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SWITCH-OFF TRANSIENTS AFFECTING THE DYNAMIC LOAD TRANSFER

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The paper deals with the relative well-known problem related to electric drives transfer or motor bus transfer. Compared to the different situations the literature presents the authors focus on the power network transients affecting the proper transfer operation. The dynamic behavior of the network can hide the transfer opportunity and the good cooperation of different electronic devices involved. The influence of different locations of the point where the initial power source is disconnected is also presented.

The case study is based on a real 400/110/6 kV industrial network and situations.

Keywords: transients, dynamic load transfer, industrial power network

1. Introduction

Some industrial processes belong to zero class of safety which means quite zero electric interruption time. Contrarily, the interruption can affect life and/or equipment important damages. The electric dynamic loads (drives, electronic regulators, etc.) involved in these processes may require to be transferred from an old source to a new one very fast and without negative consequences for the entire power systems: sources, local generators, network, or inertial loads like electric drives.

The specific literature of last two decades includes a lot of studies about motor bus transfer (MBT) or, here defined, as dynamic load transfer (DLT): scientific articles, synthesis publications, and modern smart electronic devices for DLT. A report of J9 Working Group to the Rotating Machinery Protection Subcommittee of the IEEE – Power System Relay Committee was published in 2012 [1]. The scope was to cover the main aspects related to MBT applications like system topologies, classifications, dynamic conditions, methods and techniques.

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Generally, there are two distinct situations where the DLT is important: the auxiliary load of power plants [1-3] and industrial facilities, fig. 1, the present article is related to.

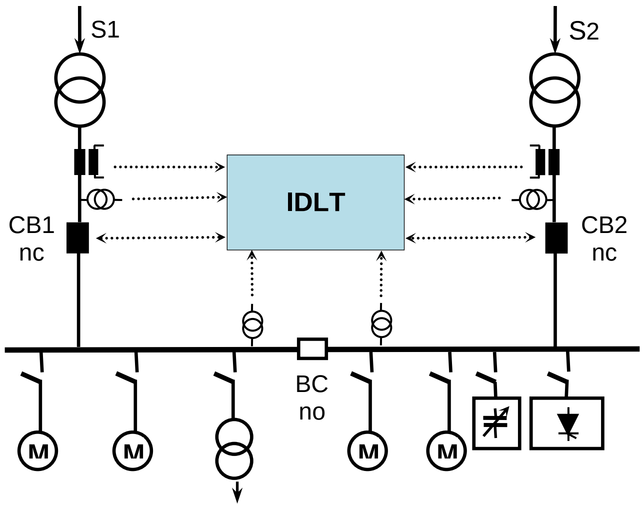


Fig. 1 Typical and simplified switchgear arrangement with one busbar sectionalizer and the main information channels between intelligent dynamic load transfer (IDLT) device and primary circuits.

One source acts like a backup supply for the second one through an automatic operation of the normally open bus coupler (BC) controlling circuit-breakers CB1 and CB1 also. Even very simple in essence, the load transfer can be complicated due to:

- very short (or zero) time interval for load transfer with a view to preserve the continuity of the process;
- the electric drives (dynamic loads) supplied initially by a source experiencing a failure are transformed in an equivalent generator with a remaining transient voltage (RTV) decreasing in amplitude and frequency;
- imprecise synchronization, in real industrial conditions, of the new source with the source represented by motors which potentially can lead to extreme severe transient torques on drives as depicted in fig. 2.

As mentioned above, the literature presents many theoretical, technical and practical details of DLT. Paper [4] describes and compares different methods while the main characteristics for the involved motors are considered. The specific authors' approach is based on auto-initiation criterion for bus transfer using a combination of bus undervoltage, underfrequency, and df/dt characteristics. Two methods, based on electro-mechanical transfer switch (EMTS) and on static transfer switch (STS) are presented in [6] where the authors investigated the effect of reactive power compensator in process of DLT as well as the performance of induction motor and spindown characteristics during the transfer process. The study was conducted by simulations using PSCAD/EMTDC package.

Fig. 2 The damaged mechanical coupling of a 6 kV, 200 kW induction motor driving an exhauster due to unsuccessful DLT.

