B&H Electrical Engineering Volume 14 January/December 2020 61-68
sciendo
DOI: 10.2478/bhee-2020-0014

Professional paper/Stručni rad

ANALYSIS OF POWER FAILURE WITH THE PHENOMENON OF AN ELECTRIC ARC IN THE ELECTRIC POWER FACILITY

ANALIZA HAVARIJSKOG DOGAĐAJA S POJAVOM ELEKTRIČNOG LUKA U ELEKTROENERGETSKOM POSTROJENJU

Ninoslav Simić[1], Jovan Mrvić[1], Ranko Jasika[1]

Abstract: This paper describes cause and effect of an electrical arc fault in industrial TS 6/0.4 kV. Results of insulation resistance test, dielectric withstand test, thermographic inspection, testing of LV installation, as well as recorded data analysis are presented in detail and an events explanation is given. The aim of this paper is to show the purpose of complex testing, both during the events of the accident and during the preventive maintenance. It has also been recommended to analyse calculations of short-circuit currents and the effect of an electric arc on the staff in power facilities, the so-called "arc flash".

Keywords: Electric arc, arc flash analysis, short circuit current, power failure

Sažetak: U radu je opisan uzrok i posledica kvara praćenog električnim lukom u industrijskoj TS 6/0.4 kV. Rezultati ispitivanja otpora izolacije, ispitivanja podnosivim naponom, termgrafskog ispitivanja, ispitivanje električne instalacije, kao i analiza snimljenih signala su detaljno prezentovani, te je dato objašnjenje događaja. Na kraju je naveden i dokumentovan uzrok havarijskog ispada postrojenja. Cilj rada je da se pokaže svrha kompleksnih ispitivanja kako tokom havarijskih događaja, tako i u toku predviđenih remonata. Takođe je data preporuka da se obave proračuni struja kratkih spojeva i uticaj električnog luka na ljude u postrojenjima, tzv. „arc flash" analiza.

Ključne riječi: Električni luk, „arc-flash" analiza, struja kratkog spoja, havarija

INTRODUCTION

In accordance with current trends, in order to increase reliability, production capacity and protect the environment, replacement of old electrical equipment is constantly planned and implemented in power plants. Modernization of equipment, at first glance, requires material resources exclusively for new equipment, but in practice the problem arises regarding the adjustment of newly installed equipment and the impact of new components on the performance of other consumers in the switching scheme. Design solutions do not fully consider the system as a whole, and are based on changes in individual parts within the system. Therefore, it goes unnoticed that increases in the value of short-circuit currents and fault times have a progressive effect on the development of the electric arc and produce consequences for equipment and people. In order to avoid injuries to personnel and higher costs, it is necessary to carry out studies to evaluate new values of short-circuit currents, the consequences of possible breakdowns before replacing the equipment, and to take appropriate measures accordingly. When selecting new components, all available technical documentation should be used and experience in the application of specific devices and equipment should be followed. Hiring a high-quality consulting firm in case of any changes to the project is indispensable. The following case is an example of an event in a plant where new investments increased the short-circuit power at a voltage level of 6 kV and replaced the main switch in the 0.4 kV power supply cabinet with a switchgear of higher rated current and different options for adjusting the response value in the event of a failure.

[1] Electrical Engineering Institute Nikola Tesla, Belgrade, Serbia
ninoslav.simic@ieent.org
Paper submitted: September 2019 Paper accepted: July 2020

1. INVESTIGATION OF THE CAUSE OF THE ACCIDENT EVENT IN THE FACILITY

1.1. Facility description, protective device settings and visual inspection

The observed 0.4 kV power facility is indoor type, produced in 2004 and consists of 10 distribution cabinets, each cabinet consisting of several retractable cassettes. The facility is supplied by the T1 6/0.4 kV power transformer, 2000 kVA, u_k = 6.25%, which is located outside the building. Bus protection device with a new switchgear, I_n = 3200 A with integrated system of overcurrent protection and overload protection is installed in the switchgear cabinet. The setting values are I >> 32 kA, t = 0 s and I >> 25.6 kA, t = 0.5 s.

