Propagation of voltage sags in industrial power networks

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Abstract. The paper analyzes the propagation of voltage sags through the distribution network of an industrial company. For this, power quality is monitoring in high voltage, 44kV, and low voltage, 400V. The theory of M. Bollen is used for the study of the sags recorded by the meters at different points of the installation. It is necessary to know the connection of transformers in order to determine the transmission of the sags.

Key words

Voltage sag, Transformer connection, Industrial loads

1. Introduction

One of the typical problems in electrical distribution systems are voltage sags. These have a great incidence on the electrical equipment connected to the network in the same area. The sags cause more damages than the rest of disturbances because these have a greater frequency of occurrence.

During a sag the voltage suffers a sudden reduction between 90% and 10%. Immediately after a short period of time the voltage recovers its value. Conventionally the duration of a voltage sag is between 10 milliseconds and 1 minute. The voltage sag depth is defined as the difference between the minimum effective value (RMS) during the sag and the reference voltage. Reductions which do not overtake the limit of the 10% will not be considered as sags.

When monitoring the voltage quality is necessary to take into account that the propagation of disturbances through the power system changeS their characteristics. We can not wait to see the same results in different voltage levels. Industrial loads are usually connected at voltage levels lower than those where the faults occur. Thus, if measured at the substation should be aware that the

disturbance will change its characteristics when it comes to load terminals.

The terminal voltages of the loads depend not only on the voltages at the PCC, but also are influenced by the connections of the windings of transformers which are between the PCC and the loads. The voltages at the terminals of the loads also depend on the type of connection to them.

2. Causes of voltage sags

A. Shortcircuits and Faults to ground.

The most common cause of voltage sags are shortcircuits and faults to ground. These cases lead to the more severe voltage falls and to most of the failures in equipment.
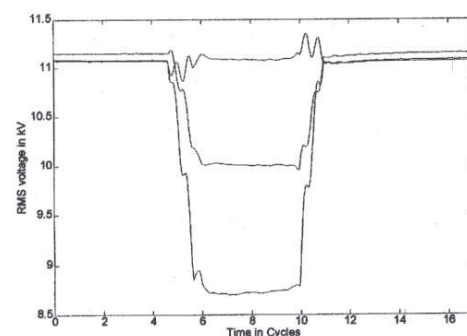

Fig.1 Voltage sag due to a non symmetrical fault.

One example of voltage sag due to fault is shown above. The case of Fig. 1 is associated with different voltage reductions in two phases while the rms value of the other one is not affected by the perturbation. Different effective values in the three phases are a common characteristic in voltage sags caused by faults. Only shortcircuits in the three phases lead to equal values. Another remarkable feature of these cases is the abrupt fall and recovery of

the voltage; associated with the initiation and the compensation, respectively.

B. Motors and Transformers.

Starting current of great induction motors is also a cause of voltage sags in power systems. The duration of this type of disturbance is much longer. Voltage sags due to a motor start show a sudden reduction with a slow recovery depending on ratio torque-speed of the load. Since induction motors are a balanced load, the reduction of the rms voltage is the same for the three phases.
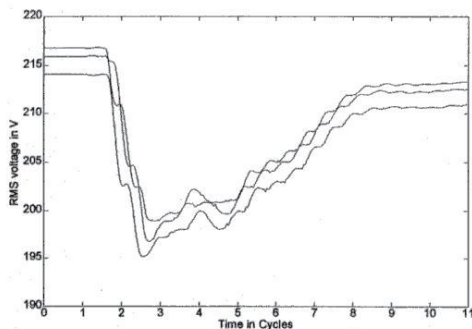

