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Power Quality Classification: An Industrial Perception in Malaysia

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Abstract: The Power Quality (PQ) is one of the main issues in the Malaysian industries. The issue is not just a power quality but also loss of profit as well. Thus, the industrial PQ problem is an important area of research in term of classification, assessment and awareness development. This study developed a framework of survey design, data collection and an analytical model for the statistical classification of the PQ problem and its severity level in Malaysia based on the practical perception of industrial respondents. A statistical classification is done by affected equipments and the matching correlation value between PQ severity level and the normalization duration. The identified PQ Severity Factors (PQSF) are considered for different types of equipment for industrial PQ problem. The findings will assist in the formulation of appropriate policies that address the industrial PQ problem in Malaysia as well as indirectly improving the industrial PQ in the country.

Key words: Power quality, severity, classification, assessment, perception, PQ severity factors

INTRODUCTION

Power quality is the most prevalent problem in the industry in worldwide and Malaysia is not an exception. The PQ problem may originate in the power system but most frequently they are generated by the equipment or load connected to it. For example, inverter arc furnaces, welders, alternators, motors, electronic devices, process controllers, frequency converters and so many industrial equipments (Michaels, 1997; Oliver *et al*., 2002; Arnold, 2001; Hannan and Mohamed , 2005; Brooks, *et al*., 2009; Mazhar *et al*., 2008). Prolonged exposure of power quality problem can gained lethality or shorten the expected life of electronic equipment and machines by Dugan *et al.* (2004). Based on damage, defect and short-life of the industrial equipment as well as quality of the final product, the voltage sag is the most faced problem in Malaysia as shown in Table 1 (Romely, 2010; Beiza *et al*., 2009).

Table 1: Industrial power quality problem summaries based on number of incidents

Power quality events	No. of incidents	PQ problems (%)
Flicker	11	36.7
Voltage sag	15	50.0
Voltage swell	8	26.7
Harmonic	13	43.3
Transient	4	13.3
Interruption	1	3.3

The number of voltage sag incidents and percentage of PQ problems are 15 and 50.0%, respectively in 30 industries. Similarly in case of harmonic, the numbers of incidents are 13 and percentages of PQ problems are 43.3%, respectively. Thus, it is found that the voltage sag, harmonics and flicker are the most faced problem in the industries. There have been several studies on the cause of PQ problem, sources, evaluation techniques, index and severity and limit that can serve as guidelines to verify whether the amount of PQ is a problem (Vannoy *et al*., 2007; Mago *et al*., 2008; Salarvand *et al*., 2010). Many techniques were proposed in the literature for the classification and assessment of the PQ problems such as optimal time-frequency representations (Wang and Mamishev, 2004) wavelet transform (He and Starzyk, 2006) s-transform and probabilistic neural network by Mishra *et al*. (2008), rule-based decision tree by Samantaray (2010), empirical-mode decomposition with hilbert transform by Shukla *et al*. (2009), adaptive prony method site-level PQ assessment by Andreotti *et al.* (2009). All of these existing methodologies are not well-developed in terms of statistical classification, flicker assessment, its severity analysis and revealing inconsistent performance by Baran *et al.* (2004). Thus, industrial PQ is an important area of research that requires assessments, awareness and decisions for the Malaysian high-tech industries, utilities and all power consumers. IEEE is defined some standards to classify the PQ events, provide limit and recommendations for better understanding on PQ monitoring, assessment and its severity level by Mazadi *et al.* (2007). Generally, PQ

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severity is expressed based on estimation, observation and regular operating conditions (Targosz and Manson, 2007; Grzegorz, 2008). PQ estimation is used to generate the best estimate of the most significant severe effect by the PQ problem.