An author proposes in [7] a digital signal processing algorithm that can measure the magnitude and phase angle of the decaying bus voltage accurately while measuring the auxiliary source voltage magnitude and phase angle at rated frequency. This paper details also an algorithm to predict the phase coincidence between the motor bus voltage and the backup source voltage. The algorithm uses the frequency dynamics (Δf, $\delta\Delta f$) and breaker closing time to predict the phase coincidence. The fast bus transfer (maximum 30^0 to 45^0 as phase angle difference, 20% voltage drops from rated value, less 30 ms as decision time and max. 100 ms for DLT), in phase transfer (100 ms for exact angle calculation, 0^0 as phase difference at the paralleling moment with 80 ms as breaker closing time) and residual voltage transfer (with a load shedding scheme) methods are possible to apply using IEC 61850 communication protocol as described in [8]. A compensated discrete – Fourier – transform – based algorithm in detailed in [9] enabling a fast and reliable DLT. The algorithm was validated using a digital simulation in PSCAD/EMTDC and Matlab packages. The practitioners have a critical opinion on the classic DLT metrics and propose new criteria based on recorded transfer inrush current and power when transfer is completed [10]. A recently published paper [11] is closed to this article idea related to power network modeling with a view to study its influence on DLT. The authors present techniques to model the asynchronous motor during the transfer as well the upstream network components: sources, power lines, transformers. A detailed motor model allows for a successful in-phase transfer based on calculating the angular difference and slip frequency between the two voltage sources.

The different sophisticated devices for DLT are commercially available. Details are offered by manufacturing companies [12-15].

2. DLT methods

Table 2 shows the main methods for DLT.

Table 1

Main methods used for DLT

Method	Details	Time interval for DLT* [s] / [cycles]	Observations
Closed DLT	The two sources are synchronized, the new one is connected before the old is tripped	0	- So called hot parallel transfer; - Check fault withstands rating of primary circuit components during the parallel operating time; - Used only for planned DLT and not during emergency situations.
Open DLT	Fast	< 0.2 / < 10	- Named cold parallel transfer - There are two modes for initial tripping of new source: a) *Sequential:* the new source is connected immediately after old one tripping confirmation followed by fast, phase-in or residual voltage methods. b) *Simultaneous*: the tripping of the new source is supervised without waiting the opening of the old source excepting the situation when the old source breaker fails to open.
	In-phase	0.2 ÷12 / 10 ÷ 600	
	Residual voltage	> 12 / > 600	
	Fixed time transfer		
* According to IEEE/ANSI Standard C50.41-2012 the resultant V/Hz at the instant of a transfer should be less than1.33 pu.			

Fig. 3 clearly shows the three techniques for DLT: fast, in-phase and residual voltage with details related to controlled variables: time, voltage difference and phase angle of the two involved sources.

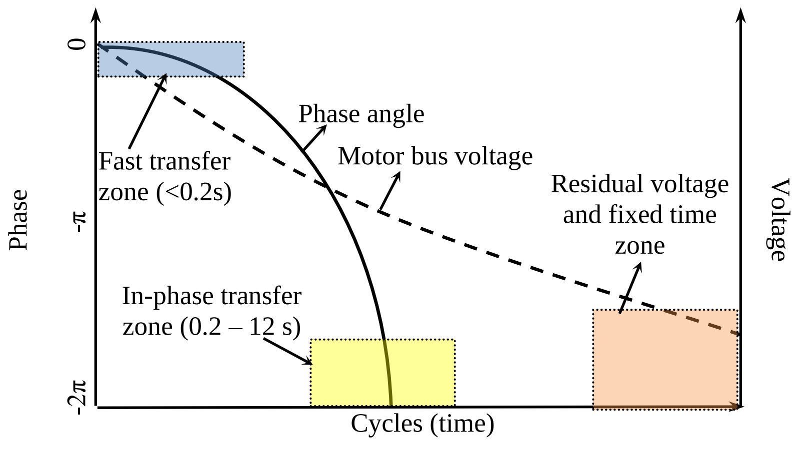


Fig. 3 Different zones for open DLT method.

3. The theoretical background

Switching operations in power systems cause voltage and current transient waves propagating at different voltage levels due to capacitive and/or inductive couplings.

