EFFECTS OF SYMMETRICAL AND UNSYMMETRICAL SAGS ON INDUCTION MOTORS

N. GOLOVANOV, G. C. LĂZĂROIU*

Voltage sags are the main cause for the malfunction of modern devices and industrial processes. The main parameters that can qualify the voltage perturbation are presented and discussed both on the theoretical point of view and with example of application. The test network chosen shows the effectiveness of the index that represents the quality of the motor supply voltage when network faults occur.

Golurile de tensiune reprezintă cauza principală a deranjamentelor în funcţionarea proceselor industriale şi instalaţiilor electrice moderne. În lucrare au fost prezentaţi şi analizaţi, din punct de vedere teoretic şi practic, pe baza unor exemple de aplicaţii, principalii parametri care definesc perturbaţia de tensiune. Reţeaua test aleasă arată eficienţa indicatorului de calitate a tensiunii de alimentare a motorului electric atunci când apar incidente în reţea.

Keyword: faults, induction motors, power quality

Introduction

The deviation of supplying voltage from the rated one can cause important damages to end user equipments. The level of these damages depends on the amplitude of the residual voltage and on the duration of the perturbation [1]. The growth of the number of devices sensitive to voltage variations and the possibility of misoperation of the electronic devices present in the control systems impose studies on various types of loads, for determining the perturbation amplitude – duration curves. For each equipment a limit curve amplitude – duration of the perturbation can be established, like CBEMA and ITIC (established for computers), but there are not curves that can be used for any type of equipment [2].

The main cause of voltage sags are the faults in the transmission and distribution networks, the duration of voltage sag depending on the action speed of the protection devices. Voltage sags can be produced also by large induction motors that absorb a starting current of several times the nominal one. The duration of the voltage sag in this case is bigger, but the voltage drop is smaller [3].

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A voltage sag due to a fault has a rectangular form, the voltage is constant during the fault and then increases suddenly to the prefault value after the protection reclosure. This does not happen when the load includes induction motors, because the rotor speed decreases during the fault and after clearing the fault the motor reaccelerates, leading to a slowly recovery of the voltage up to the prefault value.

In this paper the behavior of the three phase induction motor during balanced and unbalanced faults in the distribution network is analyzed. For every studied case the aim is to establish a critical length where any fault generating voltage sags creates conditions for the motor stop or for its disconnection. In addition, the paper estimates the induction motor supply voltage during the fault transient and determines the voltage that characterizes the sag during the whole duration of the fault. The recovery time of the motor after the fault clearing is also evaluated and discussed in the paper.

1. Voltage Variations and Critical Length

1.1. Balanced faults

Referring to the simplified circuit of Fig. 1, where the voltage drop between the load and the point of common coupling (PCC) can be assumed negligible [4], the magnitude of voltage at PCC, due to a three phase fault at the length L of a feeder supplied by PCC is

$$V = \frac{Z_F}{Z_S + Z_F} \cdot E \tag{1}$$

Z_F is the feeder impedance between the fault appearance and the PCC ($Z_F = z_F * L$), Z_S is the source impedance and E = 1 p.u. is the prefault voltage.

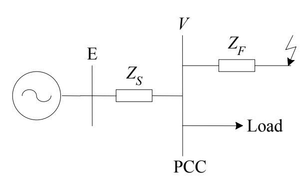

Fig. 1. Voltage divider model

The critical length for a voltage sag with a magnitude V according to [4] is:

$$L_{crit} = \frac{Z_S}{z_F} \cdot \frac{V}{1-V} \cdot \left[\frac{V \cdot \cos\alpha + \sqrt{1-V^2} \cdot \sin\alpha}{1+V} \right] \tag{2}$$

where $Z_S = |R_S + j \cdot X_S|$, $Z_F = |r_F + j \cdot x_F| \cdot L$, $V = |\underline{V}|$ and $\alpha = \arctan(X_S / R_S) - \arctan(x_F / r_F)$ is the phase angle between $\underline{Z}_S$ and $\underline{Z}_F$.

If the feeder and the source are represented by reactances only, (2) becomes:

$$L_{crit} = \frac{X_S}{x_F} \frac{V}{1-V} \tag{3}$$

The critical length L_{crit} allows to establish a distance on the feeder within any fault leads to a voltage sag on the PCC of magnitude lower than V.

