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Power quality and modeling analysis of a university campus electrical distribution system

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***Abstract*— For a few years now, electrical power quality has been a topic of interest and discussion, mainly due to issues regarding costs, continuity of service and electrical installation energy efficiency. The lack in electrical power quality can reveal itself in different ways, in reactive power costs, in frequent tripping of protections, in overheating and overloads of equipment and cables, in the significant shortening of capacitor lifespans, and, on power grid resonance events. This paper makes an electrical power quality analysis on Instituto Superior de Engenharia de Lisboa (ISEL) school campus, more precisely, two transformer substations and several building electrical distribution boards that make up the campus' electrical power grid. The acquired data enabled the graphical display of several electrical parameters, and their subsequent quantitative and qualitative analysis, regarding legislation and standards, namely, NP EN 50160; IEC 61000-2-3 and IEEE Std 1159-2019. In the paper, a *Matlab/Simulink* model of ISEL campus' electrical power grid was developed, so that, when anomalies are identified, it will be possible to analyze and verify, through simulation, the effect that different solutions produce to mitigate them.**

Keywords*— *Electric power quality, Standardization, Energy monitoring, Harmonic distortion, Dynamic model.

I. Introduction

Electrical power quality is a determining factor in the quality of life of a whole society. Electrical energy is present in all sectors and we are all very much dependent on it. From production, distribution and final consumers, it is necessary to monitoring and assure that quality is maintained, taking into account the economic factors which influence it, or depend on it [1, 2].

In many countries, distribution network service providers have a legal responsibility to their customers to provide them with high quality electrical power. To ensure that reliability and quality of supply are met, engaging in monitoring and reporting practices, reduces the failures that can have financial implications [3].

Thus, it is essential to define methods and technologies and to know the best way to use them, to monitoring the electric grid and act as efficiently as possible, to maintain its quality under the desired levels [4].

Several tools were developed during the constant evolution of electrical power grids in general and naturally, standards like NP EN 50160 [5], helped to standardize methodologies to ensure the desired levels of electrical power quality are met.

Power Quality (PQ) is nowadays a serious concern for engineers mainly due to harmonic emission increase, aggravated by the widespread use of power converters and other electronic power systems [6, 7]. Authors in [8] made an exhaustive work regarding, by analyzing and evaluating the effect of harmonic distortion in industry.

Regarding previous work done on university campus' power quality analysis [9, 10], this paper aimed to do an updated analysis of the campus and add upon it, with a numerical model to describe the analyzed electrical network, using *Matlab/Simulink* software. This model will allow the analysis and verification of different solutions to mitigate power quality problems in the campus.

The work consisted of studying the overall configuration of the electrical network; defining the measurement schedule; obtaining, processing and analysing the data; evaluating if the measured parameters are in accordance with the standards or not; creating a simulation of the electric network; and comparing results and taking overall conclusions.

II. Definitions

Several standards were taken into account to conduct the analysis of the power quality of the campus:

A. *NP EN 50160 Standard*

These standard addresses voltage characteristics and their limit values, in order to classify an installation as having acceptable power quality. This standard addresses the quality of the voltage delivered by the distributor on the delivery point. The main characteristics are:

- Frequency: It cannot exceed the limit values of 50Hz ± 1%, during 99.5% of a year or 50 Hz + 4% / -6% at all times.
- Voltage variations: The RMS value must not exceed ± 10% of Un.
- Flicker (P_{lt}): It has to have a value below 1, for 95% of the time.
- Voltage unbalance: this parameter has to be below 2%.
- Voltage harmonics: several order harmonics have to stay within maximum percentage values, relative to the first order harmonic like described in Table I.

TABLE I. MAXIMUM VOLTAGE HARMONIC VALUES

Odd Harmonics				Even Harmonics	
Non-multiple of 3		Multiple of 3			
Order h	Relative amplitude U_h	Order h	Relative Amplitude U_h	Order h	Relative Amplitude U_h
5	6.0%	3	5.0%	2	2.0%
7	5.0%	9	1.5%	4	1.0%
11	3.5%	15	0.5%	6…24	0.5%
13	3.0%	21	0.5%		
17	2.0%				
19	1.5%				
23	1.5%				
25	1.5%				

B. *IEEE Std 1159-2019 Standard: Recommended Practice for Monitoring Electric Power Quality*

This standard defines the standard procedures and equipment that should be used when addressing the monitoring of electric power quality.