The background theory usually covers the “classic” and simple cases starting with switching C, L, R circuits or combinations of them [16-17], continuing with general switching theory in power systems [18-20] and with specific switching real case studies [21-25].

The mains switching off transients studies are related to:

- non loaded power lines;
- symmetrical or non-symmetrical short-circuits;
- small inductive current;
- capacitive current.

These are main, but not only, typical situations when specific phenomena affect the power system components due to overvoltage or overcurrent waves.

Fig. 4 shows the transient recovery voltage (TRV) across the circuit breaker poles when switching off simple circuits [26].

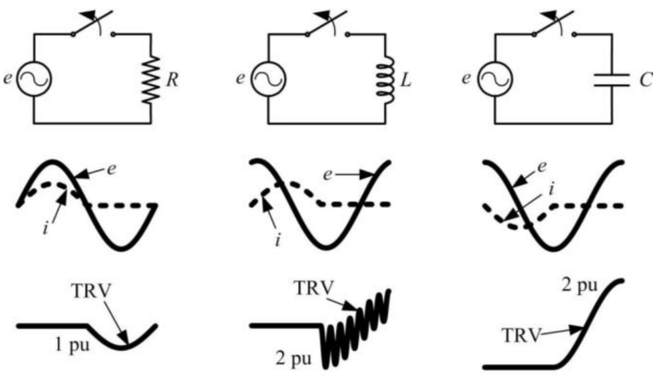


Fig. 4 Switching-off TRV for different elementary circuits; *e* is the voltage at source terminals.

Switching-off small inductive currents (unloaded transformers, asynchronous motors or compensation inductive coils) is another typical case when the generated transients can be important. We consider the single equivalent circuit diagram in fig. 5a for a solid grounded transformer, zero resistance and simultaneous opening time of the circuit-breaker poles. Fig. 5a illustrates significance of the cutting current.

For usual cases, $L_2 >> L_1$. The oscillations in the source circuit (1) are given by

$$\omega_1 = 1/\sqrt{L_1 \cdot C_1} \tag{1}$$

For the disconnected circuit (2), the oscillations frequency is less than ω_1 but still greater than the rated 50 Hz:

$$\omega_2 = 1/\sqrt{L_2 \cdot C_2} \tag{2}$$

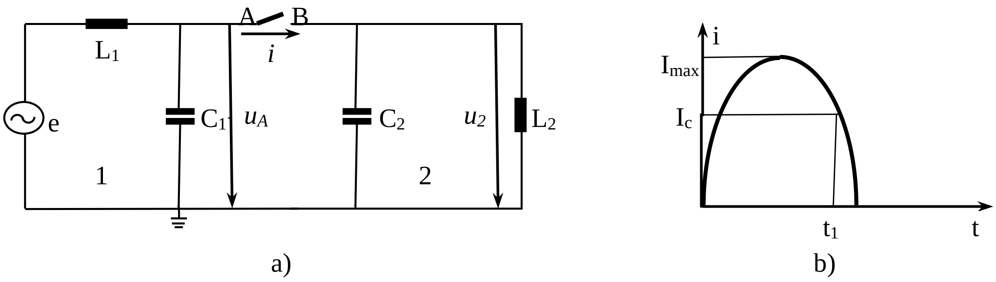


Fig. 5 The equivalent single diagram for an unloaded transformer switching-off analysis (a) and the cutting current I_c (b); *e* is the voltage source.

The amplitude of the voltage variations in the second circuit can be very high. To evaluate it we can use the energy balance method for the circuit 2 and considering the non-damped oscillations. The accumulated energy at the cutting current moment (I_c), when $u_2 = U_o$, is given by:

$$E = \frac{1}{2} L_2 I_c^2 + \frac{1}{2} C_2 U_o^2 \tag{3}$$

The same energy but fully accumulated in C_2, when $u_2 = U_{2max}$, is

$$E = \frac{1}{2} C_2 U_{2\max}^2 \tag{4}$$

Using (3) and (4) the maximum voltage in the second circuit is:

$$U_{2\max} = \sqrt{U_0^2 + \frac{L_2}{C_2} I_c^2} \tag{5}$$

The voltage between A and B is

$$u_{BA} = u_2 - u_A \tag{6}$$

and is represented by the dotted area in fig. 6a.