1.2. Unbalanced faults

1.2.1. Single phase to ground fault

For a single phase to ground fault (on phase a), on the distribution feeder, the p.u. phase voltages at PCC are [4]

$$\begin{aligned}
V_a &= 1 - \frac{2 \cdot Z_{S1} + Z_{S0}}{(2 \cdot Z_{F1} + Z_{F0}) + (2 \cdot Z_{S1} + Z_{S0})} \\
V_b &= a^2 - \frac{Z_{S0} - Z_{S1}}{(2 \cdot Z_{F1} + Z_{F0}) + (2 \cdot Z_{S1} + Z_{S0})} \\
V_c &= a - \frac{Z_{S0} - Z_{S1}}{(2 \cdot Z_{F1} + Z_{F0}) + (2 \cdot Z_{S1} + Z_{S0})}
\end{aligned} \tag{4}$$

where Z_{S1}, Z_{S0} are the positive and zero sequence of the source impedance, while Z_{F1}, Z_{F0} are the positive and zero sequence of the feeder impedances.

The phase voltages, expressed by (4) can be written as follows for putting in evidence the characteristic voltage $\underline{V}$ of the single phase fault on phase a

$$\begin{aligned}
\underline{V_a} &= \underline{V} \\
\underline{V_b} &= -\frac{1}{2} \cdot \underline{F} - j \cdot \underline{F} \cdot \frac{\sqrt{3}}{2} \\
\underline{V_c} &= -\frac{1}{2} \cdot \underline{F} + j \cdot \underline{F} \cdot \frac{\sqrt{3}}{2}
\end{aligned} \tag{5}$$

where $\underline{F}$ is the positive - negative factor being important for the complete characterization of a voltage sag. The F factor is defined basing on the positive and negative symmetric components when it is neglected the zero voltage component [5].

In this case, the critical length on the feeder for voltage sags magnitude at PCC becomes

$$L_{crit} = \frac{\left(Z_{S1} - Z_{S0}\right) + V \cdot \left(2 \cdot Z_{S1} + Z_{S0}\right)}{\left(2 \cdot z_{F1} + z_{F0}\right) \cdot \left(1 - V\right)} \tag{6}$$

1.2.2. Phase to phase fault

Considering a phase to phase fault between phases *b* and *c* along the feeder, the voltage at PCC (with $Z_{S1} = Z_{S2}$) are:

$$\begin{aligned} \underline{V_a} &= \underline{F} \\ \underline{V_b} &= -\frac{1}{2} \cdot \underline{F} - j \cdot \underline{V} \cdot \frac{\sqrt{3}}{2} \\ \underline{V_c} &= -\frac{1}{2} \cdot \underline{F} + j \cdot \underline{V} \cdot \frac{\sqrt{3}}{2} \end{aligned} \tag{7}$$

where $\underline{V}$ is the characteristic voltage of the phase to phase fault.

Writing the feeder impedance as function of length the critical length in this case becomes

$$L_{crit} = \frac{Z_{S1}}{z_{F1}} \cdot \frac{V}{1-V} = \frac{Z_{S1}}{z_{F1}} \cdot \frac{\sqrt{\frac{4}{3} \cdot V_b^2 - \frac{1}{3} \cdot F^2}}{1 - \sqrt{\frac{4}{3} \cdot V_b^2 - \frac{1}{3} \cdot F^2}} \tag{8}$$

1.2.3. Two phase to ground fault

For a two phase *b* and *c* to ground fault, considering $Z_{S1} = Z_{S2}$ and $Z_{F1} = Z_{F2}$, the phase voltages at PCC are:

$$\begin{aligned} \underline{V_a} &= 1 + \frac{(Z_{S0} - Z_{S1}) \cdot (Z_{S1} + Z_{F1})}{(2 \cdot Z_{S0} + 2 \cdot Z_{F0} + Z_{S1} + Z_{F1}) \cdot (Z_{S1} + Z_{F1})} \\ \underline{V_b} &= a^2 + \frac{\left(Z_{S0} - a^2 \cdot Z_{S1}\right) \cdot (Z_{S1} + Z_{F1})}{(2 \cdot Z_{S0} + 2 \cdot Z_{F0} + Z_{S1} + Z_{F1}) \cdot (Z_{S1} + Z_{F1})} \\ \underline{V_c} &= a + \frac{(Z_{S0} - a \cdot Z_{S1}) \cdot (Z_{S1} + Z_{F1})}{(2 \cdot Z_{S0} + 2 \cdot Z_{F0} + Z_{S1} + Z_{F1}) \cdot (Z_{S1} + Z_{F1})} \end{aligned} \tag{9}$$

