Comprehensive Hierarchy Evaluation of Power Quality Based on an Incentive Mechanism

Tao Shun, Xiao Xiangning, HadjSaid, N.

Abstract**—**In a liberalized electricity market, it is not surprising that different customers require different power quality (PQ) levels at different price. Power quality related to several power disturbances is described by many parameters, so how to define a comprehensive hierarchy evaluation system of power quality (PQCHES) has become a concerned issue. In this paper, based on four electromagnetic compatibility (EMC) levels, the numerical range of each power disturbance is divided into five grades (Grade I –Grade V), and the "barrel principle" of power quality is used for the assessment of overall PQ performance with only one grade indicator. A case study based on actual monitored data of PQ shows that the site PQ grade indicates the electromagnetic environment level and also expresses the characteristics of loads served by the site.

The shortest plank principle of PQ barrel is an incentive mechanism, which can combine with the rewards/penalty mechanism (RPM) of consumed energy "on quality demand", to stimulate utilities to improve the overall PQ level and also stimulate end-user more "smart" under the infrastructure of future SmartGrid..

Keywords**—**Power quality, electromagnetic compatibility, SmartGrid, comprehensive evaluation, barrel principle, electricity market

I. INTRODUCTION

CUSTOMERS will obtain electricity services at reliability and quality levels tailored to their individual needs with greatly reduced environmental impacts[1] under the infrastructure of future SmartGrid. Therefore, in the future electricity market it is no wonder that end-users will smartly select different demands of power quality associated with their electric bills.

Power quality (voltage quality and reliability) related to several power disturbances is described by many parameters, so how to define a comprehensive hierarchy evaluation system of power quality (PQCHES) and how to measure the consumed energy on quality demand have become a concerned issues. To support the multi-grade PQ transactions, the study on the comprehensive hierarchy evaluation of PQ that is reasonable and easily understandable for the general public, as well as on the indices and benchmark for characterizing PQ, is very necessary [3]-[8].

PQCHES study usually focuses on two issues. One is how to divide hierarchy reasonably, and the other is how to project multi-dimensional indices to one-dimensional quality grade scientifically and objectively. In this paper, each of power disturbance levels in public power networks is divided into five grades according to four different electromagnetic compatibility levels, and an objective consolidation method of the comprehensive evaluation is proposed based on an incentive mechanism. The application of PQCHES based on reward/penalty mechanism is also discussed for measuring consumed energy of customers with regards to power quality demands.

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II. PQCHES PRINCIPLE

A. Hierarchies of single index

IEC61000-2-4 international standard gives three compatibility levels at nominal voltage up to 35kV and a nominal frequency of 50Hz or 60Hz. Class 1 applies to protected supplies and has compatibility level lower than those on public networks; class 2 applies generally to point-of-common-couplings (PCCs); and class 3 applies to in-plant point of couplings (IPCs) in industrial environments. Compatibility levels for four kinds of disturbances (voltage deviations, voltage unbalance, frequency deviations and voltage harmonics) are defined in [2].

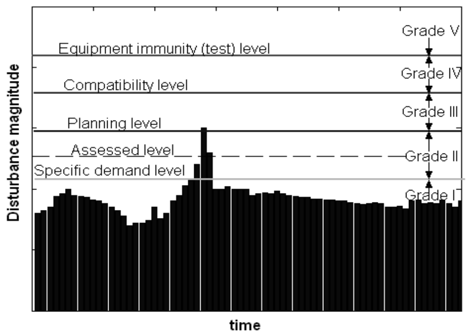

Fig.1. Illustration of PQ grades classification

In IEC61000 series standards, three levels are usually employed to describe the compatibility between power disturbance and equipment immunity. They are planning level, compatibility level and equipment immunity test level as shown in Fig.1. The planning level and compatibility level corresponding respectively to class 1 and class 2 in [2] are usually used by utilities and regulators to restrict the performance of public supply system. Poor power quality with a quantified value higher than the equipment immunity test level generally can cause customer equipments to malfunction. Besides these aspects, for some special groups of customers, such as commercial buildings (finance companies, data banks and so on) or high-tech parks, the demand of PQ level would be higher than that of the public system. Therefore, the specific limits for these special groups should be defined, illustrated as Fig.1.

