectifier and active network on short circuit calculation and new mathematical model for dimensioning and analyzing of auxiliary DC installation has to be applied.

5. Conclusion

Auxiliary DC installations in power plants and substations enable secure and reliable operation and control in the power system in normal operating mode and especially in failure operating mode.

The power plants and substations are essential elements of the power system. The outages of these key points due to failures in auxiliary DC installations can be cause of disturbance in the power system.

After local disturbance in power system caused by failure of auxiliary DC installation in Croatia started urgent review and analysis of existing DC subsystems in switchyards in the transmission network. The new criteria for design, construction, operation and maintenance of auxiliary DC installation have been adopted. The list of priority has been defined based new criteria and after that realized reconstruction the most jeopardize auxiliary DC installations in substations.

It has been brought significant improvement of reliability and security of switchyards and whole power system.
A nowadays auxiliary DC installation in switchyards of power system is based on IEC 61660-1 and IEEE 946-1992.
In the comparison with previously methodology a new standard introduced significant progress concerning short circuit current calculation, but it is based on old technology of rectifiers, and great impact of active network in front of rectifier.
The laboratory test for measurement short circuit current in defined auxiliary DC installation has been realized due to comparison results of calculation according actual standard and results of measurement.
The most important result of laboratory test was significant less influence of active network measured in reality than it has been showed in calculation according IEC 61660-1.
Due to taking into account a new technology of rectifiers and needs to limitation of short circuit current and influence of active network, actual standard IEC 61660-1 has to be changed.
New approach to short circuit current calculation will be foundations for changes of actual standard and favorable conditions for dimensioning of auxiliary DC installation.
Based mentioned conditions will be developing new equivalent scheme and appropriate mathematical model for dimensioning and analyzing of auxiliary DC installation in the future.

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