Comprehensive Evaluation of Multiple Power Qualities in Distributed Network Based on AHP and Optimal Membership

Guangyu Yang
School of Electrical Engineering
Xi'an Jiaotong University
xi'an, China
yangguangyu@stu.xjtu.edu.cn

Yi Hao
School of Electrical Engineering
Xi'an Jiaotong University
xi'an, China
yi_hao@xjtu.edu.cn

Zebin Yang
School of Electrical Engineering
Xi'an Jiaotong University
xi'an, China
shinyrain@outlook.com

Haotian Sun
School of Electrical Engineering
Xi'an Jiaotong University
xi'an, China
sunhaotian@stu.xjtu.edu.cn

Zekun Ma
School of Electrical Engineering
Xi'an Jiaotong University
xi'an, China
mazekun@stu.xjtu.edu.cn

Zhuo Fang
School of Electrical Engineering
Xi'an Jiaotong University
xi'an, China
zffz@mail.xjtu.edu.cn

Chengzhi Zhu
Zhejiang Electric Power Corporation
Hangzhou, China
Chengzhi_zhu@163.com

***Abstract*—A comprehensive evaluation approach of power quality based on AHP and optimal membership is proposed in this paper. This paper selects the appropriate power quality indexes by analyzing the characteristic of power quality. The continuous power quality indexes can be reasonably analyzed by establishing the fuzzy membership function and the transient power quality can be calculated according to IEEE 1564-2014. In addition, the weight of each index can be determined dynamically which includes both subjective part and objective part. Finally, an IEEE-18 standard test system with non-linear loads and compensation devices is applied to prove the validity of the proposed evaluation system.**

Keywords—power quality, comprehensive evaluation, AHP

I. INTRODUCTION

PQ (Power Quality) has recently become a major concern to both electric suppliers and electric customers [1] -[4]. With a large number of applications of precision sensitive loads, power customers have given increasing concern to power quality. Power quality issues such as voltage sag, harmonic, voltage deviation and so on are inevitable. According to the European LPQI (Leonardo Power Quality Initiative team report）, the industry sectors surveyed in 2007 lost 150 billion euros because of power quality issues [5].

It is difficult to comprehensively evaluate the power quality indexes of the power system when multiple indicators of power quality work together in a system. Therefore, the mathematical model of each power quality indicator should be established based on the actual situation and appropriate mathematical methods to conduct comprehensive power quality assessment. There are many power quality assessment methods, such as AHP (Analytic Hierarchy Process), Probabilistic eigenvalue, ANN (Artificial neural networks), fuzzy theory, Genetic projection pursuit method, etc. Reference [6] gives a new method, ICA, to calculate the indexes, but no simulation is applied. Reference [7] proposes a classification of power quality, but there is no theoretical calculation. Reference [8] uses ANN to analyze data in a 0.38kV distribution grid area, but no foundation is built for dividing the power quality level and the threshold.

In this paper, a new comprehensive evaluation model based on AHP and optimal memberships is proposed. A single power quality assessment is built to calculate the score of each transient indictor and continuous indictor. Then in order to combine subjective weight with objective weight, a new weight determination method based on AHP and fuzzy algorithm is proposed. To validate the proposed method, the IEEE 18-node network is simulated and analyzed.

II. SELECTION AND EVALUATION OF SINGLE QUALITY PROBLEM

Power quality comprehensive evaluation includes calculation of continuous and transient indexes. Voltage deviation, frequency deviation, unbalance, harmonics and voltage sag are the most frequent power quality issues in power systems, where voltage sag is the transient issue and others are continuous issues. According to the standards of power quality problems, the continuous and transient indexes can be built respectively.

