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TRANSIENT RESIDUAL VOLTAGE INFLUENCE ON THE DYNAMIC LOAD TRANSFER

BY

FLORIN CONSTANTIN BAICEANU*, **FLORIN MUNTEANU and CIPRIAN-MIRCEA NEMES**

"Gheorghe Asachi" Technical University of Iaşi,
Faculty of Electrical Engineering

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Abstract. The successful operation of back-up supply sources in the case of dynamic loads transfer in industrial electricity supply installation is mainly depending on the mitigation of the residual voltage that appears in fault scenarios that result in losing supply from the main grid. The decrease of the interval of presence of residual bus voltage depends highly on the local load and the network configuration. A high time constant (seconds) of the decreasing residual voltage can lead to the disconnection of critical consumers. In this paper, it is presented a simple, cost-effective method for dynamic load transfer that can replace the Motor Bus Transfer approach. The validity of the method is tested on a real large industrial site from Romania. The case study shows that the proposed approach can achieve a voltage return time of around 750 ms.

Keywords: motor bus transfer; fast transfer; residual voltage; asynchronous dynamic load.

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*Corresponding author; *e-mail*: florin-constantin.baiceanu@academic.tuiasi.ro

1. Introduction

Today, the high precision monitoring systems used in electrical networks allow the continuous monitoring and control of essential parameters of supply quality and network operation stability and security, giving the network operators the possibility to predict with improved accuracy the events that may occur in the normal and transient operation of energy systems. In industrial sites, the fast transfer systems used to switch consumer connections between alternate supply sources operate so that even synchronous motors or generators are not affected by the transfer. These systems are critical in industrial power systems that include uninterruptible processes, for which the continuity of electricity supply is essential (Munteanu *et al*., 2020). The efficiency of this equipment is analyzed in (Raje *et al*., 2003), leading to performance that greatly helps continuous flow processes by reducing the number of interruptions.

In industrial sites, the automatic transfer switch (ATS) system is used in the transfer of dynamic load on different power station architectures taking into account multiple power supplies (Kansara, 2017). The problems related to the switching of dynamic loads are extensively studied starting from the residual voltage that can occur on the busbar, and the defects of the machines (Kim *et al*., 2019; Yalla *et al*., 2020; Methebula and Saha, 2019a), and others. In (Mathebula and Saha, 2019b), the problem is solved by implementing the FBT (Fast Bus Transfer) method, reaching a voltage return time of 680 ms. This problem is often studied in the literature, but in practice it must be considered together with the the problem of implementation costs. Furthermore, in the MBT (Motor Bus Transfer) system, ultra-fast switches are also required to ensure the fast switching of dynamic loads (Wan *et al*., 2019). All this can reach high costs that enterprises often cannot sustain.

In this context, to avoid the high cost of fast load switching by MBT, the authors propose in this paper a dynamic load transfer solution for an industrial case, which it is shown to lead to to satisfactory results, using the classic system of switching based on the residual voltage, obtaining a voltage return time of around 750 ms. A case study performed in a real large Romanian industrial site provides an analysis of the quality of electricity supply at a medium voltage (MV) busbar in the local system, at the time of occurrence of a grid supply fault. In such a scenario, due to the appearance of the residual voltage at the MV busbar, the classic ATS system is misled by this voltage, and the start of the automation is delayed leading to the triggering of critical consumers. To mitigate this problem, as a result of the study, under frequency protection (ANSI 81) is proposed to be used in a certain location in the network, to interrupt the resonant circuit that creates the residual voltage, thus solving the local problem, without implementing a system of fast transfer of dynamic loads.

In the rest of the paper, Chapter 2 presents the operating principles of MTB or ATS systems. Section 3 describes the methodology used by the solution presented in the paper, and section 4, the case study, presents the analysis of the electricity supply quality on the MV busbar system of the industrial site and the results of applying the proposed solution. The paper ends with conclusions.

2. The Theoretical Background

The automatic switching of the backup power supply in the case of dynamic load (used as Automatic Transfer Switch, ATS or Motor Bus Transfer, MBT) aims to increase safety in operation, ensuring the continuity of supply, and simplifying the local power supply networks for safety switching while reducing the operating personnel.

Through ATS are used devices that, in the event of disconnection of electric drives from the main power supply for any reason, automatically connect the backup power supply.