Fig. 6 shows the voltage across the circuit-breaker after arc interruption without re-ignition (fig. 6a) and with repeated re-ignitions (fig. 6b).

The situation depicted in fig. 6b can occur when the dielectric strength of the gap between the breaker poles is not sufficient to withstand the TRV.

The conclusion is the transients when switching off are complex depending on the detailed characteristics of sources, loads (especially dynamic loads), lines, transformers, capacitors, regulating and protection devices, harmonic and/or inter-harmonic distortions and resonance, grounding solutions are to be considered for a detailed transient analysis. This could be untractable for real power networks and, usually, not necessary so, some simplifications are used by engineers.

Computer simulations compared to real measurements is the practical and relative accurate solution for DLT studies given an industrial network.

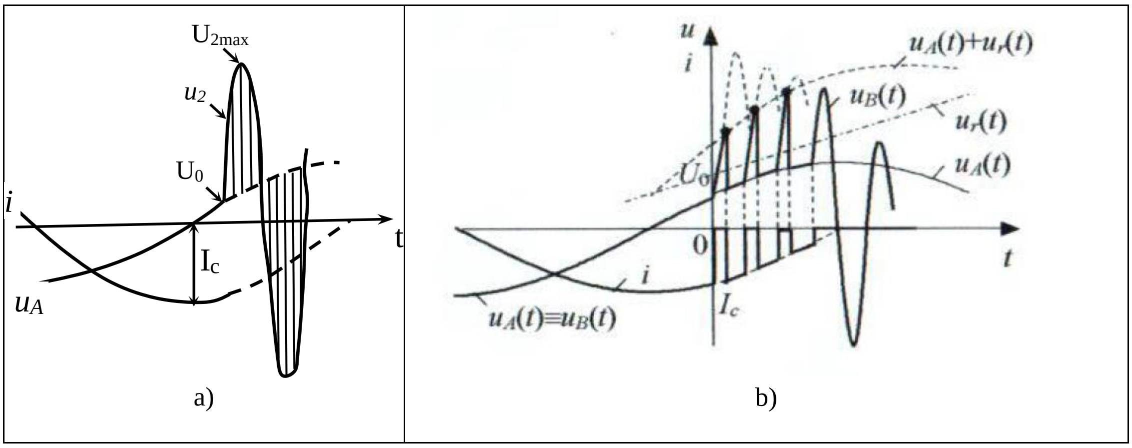


Fig. 6 Switching off voltage across the circuit-breaker without re-ignition (a) and with repeated re-ignitions (b).

4. DLT computer simulation for a real industrial network

The module Electromagnetic Transient Analysis Program - EMTAP of the Paladin Software package [27] was the instrument for DLT analysis. The power industrial power subsystem is presented in fig. 7 where the considered electric drives are connected to BUS N2 (blue area). DLT1, DLT2 and DLT3 are automatically controlled circuit-breakers in the case of 400 kV supply failure. The dashed red line shows the circuit where a detailed analysis of switching off transients was performed at different voltage levels.

All the network components were modeled as three phase elements using their longitudinal and transversal parameters. The electric drives serve a very sensitive and critical process requiring a practical zero interruption duration.

First of all, the network was frequency scanned to detect possible harmonic resonance. Fig. 8 shows harmonic resonance for 4^{th} and 17^{th} harmonic voltage with corresponding well-known consequences.

The voltage transients on BUS when de-energizing the red dashed circuit with CB1 are shown in fig. 9. The generators G1 and G2 are out of service.

It can be clearly seen the high frequency transients during first 20 ms are important and can affect the first moments when decision on the DLT method is to be taken. Fig. 10 shows the results of simulation on BUS N2 for the same situation, switching off CB1. The same transient voltage on BUS N2, with G1 and G2 connected is depicted in fig. 11.

In case of disconnecting the main supply by switching off CB5, the voltage on motor bus is like in fig. 12.