A. Evaluation Method of Continuous Power Quality Based On Fuzzy Algorithm

Fuzzy algorithm is a process of successive refinement, and its key is to select the membership function. The optimal membership degree method using the Cauchy distribution is

This paper was supported by National Natural Science Foundation of China under grant 51977172，by the Fundamental Research Funds for the Central Universities xjj2018009 and also by the Science and Technology Project from State Grid Corporation of China (52110418000S)

proposed in this paper. The Cauchy distribution is shown in (1).

$$\lambda_i = 1/(1+\alpha_i \cdot x_i^{\beta_i}) \text{ , } i = 1,2,3,4 \tag{1}$$

where , λ_i is the membership of indicator i ; x_i is the absolute value of deviation; α_i and β_i are the constant corresponding to index i.

For the power grid with nominal voltage of 0.38kv, the total harmonic distortion rate of voltage shall not exceed 5%, the voltage deviation of the three-phase public connection point of 20kV and below shall not exceed ± 7% of the nominal voltage, the normal frequency deviation of the small capacity power system (below 300MW) shall not exceed ± 0.5Hz, the three-phase voltage imbalance degree of the public connection point shall not exceed 2%. Based on this, the individual scores of each steady-state index are established.

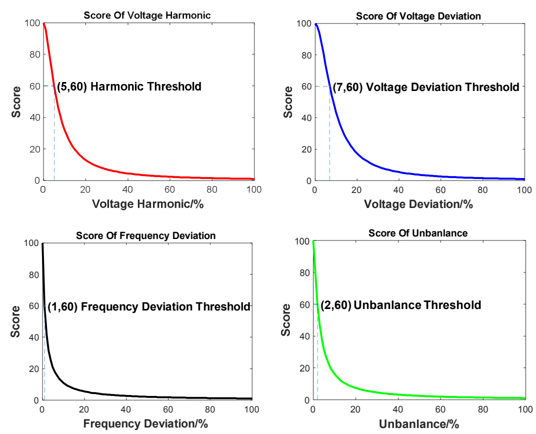


Fig. 1. The score of different power quality indexes

B. *Evaluation Method of Transient Power Quality*

As for voltage sag, the complete evaluation system for voltage sag given by IEEE 1564-2014 mainly consists of five steps: 1) acquisition of voltage monitoring parameters, 2) voltage sag characteristic value calculation, 3) calculation of individual event indicators, 4) single node indicator calculation, 5) system indicator calculation [9].

The single event indicator reflects the level of impact of a single voltage sag event on the grid. MDSI (combined magnitude duration severity index) is commonly used for single event evaluation. The frequency of voltage sag can be described by the SARFI indicator. The severity of voltage sag can be calculated as (2), (3) and (4):

$$MDSI = \frac{MSI \times DSI}{100} \tag{2}$$

$$SARFI = \frac{N_T \times T_{st}}{T_{total}} \tag{3}$$

$$CEI = MDSI \cdot SARFI \tag{4}$$

where MSI is the magnitude severity index, DSI is the duration severity index; N_T is the times of voltage sag during the monitoring period, T_{st} is the standard period, T_{total} is the monitoring period; CEI is the score of voltage sag.

$$DSI = \begin{cases} 0 & d < t_{\min} \\ (d - t_{\min}) \times (\dfrac{100}{t_{\max} - t_{\min}}) & t_{\min} \le d \le t_{\max} \\ 100 & d > t_{\max} \end{cases} \tag{5}$$

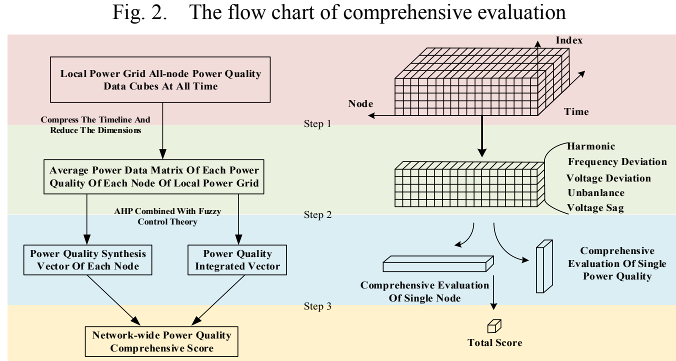
$$MSI = \begin{cases} 0 & m > U_{\max} \\ (U_{\max} - m) \times (\dfrac{100}{U_{\max} - U_{\min}}) & U_{\min} \le m \le U_{\max} \\ 100 & m < U_{\min} \end{cases} \tag{6}$$