ATS back-up command devices are used in stations and substations that have at least two independent supply paths of the busbars, the secondary path being used for a backup power supply in case of outage. The ATS system monitors the voltage of the primary and backup source and, when the failure of the primary supply is detected, the load circuit will be transferred to the other power source (if it is available); this will necessarily be conditioned by the prior disconnection of the primary supply path, and it can be achieved in two ways:

- timed, when the busbar supply is interrupted; the control voltage is chosen so ATS is not triggered when the fault (voltage drop) occurs on a different busbar.
- fast, when one of the main circuit power switches is triggered.

Dynamic load transfer can be done without or with interruption of supply (hot or cold). The first case involves putting the two sources in parallel: the backup source is connected before the disconnection of the primary source. The power supply of the dynamic load is thus never interrupted. The second case does not involve paralleling the two sources: the primary power supply is initially disconnected and then the second is connected. During these maneuvers, the motors remain briefly unsupplied, even if for a short time they change their operating mode, turning into generators with e.m.v. and decreasing speed, depending on the moment of inertia of their own moving masses. Connecting the second source requires monitoring the parameters and controlling the timing of the command launch.

A. Dynamic load transfer without interruption of supply (hot transfer)

Before initializing this dynamic load transfer mode, the difference in amplitude and phase of the two voltages must be checked: that on the motor busbar and that of the secondary supply busbar. The two voltages must be in sync, which may not be true due to the dynamic load regime.

In addition, a preventive check must be made so that if the switch of the new source is connected and that of the old source is also connected, the command to trigger it is done immediately. This allows the transfer by paralleling the two sources but prevents the consequences due to their possible wrong synchronization. Excessive fault currents that may result in these conditions may exceed the limits of the circuit breakers or those supported by the transformers. Thus, if there is a fault such that the old source switch does not trip, the new source switch must close very quickly.

Dynamic load transfer without interruption of power cannot be performed during transient or fault regimes. If the transfer is initiated due to a fault in the primary supply source, the cold transfer method must be used, that means first triggering the switch of the old source, which can be problematic, and then supervising the switching of the new source.

B. Dynamic load transfer with interruption of supply (cold transfer)

There are three methods of controlling the cold transfer that allow the switching of the secondary source when and if conditions particular to each of these methods are met (Beckwith and Mozina, 2015):

- fast;
- in phase;
- based on the residual voltage (Mozina, 2006).

Then, there are two ways to initialize the process of switching:

- sequential;
- simultaneous.

The three control methods are synthetically represented by the three areas highlighted in Fig. 1, where it is shown the evolution of the amplitude and phase difference of the voltage of the motors left unsupplied after the disconnection of the primary source.

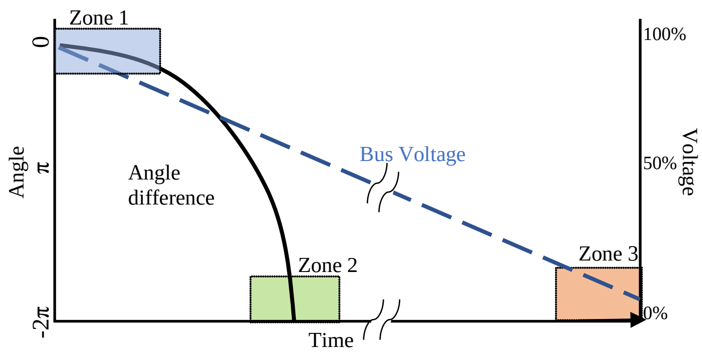

Fig. 1 – Dynamic load transfer - connection areas (Kim et al., 2019).

C. The fast transfer method

According to this method, the switch of the secondary source will be closed if the phase angle between the voltage of the motor busbar and the voltage of the secondary source is in the range of variation indicated by zone 1 from Fig. 1. The method requires synchronizing control with an ultra-fast device. The closing of the switch can also take into account upper and lower limit values of the voltage of the secondary source.

The transfer of the dynamic load to the secondary busbar requires continuous monitoring of the switching conditions of the secondary source, including rapid changes in the parameters of the dynamic mode before switching and even for the closing interval. Thus, any rapid change in the phase angle of the voltage on the motor busbar relative to zone 1, prior to the tripping of the primary source switch will cause immediate action to allow or block the closing of the secondary source switch.