For example, weighted least square method and measurement matrix can be used to determine performance criteria, linear and nonlinear map between the measured signals, the desired estimated states and the unknown variable, respectively (Woods and Wollenberg, 1984; Arrillaga *et al*., 2000). However, infeasibility or uncertainty can be problems due to singular measurements or a high number of required measurements. Also, PQ measurements rarely use state estimations due to the deterioration of the Jacobian condition number (Abur and Exposito, 2004). These drawbacks are effectively eliminated by formulating a time domain model and a measurement matrix for PQ such as flicker estimation.

Again in industry, the qualitative mapping of factors such as product quality, reliability and direct cost effects can help to develop PQ assessment techniques and an awareness of its effects by Poon *et al*. (2001). To deal with these issues, this study developed a new kind of decision based industrial PQ severity assessment that creates awareness and enables decision-making on power quality improvement.

This study deals with the data obtained from a survey regarding industrial perceptions on PQ for an assessment of classification, its severity and awareness. The PQ severity level classification system used in this study is based neither on experimental nor theoretical values but rather on the practical observations of industry personnel. Three parameters are used to determine the significant PQ severity: the weighted Average Severity Score (ASS), Severity Index Value (SIV) and Rank of Severity Index (RSIV). In ASS, 4 levels of PQ severity classification are used to represent the parameter of equipment damage. At level 1, the PQ is not a problem at all; level 2 indicates light effects resulting from PQ problem; level 3 is for moderate PQ effects and level 4 indicates severe damage caused by PQ problem.

The aim is to increase the awareness level of industry personnel and provide a decision-making tool for industry and utilities consumers. This study describes a new way to convert a practical and qualitative perception of industrial PQ into quantitative and qualitative assessments, awareness and decisions.

MATERIALS AND METHODS

In industrial PQ severity classification includes methodological framework, data collection and analytical models. Details of the assessment methods are given.

Methodology framework: The methodological framework is defined as the detailed statement of the problem, survey framework, data collection and processing, data analysis, severity class and awareness as shown in Fig. 1. The problems of the existing publications have been reviewed to develop a preliminary classification (Shen and Tam, 2002; Begum *et al*., 2007).

A survey framework was developed by creating a questionnaire and a sampling procedure. Some initial questionnaire is pretested for final questionnaire development. The most important part of this framework is data collection and processing, including data recording, entry, coding and computations in order to obtain a industrial PQ severity analysis. Several PQ parameter and indices such as ASS, SIV and RSIV were developed for PQ classification.

Data collection: Data were collected through interviews with technical personnel registered with the high-tech industry between July 2009 and March 2010 in the Klang Valley, Malaysia. In total, 30 industries participated in the data collection, including semiconductor industries, process industries, manufacturing industries, heavy industries and light industries.

The semiconductor industries includes the companies that producing the semiconductor raw material, components and packaging. Process industries are mainly composed of electronics, air-conditioning, chemical and pharmaceutical industries. Manufacturing industries includes rubber and furniture industries. Heavy industries on the other hand include glass making company, steel

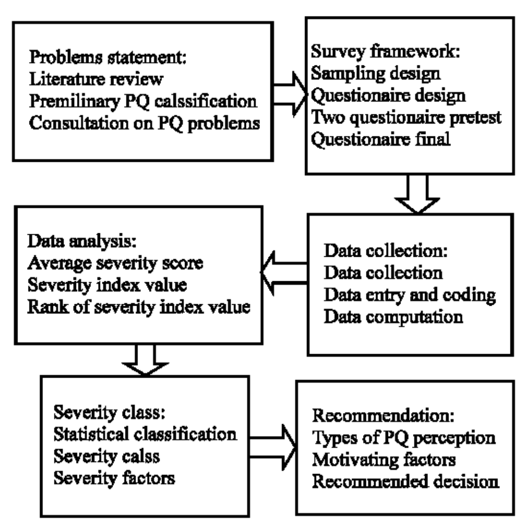

Fig. 1: Block diagram of methodological framwork used for industrial PQ serverity classification

mill, oil and gas companies. The remains are the light industries involved in making the clothes and shoes. In this study, a stratified random sampling method is applied to the 4 major groups of industries. In the 1st stage of the data collection, the samples of the types of industries in high-tech activities were selected. Then, the samples were stratified into three sub-groups in order to perform data collection, data entry and coding and data computation. The final survey was based on 30 samples of high-tech industries. The interviews were based on a set of questionnaires that were pre-tested and modified before use in the survey.

