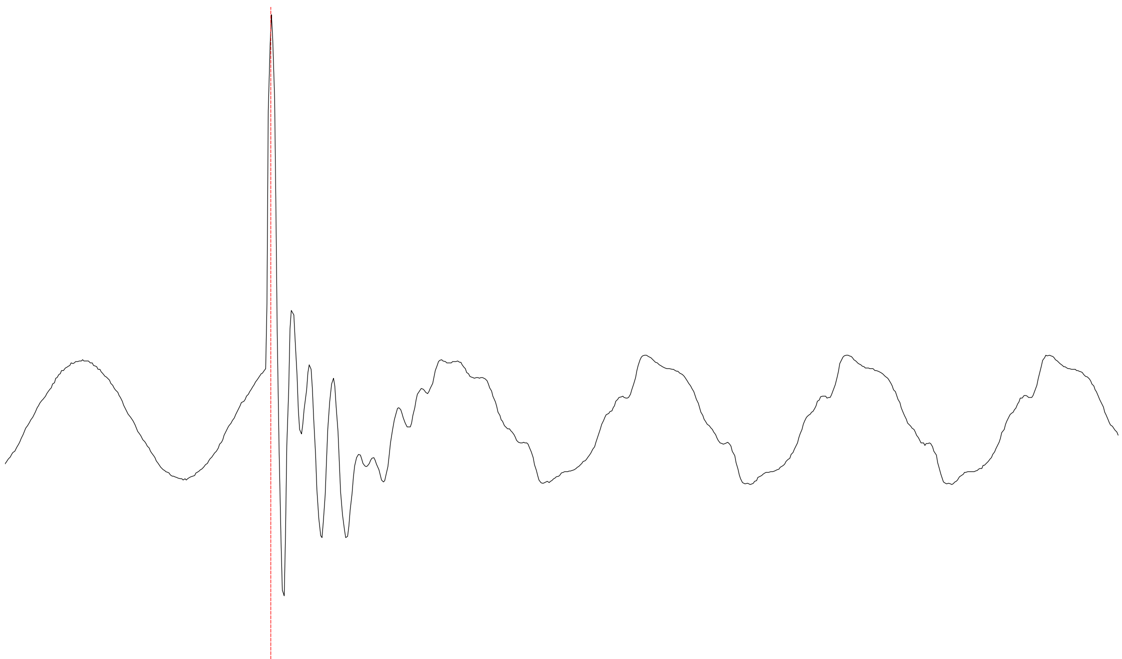
Harmonics and Transients Tech Notes



Issue # 99-1 ***February 1999*** ***Editor: Sandy Smith***

Project Manager: Tom Grebe

In this issue:

Letter from the Project Manager:

Dear PATH Members:

1999 is now upon us and the PATH Users Group is ready for a new year of challenges and opportunities. On top of the challenges presented by supplying state of the art support to deal with harmonics and transient voltage concerns, Electrotek faces the task of developing TOP into a 32-bit application and establishing SuperTran, our transients simulation software, as a usable and viable part of your power quality toolbox. Last year, we achieved a significant goal when the 32-bit version of SuperHarm was completed and released. However, even that task is not fully complete to our satisfaction.

A fairly significant bug was found in SuperHarm by Duke Power's Steve Middlekauff. As he found, when you use the SuperHarm file editor, there is no "Save As" feature, which means that you cannot open your file, modify it, and save it under another name to keep the original file intact. The file editor also does not have a "print" function. While we exercised care and diligence in developing and testing the software, the file editor was the last component completed and was rushed through the process to allow delivery of the software to you last year.

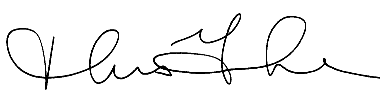
We are working to resolve this problem. Whether or not the fix is issued as a patch or as part of SuperHarm V 4.1 has yet to be determined. For now, we recommend that if you use the SuperHarm file editor and want to keep files archived, that you store a copy of the file in another directory on your hard drive or on diskette, ZIP disk, or other storage media. You can also use another file editor, such as Windows Notepad, which will enable you to "Save As" and print your files.

We apologize for the problem and encourage you to post other problems, comments, or suggestions about the program on the PATH Forum on the PATH Web site at **www.pqnet.electrotek.com/pathmemb/ path.htm**. I encourage you to visit this site on a regular basis. In addition to featuring the entire library of *Tech Notes* and presentations from this past Users Group meeting, the site also enables you to download Users Group software, as well as documentation and files to help you use the software more efficiently. If you find that you don't have your user ID and password to get into the Web site, contact Sandy Smith by sending an e-mail to **sandy@electrotek.com**.