It can be observed that the voltage on the phase *a* increases, this variation being

$$\Delta V = \frac{(Z_{S0} - Z_{S1}) \cdot (Z_{S1} + Z_{F1})}{(2 \cdot Z_{S0} + 2 \cdot Z_{F0} + Z_{S1} + Z_{F1}) \cdot (Z_{S1} + Z_{F1})} \tag{10}$$

When the zero sequence components of the impedances are equal to the positive and negative ones, the voltage on the healthy phase is constant during the voltage sag.

Also in this case can be established a characteristic voltage for the voltage sag that can be used for the establishing a critical length.

2. Voltage Variations and Induction Motor

The simplified scheme of an induction motor is shown in Fig. 2, where R_s and L_s are the resistance, respectively the inductivity of the stator coil, L_m is the magnetizing inductivity, R_r and L_r are the resistance, respectively the inductivity of the rotor coil and s is the slip.

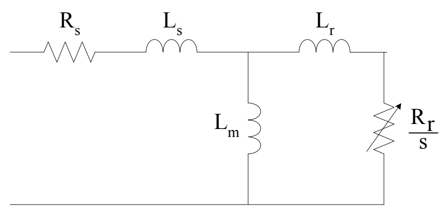

Fig. 2. Simplified scheme of the induction motor

A fault in the electrical network influences the operation of the induction motors. The voltage sags produced by the fault lead to a decrease of the electrical torque and of the motor speed. For a large voltage drop, the motor speed can decrease at a point that causes the stop of the motor.

For a voltage sag of duration Δt and magnitude V, the increase of slip s is

$$\Delta s = \frac{1 - V^2}{2 \cdot H} \cdot \Delta t \tag{11}$$

where H is the inertia constant of the motor – load system.

It can be established the value $V_{\min}$ that corresponds to a maximum admissible slip variation $\Delta s_{\max}$.

$$V_{\min} = \sqrt{1 - \frac{2 \cdot H \cdot \Delta s_{\max}}{\Delta t}} \tag{12}$$

Fig. 3 shows the variation of slip with voltage sag magnitude for an induction motor of 597kVA and the inertia constant $H = 0.5$s. It can be observed a speed reduction at small magnitudes and with large durations.

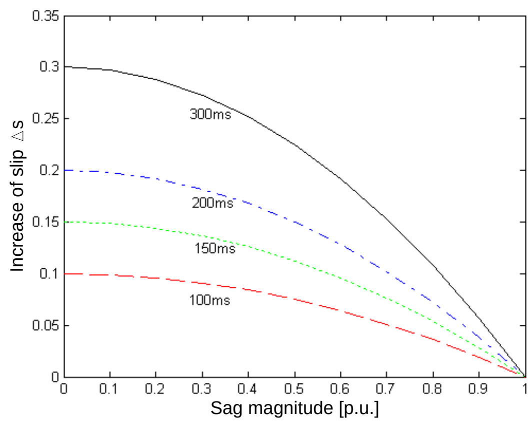

Fig. 3. Variation of slip as a function of residual voltage for various time durations of sags

2.1. Determining the critical length

Introducing in the expression of L_{crit} the voltage at motor terminals as being defined by (12), the critical length in this case can be obtained.

For a three phase fault:

$$L_{crit} = \frac{Z_S}{z_F} \cdot \frac{\sqrt{1 - \frac{2 \cdot H \cdot \Delta s_{max}}{\Delta t}}}{1 - \sqrt{1 - \frac{2 \cdot H \cdot \Delta s_{max}}{\Delta t}}} \tag{13}$$

For a single phase to earth:

$$L_{crit} = 1 - \frac{\left(2 \cdot Z_{S1} + Z_{S0}\right) \cdot \sqrt{1 - \frac{2 \cdot H \cdot \Delta s_{max}}{\Delta t}}}{\left(2 \cdot z_{F1} + z_{F0}\right) \cdot \left(1 - \sqrt{1 - \frac{2 \cdot H \cdot \Delta s_{max}}{\Delta t}}\right)} \tag{14}$$