Fig. 2 illustrates this by means of two situations rendered by the pointer of a synchronization meter representing two initial conditions: the first is in zone 1 of Fig. 1 and will allow the secondary source switch to switch on immediately and the second is just outside area 1, on the right. In this second case, as the motor busbar voltage decreases after disconnecting their power, the pointer will rotate counterclockwise as the motors decelerate. Thus, the trigger command in this second case will be timed until the phase angle re-enters zone 1.

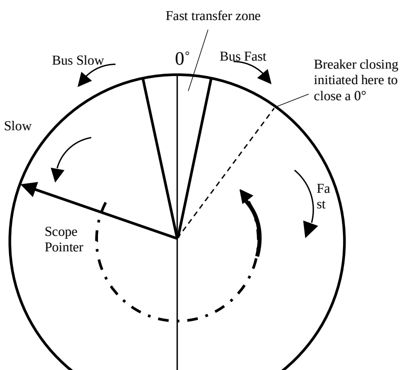

Fig. 2 – Synchronization meter (Hunswadkar *et al*., 2010).

Currently, most dynamic load transfer systems do not have fast synchronization devices. The standard devices that allow fast synchronization need an approximatively 0.1 seconds delay. Due to the time in which they respond to the phase shift of the voltage on the motor busbar, there is the possibility of missing a successful transfer. Even worse, the switch poles can remain closed, allowing transfer at high phase shift angles, thus subjecting the motors to high stresses, even to irreparable damage. Fast transfers are performed safely only if the synchronization check devices are specifically designed to control the dynamic load transfer.

i. In phase transfer method

The closing of the secondary source is made using the phase transfer method based on the estimation of the moment of coincidence of the phases of the two voltages: the first remaining on the motor busbar and the latter of the secondary source to be connected. The closing is also accompanied by the control of the upper and lower limit value of the voltage of the new source as well as by the frequency limit difference (Δf) of the two voltages. The result of the estimated calculation of the phase coincidence moment is compared with the closing moment established for the switch of the secondary source according to the "in phase" transfer method. To accurately estimate the phase coincidence moment, the device using this method must quickly detect the decrease in voltage on the motor busbar, its phase angle, the frequency derivative, and the difference between the frequency on the motor busbar and that of the secondary source, in order to compensate for the closing time of the switch. The maximum time of response of the device used is recommended to be half a period.

The purpose of this method is to continuously monitor the fulfillment, on the poles of the switch of the secondary source, which is still disconnected, of the transfer conditions, including the notification of the rapid change of these conditions, due to the dynamic phenomena before and during the transfer. Thus, if all the conditions mentioned above are met, the device is ready to allow the closing of the switch of the secondary source and each phase of it is switched on at the first zero crossing.

In Fig. 2, all the above are highlighted by the pointer of the meter. If the pointer moves at the bottom of the screen, the transfer conditions are outside any acceptable area for closing. In this case, as the frequency of the voltage on the motor busbar decreases, after the primary source tripping is triggered, the pointer will always rotate counterclockwise as the motors decelerate. As a result, the switch closing permission will be delayed until the phase angle approaches the switching moment at 0^0, the area marked by the dotted line in Fig. 2. This corresponds to area 2 of Fig. 1 in which the closing of the switch is initiated to be executed at zero phase shift between the two voltages.

ii. The residual voltage transfer method

According to this method, the switch of the secondary source will close if the voltage on the motor busbar falls below the lowest value of the allowed voltage interval. This corresponds to area 3 of Fig. 1. Because no phase angle or frequency difference is monitored, the method must prevent the secondary source switch from closing until the voltage across the motor busbar drops below a predetermined value (usually below 0.25 pu) to ensure a limit value of 1.33 pu V/Hz (Yalla, 2009). On the other hand, the transfer of the dynamic load at medium voltage must be completed before the voltage drop is so wide that the minimum voltage protection relays of the motors command their disconnection and, implicitly, affect the service provided. As a result, the settings for the minimum residual voltage must be correlated with the minimum voltage protection of the motors to prevent them from being disconnected. In the case of low voltage motors that have relays in the scheme, they are either a.c. with desensitization circuits at voltage drop, either c.c., so that on a certain time-voltage value, they will not disconnect the motors. The accuracy of the value setting and the response time of the minimum voltage relay for the motor transfer must lead to a correct operation at a frequency below the nominal one and at a substantial change in the voltage drop speed.