One more item – *Tech Notes* relies on the input of our members, especially those affiliated with universities, to make it a useful resource. If you are a university member and haven't submitted an article within the past year or so, we will be contacting you. If you are not a university member and want to share a case study or technical issue with the rest of the membership, we also encourage your input.

Thank you for your support of the PATH Users Group. We look forward to working with you throughout the rest of the year.

Sincerely,



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AN ANALYSIS OF COSTS RELATED TO THE LOSS OF POWER QUALITY

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Abstract *- This paper aims to analyze disturbance effects related to the loss of power quality on transformers, cables, induction motors, amongst others. In addition to this, the relationship between power quality and extra costs associated to the increase in power consumed for a typical industry is also taken into account. The study uses a modern computational platform known as SABER simulator that utilizes the time domain strategy to represent the system components. Qualitative as well as quantitative analysis is carried out to illustrate the phenomenon.*

Keywords: *Power Quality, Electrical Losses, Costs, Computational Simulations*

I. INTRODUCTION

Power quality has emerged as a matter of great interest for electrical power system engineering. This can be verified by the substantial amount of research and publications covering the most different subjects related to the area. In general, the main power quality issues can be identified as
:

- harmonic distortions
- transients
- voltage variations
- voltage unbalance
- voltage fluctuations
- interruptions

The consequences of one or more of the above non-ideal conditions may cause thermal effects, life expectancy reduction, dielectric stress and misoperation of different equipment. Furthermore, the quality of power can have a direct economic impact on utilities, customers, and specific equipment. As a matter of fact, several researchers [1] have estimated cable and transformer losses when they are submitted to harmonic distortions. This paper has also analysed the relationship between cost and the benefit of applying an appropriate solution for the studied case. However, the power quality context is more general than just harmonic distortions. This means that a more comprehensive study, including more realistic system operation conditions, should be carried out in order to determine the overall power quality performance for the system.

Therefore, this paper goes into the direction of considering the relationship between power quality and the increment in power consumption. This paper starts with some considerations in relation to the performance of individual components such as cables, transformers and induction motors under different conditions of power quality loss. The non-ideal conditions to be applied to the above components are described in Table 1.

Table 1 - Conditions of power quality loss.

CASES	CHARACTERISTICS
Case 1	Ideal Supply
Case 2	System submitted to 10% of voltage harmonic distortion
Case 3	System submitted to 10% of voltage unbalance
Case 4	System submitted to 10% of undervoltage
Case 5	System submitted to 10% of overvoltage
Case 6	System submitted to 10% of voltage harmonic distortion, 10% of voltage unbalance and 10% of overvoltage

By modelling the quoted components using the time domain approach, they are included into a modern computational platform known as SABER simulator. Using this strategy, it is possible to perform computational studies to evaluate the dependence between power quality and extra costs due to the increase in power losses for a typical industry.

II. LOSS OF QUALITY EFFECTS ON TRANSFORMERS

The transformer model included in the computational program is quite complete. It considers the magnetic core non-linearity and the variation of the windings resistance with the frequency (Skin Effect). Additional information about this model can be found in [2].

According to the traditional theory, the losses in the transformers can be represented by:

$$P_t = P_i + P_c + P_s \tag{1}$$

where:

P_i - iron losses
P_c - I^2R losses
P_s - stray losses

The iron losses that are not load dependent are produced by the main flux in the magnetic circuit. They have been classically recognised as hysteresis and eddy-current losses. Considering the time domain analysis, the iron losses can be calculated as:

$$P_i = \frac{1}{T}\int_0^T v_p \times i_o dt \tag{2}$$

where:

T - simulation period
v_p - primary voltage under no-load conditions
i_o - magnetising current

On the other hand, the I^2R losses depend on the transformer loading. They are a function of load current established in the windings. So, these losses can be defined as:

$$P_c = \frac{1}{T}\int_0^T \left[\left(R_p \times i_p^2\right) + \left(R_s \times i_s^2\right)\right] dt \tag{3}$$

where:

R_p - primary winding resistance
i_p - primary winding current
R_s - secondary winding resistance
i_s - secondary winding current

The stray losses are caused by stray electromagnetic flux in the windings, core, magnetic shields, tank walls and other structural parts. For many applications it is recommended the use of a practical relationship which establishes that: $P_s = 15\ \%\ P_i$. This has been used to determine the stray losses.

Therefore, the total losses in the transformers are evaluated by adding the three above power components. Once the origin of the transformer losses has been recognised, some studies are then performed with the aim of relating the operational conditions of this equipment with the loss of power quality. The transformer used has the characteristics given in Table 2.

Table 2 - Transformer parameters.