Based on the four levels of EMC, the numerical range of each power disturbance can be divided into five grades (Grade I –Grade V), as shown in Fig. 1. The smaller the number of grade is, the better the quality is, otherwise, the bigger the number of grade is, the poorer the quality is. The middle grade, Grade III, corresponds to the public network compatibility range. The assessed grade of the power disturbance is determined by the numerical interval to which the assessed index value belongs.

TABLE I, for example, gives the hierarchies of six types of power disturbances and main odd harmonics, based on the existing standards such as IEC/EMC standards, and some network performance trends and operation experiences.

TABLE I
THE CLASSIFICATION OF PQ INDICES

Kinds of PQ	Voltage range	GradeⅠ	Grade Ⅱ	Grade Ⅲ	Grade Ⅳ	Grade V
Frequency deviation (Power frequency qualification rate) %	LV-HV	>99.999	[99.999, 99.9]	(99.9, 99]	(99, 95]	<95
Voltage deviation (Voltage qualification rate) %	LV-HV	>99.99	[99.99, 98]	(98, 95]	(95, 92]	<92
Average service availability index (ASAI) %	LV-HV	≥99.999	(99.999, 99.99]	(99.99, 99.9]	(99.9, 99]	<99
Voltage unbalance % CP95	LV-HV	[0, 1)	[1, 1.5]	(1.5, 2]	(2, 3]	>3
Total harmonic distortion (THD) % CP95	LV-MV	[0, 3)	[3, 5]	(5, 8]	(8, 10]	>10
	HV	[0, 2)	[2, 3]	(3, 5]	(5, 8]	>8
Harmonic voltage component 3 order % CP95	LV-MV	[0, 2)	[2, 3]	(3, 5]	(5, 6]	>6
	HV	[0, 1.5)	[1.5, 2]	(2, 3.2]	(3.2, 6]	>6
Harmonic voltage component 5 order % CP95	LV-MV	[0, 2)	[2, 3]	(3, 6]	(6, 8]	>8
	HV	[0, 1.5)	[1.5, 2]	(2, 4]	(4, 6]	>6
Harmonic voltage component 7 order % CP95	LV-MV	[0, 2)	[2, 3]	(3, 5]	(5, 7]	>7
	HV	[0, 1.5)	[1.5, 2]	(2, 2.5]	(2.5, 3.2]	>3.2
Harmonic voltage component 9 order % CP95	LV-HV	[0, 1)	[1.0, 1.2]	(1.2, 1.5]	(1.5, 2.5]	>2.5
Harmonic voltage component 11 order % CP95	LV-MV	[0, 2)	[2, 3]	(3, 3.5]	(3.5, 5]	>5
	HV	[0, 1)	[1, 1.5]	(1.5, 1.7]	(1.7, 3.2]	>3.2
Harmonic voltage component 13 order % CP95	LV-MV	[0, 2)	[2, 2.5]	(2.5, 3]	(3, 4.5]	>4.5
	HV	[0, 1)	[1, 1.5]	(1.5, 1.7]	(1.7, 3.2]	>3.2
Long term severity of voltage flicker CP95	LV-MV	[0, 0.6)	[0.6, 0.7]	(0.7, 0.8]	(0.8, 1.0]	>1.0
	HV	[0, 0.4)	[0.4, 0.6]	(0.6, 0.8]	(0.8, 1.0]	>1.0

Notes：

1) The Grade Ⅱ ,Ⅲ and Ⅳ are almost paralleled respectively to Class 1,2 and 3 in [2].

2) According to the regulations of State Grid Corporation of P.R. China, power frequency qualification rate or voltage qualification rate are defined as the ratio of the time that values of frequency or voltage do not exceed high or low limited values to the total time of monitoring, expressed in percent.