Fig.2 Voltage sag due to a motor starting

Transformers can also provoke voltage sags when they start. The process is characterized by a repetition of short sags with duration of a few milliseconds. These type of events have a great harmonic content. The voltage recovery it is quite slow and it depends on the decomposition of the dc component in the magnetic flux. Different effective values in the three phases are also a common characteristic in voltage sags caused by transformers.
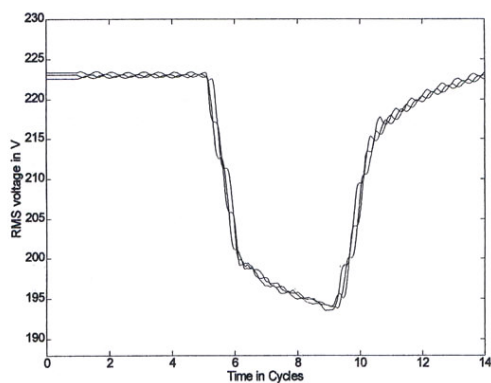

Fig.3 Voltage sag due to a transformer starting

C. Post-Faults.

A fault is a very severe disturbance of the power system, affecting as much the distribution as the load, and frequently at large distances. However, in this case the voltage recovery is not complete and does not reach the pre-fault value. The two main causes of *Post-Faults* are induction motors accelerations and transformers saturation.
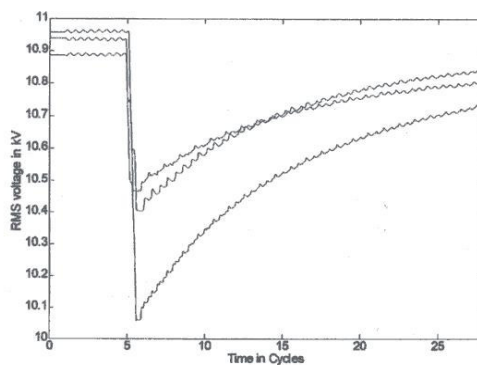

Fig.4 Voltage sag due to a three phase fault

During faults induction motors reduce speed, increasing gradually the current absorbed from the distribution system and causing a deep voltage reduction. These post-faults currents provoke post-faults voltage sags.

3. Classification of voltage sags

There are several classification methods for voltage sags:
- Classification using a magnitude.
- Classification using a magnitude and a time period.
- Classification using several magnitudes and a time period.
- Bollen's classification.

In this work the Bollen's classification is used [1]. Seven types of sags are defined which correspond to the possible shortcircuits in the three-phase network and to the sag propagation through transformers. The most common types are A, B, C and D. Their characteristic voltage, by phase, corresponds to the following expressions, Table I:

Table I.- Characteristic voltage for sags A, B,C and D.

Type 'A'	Type 'B'
$V_a = V$	$V_a = V$
$V_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}V$	$V_b = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$
$V_c = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}V$	$V_c = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$
Type 'C'	Type 'D'
$V_a = 1$	$V_a = V$
$V_b = -\frac{1}{2} - j\frac{\sqrt{3}}{2}V$	$V_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}$
$V_c = -\frac{1}{2} + j\frac{\sqrt{3}}{2}V$	$V_c = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}$