C. *IEC 61000-3-2 Standard: Limits for harmonic current emissions (equipment input current ≤16 A per phase)*

This standard defines the limit values for the harmonics of each class of equipment. Classes A, B, C and D. Other equipment of specific type and power consumption has no limits defined under this standard.

D. *CBEMA curve*

This standard was created by the Computer Business Equipment Manufacturers Association in the 1970s and adopted by IEEE to describe the tolerance of computer equipment to the magnitude and duration of voltage variations of electrical power. It consists of a graph that displays the tolerance levels for the voltage variations.

III. MEASUREMENTS, DATA ACQUISITION AND MATLAB/SIMULINK MODEL

A. *Measurement equipment*

A LEM TOPAS 1000 power quality analyzer unit was used to register all the electrical data of the campus, as seen on the example displayed on Fig. 1. It is equipped with 4 voltage probes and 4 current probes.

B. *Case study*

The object of measurement is the campus of ISEL, [11] is a Polytechnic University in Lisbon, dating back to 1852, when it was called IIL, Instituto Industrial de Lisboa. Currently, it has 4152 students, 363 teachers and 91 collaborators, over 24 engineering courses.

Courses in the field of engineering (Undergraduate and Master Degree): Applied Mathematics for Industry, Biomedical, Chemical and Biological, Civil, Computer Science, Electrical, Electronics and Telecommunications, Industrial Engineering and Management, Informatics and Multimedia, Mechanical, Quality and Environmental.

C. *Measurements*

A power quality analyzer unit was used to register all the electrical data of the campus, Fig. 1 show an example.

Fig. 1. TOPAS 1000 measuring in PT 1.

The unit was configured for the NP EN 50160 standard, with the adequate limits and triggers, as seen on Fig. 2

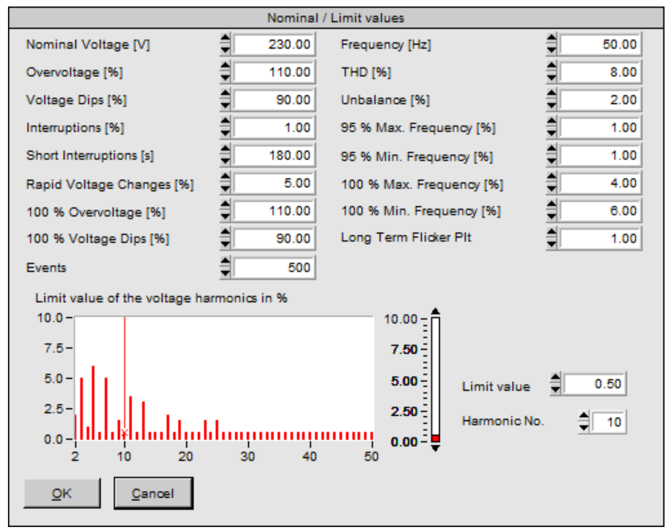

Fig. 2. Configuration on the power quality analyzer.

TABLE II. MEASUREMENTS IN PT1 AND PT2

PT1	PT2
Building E	Building A
Building P	Building F
Building M	Building C
University Residence	Calculus Center
Young Building	

The measurement schedule displayed on Table II, was met, using the power quality analyser unit. The analyser unit was placed in each of the campus power substations, PT 1 and then PT 2, in order to perform overall measurements and to perform measurements of each building by using the unit's voltage and current probes in the respective feeding power breakers. The measured buildings have the following characteristics:

- Building A - The main administrative building where ISEL management and other administrative services are located. It also has a data center, bar, and a library.
- Building C - Offices, classrooms, laboratories, elevators and air conditioning equipment's.
- Building E - Classrooms, laboratories, some with high consumption, such as the electrical machinery laboratory.
- Building F - Offices and Laboratories with computer and network equipment. It has a rare use elevator and air conditioning equipment.
- Building M - Classrooms, laboratories, and workshops. It has elevator and air conditioning equipment.
- Building G - Laboratories and classrooms. It has several feeds from PT 1
- Building P - ISEL's main atrium, offices, large amphitheater, ISEL's canteen and a bar.
- Calculus Center - It has essentially computer equipment. Low consumption.
- University Residence - Building where ISEL students live.
- Young Building - Has a reprography, a bar and study rooms.

The ISEL campus electric distribution network can be seen on Fig. 3.

