Power Quality and Transients, Appearance in Swedish industry; Evaluation of Questionnaire

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***Abstract*—During the spring of 2000 a questionnaire was sent out to about 100 Swedish industrial companies within different lines of business. The questions concerned the electrical system, the power consumption and power quality with emphasis on high frequency disturbances. The questionnaire was sent out to find out how the transients affect the supply voltage and what malfunctions can appear due to them. Damaged equipment and shut-down in the production are two serious consequences of the disturbances. These events cause large economic costs for the affected companies. To further investigate the cause and origin of the disturbances is therefore of great importance. The goal is to eliminate or mitigate the effects of the disturbances.**

***Index Terms*— industrial power systems, lightning, power distribution, power quality, power system transients**

I. Introduction

EQUIPMENT mal-operation due to 'bad power quality' is an issue that comes up regularly in discussions between electricity companies and their industrial or commercial customers. The equipment problems due to voltage dips and short interruptions are well documented [5],[6] but no clear picture exists of the problems due to higher frequency disturbances like transients. To get a clearer picture and to find possible cases for further investigation, a questionnaire was sent out to about 100 Swedish industrial companies, during the spring of 2000. The purpose of the questionnaire was to find out how transients affect the electricity supply and what type of malfunctions can result. Disturbances can be hard to categorize and malfunctions can be the cause of different types of phenomena besides transients, for example sags or harmonic distortion. The goal with the questionnaire was to find industries with power quality problems and later on do some measurements to locate and eliminate these problems. The text of the questionnaire is in appendix A. The response frequency was about 30%. About half of the industries had no trouble at all or very little trouble with their electricity supply. Some had outages once or twice a year and others had outages in some parts of the production every week. The reason for these outages cannot always be explained, though many respondents related the production outages to lightning flashes. The statistical results of the questionnaire are presented in section II of this paper. The various power-quality concerns mentioned by the respondents are discussed in section III. A translation of the questionnaire is given in appendix A.

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II. INDUSTRIAL POWER SYSTEMS

A. *Lines of business*

The industries are in the areas of manufacturing industry, paper industry, ironworks, chemical industry, timber industry, electronic industry and other areas such as real estate management and hospitals. Fig. 1. shows the distribution of lines of business amongst the companies.

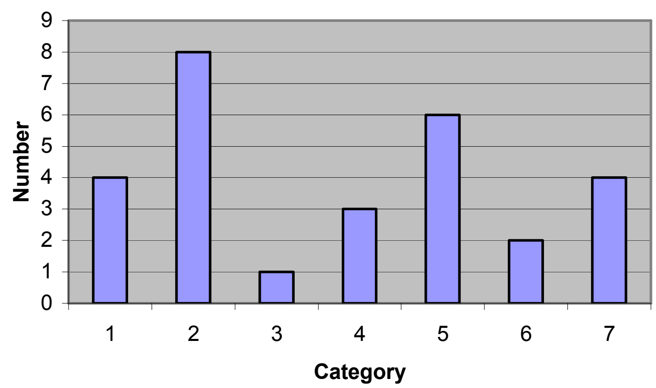

Fig. 1. Lines of business

Category:
1: Manufacturing industry
2: Paper industry
3: Ironworks
4: Chemical industry
5: Electronic industry
6: Timber industry
7: Others

B. *Voltage levels*

The contracted voltage level varies between 0,4 kV and 130 kV for the different industries. Those who are contracted for 0,4 kV are mostly electronic industries. At the 10 kV level there are manufacturing industry and wooden industry. Big paper industries are contracted for 130 kV. The industries contracted for the highest voltage level are not automatically the largest consumers of energy. Some of the industries contracted for 10 kV have higher power consumption than the ones contracted for 130 kV. Fig. 2. shows maximum load and contracted voltage levels for the different industries.