4. Propagation of voltage sags across transformers

The windings of transformers can be connected in different ways, however, only three types summarize the transfer of three-phase unbalanced sags from one voltage level to another [1]
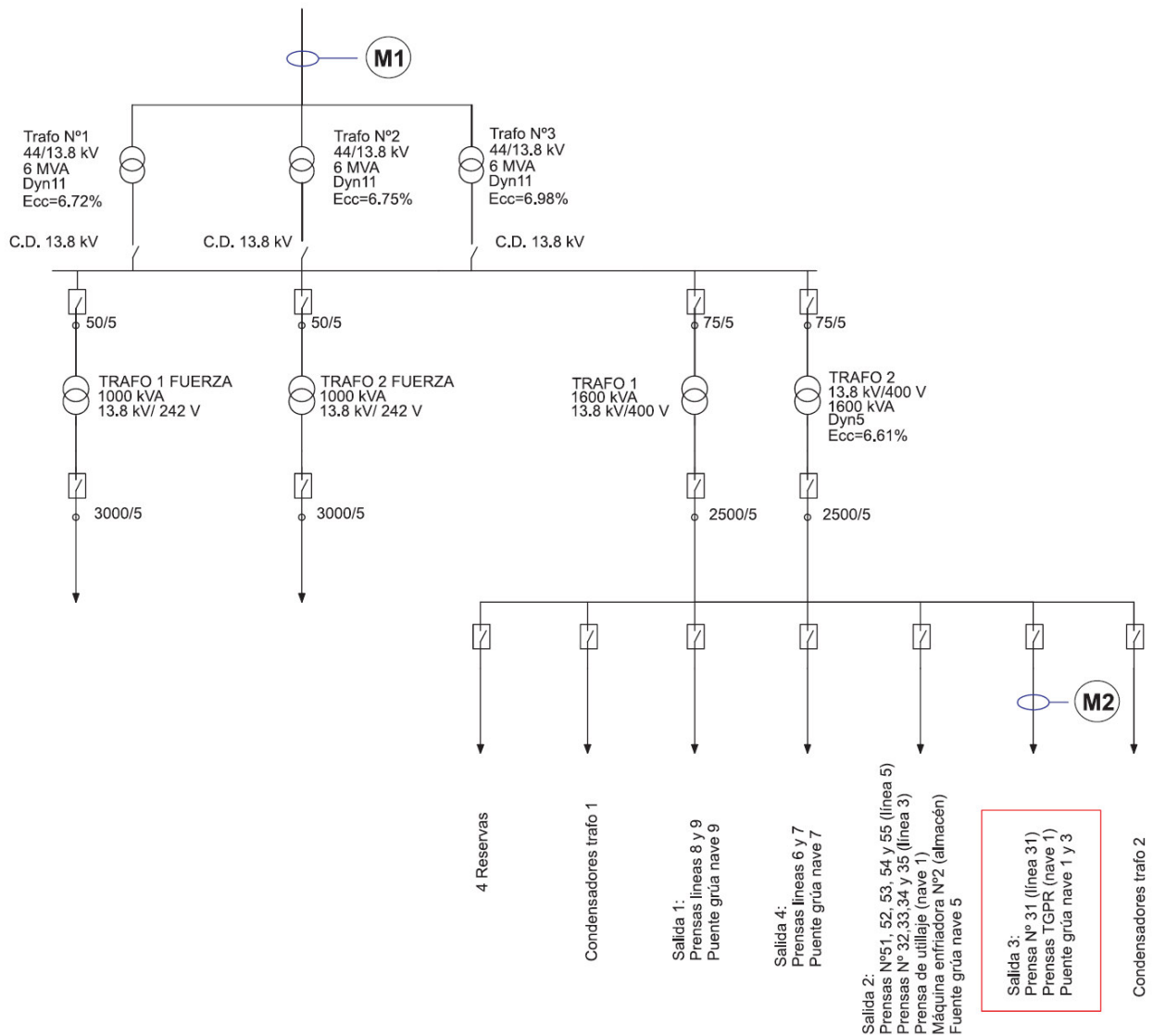
Fig. 5. General view of the electrical circuit under measurement.

1) *Transformers that do not change anything to the voltage*. Example:Star-star with both star points grounded.

2) *Transformers that remove the zero sequence voltage*. Example: Star-star with one or both star points grounded.

3) *Transformers that change line and phase voltages*. Example: Delta-star, Star-delta and Star-zigzag.

The clock number of the transformer connection leads to different phase shift between primary and secondary voltages. However, this has no influence in the equipment suffering the voltage sag.

The origin of sags and the transformation to lower voltage levels, for all seven types of three-phase unbalanced sags, are summarized in Tables II and III.

Table II. – Origin of Three-Phase Unbalanced Sags

Fault Type	Star load	Delta load
Three-phase	A	A
Two-phase-to-ground	E	F
Phase-to -phase	C	D
Single-phase	B	C