During the time required for the voltage to drop sufficiently, care must be taken that the frequency has not decreased beyond the point at which the motors stop. In this possible situation, and also when the secondary source does not have the power required to self-start (simultaneous re-acceleration of all engines that have not yet reached zero speed), the load reduction must be considered. Thus, to use this method, an analysis of the technological process provided by the drives with the motors involved is required. The effect of the resulting dynamic torque on the self-starting of the motors during and after the transfer must be limited to that corresponding to starting and, if necessary, the motors must be restarted sequentially (in turn) to prevent excessive self-starting voltage drop. In any case, an analysis of the effects on the service provided by those drives is necessary, as a result of a possible longer duration of their supply interruption.

3. Methodology

The problem of residual voltage in the industrial environment is common and creates problems leading to delays in the operation of classical ATS systems already existing in installations. A real problem that arose as a result of the presence of the residual voltage in an industrial plant in Romania resulted in damages (equipment and production failures) in the amount of millions of euros.

The operation of the ATS system is misled by the prolonged duration of the residual voltage at the busbar. One of the possible solutions would be to eliminate this residual voltage, interrupting the L-C resonant circuit created when the local system is isolated from the grid after the fault. In Fig. 3 is represented the simplified system of the large industrial site studied in the paper, in which the main elements of this circuit are represented. The high voltage cable can be considered a large capacity (C), the 110 kV/6 kV transformer is represented by an inductance (L), and through this equipment, the asynchronous (AM) MV motors related to some exhausters are powered.

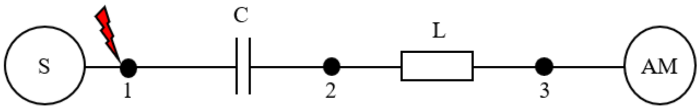

Fig. 3 –The one-line simplified *L*-*C* diagram of the industrial system.

When the system (S) has a problem and is disconnected from the main supply grid, the remaining voltage appears in the islanded network, described in Fig. 4, where the evolution of the residual voltage can be observed (red line), which has a decreasing slope for 5 seconds. From the moment $T = 0$, when the supply is tripped, the voltage on the 6 kV busbar gradually decreases, and reaches 4.2 kV (70% U_n) at moment $T = 2\ s$, when the undervoltage protection of the asynchronous machines acts. After another two seconds, the machines are also disconnected ($T = 4\ s$) and the ATS system starts operating at time $T = 5$, the voltage on the busbar returning to time $T = 5.7\ s$.

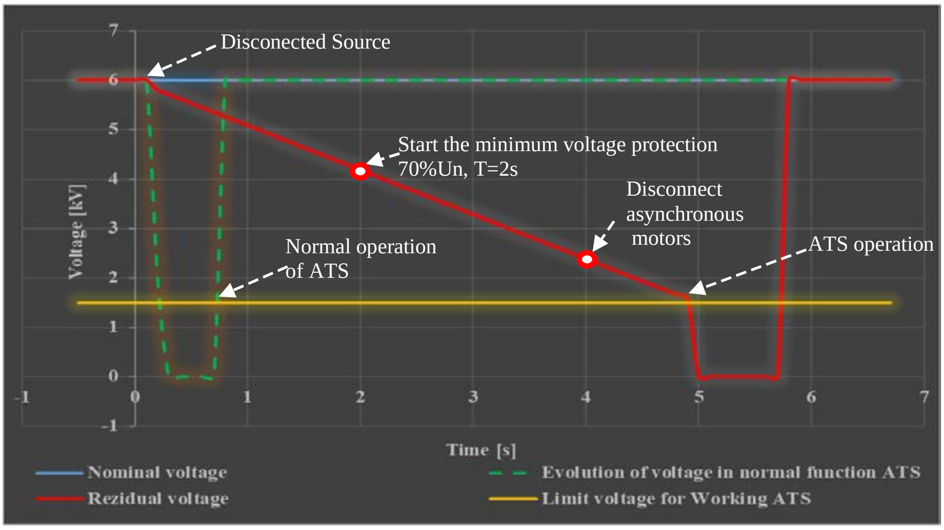

Fig. 4 – The description of ATS system operation in case of residual voltage.