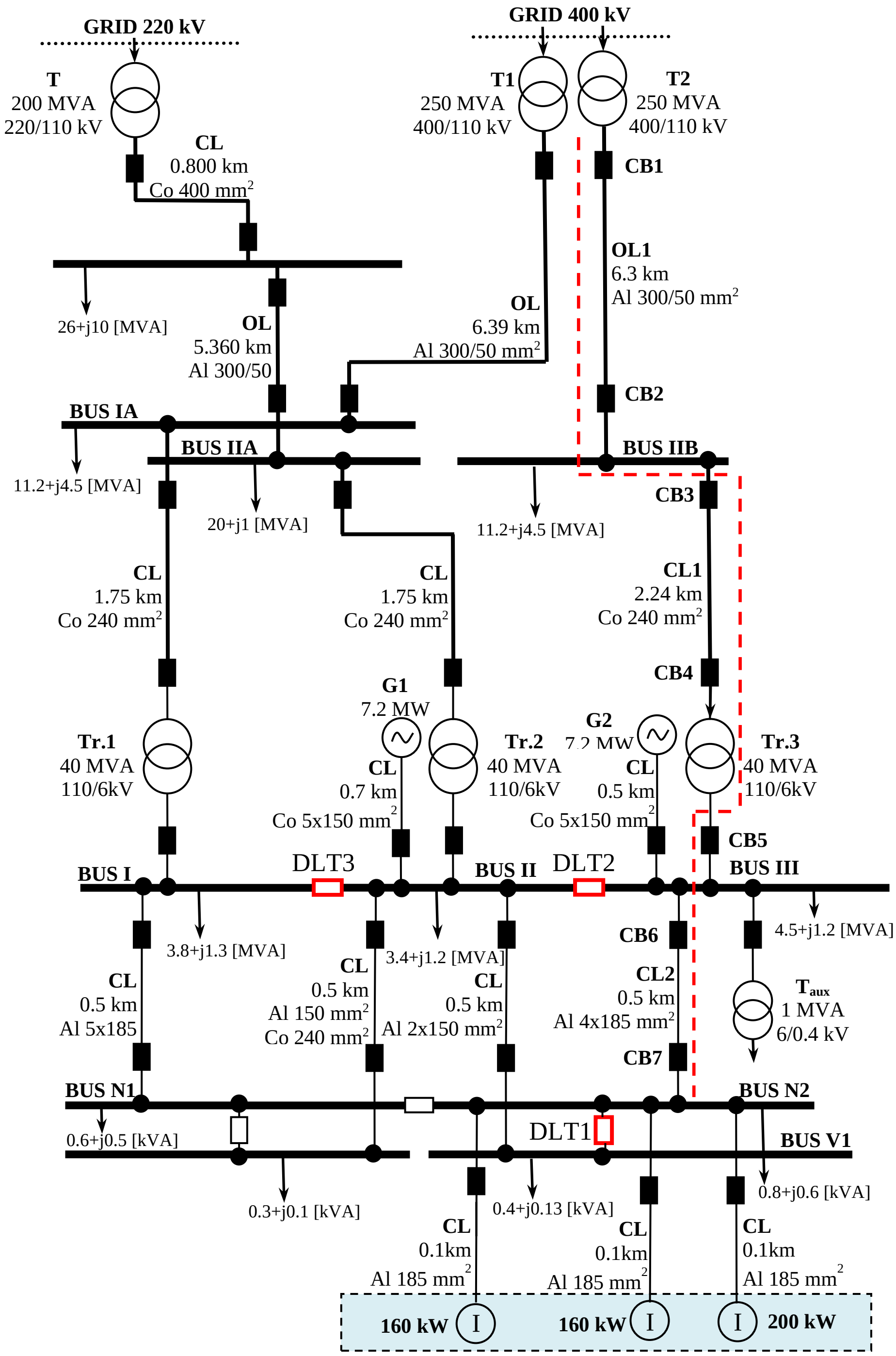
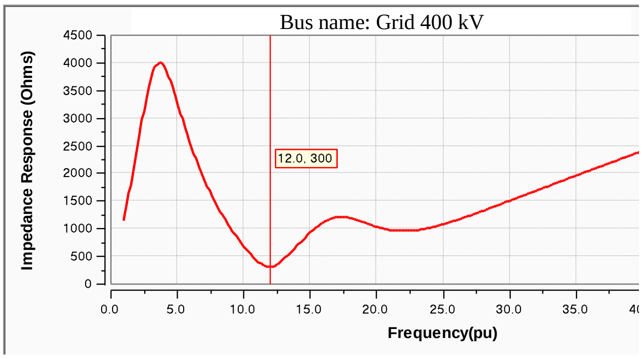
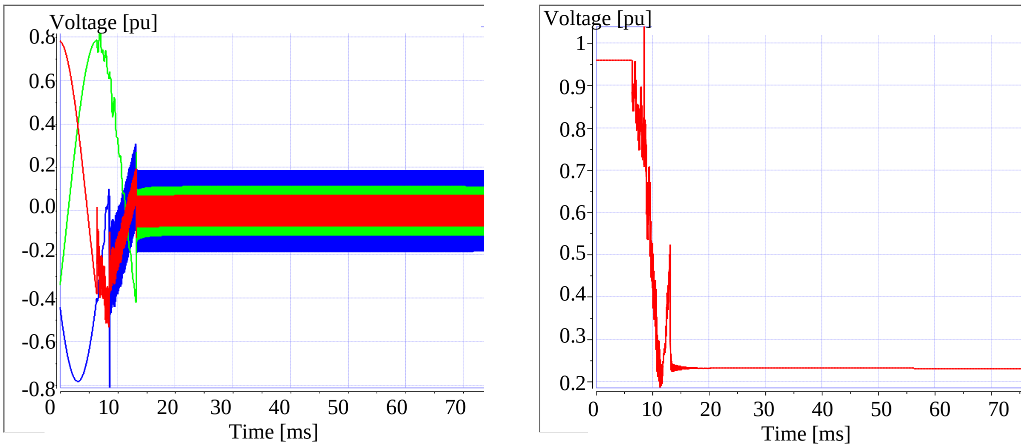