Table III. – Transformation of Sag Type to Lower Voltage Level

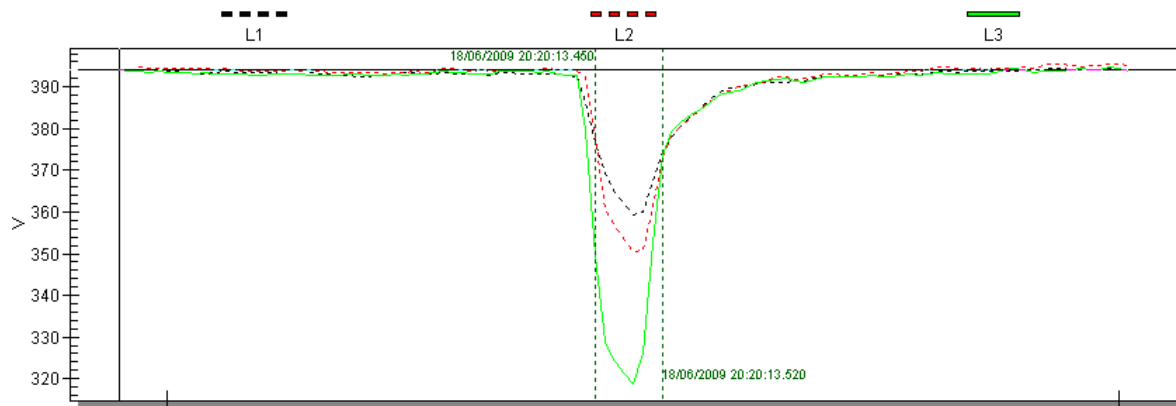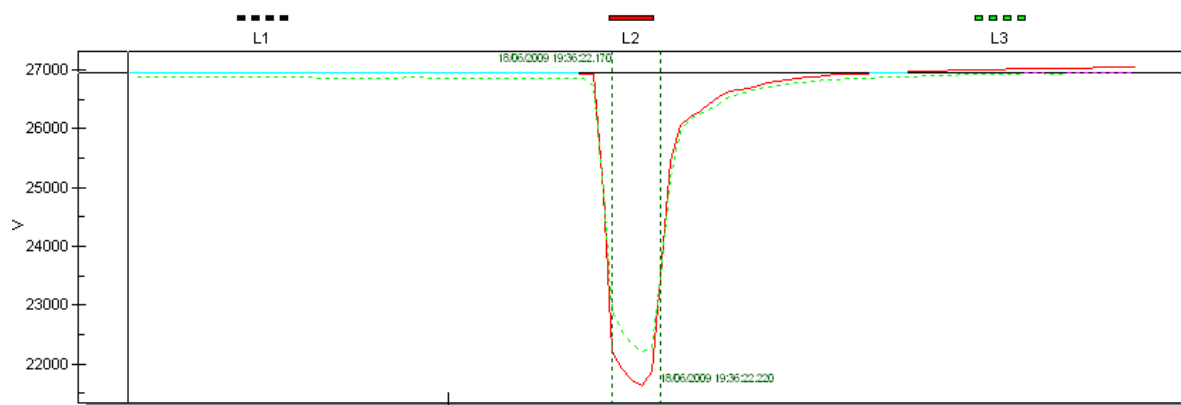| Connection	Sag on Primary Side						
	TypeA	TypeB	TypeC	TypeD	TypeE	TypeF	TypeG
YNyn	A	B	C	D	E	F	G
Yy, Dd, Dz	A	D	C	D	G	F	G
Yd, Dy, Yz	A	C	D	C	F	G	F

Fig. 6. Low voltage sag (M2).

Fig. 7. High voltage sag (M1).

5. Sags propagation in industrial plants

Figure 5 shows the electric diagram for the feeding of the factory. The feeding is done from substations at 220 kV. The feeding voltage of the plant is performed at 44 kV, with a maximum short circuit power (S_{CC}) of about 750 MVA

The industrial plant under study is fed by three transformers ratio 44/13,8kV, 6 MVA and Dyn11 connection. The voltage of 13.8 kV undergoes a second reduction ratio through two transformers 13.8 kV/400 V, 1600 kVA and Dyn5 connection. At exit number 3, the following loads are located:

1) *Press N° 31 (line 31).*
2) *TGPR Presses (Building 1).*
3) *Overhead crane (Building 1 and 3).*

Measuring equipment at M1 and M2 points are two QNA 412 Circutor brand, able to record supply quality parameters according to IEC 61000-4-30 Class A.