PARAMETERS	**UNIT**	**VALUE**
Rated Power	*MVA*	3
Primary Voltage	*kV*	13.8
Secondary Voltage	*kV*	0.48
Resistance	*%*	1
Reactance	*%*	4
Windings Connection	-	Δ-Y

Besides the non-ideal conditions previously defined, the studies are performed considering some specific operational situations such as:

- Transformer under no-load conditions
- Transformer with linear load
- Transformer with non-linear load

The results of the investigations are given below.

Situation 1 - Transformer under no-load conditions

The results shown in Table 3 are related to different conditions of power quality loss.

Table 3- Iron losses in the transformer.

CASE	**P_I (KW)**
Case 1	3.15
Case 2	3.21
Case 3	4.07
Case 4	3.08
Case 5	3.51
Case 6	4.16

The results show that there is a close relationship between the iron losses and the voltage, this should be expected. This can be particularly noticed by looking at the results associated with cases 4 and 5.

In addition to the numerical comparisons about the losses, the computational program allows for the visualisation of the voltage and current waveforms related to the operation. In order to illustrate this, Figures 1 and 2 give the primary line voltages of the transformer for cases 1 and 2, i.e., under ideal and distorted voltage supply.

Fig. 1 - Line voltage - Case 1

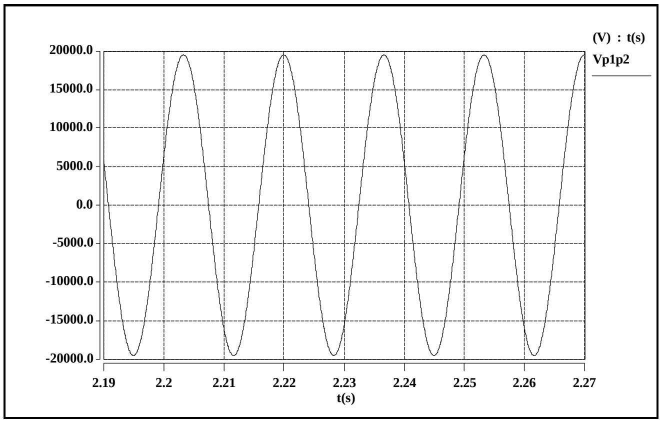
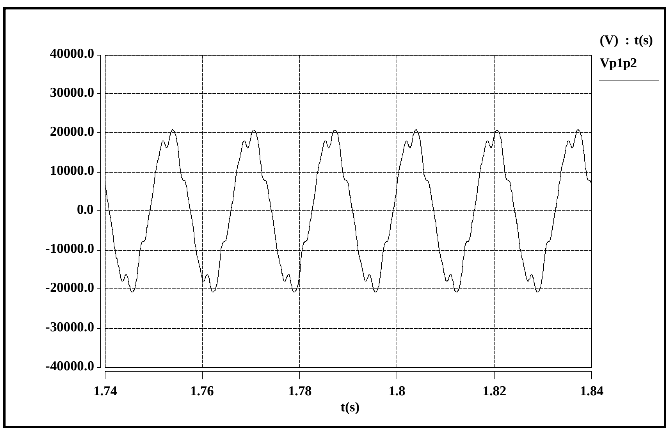


Fig. 2 - Line voltage - Case 2



Situation 2 - Transformer with linear load

In this case, the transformer losses result from the energy dissipation in the iron and the windings. By submitting the equipment to load conditions, the corresponding results are given in Table 4.

Table 4 - Transformer losses under linear load conditions

Case	P_c 9kW)	P_i (kW)	P_s (kW)	P_t (kW)
Case 1	29.19	3.15	0.47	32.81
Case 2	29.52	3.21	0.48	33.21
Case 3	29.49	4.07	0.61	34.17
Case 4	23.65	3.08	0.46	27.19
Case 5	35.31	3.51	0.52	39.34
Case 6	30.45	4.16	0.62	35.23

Again, Figures 3 and 4 illustrate the current waveforms related to this case. The currents correspond to the phase A current in the transformer primary side for cases 1 and 2.