In this paper, the authors propose the elimination of the C-L resonant circuit by triggering the switch that is installed in point 2 (Fig. 3). This can be done using underfrequency protection, because from several analyses and tests on the studied network, an instant decrease in frequency was observed at the time of islanding.

By continuously following the voltage deviation Δf, described in Eq. (1), at measurement point 1 of Fig. 3, the switch in point 2 can be triggered, eliminating the resonance and the residual voltage.

$$\Delta f = f_r - f \tag{1}$$

In Eq. (1), f_r represents the reference frequency of 50 Hz and f represents the network frequency at the islanding time.

4. Case Study

The case study is performed on a real large industrial electrical system from Romania, which is powered by 2 distinct transmission substations from the national grid, one of 220/110 kV and the second of 400/110 kV.

The local supply system used in the analysis, represented in Fig. 5, starts from source B, which is a 400/110 kV transformer station, and continues with a 110 kV cable with a length of 7 km, a 40 MVA 110/6 kV transformer, a MV cable of 3x185 mm^2, $L = 1.2$ *km*, and 2 asynchronous motors *of* 160 kW and 200 kW respectively.

In the case study, it is analyzed the influence of the residual voltage, during the back-up supply automatic switching, in the case of industrial electrical networks.

The measurements are performed by simulating the tripping of the switch afferent to source B in Fig. 5. Thus, the entire downstream system (TR2 corresponding to the 6 kV busbar II) is left without voltage and the back-up system (in this case related to the LC coupling in Fig. 5) should switch consumers to busbar I.

The back-up system is parameterized to start the automation cycle when the voltage at the 6 kV busbar reaches a level of 40% of Un. Thus, a fault, in an ideal network, switches load from one source to another in a time of 800 ms. But in the studied case, the network is made mainly of underground power lines that are characterized by high capacities, power transformers characterized by high inductances, and dynamic loads powered by these elements. All these, when disconnecting the switch afferent to the 110 kV source B, become elements with nonlinear characteristics, generating a residual voltage that has a damped evolution as in Fig. 6.

The evolution of the voltage in Fig. 6 was divided into 3 intervals. The interval t_1, begins immediately after the tripping of the switch, in which an overvoltage of 136% U_n appears, period in which the current (Fig. 7) increases from a value of 30 A to approximately 180 A. In interval t_2, the voltage decreases from its nominal value to the value at which the back-up supply automation comes into operation.

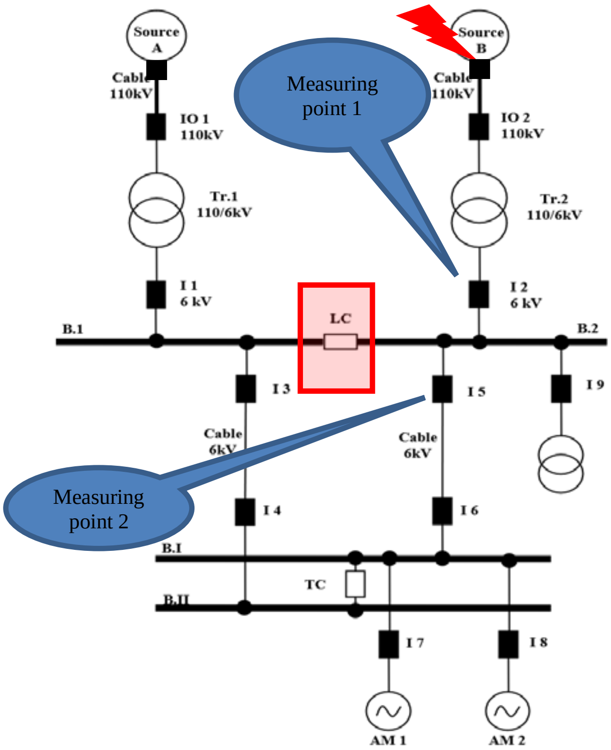

Fig. 5 – The electrical diagram of the industrial supply system.