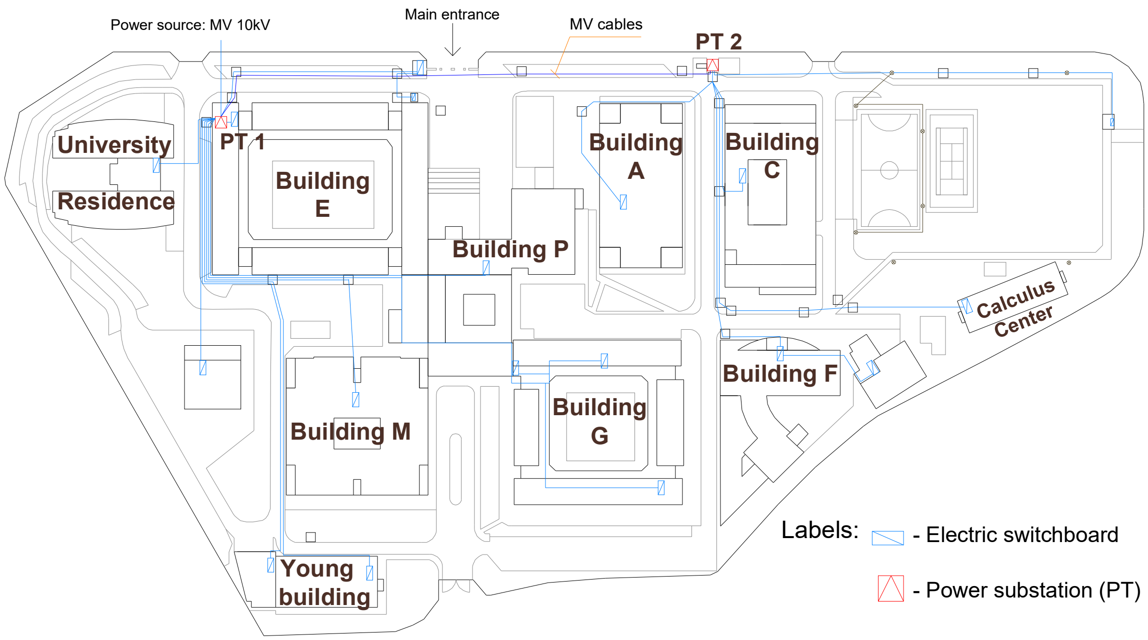

Fig. 3. Electric network of ISEL.

PT 1 substation has two 400 kVA transformers in parallel and uses TN earthing system, whereas PT 2, has one 800 kVA transformer and uses TT earthing system. Inside PT 1, there is a capacitor bank to provide reactive power compensation. The campus also has a power generator and a UPS system, both aimed at securing the power supply of a datacenter that exists on campus.

It is important to note that measuring Building G was not possible since there are several power breakers feeding that building and they could not be measured with just the single power analyser unit that was available to perform the obtaining of the data.

D. Results according to the EN 50160

Regarding the measurements performed on power substations PT 1 and PT 2, the result table presented on Fig. 4, was displayed by the power analyser.

All the parameters are in compliance with the NP EN 50150 standard, with the exception of voltage unbalance, this however, can be only some form of software error, since, all the data that was analysed, confirmed that the voltage unbalance was always below 2%, which means it's within the acceptable values of the standard, and so, also in compliance.

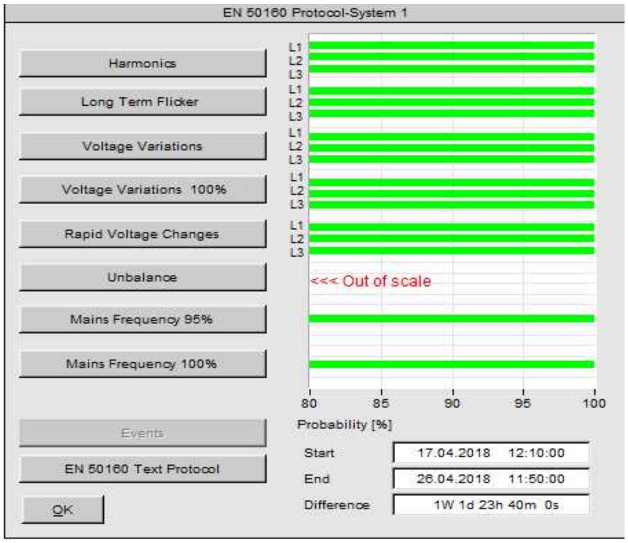

Fig. 4. EN 50160 measurement results.

E. *Voltage deformation events*

Some events were recorded that exhibited some low duration voltage deformations, caused, most likely, by the activation of capacitors, on the power factor correction module.