Fig. 3 - Phase A Current - Case 1

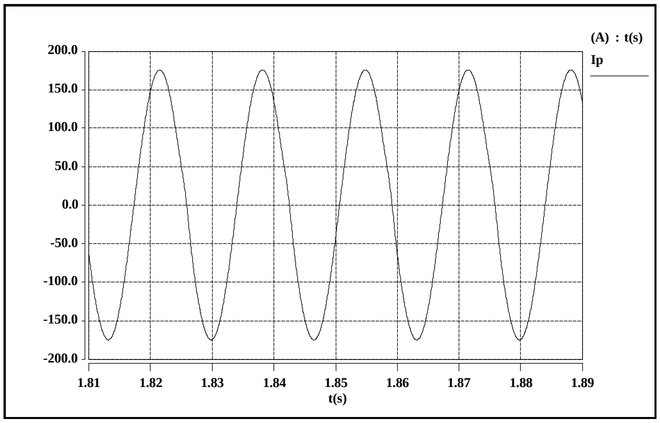
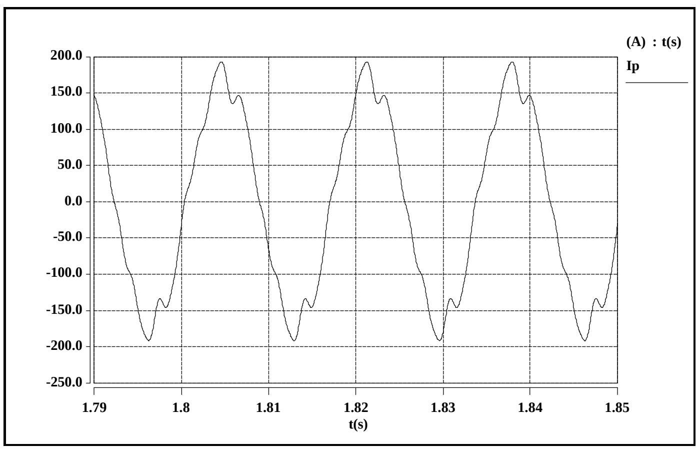


Fig. 4 - Phase A Current - Case 2



Situation 3 - Transformer with non-linear load

In this situation, the linear load in the transformer is replaced by another load with non-linear characteristics. And accordingly, 6 pulse rectifier was used. Under these conditions, Table 5 shows the individual and total transformer losses.

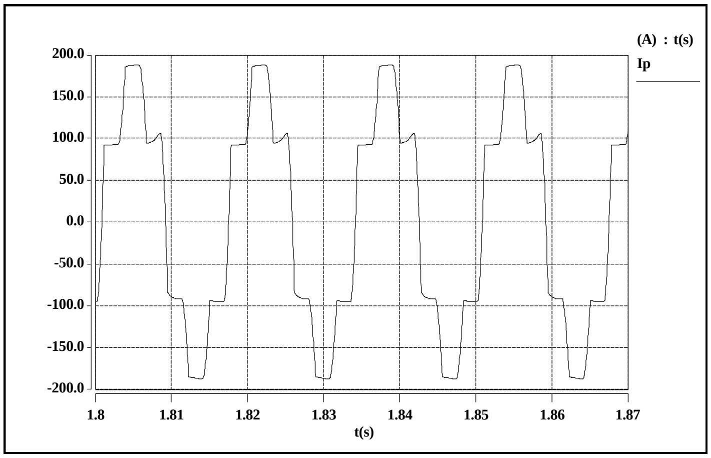
Table 5 - Transformer losses under non-linear load conditions

Case	P_c 9kW)	P_i (kW)	P_s (kW)	P_t (kW)
Case 1	31.94	3.15	0.47	35.56
Case 2	31.64	3.21	0.48	35.33
Case 3	32.06	4.07	0.61	36.74
Case 4	25.85	3.08	0.46	29.39
Case 5	38.62	3.51	0.52	42.65
Case 6	32.67	4.16	0.62	37.45

By comparing the results related to situation 3 with those in situation 2, it can be noticed that the $I^2 R$ losses in the transformer have been significantly increased. This fact emphasises that, in addition to the power quality loss dependence, there is a strong influence of the type of load connected to the transformer.

Again, this is expected. Figure 5 illustrates the phase A current in the primary side of the transformer for case 2. The waveform shows typical distortions for a 6 pulse rectifier.

Fig. 5 - Phase A Current - Case 2



III. LOSS OF QUALITY EFFECTS ON CABLES

The model associated to the cables uses classical strategies based on "pi" cells that include resistance variation with frequency [3]. By inserting this representation, it is then possible to estimate the $I^2 R$ losses. Therefore, the cable analysis under non-ideal conditions uses the following expression:

$$Losses = \frac{1}{T}\int_0^T R \times i^2 dt \qquad (4)$$

where:

R - cable resistance
i - current in the cable
T - simulation period

To illustrate the power quality impact upon losses in cables is illustrated through computational studies performed for an specific conductor. The characteristics of the chosen cable are given in Table 6.

Table 6 - Cable losses.