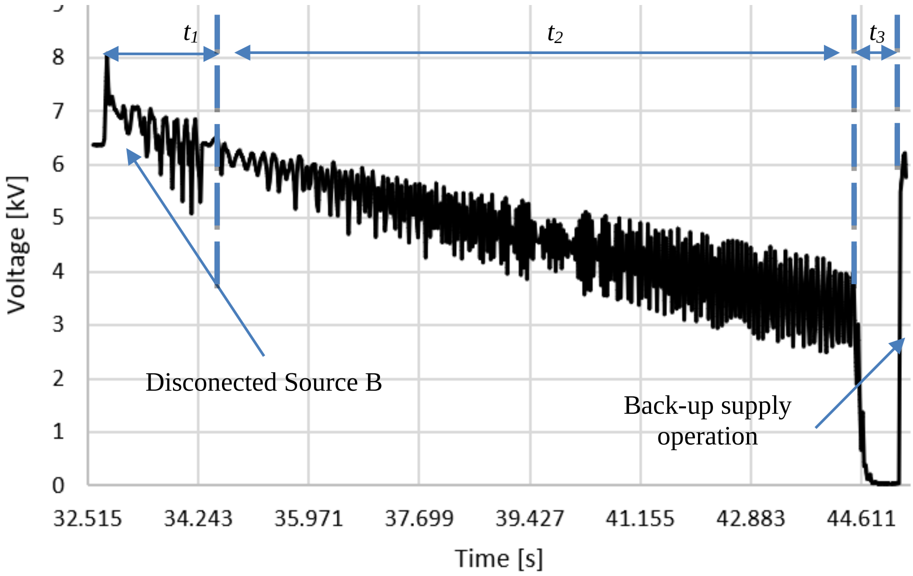

Fig. 6 – The evolution of the residual voltage at the moment of triggering source B.

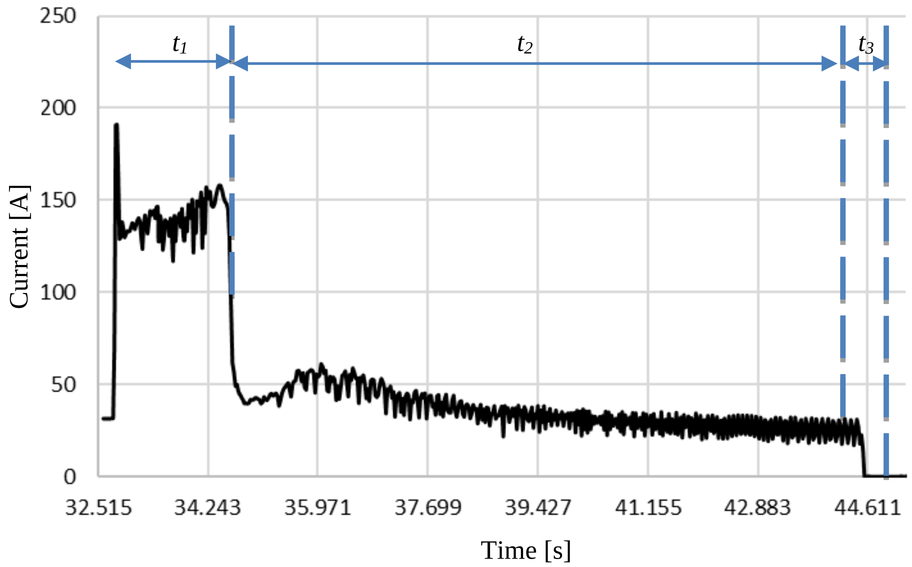

Fig. 7 – The evolution of the current at the moment of starting the source B.

In the time interval t_3, the voltage reaches zero due to the tripping of the 6 kV switch I2, from the secondary of the transformer Tr.2, followed by a return of the voltage to the nominal value due to the tripping of the circuit breaker LC.

Throughout the time interval from the beginning of t_1 to the end of t_2, by recording the spectrum of voltage harmonics, it can be noticed that they exceed the values recommended by the IEC 61000-3-6 standard (Fig. 8). This can be explained by the fact that, at the time of disconnection of the source B switch, the downstream network area remained islanded. Without having a main source of supply, each network element operated according to its nonlinear characteristics, generating harmonics of different frequencies that moved through the circuit.