Analytical model: Upon data collection, the data were analyzed by converting qualitative industrial data into a quantitative and statistical value using the SPSS (Statistical Package for the Social Sciences) software. Three models of the flicker severity and indices are as follows:

Average Severity Score (ASS): The study employed the weighted average model to assess the relative significant level of the PQ Severity Factor (PQSF) for different types of equipment in industry based on how the equipment is affected and damaged. The weighted average model is written as:

$$ASS_i = \frac{\sum_{j=1}^{4} X_j N_{ij}}{N} \quad (1)$$

Where:

ASS_i = The average significant score to the severity factor

i and X_j = The PQ severity level which is assumed to be in between level 1-4 level where 1 indicates not a problem at all, level 2 indicates a light problem, level 3 is a moderate problem and level 4 is a severe problem, respectively

N_{ij} = The number of respondents who give the factor *I* for the level X_j

N = The total number of respondents

Severity Index Value (SIV): To calculate the ASS_i, the 4 level scales for X need to be converted into numerical scales for the purpose of simplifying the PQ severity index value. To rank the significance among all the severity factors, the researchers employed the combined value of the weighted average and the coefficient of variation. The coefficient of variation measured by the Severity Index Value (SIV) is given:

$$SIV_i = ASS_i + \frac{ASS_i}{\delta_i} \quad (2)$$

Where:

SIV_i = The coefficient of variation for the severity

i and δ_i = The standard deviation of the significance score for factor i

Rank of Severity Index Value (RSIV): After calculating the SIV, the researchers ranked the PQ Severity Factor (PQSF) of the severity index value according to the RSIV significance level.

RESULTS AND DISCUSSION

There are many ways to assess industrial data that has been collected in qualitative and quantitative forms. However, we have limited the focus to only the PQ severity assessment and awareness in this study. About 30 different types of industries were surveyed for this study. The participating industries were categorized as semiconductor industries, process industries, manufacturing industries, heavy industries and light industries.

The percentages of industries participating in this study are shown in Fig. 2. It shows that 40.00% of the survey respondents were from process industries such as air-conditioning, chemical and pharmaceutical industries; 26.67% were from the semiconductor industries; heavy industries comprised 11.54% and the remaining respondents were from light industries.

Statistical classification of industrial power quality: The PQ severity was assessed from the perception of the industrial personnel. As mentioned earlier, the level of PQ severity is classified into 4 levels based on equipment damage parameters. Figure 3 shows that 26.67% of industries faced severe PQ problems (L4) and 30.00% were faced faced severe PQ problems (L4) and 30.00% were faced with moderate problems (L3). The percentages of industrial PQ problem at level L2 and L1 were 40.00 and 3.33%, respectively.