F. *Summary table*

Regarding the relevant power quality parameters, Fig. 5 shows a quick summary of all the measurement results of both power substations and individual buildings.

Building	RMS Voltage limits	Flicker	Voltage unbalance	Voltage harmonics	Rapid voltage changes	Frequency
PT 1	OK	OK	OK	OK	OK	OK
PT 2	OK	OK	OK	OK	OK	OK
Buidling A	OK	N/A	OK	OK	OK	OK
Buidling F	OK	N/A	OK	OK	OK	OK
Buidling C	OK	N/A	OK	OK	OK	OK
Calculus Center	OK	N/A	OK	OK	OK	OK
Buidling E	OK	N/A	OK	OK	OK	OK
Buidling P	OK	N/A	OK	OK	OK	OK
Buidling M	OK	N/A	OK	OK	OK	OK
University Residence	One power outage	N/A	OK	OK	OK	OK
Young building	OK	N/A	OK	OK	OK	OK

Fig. 5. Power quality summary table.

G. *Matlab/Simulink model electrical distribution system*

After obtaining, processing and evaluating all the data from the power analyser, the next step was to build a *Matlab/Simulink* model. First, it was required to obtain all the datasheet values of the power transformers in the campus substations. The transformer characteristics and its calculated parameters can be seen in Table III to Table VI.

The T model seen on Fig. 6 of each transformer was adopted, according to [12], to calculate the required parameters to insert in the Simulink blocks (APPENDIX VI).

TABLE III. PT 1 TRANSFORMER CHARACTERISTICS

Parameter	Transformer 1	Transformer 2
Brand	France Tansfo	EFACEC
Type	Oil	Oil
Power [kVA]	400	400
ucc [%]	4	4,4
Connection type	Dyn05	Dy11
Current MV [A]	23.1	23.09
Current LV [A]	577	577.4
Voltage LV [V]	400	400
Power losses, no load [W]	930	930
Power losses, with load [W]	4550	4550
Magnet. current (no load) [A]	4.8	4.8

TABLE IV. PT 1 TRANSFORMER CALCULATED PARAMETERS

Parameter	Transformer 1	Transformer 2
Gm [S]	9.30E-06	9.30E-06
Bm [S]	-4.80E-04	-4.80E-04
Rm [Ω]	1.08E+05	1.08E+05
Xm [Ω]	-2.08E+03	-2.08E+03
Lm [H]	-6.63E+00	-6.63E+00
Zt [Ω]	1.60E-02	1.76E-02
Rt [Ω]	1.37E-02	1.36E-02
Xt [Ω]	8.32E-03	1.11E-02
$R_1 = R'_2$ [Ω]	6.83E-03	6.82E-03
$X_1 = X'_2$ [Ω]	4.16E-03	5.56E-03
$L_1 = L_2$ [H]	1.32E-05	1.77E-05

TABLE V. PT 2 TRANSFORMER CHARACTERISTICS

Parameter	Transformer
Brand	France Transfo
Type	Oil Hermetic
Power [kVA]	800
ucc [%]	4
Connection type	Dyn05
Current MV [A]	46.19
Current LV [A]	1154,7
Voltage LV [V]	400
Power losses, no load [W]	1500
Power losses, with load [W]	8315
Magnet. current (no load) [A]	8.87

TABLE VI. PT 2 TRANSFORMER CALCULATED PARAMETERS

Parameter	Transformer
G_m [S]	1.50E-05
B_m [S]	-9E-04
R_m [Ω]	6.67E+04
X_m [Ω]	-1.13E+03
L_m [H]	-3.59E+00
Z_t [Ω]	8.00E-03
R_t [Ω]	6.24E-03
X_t [Ω]	5.01E-03
$R_1 = R'_2$ [Ω]	3.12E-03
$X_1 = X'_2$ [Ω]	2.51E-03
$L_1 = L_2$ [H]	7.98E-05

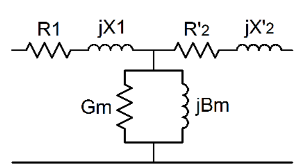

Fig. 6. T model of a transformer.

In Fig. 7, the model representation of PT 1, with two 400 kVA transformers in parallel. The block that represents PT 2 has only a single 800 kVA transformer.