According to the ITI-CBEMA characteristic, this event is characterized by 2 main deviations: an overvoltage of 136% U_n (see point 1 of Fig. 9) and a short interruption (see point 2 of Fig. 9), and several variations short-term voltage within the permissible limits, characteristic of the period t_2 (Fig. 6).

After the implementation of the solution proposed by the authors, in Fig. 10 it is noticed that the total return time of the voltage on the B2 busbar, is about 750 ms. The remaining voltage has a much faster downward slope, t_1, which leads to the proper functioning of the ATS system.

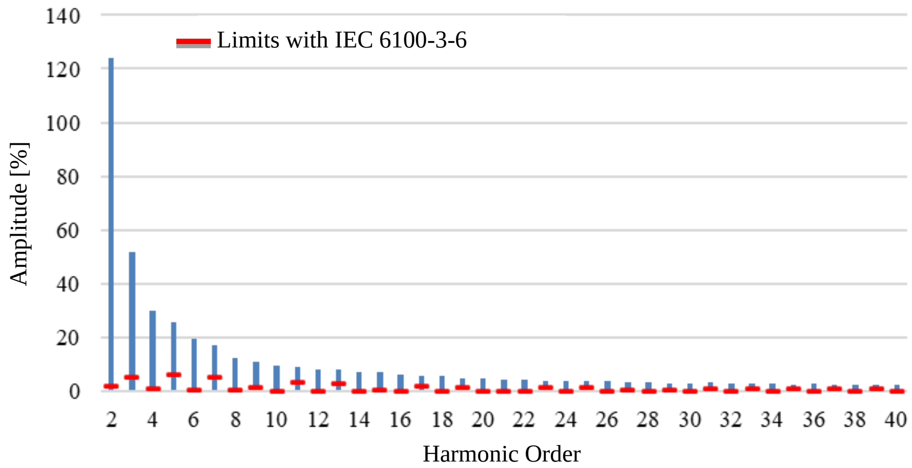

Fig. 8 – The Spectrum of voltage harmonics after triggering source B.

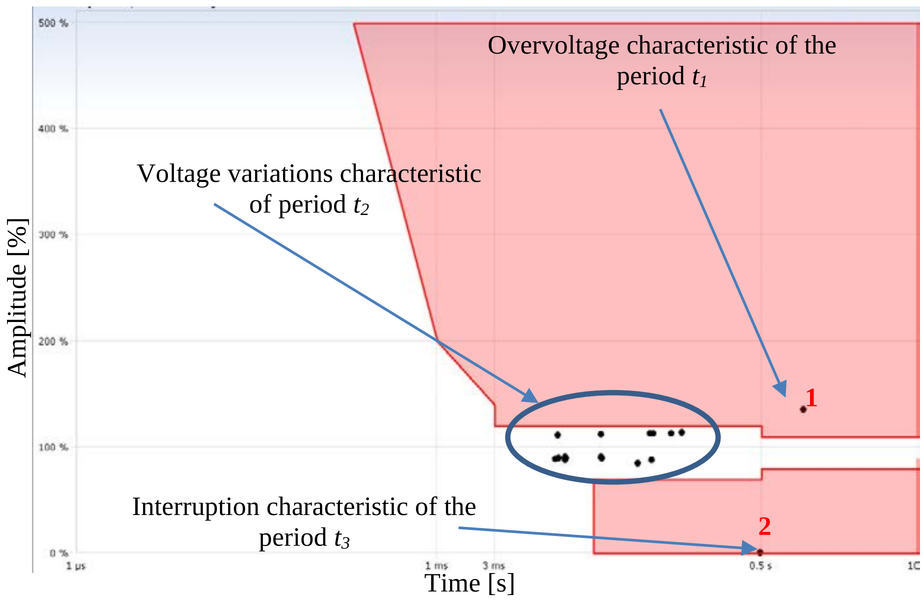

Fig. 9 – The representation of voltage disturbances occurred in the operating cycle of the ATS, on the ITI-CBEMA curve.