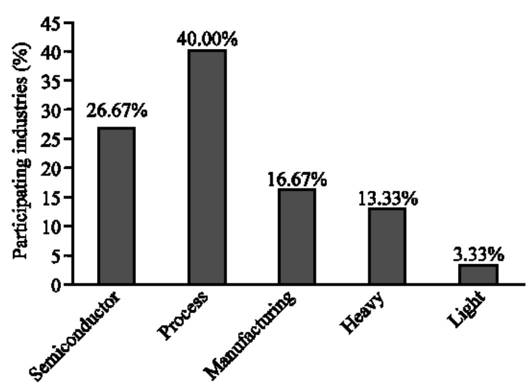

Fig. 2: Types of participating industries in the survey

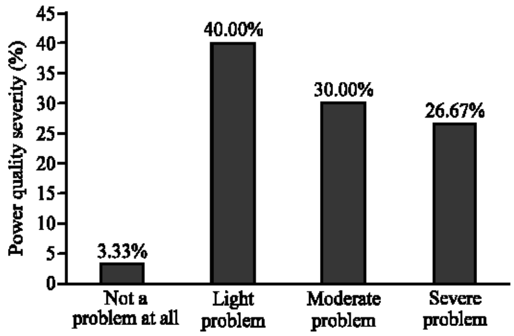

Fig. 3: Industrial power quality severity in percentage

Thus, it can be concluded that the PQ severity level in Malaysia is a significant problem in a number of industries. The industrial PQ problem classification is made based on analytical model as mentioned. The classifications were given some information about which PQ problems are more severe in Malaysia. In this study, six PQ problems are being classified and ranked such as flicker, voltage sag, voltage swell, harmonic, transient and interruptions as shown in Table 2. In order to assessment, the ranking significance of the industrial PQ problems, we have used the combination of the weighted average and coefficient of variation.

Table 2 also shows the result of the PQ severity index value and the ranks of the industrial PQ problems. The result shows that the highest PQ severity index value is 1.48 for the voltage sag. Thus, voltage sag becomes the most PQ problem that occurred in Malaysian industries. While the interruption is the lowest ranking of the PQ problem as it has the lowest PQ severity index value 0.19.

Similarly, the other parameters such as problems, mean and standard deviation are higher in case of voltage sag, the most severe PQ problems in the industries. The sensitive industrial equipments that being affected by the PQ problems are also classified using analytical model as shown in Table 3.

The analysis is done to ensure that which equipments are most vulnerable upon PQ problems through severity index value, SIV and its ranking, RSIV. The result shows that the highest PQ severity index value is 1.701 for inverter.

Thus, the inverter becomes the most vulnerable equipment in Malaysian industries. While the compressor is the lowest ranking of the vulnerability as it has the lowest PQ severity index value 0.19. Table 3 showed the equipments classification based on PQ effects using mean, standard deviation, SIV and RSIV. Thus, the analysis concluded that which equipments would suitability of this vector in representing the flicker.

Table 2: Industrial power quality classification based on combination of the weighted average and coefficient of variations

PQ problems	Problems No.	Problems Percent	Mean	Std. dev.,δ	SIV	RSIV
Flicker	11	36.7	0.37	0.490	1.13	3
Voltage sag	15	50.0	0.50	0.509	1.48	1
Voltage swell	8	26.7	0.27	0.450	0.87	4
Harmonic	13	43.3	0.43	0.504	1.28	2
Transient	4	13.3	0.13	0.346	0.51	5
Interruption	1	3.3	0.03	0.183	0.19	6

Table 3: Classification of affected equipments due to the power quality problems

Equipments	Mean	Std. dev.(δ)	SIV	RSIV
Induction motor	0.53	0.507	1.575	2
Synchronous motor	0.17	0.379	0.619	7
DC motor	0.23	0.430	0.765	5
Microprocessor controller device	0.47	0.507	1.397	3
Inverter	0.57	0.504	1.701	1
Generator	0.07	0.254	0.346	8
Arc furnace	0.03	0.183	0.194	9
Static rectifier	0.23	0.430	0.765	5
Lighting	0.33	0.479	1.019	4
Compressor	0.03	0.183	0.194	9

The performance of these equipments were tripped or stopped when the PQ problems happened. Then, the others process that related to these equipments will also get trouble. Sometimes, these equipments damage and need to be changed with the new one. Even though, the power quality problem only occurred <1 min, the process to recover from this problem may take almost 12 h. The statistical classification is made based on the correlation between the variables and the parameter. The aspect is considered the distance between the similarities of the variables to normalize the correlation transform results into 0-1 scale.

The transformation is made using Pearson product moment correlation coefficient methodology. The transformation is the sum of the products of the standard scores of the 2 measures divided by the degrees of freedom. The result of the relation is shown in Table 4 for ease interpretation. Transformation value >0.5 is suggested as a matching criterion.