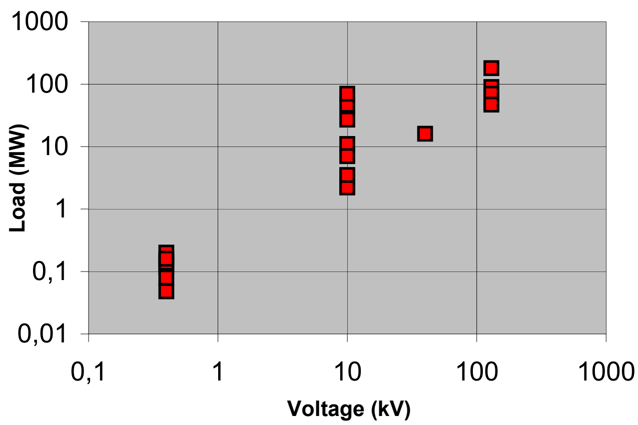

Fig. 2. Maximum load and contracted voltage level

C. Load characteristics

The maximum load varies from 12 kW to 180 MW. The annual consumption of energy lies between 90 MWh and 1240 GWh. Those consuming a lot of energy are paper industries and ironworks, while electronic industries are the low-consumers.

D. Conductor system

Most of the industries have mixed four-wire and five-wire systems in their plants. Some have five-wire systems in the newer parts of the plant and four-wire system in the older parts. Others have four-wire systems between distribution busses and five-wire systems between different apparatus in the plant. Only about 15% of the industries have five-wire systems in the whole plant. These are one electronic industry, one engineering industry, one hospital and industries for manufacturing drugs and paper. The drug manufacturing industry has problems with new laboratory equipment tripping and the supplier of this equipment is blaming the conductor system for the failure. The rest of the industries with five-wire installations have almost no trouble at all with their energy supply. If this fact is related to the five-wire installation is not possible to establish form this investigation, as most of the industries with four-wire installations do not report any trouble. The questions were not concerning 50 Hz-fields or magnetic fields. These fields are more common in four-wire installations due to stray currents, when the current instead of in the return cable flows through heat conduction pipes or water pipes. Around these pipes there occurs magnetic fields that sometimes cause disturbances [8].

E. Redundancy and reserve power

About 60 percent of the industries have some level of redundancy in their system. Two of the industries, one hospital and one paper industry have reserve power units to support the whole plant. Several of the industries have partial reserve power supply for computers and lighting. Some of the industries have UPS for computers. About one third of the industries have no reserve power at all. The most common types of reserve power supplies are diesel-generators, gas turbines and battery-packs. Fig. 3. shows the connection between contracted power level and redundancy/reserve power in the plants. There is no relation between contracted voltage level and level of redundancy.

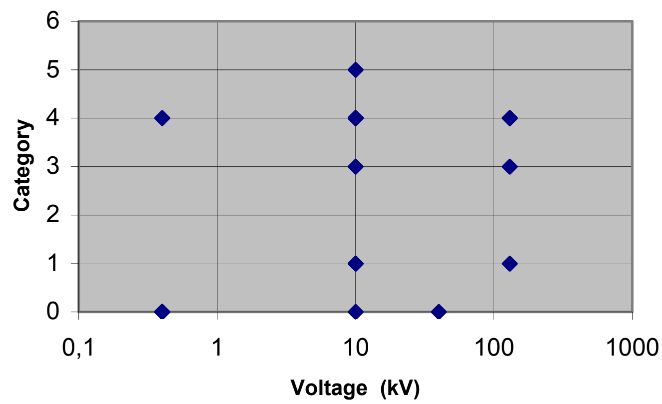

Fig. 3. Contracted voltage level and redundancy/reserve power

Category:
0:No redundancy, no reserve power
1: No redundancy, partial reserve power
2: No redundancy, full reserve power
3: Redundancy, no reserve power
4: Redundancy, partial reserve power
5:Redundancy, full reserve power