Fig 7. The industrial power subsystem modeled for 400 kV switching-off transients: CL – cable lines, OL – overhead lines, I – induction motors.



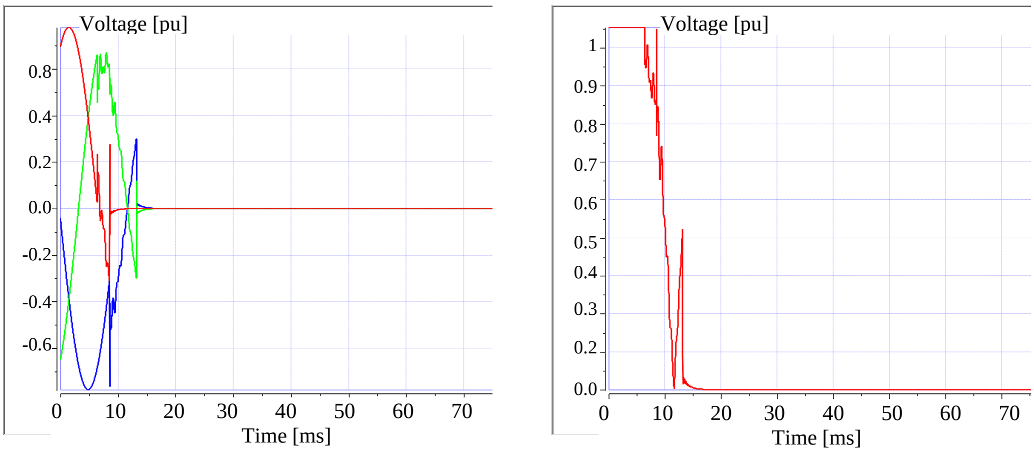
a)

Fig. 8 Equivalent network impedance for different frequencies.



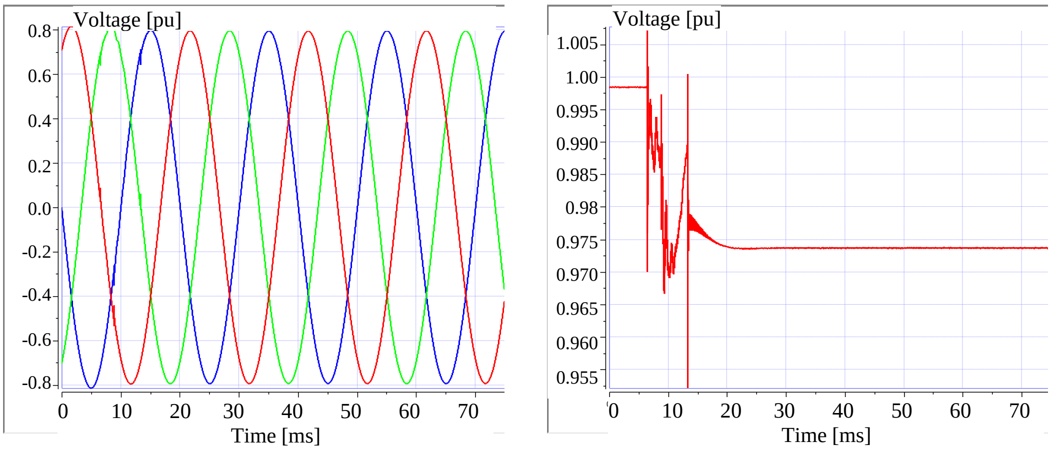
a) b)