Where $t_{\min}$, $t_{\max}$ is the time characteristic value on tolerance curve, $U_{\min}$, $U_{\max}$ is the amplitude characteristic on tolerance curve, d is the duration of voltage sag , m is the amplitude of voltage sag . According to the definition of voltage sag (voltage sag is the effective value of supply voltage rapidly drops to 90% - 10% of the rated value, and the duration is 0.5 cycles - 1 minute).In this paper , $t_{\min}$ is 0.01s, $t_{\max}$ is 60s , $U_{\min}$ is 0.1Uref and $U_{\max}$ is 0.9Uref.

III. COMPREHENSIVE EVALUATION OF MULTI-NODE AND MULTIPLE INDICATORS

Comprehensive power quality evaluation focus on how to scientifically and objectively transform multiple events into a single event, which means to converse the power quality indicator point from high dimensional space to low dimensionality space. This paper proposes a power quality assessment method based on AHP (analytic hierarchy process) and fuzzy algorithm. The process of comprehensive evaluation is shown in Fig.2.

Fig. 2. The flow chart of comprehensive evaluation



Step 1, reduce the dimension of time to get a matrix of nodes and indicators. By evaluating the power quality of each time period, a three-dimensional cube containing indicators, time, and nodes can be turned into a two-dimensional cube containing indicators and nodes.

Step 2, reduce the node dimension to get the score of each node or reduce the indicators dimension to get the score of each indicator.

Step 3, get the total score of the network by each indicator score or each node score, as shown in Fig 2.

AHP is a technique for organizing and analyzing complex decisions [10]. Its basic principle is to establish a hierarchical structure to break down complex decision problems by the means of comparing between any important indicators. Each priority of indicators is given by experienced experts. Then the subjective weight could be calculated by (5):

$$W = (w_i)_{1*n}, (j = 1, 2..., n) \tag{5}$$

Where w_i is the subjective weight of the index i.

In order to make the score more accurate to reflect the evaluation results, the indicator with low score has a high weight. The objective weight is simplified as (6):

$$v_i = \frac{1}{\lambda_i} / \sum_{k=1}^{n} \frac{1}{\lambda_k} (i = 1, 2..., n) \tag{6}$$

Where v_i is the objective weight of indicator i; λ_i is the membership of indicator i.This paper combines the subjective weight and objective weight to calculate the weight comprehensively, as shown in (7):

$$\xi = (\xi_i)_{1*n} = \frac{w_i v_i}{\sum_{j=1}^{n} w_j v_j}, (i = 1, 2, ..., n) \tag{7}$$

Where v_i is the objective weight of indicator i, w_i is the subjective weight of the index i, ξ_i is the comprehensive weight of indicator i. The overall rating can be calculated as (8):

$$S = A \cdot \xi^T \tag{8}$$

Where S is the score of comprehensive evaluation , A is the score of single evaluation, ξ_i is the comprehensive weight.

IV. CASES ANALYSIS AND SIMULATION

The comprehensive evaluation is illustrated using the 18 bus balanced three-phase system shown in Fig. 3. This system contains 16 busses at 12.5 kV, and 2 buses (#50 and #51) at 138kV, as shown in Fig. 3(a). Then this system adds six-pulse line commutated converter, located at bus 4, 7and 24, serves as a source of interference source, as shown in Fig. 3(b). Finally, in order to improve the power quality, the reactive power compensation device and the supporting capacitor are respectively added, as shown in Fig. 3(c).

A. Case I: Intensification of power quality issues

The broken line graph in Figure 4 (above) represents the comprehensive scores of various power quality indicators of the regional network, including 5 broken lines, which respectively represent harmonics, frequency deviation, voltage deviation, imbalance, and voltage sag. The radar graph in Figure 4 (above) contains the real-time scores of 18 nodes.