The protection of individual loads energized from cassettes is provided in each cassette, according to the type of load. The load in a 0.4 kV cabinet number 11/cassette 3 is a three phase induction motor P= 75 kW, I_n = 140 A. The overcurrent setting is I >> 1.28 kA, t = 0 s. Transformer protection on the primary side of 6 kV is provided by microprocessor protection device and designed to record electrical quantities (setting I >> 1.6 kA, t = 0 s). According to the available data, during the time before the protection device response of the primary side T1 6/0.4 kV transformer, the AC induction motor was switched on for about 20 minutes, with constant load. At the same time, an alarm on the fire control panel was recorded. The plant has been in operation for three years without shutdown by the time of the accident. Upon arrival to the facility, the expert crew faced the following circumstances: the failure of the plant from operation, due to the consequences of fire, and the engaged firefighters on site (Figure 1). Major material damage was caused primarily due to the outage of the production process.

By visual inspection of the dismantled cabinet, it was found that the first three cassettes (numbered from top to bottom) were exposed to high intensity electric arc [1]. The first two cassettes were switched off, without load, as reserve cabinets. In these two cassettes, damage to the partition sheets on the underside of the cassettes is evident. The most damaged was the third cassette, which energizes the induction motor, where complete evaporation of the connectors is observed (bus bar connection, copper with a circular cross-section 18 mm in diameter, 5 cm in length in all three phases). The dimensions of the cassette are length/width/height: 50 cm/40 cm/30 cm, the distance between the phase conductors in the cassette is 4 cm, while the distance of the connectors to the grounded metal parts is 2 cm. The busbar connector is at the top of the cassette, while the load connector is at the bottom. The terminal insulators were completely burned during the event. The cassette partition frame above the busbar terminals was punctured in several places in length corresponding to existing length of the electric arc on the cassette terminals, i.e. the electric arc existed in the upper part of the cassette for a long time, at the place of the cassette terminals on the busbars, and in moments of maximum intensity it damaged two cassettes, located above. The deformations of the cassette are visible and, thanks to the partition panel, all the electrical equipment inside the cassette was preserved, while insulation on the conductors closer to the fault location melted. Examination of the electrical conductors inside the cassette, revealed that these conductors were undamaged and that there were no conductor parts to indicate the existence of a prolonged high temperature inside the cassette elements prior to failure, which could cause the aforementioned event. All the elements of the equipment in the cassette point to the effects of the electric arc, which existed in the insulated area around the cassette connectors. The electric arc existed at all phases and in conjunction with the metal frame of the cassette, in the narrow space between the partition frames. In these circumstances, when there is insufficient ventilation, multiple arches can be expected in an area filled with hot air and evaporated metal. The AC motor cable is without damage, the cable connectors were preventively replaced, the insulation of the motor and the cable was tested with DC 5 kV/1 min and connected to the another LV cabinet, after which the load was switched on. The AC motor normally runs at 2–3 hour intervals, several times a day.

1.2. Analysis of the recordings of fault currents

By analysing the recordings of fault currents from monitoring device at the voltage level of 6 kV, multiple on/off switching was observed. The recordings do not show the initial fault current because the memory capacity of monitoring device is of limited capacity (max eight events, each subsequent event deletes the first record). Therefore, neither the exact type of first failure nor the intensity of the initial current can be determined. The monitoring shows the time period in which several occurrences of a fault current were seen and the last recorded fault current when the



Figure 1: The motor distribution cabinet after the event

switchgear was switched off. The currents shown in the following figures have been converted to a true value at the voltage level of 0.4 kV. Figure 2 shows the specificity of the fault in terms of a very variable value of current and fault duration. It can be seen that the maximum values of the fault currents are less than 10 kA and the duration time range between 10–30 ms. In this case, if a time axis of 0.07–0.17 seconds is observed, a two-phase failure (red and green) is seen, and the next failure of 0.17–0.22 seconds is a two-phase between the red and blue phase, which then grows into three-phase fault. Obviously, the space was very ionized, and multiple arches are inevitable. In this case, the fault currents were lower than the set protection response current, and the fault persisted until the moment shown in Figure 3, when the current exceeded the limit value.