	Voltage class (kV)	Length (km)	Cable Size (mm^2)	Ampacity (A)
Cable	13.8	1	25	129

IV. LOSS OF QUALITY EFFECTS ON INDUCTION MOTORS

Among the options for the induction motor modelling using time domain techniques, a choice was made towards the representation based on windings entwined fluxes equations and conjugate balance equations. This strategy is known as “abc” model and it leads to a group of non-linear differential equations representing the machine operation [4].

Such as in any type of electrical machine, the induction motor losses are similar to those already mentioned for transformers, increased by the mechanical losses (P_m). S o, the total losses for these machines are:

$$P_T = P_i + P_c + P_s + P_m \quad (5)$$

The easiest way to evaluate the above total losses is given by the difference between the motor input power and the mechanical output power, i.e.:

$$P_{in} = \frac{1}{T}\int_0^T v \times i dt \quad (6)$$

and

$$P_{out} = Torque \times w \quad (7)$$

where:

- P_{in} - motor input power
- P_{out} - motor output power
- Torque - motor torque
- ω - motor speed
- T - simulation period
- v - motor applied voltage
- i - motor current

Then the losses can be defined as:

$$Losses = P_{in} - P_{out} \quad (8)$$

To illustrate the impacts caused by the loss of quality in induction motors, a typical motor was submitted to situations quoted in Table 1. The main motor parameters are: 800 cv, 4 poles, 60 Hz, 0.44 kV rated loading. Table 7 presents the loss values as well as the motor efficiency.

Table 7 - Losses and motor efficiency.

Case	P_{in} 9kW)	P_{out} (kW)	Losses(kW)	η %
Case 1	563.70	520.44	43.26	92.3
Case 2	564.51	520.64	43.87	92.2
Case 3	566.53	520.42	46.11	91.86
Case 4	561.48	518.93	42.55	92.4
Case 5	565.26	520.88	44.38	92.1
Case 6	565.93	520.02	45.91	91.8

Quantitatively, Table 7 shows that the voltage unbalances and overvoltages are responsible for the most significant losses in the induction motor.

The following figures illustrate typical motor behavior for different operational conditions. The load and motor torque for case 1 are plotted in Figure 6.

Fig. 6 - Motor and load torque - Case1

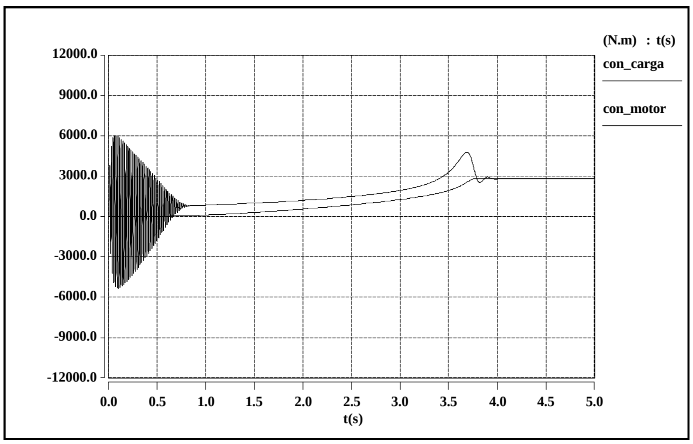
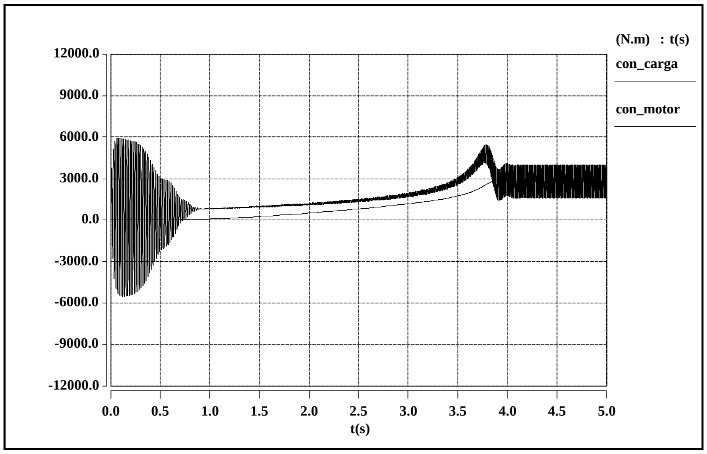


Figure 7, associated with case 3, indicates corresponding load and motor conjugate. It can be noticed as expressive oscillations in the machine axle. This is a result of the interaction between the opposite conjugates produced by the negative sequence currents produced by the unbalance.

Fig. 7 - Motor conjugate and load conjugate - Case 3



V. ECONOMIC ANALYSIS

The first part of this paper discussed individual analysis of power quality conditions upon specific equipment. At this stage, using the same computational program, an overall industrial electrical system will be submitted to non-ideal conditions. This study aims to estimate the extra annual costs related to the increase in power consumed (MWh) necessary to supply the extra losses caused by the non-ideal conditions to be established.