III. POWER QUALITY CONCERNS

A. Disturbances and interruptions

A large part of the power quality problems reported are related to lightning strokes. Several of the paper industries report long production outages caused by lightning strokes. The lightning leads to a short voltage disturbance, which in turn may lead to long production outages. Production outages of 10 to 15 hours have been reported, occurring up to seven times per year. The economical consequences due to this fact have not been investigated. About half of the industries have problems with inexplicable disturbances in the power supply. This is a high fraction and it shows that further investigation is needed to find out the cause of the disturbances. The high frequency disturbances are most likely originated within or close to the factory, as these disturbances do not travel far. One investigation shows that 60% of the voltage transients are originating within the plant [1]. However some of the disturbances may originate from higher voltage levels and propagate through the networks. Without measurements it is difficult to find out where the disturbances originate from and thereby be able to eliminate them. Some of the industries in the questionnaire are performing measurements themselves to investigate the causes to the production outages. Out of the 14 industries that reported inexplicable disturbances only 4 are investigating the causes. Problems that reported due to disturbances in the electricity supply network are:

- Machines tripping once/twice a week (3)
- Electronic circuitry is damaged regularly (4)
- Problems with engine-drives (2)
- Tripping of frequency converters (3)
- Computers (with no UPS) are damaged (2)
- Laboratory equipment is damaged (1)
- Capacitors are damaged (1)

The number of industries having the different disturbances is shown in the brackets. Some of the industries have more than one kind of disturbance.

Not all these problems are due to high-frequency disturbances in the networks. It is not always possible to tell which problems are due to transients and which are caused by other power quality phenomena. The tripping or frequency converters is probably caused by voltage dips [5]. Transients caused by capacitance charging can also affect frequency converters [7], but synchronized switching of capacitor banks is commonly used in Sweden. Malfunction of rotating machines can be caused by harmonics [7] while damage to electronic circuitry and computers is more likely due to transient overvoltages.

B. Lightning related problems

As mentioned before, several respondents mentioned equipment maloperation during periods of lightning activity. The effect of a lightning stroke is to induce a large overvoltage on the line. If this voltage exceeds the insulation withstand level it results in a short circuit, otherwise the voltage peak will start to propagate through the system. If the peak voltage is not high enough to cause a flashover on the line, it might still trigger a spark gap or a (ZnO) varistor. A spark gap mitigates the overvoltage by creating a temporary short circuit, which in turn causes a sag for one or two cycles. A varistor will only cap the overvoltage. A conclusion from one of the first power quality surveys [11] was that the number of voltage transients did not increase in areas with more lightning; instead the number of voltage sags increased. A nearby lightning stroke may induce overvoltages that damage equipment [6], but a more likely chain of events is that a direct stroke to a transmission line or tower leads to a flashover resulting in a short circuit. End-user equipment experience a voltage dip during the short circuit. Several large monitoring surveys show a clear increase in the number of voltage dips during summer, when lightning activities is highest [3]. In one investigation [10] registration of voltage sags have been performed in different stations all over Sweden on VHV and HV levels. The occurrence of voltage changes as voltage sags or interruptions ranging >5%, >10% and >50% drop in voltage with a duration >10 ms from registrations during 8-10 months in six 400/220 kV stations are shown in fig.4. This measurement strongly indicates more voltage dips during summer and early autumn when lightning activities are higher. Reference [4] also shows a strong correlation between lightning activity and voltage dip frequency. The different investigations show that maloperations due to lightning activity both can be caused by transient overvoltages and voltage dips. The cause in every special case can sometimes be decided by examining the damages but this issue is a question of further investigation.