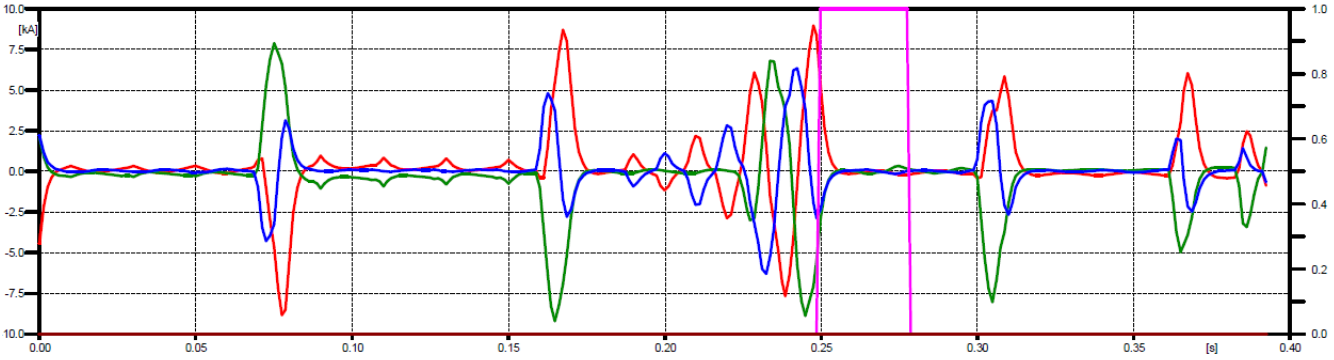


Figure 2: A snapshot of the fault current at 6 kV converted to a voltage level of 0.4 kV. The currents are represented by red, green and blue curves. The values of currents in kA are given in the ordinate on the left, and the abscissa gives the time in seconds. The protection signal (first alarm, without switching off) is represented in pink colour, status 0/1 shown on the ordinate on the right.

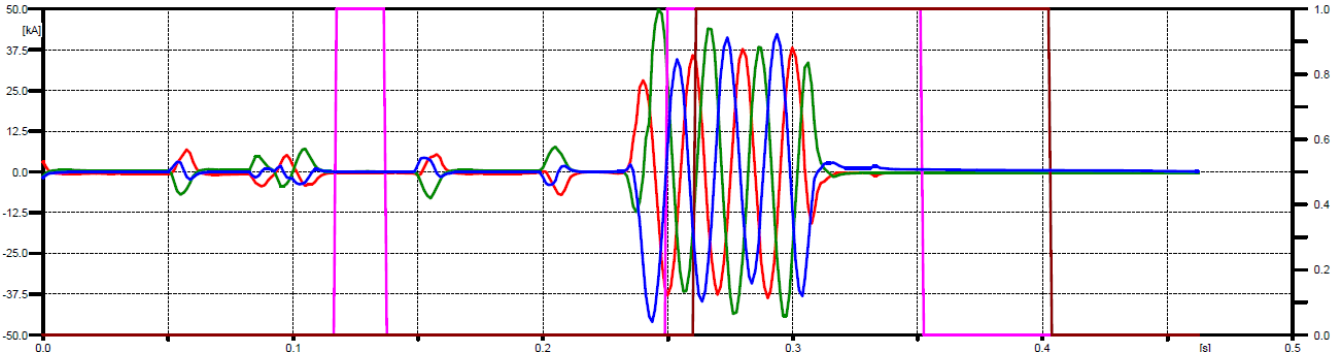


Figure 3: A snapshot of the fault current at 6 kV and the response of the protection device. The currents are converted to a voltage level of 0.4 kV and are represented by the red, green and blue curves. The values of currents in kA are given in the ordinate on the left, and the abscissa gives the time in seconds. Protection signal is presented in brown colour, status 0/1 shown on the ordinate on the right.

2. MV/LV SUBSTATION TESTING

2.1. Insulation DC resistance test and dielectric AC withstand test

In order to restore the 0.4 kV substation to function, after cleaning, the tests were performed. In compliance with the standard SRPS HD 60364-6:2012 [2], the test was carried out by connecting the U = 500 V DC between the tested phase and the other two phases connected with grounded parts. The following insulation resistance values were recorded: phase L_1 = 4.2 MΩ, phase L_2 = 5.7 MΩ, and phase L_3 = 11.3 MΩ. The facility was then tested at the voltage U = 1890 V, 50 Hz, for 1 s, in compliance with the standard [3], and the following test results were obtained: phase L_1 – insulation withstood test voltage without breakdown, phase L_2 – insulation withstood test voltage without breakdown, phase L_3 – insulation breakdown at 1500 V. After sectioning the cabinet parts and doing a thorough search, an insulator was found in the cabinet 8, on which a current path was observed (Figure 4).



Figure 4: The insulator after electrical breakdown

Satisfactory results were obtained after replacing the damaged element and repeating the test, and the facility was energized again.