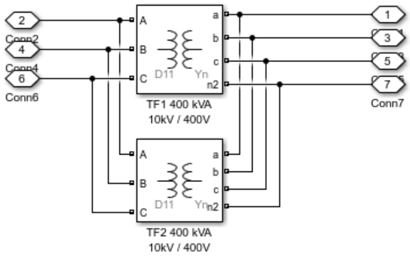

Fig. 7. Simulink representation of PT 1.

For the buildings, blocks with current sources were created, with the injected current values taken from the data files containing the current values obtained by the power analyzer. An example of a building simulation block can be seen on Fig. 8.

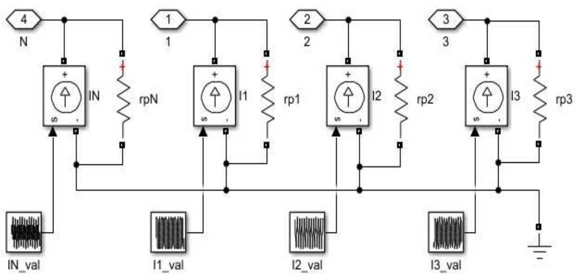

Fig. 8. Simulink block, simulation example of a building as an electrical load.

IV. Results

Comparing the waveforms and harmonic spectra of PT 1 and PT 2 obtained in the simulation, against the values that were measured by the power analyzer, the results are not quite the same, but since it was not possible to measure Building G, which is powered by PT 1, this did certainly have an impact on the results not matching very well, as observed on Fig. 9.

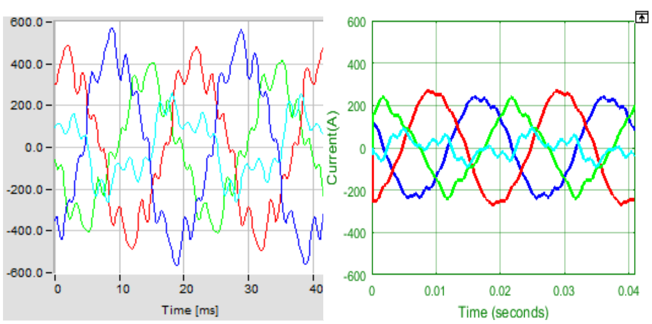

Fig. 9. Current waveforms PT 1 - measured (left); simulation (right). L1 (dark blue); L2 (red); L3 (green); PEN (light blue).

In Fig. 10, the waveforms of both the measured values and the simulation, in PT 2, can be observed.

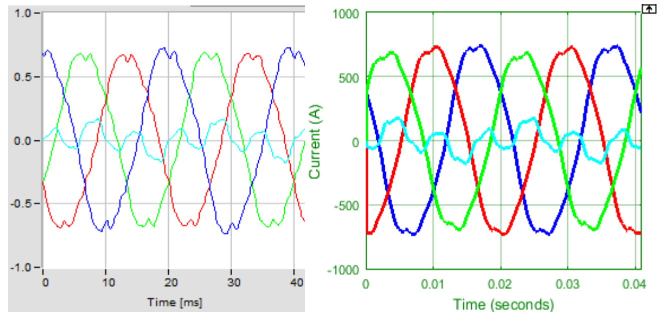

Fig. 10. Current waveforms PT 1 - measured (left); simulation (right). L1 (dark blue); L2 (red); L3 (green); N (light blue).

It was not possible to study compliance with the 61000-3-2 [13, 14] standard, since the measurements were not of individual equipment types, but rather, entire buildings. The vastness of the different types of equipment in such a large installation would make it very difficult to fully measure their impact with regards to the harmonic distortion of the electric currents. Nonetheless, it was clear that there were harmonic currents present, although, in both power substations (PT 1 and PT 2) their relative values were lower than expected. As we can see in the example on Fig. 11 of phase 1 in PT 1, the harmonic spectrum in both the measured values and the simulation values, are small compared to the 50 Hz first order harmonic.

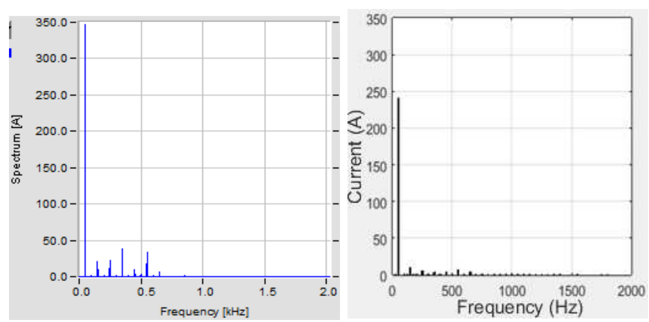

Fig. 11. Harmonic spectrum PT 1, L1 - measured (left); simulation (right).

