A NEW POWER QUALITY OBSERVATION ALGORITHM TO POWER DISTRIBUTION NETWORK

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ABSTRACT
Nowadays, the number of nonlinear loads is increasing dramatically. Such loads not only cause power quality problem but also are sensitive to them. Accordingly, the measurement and analysis of power quality indices has received much attention. Due to financial and technical limitations, the measurement of all points is not possible and therefore, it is necessary to arrange an algorithm by which to make the system observable despite the number of meters is less than unknown state variables.

This paper presents a method to make the power distribution system observable by limited measurements and proposes global indices to compare different points. The aim of this project was to demonstrate the power quality overview to the managers of utility companies, to empower them to better decide to resolve the network problems. The algorithm has been evaluated in a sample electric power distribution network. Finally, to ensure a quick and easy calculation, software was designed using MATLAB.

INTRODUCTION
Widespread use of nonlinear loads has resulted in power quality problems in electric power networks. Recognition and improved of the power quality indices enables better operation and future programing in utilities. To solve this problem, two points must be considered: first, the number and placement of power quality measurement points; and second, calculation of indices and comparing of them. Due to financial and technical limitations, the measurement of all point is not possible; thus, it is necessary to arrange an algorithm to make the system observable despite the number of meters is less than unknown state variables. There are three methods to select measurement points which shows network power quality status [1]. First method requires a lot of sample points and time-consuming measurement [2]. Second one is based on current waveform. The best and most effective method is to categorized loads in terms of the consumption types such as residential, commercial, official and industrial. Majority of projects in power quality study have used this method [3], especially EPR1 project. United State Power Center has performed EPR1 project since 1990 till 1995 to identify and improve power quality indices. In this paper, third method was selected, improved and then evaluated in Gilan electric power network. Gilan is a province in north of Iran covering 14044 Km², with 1,200,000 customers.

In this paper, loads are divided into three categories based on region, type and power transformer capacity. Load types are residential, commercial and industrial. According to limitation measurement, some control variables such as total number of measurement points, weighted load coefficient, percentage of upstream feeders, minimum transformer capacity and industrial loads coefficient were considered. Then a strategy was proposed and different scenarios were considered. According to situation and variables, different scenarios were defined to determine measurement points. By measuring, the single power quality indices such as THD, TDD, unbalanced voltage coefficient, etc. were calculated. However, they represent only intensity of each phenomenon separately; thus, it is necessary to have an index which includes all power quality phenomenon of a sample point.

In this paper, the global power quality indices (GPQI) were investigated by comparing the ideal and measurement wave shape, combining individual indices and considering economic impact of power quality distortion on customers [4-8]. Finally, two new indices were proposed to present power quality situation of each point which called improved UPQI and \( K_{\text{margin}} \). The second one is based on the combining of single indices on each PQ disturbances.

To ensure a quick and easy calculation, software has been designed. It perform the processes automatically and consecutively.

THE STRATEGY FOR SELECTING MEASUREMENT POINTS
There are three methods to select measuring point which shows network power quality status [4]. First method was used to predict harmonic injection in the future. It requires a lot of measuring and is time-consuming. The data collected in this method consist of regions, load type, hours of work and nominal power of the tools [2]. Second method is based on current waveform. The loads are categorized into linear and nonlinear groups [5]. This method is used for forecasting of harmonic growth. The best and most effective method is to categorized loads in terms types of consumption such as residential,
commercial, official and industrial. The majority of projects in power quality studies have used this method [3] especially EPRI project. In this paper, third method was used, but it was improved according to sample point’s limitation.

**Proposed Method**

In this paper, third method was used to select sample points. For this purpose, a matrix was defined with columns representing geographic area and the rows representing different types of load. EPRI project has selected sample points randomly but it has been done intelligently in this paper. To categorize sample region, these steps were followed:
- division of the stations (20kv/400v) and substation (63kv/20kv) according to power
- division of the geographical area according to power
- division of loads according to power type (residential, commercial-official and industrial)
- Division of industrial loads according to power and types (metal, wood and paper, food production, Chemical and Petrochemical, Rubber and plastic, etc.)
- division of nonindustrial loads according to power (Urban and rural)

The selection process had two steps: first, doing the above steps; second, combining of all constrains and selecting final sample points. Equation 1 expresses the power of each city in terms of percentage of total network power.

\[
\text{portion of geographical area(pg\%)} = \frac{\text{power of geographical area}}{\text{network nominal power}} \times 100
\]

The nominal power of the case study network was 3400MW and 40 sample points were selected. So the number of sample point was given by equation 2.

\[
\text{number of each area sample points} = \text{pg(\%)} \times 40
\]

In the same way, the portion of load types, station, substation and different types of industrial loads were obtained. Final stage, combining all constrain was done experimentally.

Software was designed to perform all steps automatically, so it’s necessary to define some control variables and scenarios to do the final step.