2.2. Testing of low voltage electrical installations in the 0.4 kV substation (continuity of protection conductors, earth fault loop impedance, the verification of effectiveness of the measures for fault protection by automatic disconnection of supply)

Equalization of potentials of all cabinets in the substation was carried out and the maximum value of the measured resistance was 0.02 Ω. The results of testing the continuity of the protective conductor and the fault loop impedance in compliance with [4] and [5] are given in Table I.

Explanation of the results: The measuring range of the instrument is up to a fault current of 40 kA. If the fault current is higher, "> 40 kA" is displayed on the instrument display.

Two fault loop impedance and corresponding fault currents were measured:

1. The first measurement at Switchgear transformer cabinet No. 6 was performed and the obtained values are higher than 40 kA, i.e. higher than 32 kA (protection device settings),
2. As the worst case scenario is that the fault occurs on the last cabinet No. 11 at the busbar, a value in the Table I shows the results of measurements at entry terminal of the cassette. Due to the inaccessibility of the buses, only one value in phase L_1 was measured and the fault current is greater than 40 kA. The values at the exit terminals of the cassette were then measured and the values obtained were in the range 11–17 kA. These values are certainly higher than the cassette protection setting ($I >> 1.28$ kA, $t = 0$ s).

Measurements show that the fault currents are very high, which is a consequence of the small distance from the transformer to the cabinets. The fault loop impedance therefore has extremely low values and if there is some transient resistance in the circuit its influence will be dominant, which determines the settings of protection device.

2.3. Testing of voltage and current signals at the busbars 0,4kV

Voltage and current signals are recorded directly on the substation busbars. Figures 5 and 6 show the currents and voltages recorded in the transformer switchgear cabinet No. 6 in the 0.4 kV facility. The currents are shown in blue, red, and pink, respectively, and current values [A] are given on the ordinate. The green colour shows one phase voltage, the values of voltage [V] are given on the right.

During the recording, one of the other induction motors was started. The graph shows that the grid is extremely solid (the voltage is represented in green, the value of the ordinate voltage on the right [V], Figure 7).

Table I: Verification of continuity of protection conductors and measurement of fault loop impedance

Description of LV Cabinet / phase /Power circuit	continuity PE/PEN	protection device setting I_n [kA]	Z_s [Ω]	I_{sc} [kA]
Switchgear transformer cabinet No. 6				
L_1	ok	$I >> 32$ kA, $t = 0$ s	0.005	> 40
L_2	ok		0.005	> 40
L_3	ok		0.005	> 40
Cabinet No. 11, cassette load AC induction motor				
L_1 before cassette	ok	$I >> 32$ kA	0.006	> 40
L_1 after cassette	ok	1.28 kA	0.019	12.5
L_2 after cassette	ok	1.28 kA	0.020	11
L_3 after cassette	ok	1.28 kA	0.014	17

PE/ PEN - protection conductor, TN C/S System
Z_s - earth loop impedance
I_{sc} - fault current