The industrial electrical system used for simulation is given in Figure 8. Tables 9, 10 and 11 give the data of the main equipment represented in Figure 8.

Fig. 8 - Electrical system used for simulation.

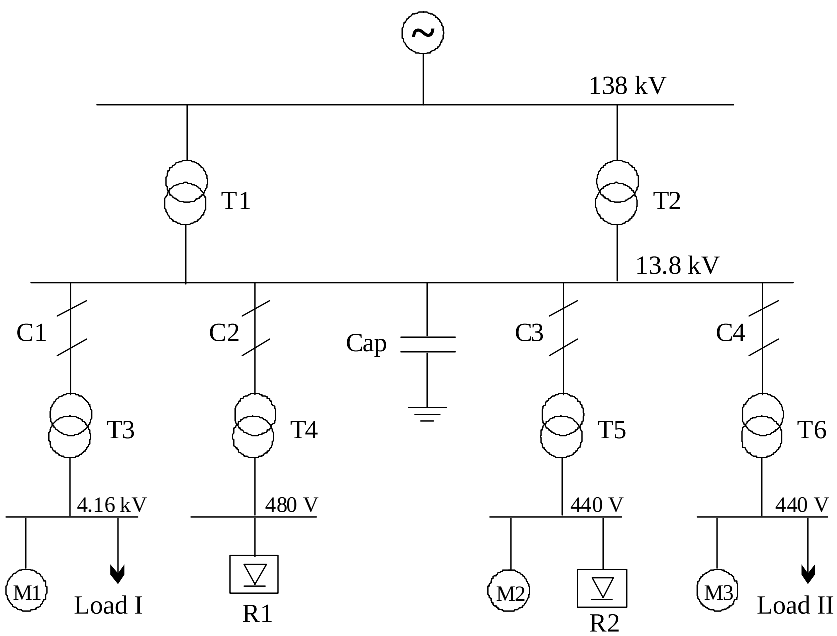


Table 9- Transformer parameters.

	T1	T2	T3	T4	T5	T6
P (MVA)	7.5	7.5	3	3	2	2
V_p (kV)	138	138	13.8	13.8	13.8	13.8
V_s (kV)	13.8	13.8	4.16	0.48	0.44	0.44
connection	Y-Δ	Y-Δ	Y-Δ	Y-Δ	Y-Δ	Y-Δ

Table 10- Motors parameters.

Motor	P (cv)	Vn (kV)	f (Hz)	np
M1	800	4.16	60	4
M2	800	0.48	60	4
M3	300	0.44	60	4

Table 11- Additional information.

Components	Values
Cables: C1 C2 C3 C4	13.8 kV / 25 mm^2 / 129 A / 1.5 km 13.8 kV / 25 mm^2 / 129 A / 1.0 km 13.8 kV / 25 mm^2 / 129 A / 2.0 km 13.8 kV / 25 mm^2 / 129 A / 0.8 km
Capacitors (cap)	1.5 MVAr
Load I	1500 kVA, cosφ = 0.85
Load II	1000 kVA, cos φ = 0.9
R1	2.5 MW / 650 V
R2	1 MW / 600 V

The non-ideal conditions used for simulation are taken as steady state situations and they consider the following:

- Situation 1 - System in normal operational condition
- Situation 2 - System submitted to 10% of voltage unbalance
- Situation 3 - System submitted to 10% of overvoltage
- Situation 4 - System submitted to 10% of voltage unbalance and 10% of overvoltage

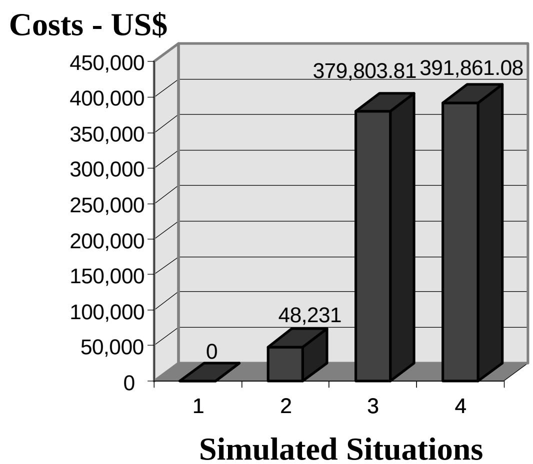
The following table gives a general idea about the total power consumed in the plant as given by the simulation. Therefore, they are related to the 138 kV busbar.