For a phase to phase fault

$$L_{crit} = \frac{Z_S}{z_F} \cdot \frac{V}{1 - V} = \frac{Z_S}{z_F} \cdot \frac{\sqrt{\frac{4}{3} \cdot \left(1 - \frac{2 \cdot H \cdot \Delta s_{max}}{\Delta t}\right) - \frac{1}{3}}}{1 - \sqrt{\frac{4}{3} \cdot \left(1 - \frac{2 \cdot H \cdot \Delta s_{max}}{\Delta t}\right) - \frac{1}{3}}} \tag{15}$$

3. Voltage Variations at Motor Terminals During Fault Transients

Because an induction motor feeds the fault, the voltage during the sag on the faulted phase it has a value greater than in the case without the motor. After the fault clearing, the motor absorbs a large current appearing a post fault sag, the voltage recovering to the prefault value after an interval. The post fault sag can become significant if there are many large induction motors fed from the same busbar in some cases being required the disconnection of the motor due to the impossibility to reaccelerate. The undervoltage protection of some devices that hasn't acted during the initial voltage sag, of duration relatively small, can be disconnected due to the postfault sag, having duration larger than the threshold of the protection [6].

For analyzing the behavior of induction motors during the above related fault conditions, the electrical network shown in Fig. 4 is considered [7]. The electric utility supply is provided at a 132 kV busbar with a fault level of 4115 MVA. Two 132/6 kV transformers, T1 and T2, connect through the L1 bars the busbar B supplying a 6 kV distribution network. Useful data concerning transformers, bars L1 and the two feeders, L2 and L3, are reported in Table 1.

A three phase static controlled converter (U2), with a 2.5 MW demand and power factor of 0.7, is supplied from busbars B. A power factor correction device rated 1.92 MVAr (C2) is also connected at the same busbars. From B1 a 1 MW rated three phase uncontrolled converter (U1) equipped with 5^{th} (F1) and 7^{th} (F2) harmonic current tuned arm filters is supplied. The filters characteristics are reported in Table 2.

At busbar B2 two large induction motors, M1 and M2, respectively 1 MW and 0.4 MW rated, as well as a 0.48 kVAr (C_M) power factor connection are equipped. The motors were considered with the neutral not grounded.

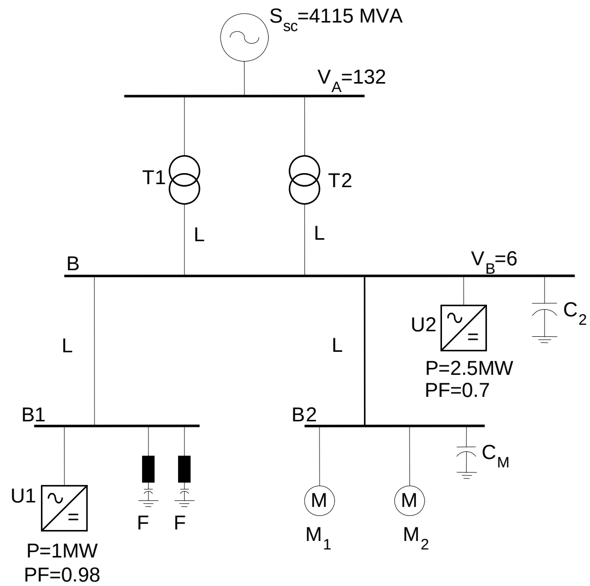

Fig. 4. Layout of the system used for test

Table 1.

Data of the test system

Transformers (T1 and T2)		S_n [MVA]	V_{n1}/V_{n2} [kV]		V_{sc} [%]	P_{sc} [kW]
		5	132 / 6		10	40
L1		R[Ω]			X_L[Ω]	
		0.0112			0.024	
Feeders	V_n [kV]	L [km]	s [mm^2]	r [Ω/km]	x_L [Ω/km]	C [μF/km]
L2	6	0.1	25	0.945	0.188	0.2
L3	6	0.1	70	0.353	0.165	0.29

Table 2

Filter Characteristics

Filters	V_n [kV]	I_n [A]	L [mH]	C [μF]
F1	6	22	45.16	8.97
F2	6	15	23.04	8.97

In the following the dynamic behavior of the voltage at motor M1 terminals will be investigated for different faults at busbar B, using the software tool ATP where the different system components are modeled as indicated in [8].