Figures 6 and 7 show an example of the graphical output of the monitoring software, both in the high voltage and the low voltage measurement points.

Table IV. – Summary of the results classified by sag type.

Fault	*High voltage (M1) Dyn11-Sag1*	*Sag2*	*Low voltage (M2) Dyn5-Sag3*
1 ph-gnd	B	C	D
2 ph	C	D	C
2 ph-gnd	E	F	G
3ph	A	A	A

Table IV summarizes how sags change from high voltage to low voltage, taking into account the winding connections of the transformers and the type of fault that causes the disturbance. The column Sag1 corresponds to what is monitored in the point M1. The column Sag2 corresponds to the type of sag that will appear between both transformers, that is, at 13.8 kV. The column Sag3 corresponds to what is monitored in the point M2, that is, low voltage monitoring.

For a three-phase fault, at any voltage level and for any connection, the sag is type A. For phase-to-phase fault, the load being star-connected, the resulting sag1 is type C, sag2 is type D and sag3 is type C again. For single-phase faults, there will be a sag1 type B. A star load will suffer a sag2 type C, and a delta load will experience a sag2 type D. For the load connected at low voltage (M2)

the thing changes: A star load will suffer a sag3 type D, and a delta load will experience a sag3 type C.
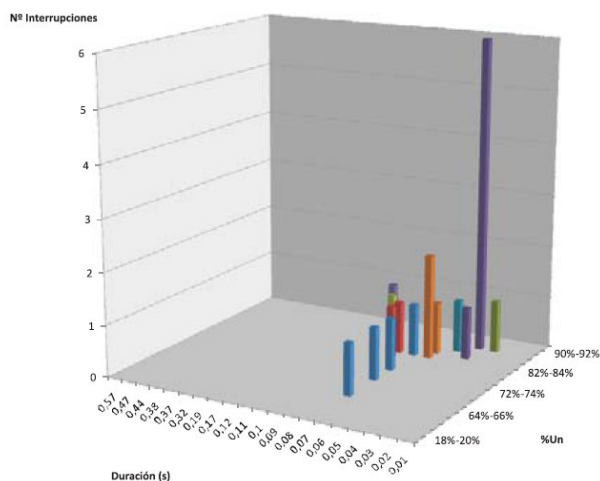

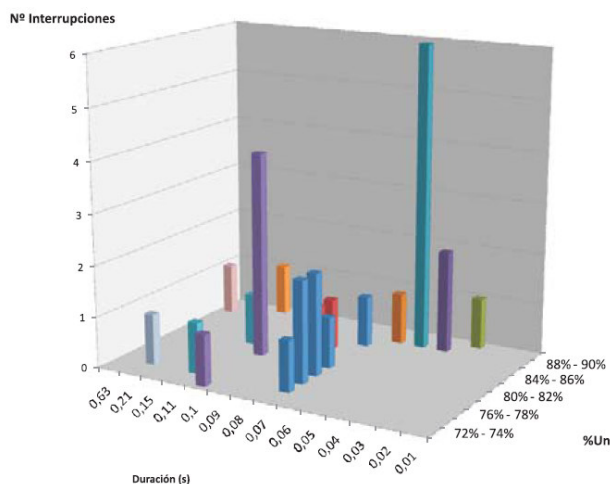Fig. 8. Summary of sags in the AT side. Year 2009.

Fig. 9. Summary of sags in the BT side. Year 2009.

M1 Measurement Results
Figure 8 summarizes the distribution of sags in 2009 on the side of AT (44 kV), grouped by duration and amplitude. The most severe sags in the period studied show a depth of l% and a duration of seconds.

M2 Measurement Results
Figure 9 shows the summary of sags in the BT side during 2009, grouped by frequency, depth and duration.

Conclusion

This work studies the actual case of a company, which suffers frequently power quality problems; the transmission of the most common electrical disturbance, voltage sags, which causes major economic losses in the industrial sector. By monitoring two measurement points, the propagation of the sags through the electrical installation will be analyzed, taking into account the theory presented in this subject by M. Bollen.

Acknowledgement

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