3) Voltage sags and short duration interruptions became concerned problems [9]. Based on the average economical equivalent interruption hours of customers for sags, average service availability index (ASAI) or reliability of service (RS) in the table may be corrected to consider voltage sags and short duration interruptions [10]-[11] as:

$$ASAI^* = (1 - \frac{SAIDI + SASDI}{8760}) \times 100\%$$

where, SASDI is System Average Sag economical equivalent interruption Duration Index.

4) CP95 means 95% probability weekly values.

5) The levels in the table are based on IEC61000 series standards, G5/4 of the United Kingdom, CIGRE C4.07 Final WG Report and GB 12326 and GB/T 14549 of P.R. China.

6) LV: Un≤ 1kV, MV: 1kV<Un≤ 35kV, HV: 35kV<Un≤ 230kV, where Un is nominal voltage of PCCs.

B. *Comprehensive hierarchy evaluation*

（1）The “barrel principle” of PQ

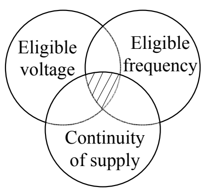

Fig. 2. Basic requirements of power quality

It is well known that the quality of supply mainly consists of three basic requirements: eligible voltage, eligible power frequency and continuity of supply. Fig.2. shows the interdependence and mutual restraint relationships among these requirements. In order to ensure the safe operations, customer equipments should run in the electricity environment of the shadow of Fig.2. When the electricity environment changes in any direction outside the shadow, the required parameter in the anti-direction will affect the equipment operations.

Let’s study a case happened in an industrial plant. A large ac three-phase motor malfunctioned twice a year. After PQ monitoring and diagnosing, the reason was only that power

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loads in the plant distributed inconsequently among three phases such that the voltage unbalance rate was up to 3.2%, which would be Grade Ⅳ in TABLE I. It was voltage unbalance that induced the motor failure, although the deviation of voltage and frequency, and total harmonic distortion were all within acceptable limits, up to Grade II. Motor's operation capacity must be decreased to 90% due to 3% voltage unbalance rate in accordance with NEMA Standards Publication No.MG-1-1987. Therefore, from the view point of power quality, the maximum permissible power (P_{max}) for safe operation of the machine follows the "barrel principle" (See Fig.3.), which is to say, among all planks assembling a wooden barrel, the shortest plank determines the barrel's volume. In this case the assessed value of voltage unbalance = 3.2%/2% =1.6 per unit, (where, 2% is the compatibility level in IEC 61000-2-2 : 2002) that is the shortest plank of the PQ barrel. From the view point of derating, P_{max} is less than 90% of rated power. That is to say the derating factor of the motor caused by power disturbances only depends on the voltage unbalance disturbance with Grade IV and not on the other disturbances with Grade II.

An assumption is implied here, of course, that the bench mark of each disturbance is rational and scientific.

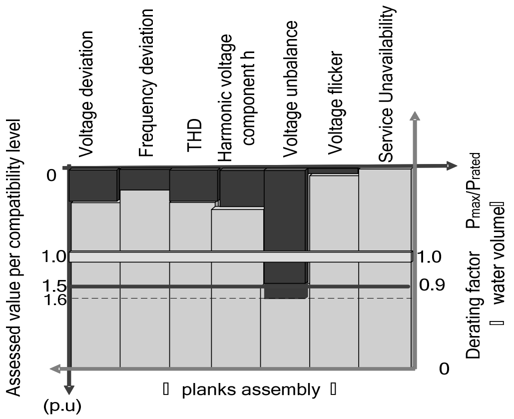

Fig. 3. Plan of the PQ "barrel"

The barrel principle is also known as the shortest plank effect, an incentive mechanism. In order to improve the wooden barrel volume, the most effective way is to find and lengthen the shortest board. In the above-mentioned case, the voltage unbalance was significantly mitigated after the power loads re-allocation. The voltage unbalance rate is about 0.9% and the motor has never malfunctioned like before.

Therefore, based on the reasonable and acceptable standard limit levels of power disturbances, the comprehensive hierarchy evaluation method of power quality, following the "barrel principle", is valid to assess the overall PQ influence on end-users. The defined PQCHES can highlight the major issues that determine the overall PQ grade and the running status of end-users' equipment.