3.1. Three phase fault

During the fault in busbar B the motor feeds the fault during the first cycles such that the positive sequence voltage at motor terminals is not zero. The voltage at motor terminals decreases causing a decrease of speed. Due to speed reduction, the positive sequence impedance, dependent on the slip, decreases and so also the voltage. Fig. 5 shows the variation of the positive and the negative sequence voltage during the fault. After fault clearing, a post fault can be noticed, its severity depending on the motor size.

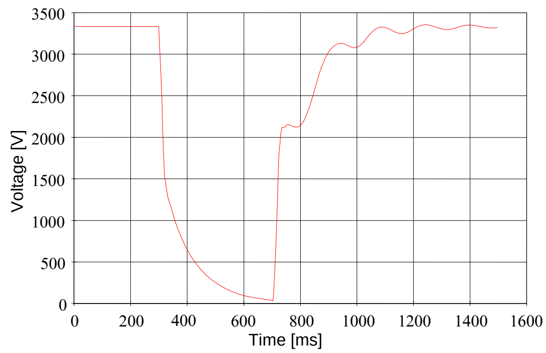

Fig. 5. RMS value of the positive voltage component

Fig. 6 shows the voltage on phase *a* at M1 terminals due to a fault on busbar B.

In this case the characteristic voltage is the rms value of the phase voltage and it is equal to 35 V. The critical length assumes the value of 0.01 km and the post fault duration is 195 ms.

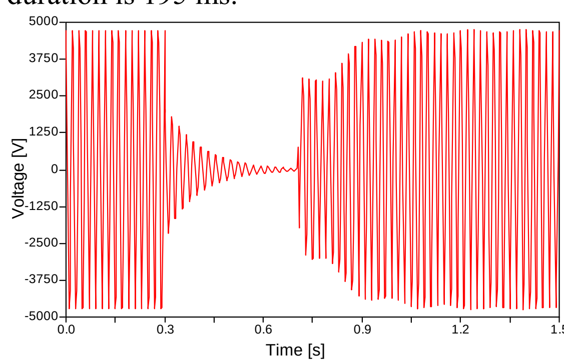

Fig. 6. Variation of the voltage on phase *a* at motor terminals due to a three phase fault

3.2. Two phase to ground fault

The presence of the induction motors in the load produces a voltage at motor terminals during the fault different from zero. Fig. 7 and 8 report the voltage variation at motor terminals for the faulted phases, while Fig. 9 is related to the healthy phase. In Fig. 10, the voltage suffers an increase at the moment of fault initiation, followed by a slowly decay.

The negative sequence impedance, being much smaller than the positive one, produces a decrease of the negative sequence voltage in rms value, leading in this way to a non zero value the faulted phase voltage.

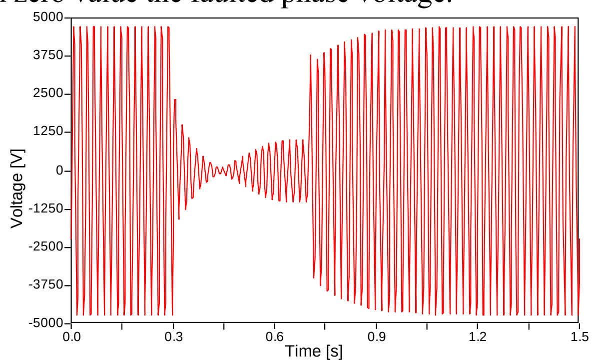

Fig. 7. Variation of the voltage on phase *b* at motor terminals due to a two phase to ground fault

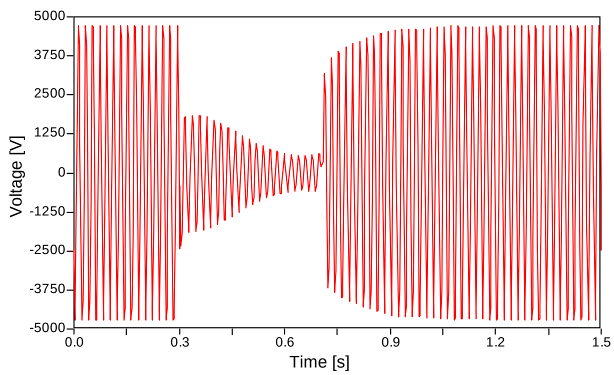

Fig. 8. Variation of the voltage on phase *c* at motor terminals due to a two phase to ground fault