Fig. 9 Transient voltage on BUS IIB after switching off CB1 (see fig. 7): line to ground instantaneous (a) and line to line RMS (b).



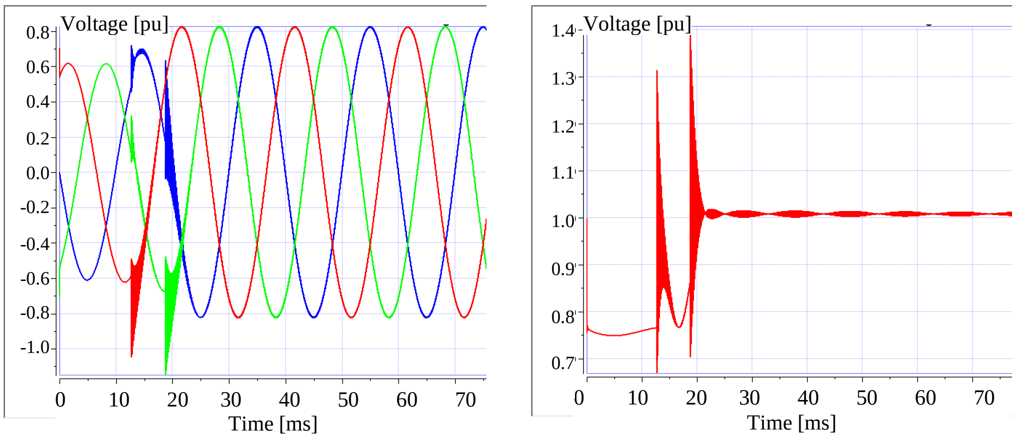
a) b)

Fig. 10 Transient voltage on BUS N2 after switching off CB1 (see fig. 7): line to ground instantaneous (a) and line to line RMS (b).



a) b)

Fig. 11 Transient voltage on BUS N2 after switching off CB1 with G1 and G2 connected: line to ground instantaneous (a) and line to line RMS (b).



a) b)

Fig. 12 Transient voltage on BUS N2 after switching off CB5, with G1 and G2 connected: line to ground instantaneous (a) and line to line RMS (b).

5. Conclusions

The fast transfer method for DLT is a suitable one in the case of critical loads when the switching of backup supply must be zero.

The authors analyzed the DLT in the case of a real industrial power network supplying extremely sensitive 6 kV asynchronous loads of hundreds of kW.

The dynamic load transfer, especially the fast transfer method and/or high-speed circuit-breakers utilization, must consider the initial transients, vital for IDLT decision to switch on the back-up supply. These transients are important mainly during the first 10-15 ms which are vital for fast transfer method which needs no more 20 ms for a successful operation. For example, fig 12b shows a 40% line to line voltage. Figures 9-12 indicate also very fast transients which can lead to the malfunction of sensitive electronic devices involved in DLT. The transients can hide the initial moments of the main supply failure.

Obviously, one or more local sources, like G1 and G2, designed to supply the critical loads from power and voltage regulation speed can be a solution. Unfortunately, the real generators in the network are too slow to react during the first 10-20 ms with a view to keep the voltage between admissible values.

For a given network structure, the voltage and current transients are depending on the location of main source interruption and can hide, or delay the lack of supply. From where the current and voltage are collected as inputs for IDLT are also of a great importance.

Future work has to be dedicated to the practical solutions for a successful fast DLT and for a logical correlation of the operation of DLT1, DLT2 and DLT3 in the network.

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