A similar comparison, but regarding PT 2 can be observed in Fig. 12. Again, some difference between measured and simulated values, mostly, regarding the first order harmonic. Similar discrepancies were observed on L2, L3 and PEN or N.

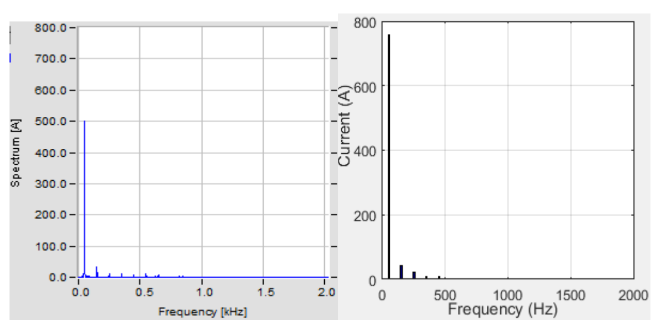

Fig. 12. Harmonic spectrum PT 2, L1 - measured (left); simulation (right).

With regards to the CBEMA curve, only one event was registered in PT 1 and it is within compliance limits as seen on Fig. 13.

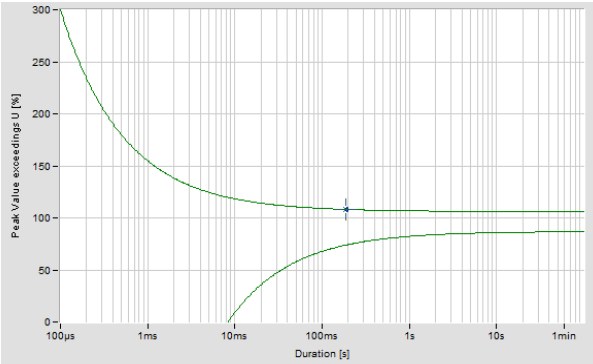

Fig. 13. CBEMA curve results.

V. CONCLUSION

Essentially, in the ISEL power grid, the voltage did not show significant variations or interruptions except in one measurement, which certainly corresponded to a scheduled power interruption. It did not present, according to NP EN 50160, pits, overvoltages, flicker, nor did it present relevant harmonic distortion of the voltage. Another point of interest were several buildings that displayed some load unbalance, provoked by single-phase loads. Better distribution of these loads along the three-phase, will provide for better installation efficiency, and lower heating on cables.

With the created simulation model, it is possible to test solutions to improve power quality and mitigate electric network problems, for instance, the use of passive or active filters. Future work involves changing the model by substituting the current sources with non-linear load models that can simulate the load behavior that each building represents.

VI. APPENDIX

From the nominal voltage U_n, the magnetizing current I_m and the no load losses P_0, it is possible to determine the transformer magnetizing reactance and resistance. The magnetizing conductance is given by (1).

$$G_m = P_0/{U_n}^2 \tag{1}$$

The magnetizing resistance R_m (2) is obtained from the magnetizing conductance G_m (1).

$$R_m = 1/G_m \tag{2}$$

From the magnetizing current I_m and the magnetizing conductance G_m, it is possible to determine the magnetizing susceptance B_m (3).

$$B_m = -\sqrt{(I_m/U_n)^2 - {G_m}^2} \tag{3}$$

The magnetizing reactance X_m is given by (4).

$$X_m = 1/B_m \tag{4}$$

The magnetizing impedance is much higher than the series branch impedances (Fig. 6). Then, from the short-circuit test, it is possible to obtain the short-circuit impedance $Z_{cc}=U_{cc}/I_{cc}$ and the total resistance R_t (5) from the transformer primary and secondary windings, knowing the short-circuit voltage U_{cc}, necessary to guarantee the current nominal value I_n and the short-circuit losses P_{cc}.

$$R_t = P_{cc}/{I_n}^2 \tag{5}$$

Then, from $Z_{cc}=U_{cc}/I_{cc}$ and (5) it is possible to determine the leakage reactance X_t (6).

$$X_t = \sqrt{(U_{cc}/I_n)^2 - {R_t}^2} \tag{6}$$

The resistance (7) and leakage reactance (8) from the primary and secondary windings may be assumed to be equal (Fig. 6).

$$R_1 = R'_2 = R_t/2 \tag{7}$$

$$X_1 = X'_2 = X_t/2 \tag{8}$$

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