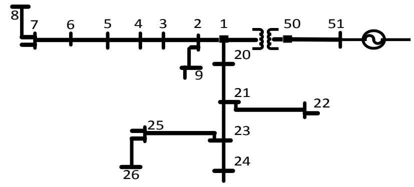


Fig 3(a): IEEE 18 node schematic diagram

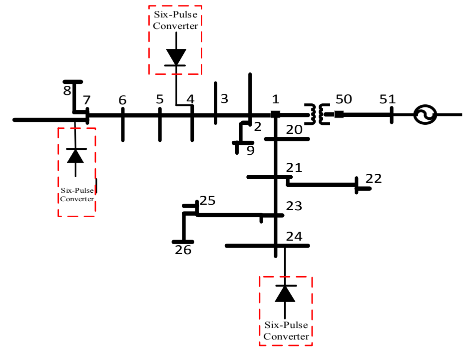


Fig 3(b): Regional grid with non-linear load before compensation

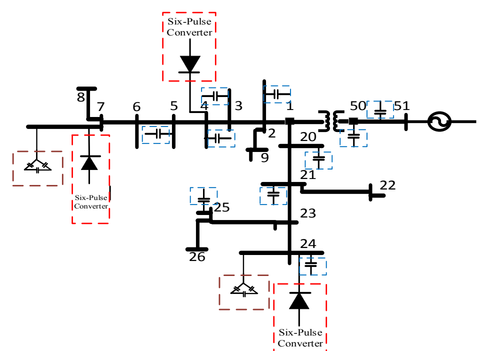


Fig 3(c): Regional grid with non-linear load after compensation

Fig. 3. The 18-Bus Study System

The broken line graph in Figure 4 (lower) represents the total score of the regional network; the radar graph in Figure 4 (lower) contains the real-time score of five indicators.

It can be seen that before 200ms, the power quality score of the grid was close to 90 points, but after 200ms, the voltage imbalance score and voltage deviation score dropped sharply to close to 0 point, at the same time, the voltage sag and frequency deviation harmonic remained 90 point, and then we can analyze that the unbalanced load was added at 200ms, so the network score dropped to 40 point, and the decrease of voltage deviation fraction may be due to unbalanced load coupling. At 400ms, the harmonic fraction is reduced from 100 to 20, while the scores of other indexes are basically unchanged. We can analyze that harmonic causes further degradation of power quality. For the scores of each node, it is also shown in Fig. 4. It can be seen that the power quality of other nodes does not exceed the pass line after 200ms, except for the nodes 17 and 18 at the initial end of the network. Through the results of the invention, we clearly know that the point of imbalance and harmonic in the network are obviously over standard. Therefore, we can add reactive compensation device and auxiliary capacitor respectively as shown in Figure 3(c)

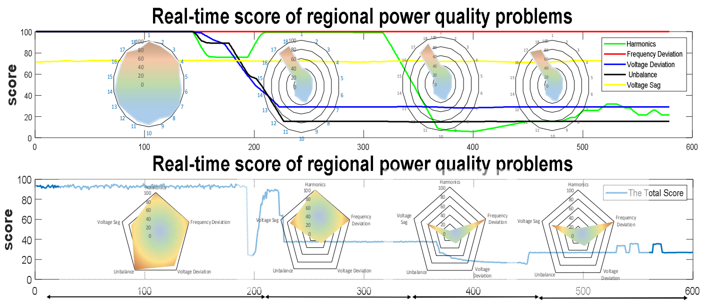


Fig. 4. The Real-time score during deterioration

B. Case II: Mitigation of power quality issues after compensation

In order to improve the score of harmonics and voltage deviation, the support capacitor and reactive load are added, Referring to paper (11).

The broken line graph in Figure 5 (above) represents the comprehensive scores of various power quality indicators of the regional network, including 5 broken lines, which respectively represent harmonics, frequency deviation, voltage deviation, imbalance, and voltage sag. The radar graph in Figure 5 (above) contains the real-time scores of 18 nodes. The broken line graph in Figure 5 (lower) represents the total score of the regional network; the radar graph in Figure 5 (lower) contains the real-time score of five indicators.