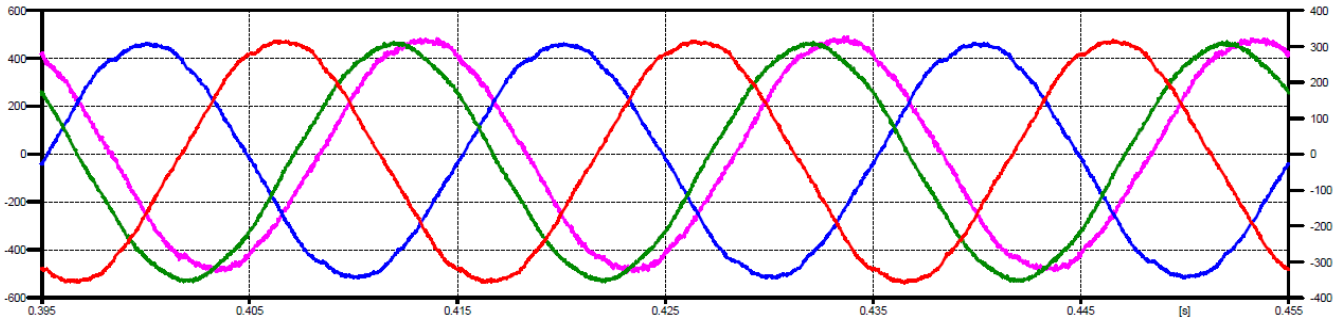


Figure 5: Record of the currents and voltages, steady state, AC motor on

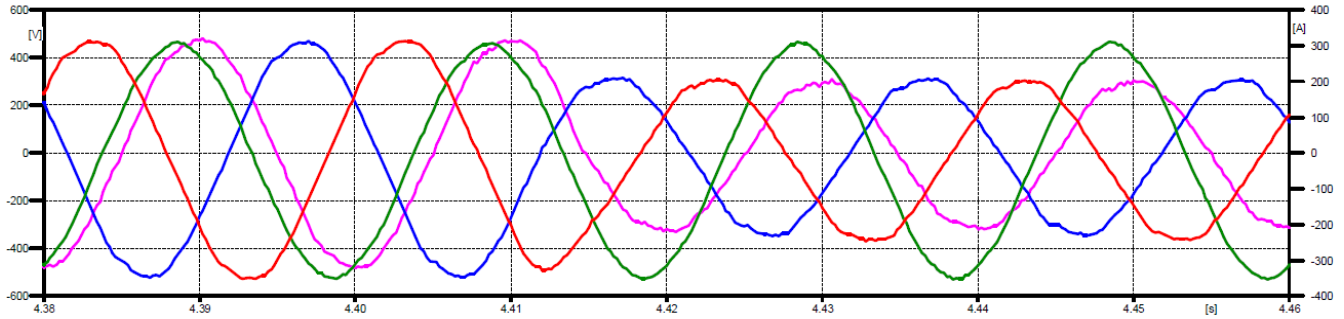


Figure 6: Record of the currents and voltages, the moment of disconnection of AC motor

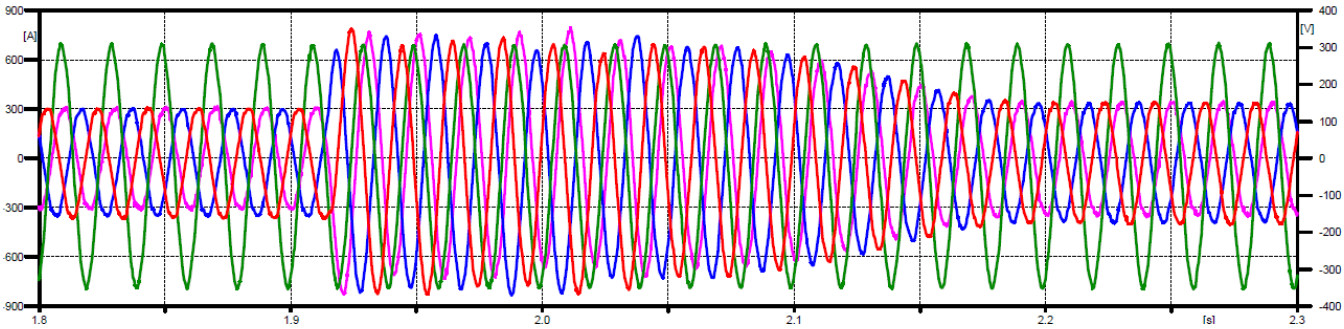


Figure 7: AC motor start (currents: red, pink, blue, values given on the left, voltage: green on the right)

All the recorded values and transients are expected, without the presence of an overvoltage. The power network is stable, i.e. the start and stop currents of the motor do not affect the shape and value of the voltages on the busbars [6].

2.4. Power quality

Figure 8 shows an example of current in one phase in AC motor. Since there are no semiconductor devices in the facility, all voltages and currents have the expected signal shape for a 50 Hz frequency.

The harmonic analysis of the recorded signal is shown on Figure 9.

Based on the difference of currents before and after starting the AC motor, it is calculated that the motor current is 122 A, and the Fourier analysis of the phase current waveform shows a low content of higher harmonics. Similar results are obtained by considering currents in the other two phases. Accordingly, the results of the recorded voltage signals are below the limit values (total THD < 8%) permitted by the standard [7]. By recording the signals on the busbars, it was found that there were no harmonics that could affect the insulation breakdown [8].