（2）Comprehensive hierarchy evaluation of sites

The comprehensive hierarchy evaluation of a given site should exactly reflect the actual overall PQ grade of users supplied at the site. The result of PQCHES at the monitoring sites of power systems is an indicator for consumers to select their entry bus at which the PQ grade would meet their demands.

The first step of the evaluation is to measure all relevant parameters and to calculate all assessed values of indices defined in PQ standards (at 10 min interval for continuous-type disturbances) or in the PQ contracts accepted by utilities and customers.

The next step is to evaluate the grades of all power disturbances in accordance with the principle of hierarchy classification, as an example shown in TABLE I. The overall PQ grade is the biggest number among all separate disturbance grades. Therefore, an indicator of a site's overall PQ can be calculated simply and objectively without any human intervention.

The single PQ grade indicator facilitates the site ranking. It is also to allow the prioritizing of sites for PQ improvement. The assumption will be correct that the site which ranks last ought to be the one at where customers are badly influenced by power disturbances, and that the power disturbance which ranks last is the major problem of the site and need to be mitigated, as long as the standard limit levels of power disturbances are rational.

(3) Comprehensive hierarchy evaluation of power system

It is not practical to set PQ measurements at all PCCs throughout the power system with expensive costs. Therefore, measurements are often conducted at wide and representative monitoring sites for characterizing system quality. Based on the evaluation results of these sites, the PQ grade of the system can be evaluated.

Weighting factors are always introduced to take into account the sites not monitored and the difference in importance between different sites. Weighting factors can be based on the number of customers, or the rated power represented by each site, or the load sensitivity [6]. The overall PQ grade of a power system was defined as (1) in this paper.

$$C_S = \frac{\sum_{i=1}^{k} L_i \times C_{M(i)}}{L_T} \tag{1}$$

where, C_S is overall PQ grade of the power system, C_M overall PQ grade of site i, k the total number of monitoring sites, L_i connected kVA served from the site i. and L_T the total connected kVA served from the system being assessed.

The single PQ grade indicator will not exactly represent the quality level of service provided to each customer served from the assessed system. However, the PQ grade can be used as a benchmark against which PQ grades for various parts of the network could be compared.

III. EXAMPLES

The measurements were carried out over one week at the selected PCCs of three substations in China P.R. The statistical items of PQ were voltage qualification rate, power frequency qualification rate, voltage flicker, voltage unbalance and distortion.

Site A is 110kV PCC of a 220 kV substation served for electrified locomotive. Site B is 110kV PCC of an 110kV substation mainly served for a high-tech park. Site C is 0.38kV bus of a 10kV power distribution room served for a university campus.

The comprehensive hierarchy evaluation is carried out using the monitoring data, shown in TABLE II. The overall grade of Site A is Grade V, and the environment of EMC is the poorest. The main issues of Site A, that determine the overall grade, are voltage distortion, deviation of voltage, and voltage unbalance because of the heavy and electrified AC-DC locomotive loads. The overall grade of Site B is Grade II, which means that this is a premium power zone for high-tech industries. Though Site C has the same grade as Site A, Grade V, the concerned power disturbance is only the voltage distortion, especially harmonic voltage component 3 because the power loads almost are computers and laboratory instruments with single-phase rectifier, and compact fluorescent lamps.

The case study shows, the single overall PQ grade qualitatively indicates the level of electromagnetic environments and also expresses the load characteristics of the site.