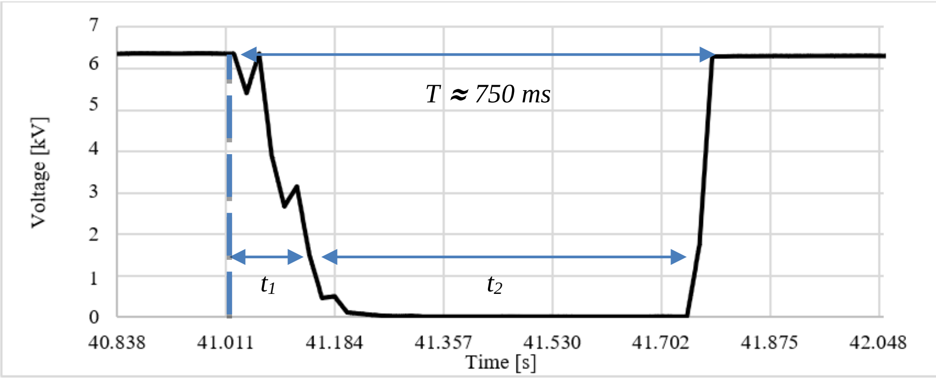

Fig. 10 – The evolution of the voltage at the moment of triggering the source B, after implementing solution.

Fig. 11 presents the evolution of the current, in the 2nd measuring point, during the operation of the ATS, after the implementation of the solution proposed in the paper.

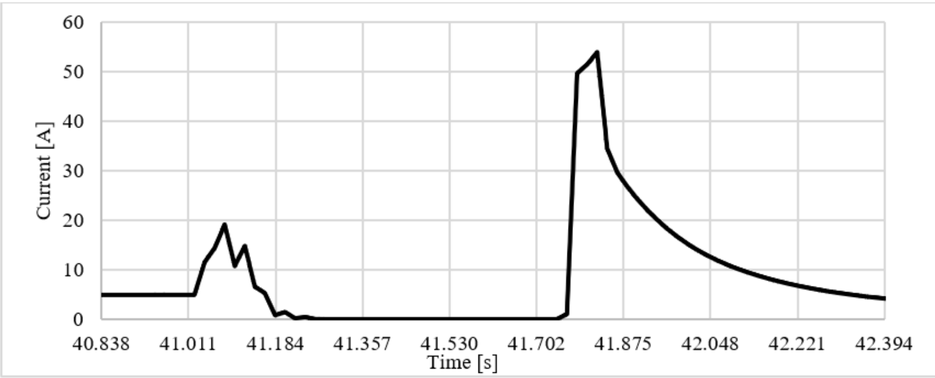

Fig. 11 – The evolution of the current at the moment of triggering the source B, after implementing the proposed solution, in measuring point 2.

5. Conclusions

The triggering of a source in the industrial supply system analyzed in the paper leads to the appearance of a residual voltage which is associated with a resonance phenomenon in the period t_1 (Fig. 6 and Fig. 7).

The residual voltage that appears after the islanding from the main grid leads to the delay of starting the ATS set to act when the voltage reaches 25% U_n, in order to protect asynchronous machines, during dynamic load transfer. In the specific case of the installation analyzed in the paper, this voltage level is reached after 11 seconds from the islanding.

The implementation of the ANSI 81 underfrequency protection, in order to separate the power transformer from the rest of the circuit, led to the decrease of the slope of the residual voltage and to the proper functioning of the ATS system. The main advantage of the solution proposed by the authors is that of significant cost reduction, compared with implementing MBT.

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INFLUENȚA TENSIUNII TRANZITORII REZIDUALE ASUPRA TRANSFERULUI SARCINII DINAMICE

(Rezumat)

Funcționarea cu succes a sistemelor de anclanșarea automată a rezervei în cazul transferului sarcinilor dinamice în cadrul instalațiilor electrice industriale depinde în principal de eliminarea tensiunii reziduale ce apare în momentele separării de sistemul electroenergetic. Scăderea duratei prezenței tensiunii reziduale pe barele de medie tensiune depinde foarte mult de sarcina locală și de configurația rețelei. O durată crescută a prezenței tensiunii reziduale conduce la declanșarea consumatorilor critici. În această lucrare este prezentată o metodă eficientă din punct de vedere al costurilor, necesară transferului sarcinilor dinamice, metodă ce poate conduce la evitarea implementării sistemelor costisitoare de Fast Transfer. Viabilitatea metodei este testată pe o instalație electrică reală aflată în sistemul industrial din România. Studiul de caz arată ca această metodă conduce la un timp de revenire a tensiunii pe sistemele de bare în aproximativ 750 ms.