Table12 - Power consumed in the industry.

	Power Consume (MW)
Situation 1	6.48
Situation 2	6.64
Situation 3	7.74
Situation 4	7.78

The result of calculations for the extra costs related to the additional power consumed is given in Table 12. These were performed considering that the industry operates 24 hours a day and throughout the whole year. Thus, using a typical value of US$ 34.41 for the kWh cost, it is possible to estimate the increase in the electrical energy annual bill. It must be reminded that these values do not represent any value related to the demand contract.

Fig. 9 - Annual extra costs.



It is important to emphasise that the situation defined as 1, presents significant level of harmonic distortion due to the rectifiers operating in the industrial system. Under this operation condition, the annual power consume is US$ 1,953,276.76. Therefore, the increase of the losses in the system under additional conditions of loss of quality resulted, for the situations 2, 3 and 4, in extra costs of 2.5%, 19.4% and 20.0%, respectively.

VI. CONCLUSIONS

This paper has analyzed disturbance effects related to power quality upon individual system components and on a typical industrial system. Although, the authors recognize that different investigations about the consequences of a poor quality supply in some equipment have been reported, very little has been said about the financial aspects of this phenomenon. In this way using models and computational simulations, the physical origins of the extra losses were emphasised and the energy and financial effects associated with power quality were evaluated. The results showed that the solutions to solve the quality problems can not consider only technical aspects, but also the financial implications. This can contribute decisively to pay back analyses that follow any solution choice process. Finally, it is important to emphasise that the disturbances in this paper are taken as steady state conditions, which may not always be true. So, statistic/ probabilistic treatment to the matter must be considered in a more realistic study.

VII - REFERENCES

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ON THE THEORETICAL ANALYSIS OF VOLTAGE SAGS

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1. INTRODUCTION

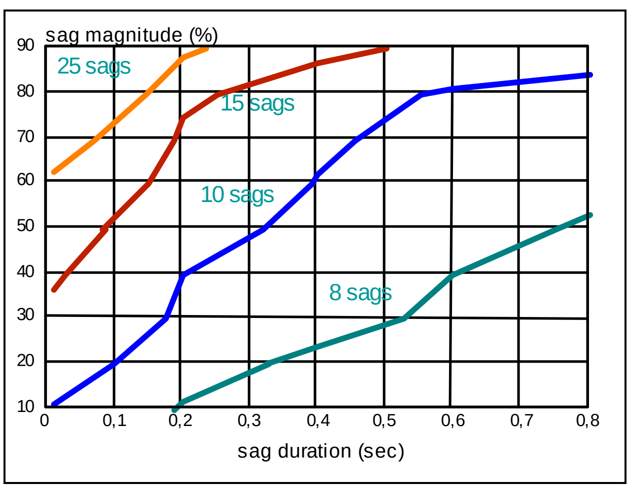
A voltage sag (or voltage dip) is a situation in which the rms voltage drops outside its normal operating margin for a short time, typically less than 1 second. Voltage sags are mainly due to short circuits in the distribution or transmission system. Thanks to power quality monitoring, the power community is gradually getting an impression of the number of voltage sags experienced by the average customer. Before the large amount of data obtained by power quality surveys can be fully utilized, some theoretical foundations are needed. This paper discusses some of the work done recently. Emphasis will be placed on characterization of voltage sags, and on a fast stochastic prediction method.

2. VOLTAGE SAG CHARACTERIZATION

During a typical voltage sag the voltage drops to a lower value (the magnitude), remains at this value for a certain time (the duration), and comes back to the pre-sag value. Voltage sags are normally characterized through this magnitude and duration. To quantify the quality of supply, the number of sags as a function of magnitude and duration has to be determined. Nowadays, several methods are being used for this. The revision of IEEE Std 493 (better known as the Gold Book) will recommend using a so-called coordination chart for this, an example of which is shown in Figure 1. The lines connect points in the magnitude-duration plane with equal number of sags. For the supply characterized by Figure 1 there are thus, for example, 10 sags per year with magnitude less than 40% and duration longer than 200 ms.

But equipment sensitivity is determined not only by magnitude and duration of sags, but also by phase-angle jump and three-phase imbalance. Research in our group has contributed to a better understanding of these phenomena.