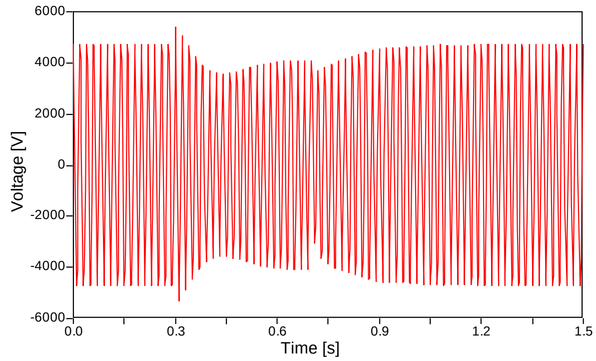

Fig. 9. Variation of the voltage on phase *a* at motor terminals due to a two phase to ground fault

The positive, negative and zero components of the voltage at the motor terminals are shown in Fig. 10.

As it can be seen, the negative and zero voltage components are constant during the entire interval of the voltage sag, while the positive component increases slowly after fault clearing due to the dependence of positive sequence impedance on slip. Usually the induction motors are connected in delta or wye ungrounded, such that the zero voltage component does not suffer any modification due to the presence of the motor. Moreover, for the distribution network, in which the zero sequence impedance has a significant value, during a two phase to ground fault a voltage increase on the healthy phase appears. This voltage increase on the healthy phase, expressed by (10) should be taken into consideration for studying the characteristic voltage.

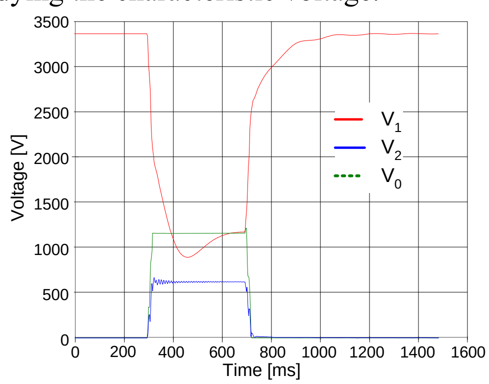

Fig. 10. RMS values of the positive, negative and zero voltage components

This latter is determined on the following basis [9]:

- The rms values of the phase voltages and of the line voltages. The minimum value between these 6 values represents the characteristic voltage.
- The positive, negative and zero sequence voltages (Fig. 11).

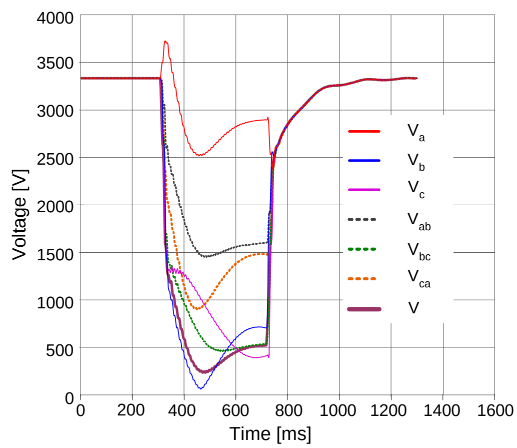

Fig. 11. RMS values of the phase and line voltages and the characteristic voltage V

In Fig. 11 it can be observed the using the algorithm based on the symmetrical components allows the determination of the voltage on the entire fault interval. The greatest rms monitored at motor terminals is the voltage on the healthy phase. This one can be used, besides the characteristic voltage, for characterizing the voltage sag. For characterizing the motor dynamics on the terminal voltage observation, the following parameters are taken as reference: the characteristic voltage, the rms value of the voltage on the healthy phase and the duration of the recovery process up to 0.9 p.u. of the prefault value [10]. In the case of the example, the above parameters assume these values: V = 247 V, V_{max} = 3733 V, L_{crit} = 0.08 km, post fault duration is 130ms.

3.3. Single phase to ground fault

During a single phase to ground fault (phase *a*), the voltage of phase *a* at motor terminals is not zero while the voltages on the healthy phases suffers an increase on fault beginning, as it is shown in Fig. 12 - 14.