At 400ms, the voltage deviation and harmonic score are significantly improved, from failing grade to nearly 90 points. It can be indicated that the effect of compensation is significant, while the voltage imbalance still needs management.

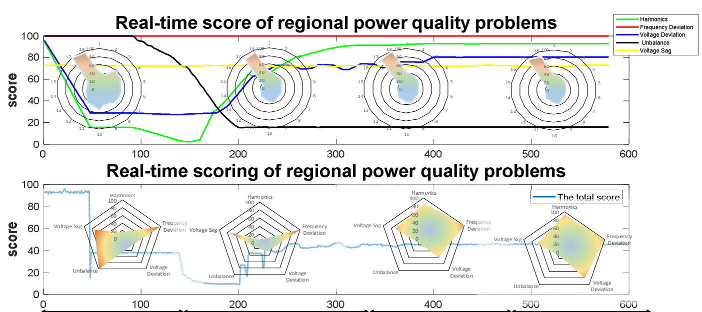


Fig. 5. The Real-time score after compensation

V. CONCLUSIONS AND FUTURE WORK

In this paper, the objective weight of different indexes is determined by spatial structure and the subjective weight is determined by the experienced expert to avoid unilateral evaluation. Moreover, this method provides an effective guide to the improvement of power quality and reduces the difficulty of find which factor affects network power quality in the future, the validity of this method can be proved in the IEEE 18-node network.

ACKNOWLEDGMENT

This work was supported by National Natural Science Foundation of China under grant 51977172 , by the Fundamental Research Funds for the Central Universities xjj2018009 and also by the Science and Technology Project from State Grid Corporation of China (52110418000S)

REFERENCES

[1] WEN Jifeng, LIU Pei. A new method for detection of power quality disturbances. Proceeding of the CSEE, 2002,22(12) : 17-20.

[2] Loredana C, Alessandro F, Simona S. A distributed system for electric power quality measurement. IEEE Trans. on Instrumentation and Measurement, 2002, 51(4):776-781.

[3] L. Xiong, X. Liu, C. Zhao and F. Zhuo, "A Fast and Robust Real-Time Detection Algorithm of Decaying DC Transient and Harmonic Components in Three-Phase Systems," in IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 3332-3336, April 2020.

[4] L. Xiong et al., "Static Synchronous Generator Model: A New Perspective to Investigate Dynamic Characteristics and Stability Issues of Grid-Tied PWM Inverter," in IEEE Transactions on Power Electronics, vol. 31, no. 9, pp. 6264-6280, Sept. 2016.

[5] Targosz R, Manson J. European LPQI PQ survey[C] //Vienna:CIRED 19th International Conference on Electricity Distribution,2007.

[6] M. Liang and Y. Liu, "A new method on power quality comprehensive evaluation," 2009 9th International Conference on Electronic Measurement & Instruments, Beijing, 2009, pp. 3-1057-3-1060.

[7] D. Ze-jun, Z. Yong-qiang and X. Yu, "New Idea of Comprehensive Evaluation of Power Quality," 2010 International Conference on Intelligent System Design and Engineering Application, Changsha, 2010, pp. 993-996.

[8] S. Yuan, W. Tong, C. Tong and Z. Li, "A Novel Method for Power Quality Comprehensive Evaluation Based on ANN and Subordinate Degree," 2008 Fourth International Conference on Natural Computation, Jinan, 2008, pp. 62-65.

[9] M. Liang and Y. Liu, "A new method on power quality comprehensive evaluation," 2009 9th International Conference on Electronic Measurement & Instruments, Beijing, 2009, pp. 3-1057-3-1060.

[10] IEEE Std 1564-2014. IEEE Guide for Voltage Sag Indices[S]. 20 June 2014

[11] Sipahi S, Timor M. The analytic hierarchy process and analytic network process: an overview of applications[J]. Management Decision, 2010, volume 48(5):775-808(34).