The transformation value can be obtained by matching the correlation value of certain column vector with the corresponding row vector. For example, matching PQ severity level 2 (light problems)with voltage flicker yields 0.288 which is <0.5. This means the 2 vectors are not related.

The normalized duration of PQ for the health hazard is 0.55 while >0.5 indicates severe PQ problem. Similarly, the normalized correlation between parameters vector values are shown in Table 4. The duration did not have a compact pattern that enables it to classify the PQ

Table 4: Pearson matching correlation of power quality severity scales

Power Quality Severity Factor (PQSF)	PQ severity level: Not a problemat all	Light problem	Moderate problem	Severe problem	Normalized duration of PQ that occurred
Flicker	0.400	0.288	0.638	0.566	0.171
Voltage sags	0.456	0.412	0.359	0.725	0.000
Voltage swell	0.309	0.590	0.690	0.727	0.293
Harmonics	0.412	0.316	0.200	1.000	0.356
Transient	0.387	0.445	0.107	0.998	0.044
Machine shut down	0.400	0.288	0.315	0.908	0.060
Less quality problem	0.425	0.344	0.437	0.504	0.275
Health hazard	0.456	0.412	0.478	0.387	0.550
Tripping industry devices	0.425	0.344	0.247	0.918	0.073
Loss of production	0.547	0.551	0.557	0.649	0.352
Process line shut down	0.344	0.339	0.523	0.668	0.266
Voltage fluctuation	0.309	0.438	0.403	0.727	0.265
Status monitoring and lighting	0.400	0.483	0.315	0.737	0.362
Loss of raw materials	0.440	0.375	0.298	0.830	0.540

severity. However, it is possible to obtain the probability of the duration of PQ that likely contribute to the certain level of severity. Analysis must be done to ensure the suitability of this vector in representing the PQ severity class. The most suitable methodology is to use the median so as to know any pattern that relates the duration and the severity. Thus, a comfortable conclusion can be made that the severity does indeed dependant on the duration. Prolonged duration of PQ problem proved to be lethal to the system and it must be solved fast. In this sense, median can be use to signify the severity of PQ problem. This study presents 10 PQ Severity Factors (PQSFs) in terms of equipments for an industrial PQ assessment. The identified severity factors are considered as having different effects on the different types of equipment in Malaysian industries.

The estimated results of the weighted value of the ASS, standard deviation δ, Severity Index Value (SIV) and the Rank of Severity Index Value (RSIV) are shown in Table 5. The relative significance levels from the 30 respondents for each severity factor shows that the highest ASS is 4.00 for the synchronous motor (PQSF-2), arc furnace (PQSF-4), compressor (PQSF-9) and generator (PQSF-7). This indicates that PQSF-2, PQSF-4, PQSF-7 and PQSF-9 cause the least severe effects or less significant damage.

Similarly, the ASS values for the severity factors are between 4.00 and 3.00 such as inverter (PQSF-6), induction motor (PQSF-8), microprocessor controller device (PQSF-3) and lighting (PQSF-10) are the most severe effects or damage due PQ problems. PQSF-1 and PQSF-5 indicates DC motor and static rectifier, respectively.

This study used the combined value of the weighted average and the coefficient of variation to rank the significance of the flicker severity factors. It should be mentioned that the ASS is a weighted average and can be used to rank all of the PQSFs. However, a commonly recognized weakness of using the weighted average is that it does not consider the degree of variation between individual responses. In fact, a smaller variation between individual responses can give a better weighted average value. Therefore, when 2 factors have the same or very close average values, the factor carrying the smaller variation should be given a higher rank. One common technique is to mitigate the weakness of ranking attributes using weighted average value and apply a measure called the coefficient of variation which is obtained by dividing the weighted average by the standard deviation. Thus, an effective classification of ranking attributes should consider both the weighted average and the coefficient of variation. The coefficients of variation are measured by the SIV model.