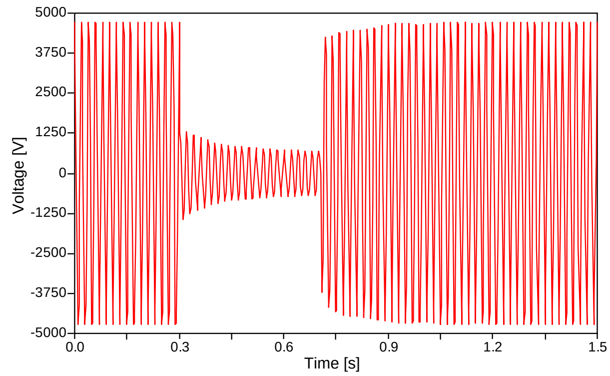

Fig. 12. Variation of the voltage on phase *a* at motor terminals due to a single phase to ground fault

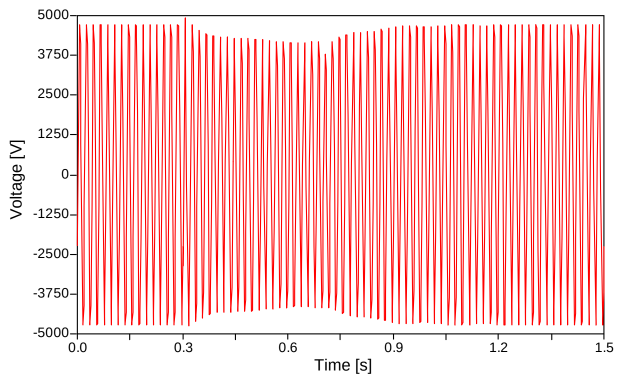

Fig. 13. Variation of the voltage on phase *b* at motor terminals due to a single phase to ground fault

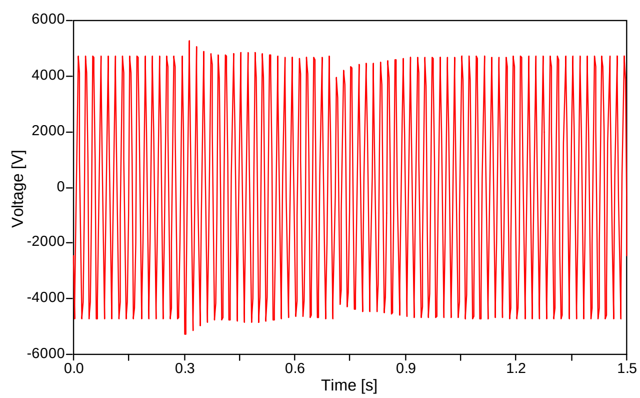

Fig. 14. Variation of the voltage on phase *c* at motor terminals due to a single phase to ground fault

The symmetrical components of the voltage at motor terminals are shown in Fig. 15. In Fig. 16 it can be seen that negative and zero sequence voltage remain constant during the sag, but that the positive sequence voltage shows a steady decay, due to the decrease in positive sequence impedance when the motor slows down.

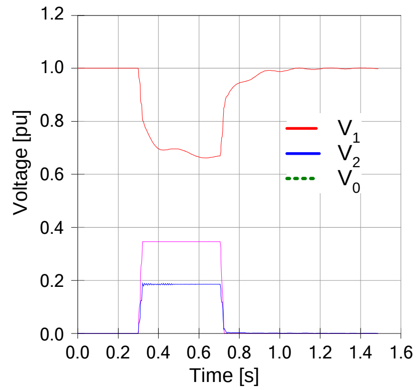

Fig. 15. RMS values of the positive, negative and zero voltage components

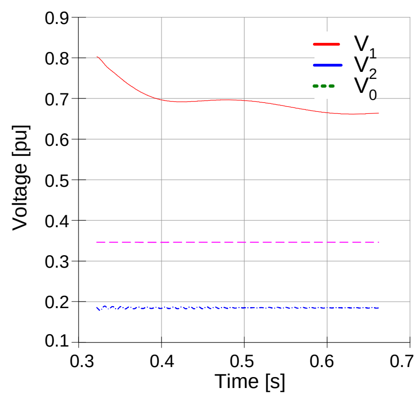

Fig. 16. RMS values of the positive, negative and zero voltage components during the fault

For obtaining the characteristic voltage for a single phase to ground fault the two above mentioned methods are used.

In Fig. 17 the characteristic voltage established with symmetrical components leads to a smaller value with respect to the voltage on the faulted phase, which would be the characteristic voltage using the six rms values algorithm, i.e. the voltage V_a. Then a variation of the voltage on the healthy phases can be observed.