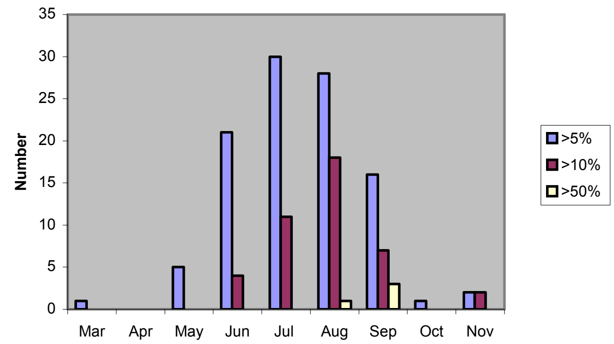

Fig. 4. Occurrence of voltage sags and interruptions from registrations during 8-10 months in six 400/220 kV stations in Sweden

C. High-frequency disturbances

The main voltage disturbances of concern to costumers at the moment are voltage sags and interruptions. High-frequency disturbances are generally considered as causing little inconvenience; and the understanding of them is also rather small. The reason for more deep investigations of transients is the likelihood that high-frequency disturbances in the power system will increase by the introduction of more power-electronics equipment using faster switching devices. Also, future end-user equipment or interfaces with renewable sources of energy may be more sensitive to high-frequency disturbances than existing equipment. A better understanding and quantification of high-frequency disturbances in the power system is needed to develop and improve EMC standards governing the interaction between equipment and the power system. Another aspect of studying transients more thoroughly is the economical consequences due to the production stoppages. Many of the problems related to lightning can be avoided with lightning-protection systems and an appropriate philosophy when constructing new buildings. The heating system and water conduit also needs to be considered in the construction process. The main reasons for transient appearing in the power systems are lightning strikes, switching actions in the network or near the load and malfunctions in the network. Transients are usually divided into two main categories, impulse-transients that are short disturbances of high frequency, and oscillating transients that are temporary fast disturbances with decreasing amplitude. Impulse transients are often caused by atmospherical interference while oscillating transients are due to switching actions. An investigation done in a number of rural industries [2] shows the following problems due to voltage transients and impulses:

- pressure switch failure
- operational problems with electronic controllers
- damaged TV,VCR and satellite dish
- power bar burnup
- computer monitor and printer damaged beyond repair

The IEEE Emerald Book [9] gives a list of the effects of voltage transients on end-user equipment:

i. electrical insulation breakdown or sparkover
ii. surge protection device failure
iii. semiconductor device failure
iv. power conversion equipment nuisance trip
v. data-processing equipment malfunction
vi. light bulbs fail prematurely

For several of these effects, the rate of rise of the voltage is as much concern as the peak amplitude.
The most common protection against surges and transients are surge diverters, filters and isolating transformers.

IV. CONCLUSIONS

The questionnaire shows that there are problems with power quality in the Swedish industry. One of the conclusions is that a number of the industries more or less accept a certain amount of disturbances in the production caused by power system phenomena. Only a few of the industries in the questionnaire perform measurements to locate the reason for the disturbances. The problems can sometimes be easily fixed as restoring a fuse while sometimes a whole machine is damaged and the whole production process is stopped. Most likely the industries are not aware of the economic consequences due to these disturbances. As high-frequency transients do not travel far it is important to make the costumers aware of the fact that the power quality problems often are caused by themselves. Lightning strikes and switching actions in the networks cause the remaining part of the transients. The majority of the high-frequency disturbances are generated in normal operation and only a small part in exceptional cases such as during short-circuit conditions. Many of the production outages can be related to voltage dips due to lightning strikes, but when the voltage is not high enough to create a short circuit or a temporary short circuit the peak will start to propagate through the system. How far the peak will propagate and how much damage it will cause depends on the system construction. One further goal of this investigation is to do an economical evaluation of the mal-operations due to transient disturbances and to perform measurements at industries where problems often occur. This would further illuminate the importance of investigating origin and propagation of high-frequency disturbances.

V. APPENDIX A

A. The questionnaire

The questionnaire as sent to about 100 Swedish industries was originally in Swedish. An English translation is given below. The Swedish text is available form the authors.