Table 5: Weighted value of ASS and severity index value for different power quality severity factors

PQSF	ASS	δ	SIV	RSIV
1	3.25	0.71	7.85	6
2	4.00	0.00	0.00	7
3	3.33	0.62	8.73	3
4	4.00	0.00	0.00	7
5	3.67	0.82	8.16	5
6	3.71	0.49	11.33	1
7	4.00	0.00	0.00	7
8	3.50	0.58	9.56	2
9	4.00	0.00	0.00	7
10	3.30	0.67	8.19	4

Table 5 also shows the results of the SIV and the Ranks of the Severity factors (RSIV). The results show that the highest SIV is 11.33 for the inverter (PQSF-6) and the lowest SIV is 0 for the synchronous motor (PQSF-2) arc furnace (PQSF-4), compressor (PQSF-9) and generator (PQSF-7). In fact, the result shows that the ranks of the PQ severity factors did not change much for the 2 criteria of ASS and SIV. It is reasonable to assume that the ranks established by either ASS or SIV effectively provide a PQ severity assessment for the industrial devices. Thus, PQ severity is perceived through the average score of severity, standard deviation, severity index value and provided the rank of severity index value for implementing the industrial PQ classification. The result, therefore can be greatly used as a guide to consider the steps to be taken in order to counter the damaging effect due to PQ problems in the industries. It also provide guidelines to start being alert and aware from PQ problems. Thus, the industry should take precautions in order to avoid loss and damage due to PQ problems.

CONCLUSION

This study classifies various types of PQ problem by analyzing statistical method. The statistical classification shows that 26.67% of the industries face severe problems and 30.00% of industries have a PQ severity level of 3 which is considered lethal and unhealthy for the industries. The findings are indicated that among the PQ events, the voltage sag is the most faced (50.00%) problem, followed by harmonics (43.30%), observed by 30 participating industries. Again, PQ severity level is classified its rank based on affected equipment through median, standard deviation and SIV and median duration. It was found that prolonged median duration and higher SIV could be lethal to the industries.

The normalized correlation transform between parameters vector values are indicating the class of PQ severity index level. Transformation value >0.5 is suggested as a matching criterion. For example, the normalized duration of PQ for the health hazard is 0.55 while >0.50 indicates severe PQ problem. Similarly, matching PQ severity level 2 i.e., light problems with PQ problem yields 0.288 which is <0.5. This means, the 2 vectors are not related. The classification quantifies the PQSF as mentioned earlier.

According to the respondents, inverter is the most significant PQSF that contributes PQ problem while the synchronous motor, arc furnace compressor and generator are the least significant in Malaysian industries. Thus, the average flicker severity score, severity index value and severity index value ranking would provide valuable information for classification industrial equipment and also create enough sense on PQ problem.

RECOMMENDATIONS

A guideline can be recommended through evaluating the various types of classification to make an appropriate policy on industrial PQ problem in Malaysia. Thus, local authorities in industry or the government should provide guidelines for industry personnel specifying PQ factors for the equipment via government industrial ordinance.

NOMENCLATURE

ASS_i	=	Average significant score to the severity factor i
X_j	=	Flicker severity level
N_{ij}	=	Respondents number of factor i for the level Xj
N	=	Total respondent's number of complex time-varying Fourier coefficient
SIV_i	=	Severity index value of coefficient variation of factor i
δ_i	=	Standard deviation of the significance score for factor i
PQ	=	Power quality
PQSF	=	Power quality severity factor
PQSF-1	=	PQSF of DC motor
PQSF-2	=	PQSF of synchronous motor
PQSF-3	=	PQSF of microprocessor controller
PQSF-4	=	PQSF of arc furnace
PQSF-5	=	PQSF of static rectifier
PQSF-6	=	PQSF of inverter
PQSF-7	=	PQSF of generators
PQSF-8	=	PQSF of induction motor
PQSF-9	=	PQSF of compressor
PQSF-10	=	PQSF of lightning

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