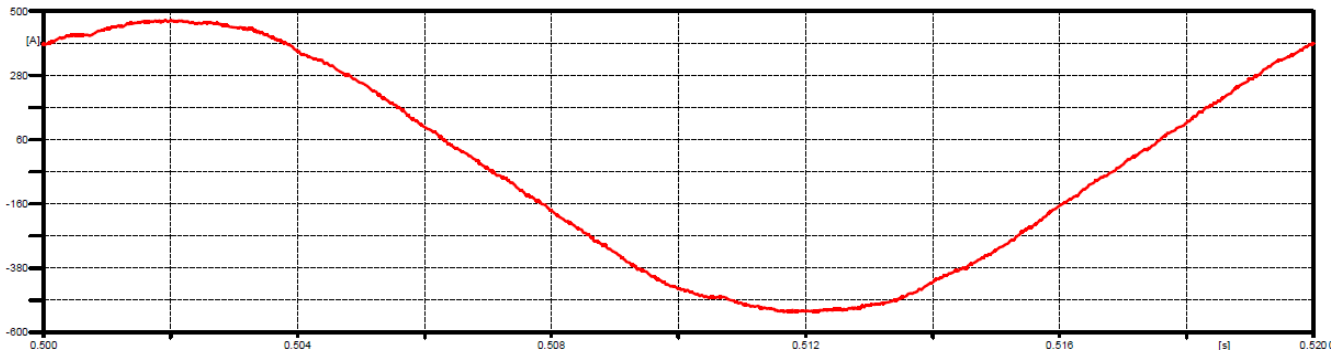
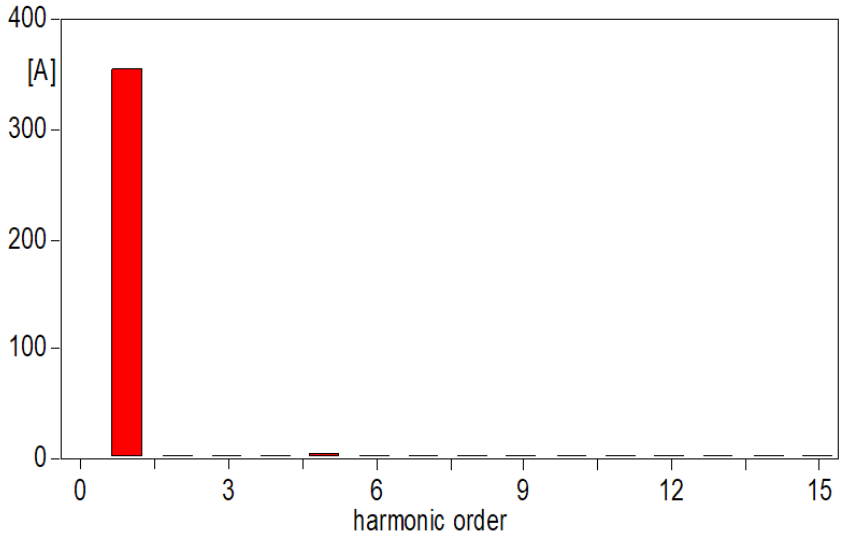


Figure 8: Phase current L_2, steady state after AC motor start



harmonic	*I* [A]	phase [°deg]
1	352.7	55
2	0.6	39
3	2.2	-26
4	0.3	-45
5	4.8	113
6	0.2	34
7	2.4	134
8	0.1	-75
9	0.2	-133
10	0.1	-43
11	2.2	137
12	0.1	-48
13	1.1	57
14	0.2	37
15	0.06	-100
THD=1.83%		

Figure 9: Harmonic analysis of phase L_2 current, steady state after AC motor start

2.5. Thermographic inspection of the electrical equipment in 0,4kV substation

During this inspection, the maximum temperature of 37 °C of the tested equipment was measured at the joints (Figure 10). There was no significant temperature difference between the phases or equipment, and ambient temperature was 22 °C. No overheating was observed on the surfaces of the tested equipment. Considering that there are no hot spots that are heated above the permitted values, it is concluded that all joints and elements that have been subjected to testing are correct with regard to heating [9].

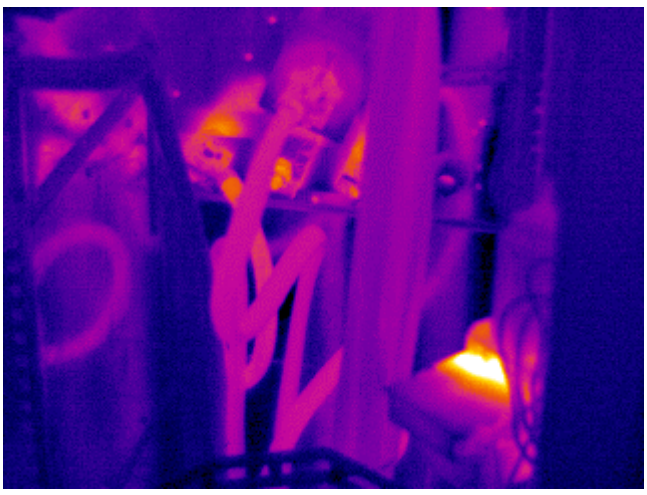


Figure 10: Thermographic (thermal) image of the cable terminals in the LV cabinet