Figure 1, Voltage sag coordination chart

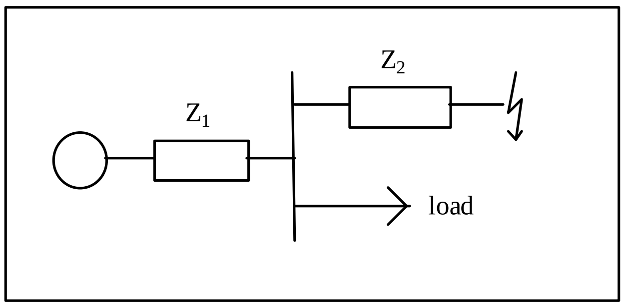


The phase-angle jump is the difference in phase angle between the pre-sag and the during-sag voltage. Two phenomena contribute to the occurrence of phase-angle jumps at the equipment terminals. The first one is the difference in X/R ratio between source and feeder. This phenomenon is best understood by considering the voltage divider shown in Figure 2. A fault will cause a voltage drop at the point-of-common coupling between the load and the fault. The voltage at the point-of-common coupling is given as:

$$\overline{V}_{sag} = \frac{\overline{Z}_2}{\overline{Z}_1 + \overline{Z}_2} \qquad (1)$$

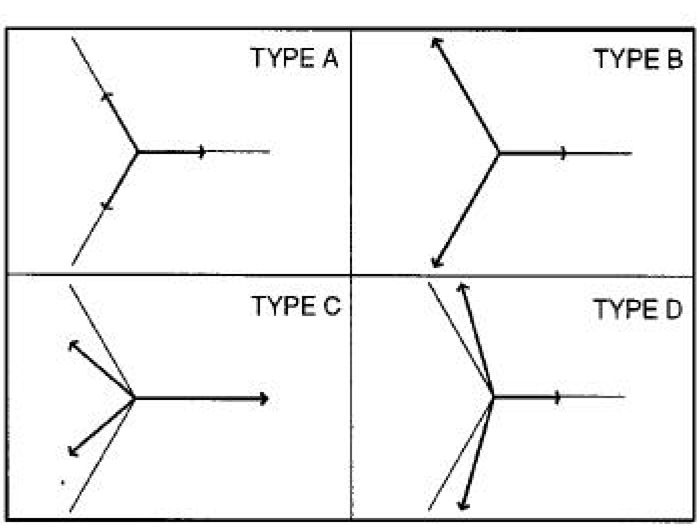
Because the impedances are not of equal X/R ratio the voltage will not only drop in magnitude but also change in phase angle, visible as a shift in zero crossing between pre-sag and during-sag voltage

Figure 2, Voltage divider model



The second phenomenon leading to a phase-angle jump at the equipment terminals is the transfer of sags through transformers. Due to the winding connection of transformers, an imbalanced sag (e.g. a voltage drop of 50% in one phase only) changes when transferred to a lower voltage level. An investigation into the transfer of sags resulted in a classification of three-phase sags into four types. These four types are shown in phasor form in Figure 3. The definition of magnitude and phase-angle is such that they normally do not change when passing a transformer. It is easy to prove now that the voltage at the equipment terminals can experience a phase-angle jump even when there is no difference in X/R ratio.

Figure 3, Four types of sags



3. THE METHOD OF CRITICAL DISTANCES

Due to the random nature of voltage sags, stochastic prediction techniques are an essential part in assessing the need for mitigation measures. Power quality surveys can be of some help, but especially for fairly uncommon events the monitoring time needs to be very long. A straightforward but time-consuming method for stochastic assessment of voltage sags is recommended in IEEE Std 493. An alternative method has been developed, which requires less system data, no computer program, and which gives more insight into the faults leading to equipment tripping.

The basis of the method is again the voltage divider model in Figure 2. The impedance between the PCC and the fault is now written as an impedance per unit length times the distance to the fault:

$$Z_2 = z \times L \qquad (2)$$

From (1) it is now possible to calculate the distance at which a fault will cause the voltage to drop to a certain value. Assuming equal X/R ratios (which turns out to be an acceptable approximation for most systems), the following expression for this so-called critical distance can be derived:

$$\mathrm{L}_{\mathrm{crit}} = \frac{\mathrm{Z}_1}{\mathrm{z}} \times \frac{\mathrm{V}}{1-\mathrm{V}} \qquad (3)$$

All sags within this critical distance lead to a sag with a magnitude less than V. To estimate the number of sags with a magnitude less than V, one only needs to add the failure rate of all equipment within the critical distance from the PCC. This has to be repeated for all possible PCCs, which is in practice for all voltage levels.

The method has been extended with equations for some non-radial configurations (parallel feeders, small loops, generator infeed), imbalanced sags, and sag duration.

4. FUTURE WORK

The work on sag characterization and stochastic assessment will continue, in cooperation with Swedish and overseas utilities. An important step to take is a comparison of both the classification and the stochastic assessment methods with the results of power quality monitoring. Also the influence of sags with different characteristics on equipment behavior will be studied.

5. FURTHER READING

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