TABLE II
PQCHES RESULTS OF A CASE STUDY

Sites	Site A		Site B		Site C	
Items	Assessed Values	PQ Grade	Assessed Values	PQ Grade	Assessed Values	PQ Grade
Voltage qualification rate %	74.41	V	100.00	I	100.00	I
Power frequency qualification rate %	100.00	I	100.00	I	100.00	I
Long term severity of voltage flicker	0.45	II	0.55	II	0.38	I
Voltage unbalance %	3.81	V	0.37	I	0.26	I
THD %	5.06	IV	1.38	I	11.89	V
Harmonic voltage component 3 order %	2.26	III	0.39	I	11.60	V
Harmonic voltage component 5 order %	2.83	III	1.25	I	1.49	I
Harmonic voltage component 7 order %	2.39	III	0.53	I	1.44	I
Harmonic voltage component 9 order %	2.81	V	0.14	I	1.42	III
Harmonic voltage component 11 order %	2.46	IV	0.11	I	0.85	I
Overall PQ Grade	--	□	--	II	--	V

IV. APPLICATION DISCUSSION

Over the coming years, in the SmartGrid development infrastructure, not only energy supply will become more and more tailored to customer needs, but also the quality of power supply, as an ancillary service, will be selected by end-users. Compared with energy market real-time pricing and trading, power quality prefers to be guaranteed with long-term (or one-year) quality contract and the reward/penalty mechanism (RPM) can be built as shown in Fig. 4 based on PQCHES for example. Grade III acts as a numeraire. p_X is reward/penalty payment of X PQ grade evaluated over a week. If power quality of consumed power energy over a week can be characterized and evaluated by smart electric energy meters, consumed energy with X PQ grade, e_X, can be measured. Consumed energy with different PQ grades is cumulated respectively over a year, for example as shown with the dotted line in Fig.4. The RPM payment *RPP* obtained by the distribution system operator (DSO) is calculated using (2).

$$RPP = e_I p_I + e_{II} p_{II} - e_{IV} p_{IV} - e_V p_V \qquad (2)$$

If end-users (or virtual load plant) sensitive to power quality demand high quality guarantee, Grade I or Grade II, *RPP*>0 and DSO would attain a rewards payment. On the other hand, some users prefer to select quality below compatible levels of the public system, Grade IV or even Grade V, and in turn can acquire the compensation payment from the DSO (*RPP*<0).

Therefore, the consumed energy on the basis of "quality demand" can be measured and the DSO would improve the lowest level quality item to the "mean level" based on the shortest plank principle of PQ barrel and the RPM.

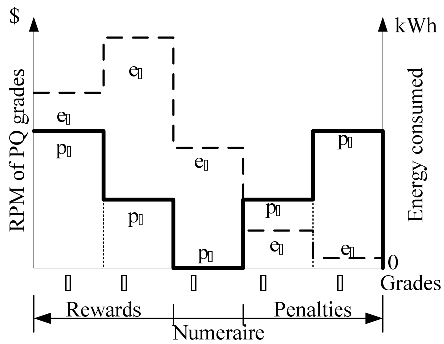

Fig. 4 Reward/penalty mechanism of PQ grade

Survey results show that the vast majority of users (including residents) are affected by power disturbances and the losses accumulated are considerable, but they are not willing to pay additional costs for PQ improvement. Therefore, by maintaining a certain profit-condition the utilities have to keep the public supply system quality grade to Grade III.

It should be pronounced here that this paper only focuses on the voltage quality. Pollution sources of harmonics, flicker and unbalance disturbances always exist near the sites of Grade Ⅳ or Grade Ⅴ. The pollution sources need to purchase pollution emissions rights [12] base on current quality, which is not discussed here.

V. Conclusion

A comprehensive hierarchy evaluation method of PQ is proposed based on an incentive mechanism of "the shortest plank effect". The numerical range of each power disturbance is divided into five grades in accordance with special demand levels for sensitive customers, planning levels, compatibility levels and equipment immunity levels of EMC. The assessed grade of a power disturbance is determined by the numerical interval to which the assessed index value belongs and the overall grade of a site is the biggest number among all power disturbance grades, and the PQ grade of a power system is defined by weighting factors.

The hierarchy evaluation system of PQ is defined such that it is easily to be understood and manipulated by operators, customers and regulators, and it also can be easily embedded in smart energy meters. The consumed energy of customers whether on reliability and quality demands can be measured. Based on the reward/penalty mechanism, demand response and demand side management will be more flexible. The power suppliers can be stimulated to lengthen the shortest plank of PQ, thus the overall PQ grade will be improved.

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