3. SUMMARY OVERVIEW OF TEST RESULTS AND RESEARCH

On the basis of visual inspection, it was determined that in the area of cassette No. 11 connectors, next to the vertical partition panel to the busbars, there was an electric arc, which caused the damage to this cassette and two cassettes above. Large deformations of the cassettes and the evaporation of copper indicate the high value and extended time of the electric arc, which eventually existed as three phase fault to ground. The load in the cassette is an induction motor that was operated before the failure occurred. There is no damage to the motor and the motor power cable, so it is determined that the failure was not caused by the motor. The cassette was enclosed with metal partitions to prevent the entry of small animals. Considering that it is low voltage, and that the plastic insulators of the fixed contacts for the cassette connection are made in one piece and in ten points firmly fixed for the partition plate (Figure 11), and that there are no welding marks on the partition plate towards the busbars, the possibility of failure of the insulator causing the malfunction is excluded.



Figure 11: Insulator at fixed contacts and spring residues from the damaged cassette

The malfunction is most likely caused by the presence of a foreign metal part directly in the cassette connectors. The only element in this space of sufficient length to make a connection of metal parts is a spring of the contact system, which is not protected against falling out in the event of cracking. When straightened, it is 6 cm in length, which is longer than 4 cm of interphase distance, or 2 cm of phase distance from the metal grounded part. A spring can be broken due to the material aging or the current flow through it. During the exploitation contacts have to be maintained correctly. It means that the cassette has to be pulled out at least once per year. The process is known as the self-cleaning of contacts. Unfortunately, in this case, due to production`s demands it has not been possible for several years. At the end, contact resistance increased and the electrical current started to flow through the spring. The spring was overheating, especially at the attachment point, and this occurrence caused the spring to break. Usually, in the event of cracking, and due to gravity, the spring unbends and falls towards to the bottom of the cassette. When it falls, it must touch cassette load connector, thereby triggering the AC motor protection. Of course this does not happen at first, because the low-mass spring goes upwards, due to an extending of the electric arc in the ventilation cassette gap. At the moment when the electric arc extinguishes, the spring falls down and the event can be repeated. It is happening in a very short time, so the protection device cannot be triggered and AC motor continuously works. Due to the geometry of the cassette and the existence of a narrow gap between the two vertical partition plates, the electric arc of the first failure extends upward and remains trapped in the space of the cassette bus bars connectors, where it repeatedly turns on and off, eventually creating a pressure that deforms the cassettes and creates the necessary vent. In this case, when the AC motor protection device triggered, the down connectors were switched off, but the upper connectors were situated in ionized area and energized. After a few electric arc occurrences, the conditions were changed enough to provide the bus bar protection device response (Fig 3, $I >> 32$ kA, $t = 0$ s).

Analysis of the fault current recordings from the event monitoring confirms multiple occurrences of the electric arc. It is also evident that the protection device responded according to settings at the moment when the fault current exceeded the set point. Figure 11 also shows the springs found in the cassette remnants. Based on the measurement of the fault loop impedance, it is concluded that the fault currents are very high, which is a consequence of the small distance from the transformer to the LV facility and the characteristics of the selected transformer. The overall impression obtained from the thermographic test is that all the equipment in the facility is designed appropriately and there is no overheating.

Records of current and voltages during starts and disconnections of AC motor show that there is no influence on other loads and power network.

The insulation testing of the substation after the accident revealed a small value of the insulation resistance (U = 500 V DC, R = 3.1 MΩ) and it is noted that the insulator broke down at the test voltage 1500 V, 50 Hz. After replacement of the element and thorough cleaning, the final test confirmed that the substation met the requirements of the stated standards. The direct consequences of the fire are soiling of the insulators and damaging the dielectric strength of the insulation. By recording the voltage signals at the busbars, no higher harmonics could be observed which could affect the insulation breakdown, and THD values are within the standard limitations. Several conclusions are imposed. The contacts' spring has to have a protection cover. Indeed, the cover is provided in the latest product series. Also, the equipment designed before 2000 requires preventive maintenance. Finally, installation of the new equipment can cause faults that did not exist in the past, so selecting and adjusting protective devices is crucial. According to the explanations and test results presented above, the facility is energized. It is recommended to have an inspection of the contacts in all the cabinets, as well as a mandatory periodic thermographic inspection at maximum load. It was pointed out that in order to achieve the self-cleaning of the contacts, it is obligatory for each of the cassettes to be pulled out and returned to their tray at least once a year. Possible consequences for the staff are outlined and it is recommended to reset the protective devices.