For a single phase to ground fault the voltage recovery time after fault clearing is smaller than in the case of a two phase to ground fault.

In the case of the example, the above parameters assume these values: $V = 437$ V, $V_{max} = 3724$ V, $L_{crit} = 0.15$ km, post fault duration is 40ms.

Conclusions

The voltage supply of induction motors connected to a distribution network is affected by faults in the network feeders or busbars: voltage sag can even stop the motor. In this paper, the establishment of a critical length in which any fault lead to motor stop has been proposed. This distance is important in determining a zone in which the performance of the motors can be guarantee.

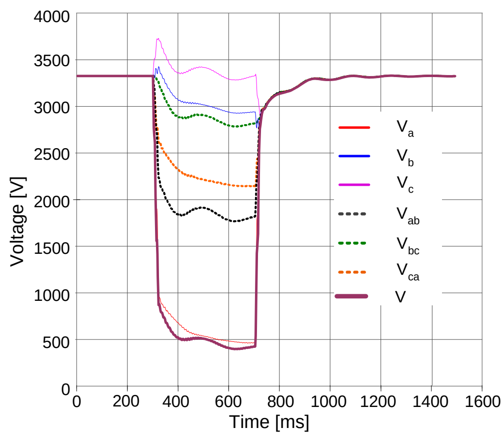

Fig. 17. RMS values of the phase and line voltages and the characteristic voltage V

In this paper various types of faults are presented and for each of them the values that characterize the voltage sags at motor terminals are highlighted and calculated on a test network. In this test network, the motor is at the same voltage level with the fault location and is supplied without transformers that could block the zero sequence voltage component. The analyzed motor does not have grounded neutral point and the zero sequence voltage is not influenced by the motor operation.

The use of symmetrical components leads to the determination of a characteristic voltage for the voltage sag on the entire fault interval, for every fault analyzed. For characterizing the motor behavior it is also proposed to use the maximum value of the voltage on the healthy phases, and the interval in which the voltage recovery reaches 0.9 p.u. of the prefault value. The postfault sag, having a significant duration in case there are many induction motors fed from the same busbar, influences the equipments, because their undervoltage protection will act due to the exceeding of the time threshold.

REFERENCES

1. *C. Golovanov and M. Albu*, Modern measuring problems in electroenergetics (in Romanian Probleme moderne de măsurare în electroenergetică), Bucharest, Ed. Tehnică, 2001, pp. 758 - 765
2. *J. Arrillaga, N. R. Watson and S. Chen*, Power Quality Assessment, John Wiley & Sons, 2000, pg. 30 – 33
3. *R. C. Dugan, H. W. Beaty and M. F. McGranaghan*, Electrical power systems quality, New York: Mc.Graw-Hill, 1996, pp. 52 – 55
4. *M. H.J. Bollen*, Understanding power quality problems: voltage sags and interruptions, IEEE Press, Wiley-Interscience, 2000, pp. 139 – 174
5. *E. R. Collins and M. A. Bridgwood*, The impact of power system disturbances on AC – coil contactors, in Proc. IEEE Annu. Textile, Fiber, Film Industry Tech. Conf., 1997, pp. 9.1 – 9.6
6. *M. H.J. Bollen and P. M. E. Dirix*, Simple model for post-fault motor behavior for reliability/power quality assessment of industrial power systems, in IEE Proc.-Gener. Transm. Distrib., vol. 143, January 1996, pp. 56 – 60
7. *R. Lamedica, A. Prudenzi, E. Tironi, D. Zaninelli*, "Harmonic analysis procedures: a comparison between IEEE and IEC guidelines", in Proc. 1998 Int. Conf. on Harmonics and Quality or Power, pp. 470 – 475
8. EMTP Theory Book. Hannover, Germany: European EMTP-ATP Users Group, Bonneville Power Administration
9. *M.H.J. Bollen*, Algorithms for characterizing measured three – phase unbalance voltage dips, in IEEE Transactions on Power Delivery, vol. 18, July 2004, pp. 937 – 944
10. Power quality measurement methods, IEC Standard 61000-4-30, 2003
11. *C. Mihăileanu, D. M. Potlog*, Goluri de tensiune în sisteme electroenergetice. Efecte asupra consumatorilor, Bucharest, Ed. Tehnică, 1979
12. *V. Rugină*, Ph D. Thesis