1) Electric power distribution

1 What voltage level do you subscribe to?
2 What voltage levels are present in the network?
3 What type of grounding is used in the network? If there are different types for different voltage levels, specify this.
4 Is there redundancy in some parts of the network?
5 Is five-wire system used in the whole network? If not specify the type of wiring system.
6 Indicate your power distributor
7 Indicate your owner
8 Indicate your maximum load
9 Indicate your total energy consumption for one year
10 Attach a lay-out of the network

2) Disturbances/outages

1 How often are you affected by unexpected outages?
2 Indicate, if possible, the cause of these outages
3 Estimate the length of these outages
4 How often do you have planned outages?
5 Estimate the length of these outages
6 Are you sometimes affected by 'inexplicable' disturbances that could not be explained by external influences?
7 If this is the case, estimate the frequency of occurrence
8 Do you have trouble with equipment being damaged without explanation or with short life for certain components? What equipment and which components are affected?
9 Are you affected by equipment damage in situations you can explain, for example special load situations or by outer influence from some industry nearby?
10 Are you aware of nearby industries having the same types of problems as you have?

3) Load situation

1 What type of loads are fed by the power system (indicate in percentage levels)
  - Constant load
  - Fluctuating load (sec)
  - Fluctuating load (min)
  - Fluctuating load (hrs)

2 Indicate the operational situation
  - Daytime operation
  - 24 hrs operation
  - Other operation, shift operation

3 What types of loads are connected to the network
  - Motors (medium level voltage)
  - Motors (low level voltage)
  - Lighting
  - Electrical heating
  - Load with rectifiers
  - Other load (indicate the type)

4 Other information about the load

4) Preventive actions against disturbances

1 Do you have reserve power units to support the plant or parts of the plant?
2 Indicate type and size
3 Are there any filters installed in the plant, for example harmonic reduction or suppression filters?

4 Indicate type and size
5 Is any control equipment installed in the plant?
6 Indicate type
7 Is the grid-owner able to help when there are inexplicable disturbances?
8 Does the grid-owner inform you about changed situations in the running of the network, for example changed load on transformers?

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VII. REFERENCES

[1] Roland B. Standler, Transients on the mains in a residential environment, *IEEE Trans.on Electromagnetic Compatibility*, vol 31, no.2, May 1989.
[2] D.O. Koval , Power quality of small rural industries, *IEEE Trans. on Industry Applications,* vol.26 no.4 July/Aug 1990, pp. 719-725.
[3] D.S. Dorr Point of utilization power quality study results, *IEEE Trans. on Industry Applications*, vol 31, no.4, July 1995, pp.658-666.
[4] E.W.Gunther, H.Metha, A survey of distribution system power quality-preliminary results, *IEEE Trans. on Power Delivery,* vol.10 no.1, January 1995, pp.322-329.
[5] M. H. J. Bollen , Understanding power quality problems- Voltage sags and interruptions. New York, IEEE Press 1999.
[6] R. C. Dungan, M. F. McGranaghan, H.W. Beaty, Electric power system quality, New York, McGraw Hill 1996
[7] Börje Kjellén, Driftstörningar inom verkstadsindustrin, Elforsk report 97:24 B, november 1997 (in Swedish)
[8] Ener Salinas, Mitigation of power-frequency magnetic fields, Ph.D Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2001, ISBN 91-7291-064-x
[9] IEEE *Recommended practice for power and grounding electronic equipment* (Emerald Book), IEEE Std. 1000-1099.
[10] M.Häger, K. Ahlgren, U. Grape, ” Power Quality Limits and Responsibility Sharing in the Swedish Transmission and distribution System”, in *PQA ’97 Europe*, June 1997, Stockholm, Sweden
[11] M.Goldstein, P.D. Speranza, Thequality of U.S. Commercial AC power, *Int. Telecommunications Energy Conf. (INTELEC*), October 1982, Whashington D.C. pp.28-33

VIII. BIOGRAPHIES

Anna Tjäder received her MSc. from Chalmers University of Technology in 1998. From 1996 to 1998 she worked for ÅF-Elprojekt AB, mainly on electromagnetic compatibility issues. Since 1998 she is employed as a research assistant/PhD student in the Department of Electric Power Engineeering at Chalmers University of Technology, working toward her PhD in the area of power quality with main emphasis on high frequency disturbances.

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