4. CONCLUSION

Today's strategy in many companies is to avoid preventive maintenance of the power facilities due to the cost savings. World trends are moving from preventive maintenance to maintenance by condition. In the region, recommendation to stop the facilities periodically for inspection and testing purposes is avoided on the pretext of heavy losses if there is no production. Often, maintenance is understood as a set of emergency work to eliminate problems leading to production interruption, or the consequence of fires and accidents. Lack of quality spare parts, lack of trained and experienced professional staff, limited budgets, shortage of spare parts in warehouses, complicated administrative procedures, old rules and the like are the problems professional staff are constantly facing. In response to newly created conditions, a series of actions is presented in this paper to ensure readiness of the facility for restart in the short term after the accident. Complex research into the cause of a failure, the application of multiple test methods, the application of standards, quality testing equipment, and the training of expert teams all result in the avoiding of repeated failure caused in the same way. In addition, the reason for the increasingly devastating consequences of the electric arc lies in the tendency to increase production capacity on the basis of existing equipment. There is a noticeable increase in the demand factor (the ratio of the sum of the maximum demand to the total connected load) on the system and the replacement of older loads by larger and more complex loads. Therefore, there is a need to install higher power transformers in the existing facilities that were designed in the past and oversized, and as such were much more resistant to the impact of the electric arc. Transformers and in-built generators often work in parallel to reduce electricity costs. Fault currents are accordingly

increased, the impact of induction motors during failure is more significant and, ultimately, the electric arc is more destructive to equipment and more dangerous to people [10]. Considering that the equipment utilization limit is constantly rising and today's projected values are very close to the values declared by manufacturers, it is true that we are facing dangerous consequences in the case of failure. While only the protection against electric shock is mainly emphasized in our country today, in the world the protection of personnel from various other influences of electrical current in the workplace is already in focus [11]. Therefore, it is strongly recommended that, in addition to the usual design solutions, the impact of the electric arc on staff, i.e. the arc-flash analysis and the use of protective suits should be introduced. Based on the experience so far, as a result of the analysis, different values of the protective devices settings can be obtained, as well as a shortening of the fault duration. This way, it is possible to renew electrical equipment, at the same time increase the reliability of the system and raise the safety of the people in the facility to a higher level.

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BIOGRAPHY

Ninoslav Simić was born in Drvar in 1974. He graduated in 2000 and obtained his master's degree in 2009 at the Faculty of Electrical Engineering Belgrade. He is currently employed as a senior advisor at the Electrical Engineering Institute Nikola Tesla in Belgrade. He is the author and co-author of about thirty papers in the field of medium and high-voltage switchgear, power facilities, thermographic inspection, power cables. He is a chairman of TC N064 Electrical Installations in Institute for standardization Serbia and active member of CIGRE SERBIA SC A3 (High-voltage Equipment).

Jovan Mrvić was born in 1965 in Belgrade, where he graduated from high school and Faculty of Electrical Engineering. In 2014 he defended his master's thesis entitled "Voltage transformers and feroresonance in isolated networks" at the Faculty of Electrical Engineering, University of Belgrade, Since 1993 he has worked at the Nikola Tesla Institute, in the field of high voltage engineering, mostly on theoretical and experimental studies of transient voltages and currents in the power system, electric and magnetic field tests and voltage and current research in the high voltage laboratory. He has published more than 30 papers at domestic and international conferences, national journals and proceedings of the Nikola Tesla Institute. He participated in several studies at the Nikola Tesla Institute and as a researcher in several projects of the Ministry of Science and Technology Development of the Republic of Serbia.

Ranko Jasika was born in Prijepolje on March 30, 1992. He received his B.Sc. in 2015 and M.Sc degrees in electric engineering from Faculty of Electrical Engineering Belgrade, in 2016. He is currently employed as associate at the Electrical Engineering Institute Nikola Tesla in Belgrade. His current areas of research include electromagnetic transients, overvoltages, insulation coordination, electric and magnetic field tests and voltage and current research in the high voltage laboratory. He is the author and co-author of several papers in the field numerical simulations transient phenomena in HV and MV power network.