<table>
<thead>
<tr>
<th>states</th>
<th>Load type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight coefficient(mesh)</td>
</tr>
<tr>
<td>Upstream feeder(%)</td>
<td>Minimum capacity of station(kW)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
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<td>3</td>
<td>1</td>
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<td>4</td>
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</tbody>
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**POWER QUALITY SYSTEM INDICES**

Global power quality indices (GPQI) are important in characterizing the quality of voltage waveforms. In particular, these indices provide overall indication regarding different aspects of power quality disturbance. They are categorized to three groups:

- **GPQI based on comparing ideal voltage and real waveform [6-8]**

This index determines discrepancy between the waveforms of real and ideal voltage of network. It was defined as the normalized RMS error [7-8], the normalized three phase global index [9] and the voltage quality deviation factor [7-8].

- **GPQI based on combining the single indices of each points [4, 9-11]**

This index shows the voltage quality on power buses. To calculate the index, first, the single indices were measured and then normalized; and finally they are combined to give a number. There are some methods to combine single indices such as global indicator (k0),[10] unified power quality index (UPQI)[12], and average indicator (I\_AVL).

- **GPQI based on the economic effect of disturbance to customer [13]**

This index, called service quality index, is based on disturbance economic effects. When the cost of blackout is determinate, the cost of small disturbances such as voltage sag could be defined as a percentage (weighted factor) of blackout cost. Cost is a function of customer type, so SGI should be calculated for each type of customer separately.

**PROPOSED POWER QUALITY INDICES**

The three GPQI categories presented in previous section have had some limitations. So new indices were presented and calculated in case study.

**Indices proposed by combining of single indices on each PQ disturbance**

To obtain this type of indices, first all power quality indices were measured and calculated for each PCC and then disturbance indices were combined. They were categorized in terms of voltage disturbance, current disturbance and load type.

For example, the 3rd voltage harmonic was measured on chosen PCC and then the results were combined. It would indicate the 3rd harmonic qualification of network. However, the most important issue is that there is not any standard to evaluate such indices. To solve the problem, this paper suggested specific levels. A certain percentage of normalized local index was considered as a benchmark and then acceptable levels were determined by system operators and local legislator.

Integrated harmonic voltage index is defined as follow:

\[
V_{h}^{eq} = \sqrt{\sum_{k=1}^{N}(a_{k} \times V_{h,k})^{2}} \]

\[
a_{k} = (P_{\text{loading}} \times V_{1})_{k}
\]

where \(V_{h}^{eq}\) denotes harmonic voltage index of network, N is the number of chosen points, \(V_{h,k}\) are \(h_{h}\) harmonic voltage and weight coefficient of \(k_{h}\) sample point, respectively. A similar equation defined for THD.

\[
\text{THD}_{h}^{eq} = \sqrt{\sum_{k=1}^{N}(a_{k} \times \text{THD}_{h,k})^{2}}
\]

\(\text{THD}_{h}^{eq}\) denote \(h_{h}\) global total harmonic distortion index.
of voltage, THD<sub>k</sub> is total harmonic voltage distortion of k<sub>th</sub> sample PCC. a<sub>k</sub> denotes weighted coefficient which is based on the importance of voltage distortion on k<sub>th</sub> sample PCC. P<sub>loading</sub> depends on the loading of k<sub>th</sub> bus. The higher the loading, the more the importance of voltage distortion. a<sub>k</sub> is percentage which is correlated by the main component of voltage.

All these equation could be defined for current harmonic distortion.

Unbalanced voltage index is as follow:

\[
K_{\text{eq}} = \sqrt{\frac{\sum_{k=1}^{N}(a_k \times k_{d,k})^2}{\sum_{k=1}^{N}(a_k)^2}}
\]

(6)

K<sub>eq</sub><sub>b</sub> is system voltage unbalanced index. K<sub>th</sub> is unbalanced factor of k<sub>th</sub> chosen PCC.

**Case study**

To evaluate the proposed indices, they were measured and calculated in Gilan utility network. The 43 points were chosen based on the proposed method. First, three standard levels were defined to make these indices comparable.

- **SI<sub>max</sub>:** It is calculated as maximum single index of each measurement.
- **TOP<sub>max</sub>:** Maximum single indices of all sample points were specified during measuring and then maximum value was selected.
- **Average<sub>max</sub>:** Maximum single indices of all sample points were specified during measuring like in case of TOP<sub>max</sub> and then the average of them was calculated. The THD, SI<sub>max</sub>, TOP<sub>max</sub> and Average<sub>max</sub> of all chosen point are shown in Fig2. THD<sub>50</sub>, for this case was obtained at 3.85 percentages so it was not at desired level.

These indices could be measured and calculated for all load types.

**Fig 4** voltage system indices which are classified by load types (ind:industrial, trans:transformer)

SI<sub>max</sub>, TOP<sub>max</sub> and Average<sub>max</sub> of voltage are illustrated in Fig4, which are classified by load type (industrial, nonindustrial and substation). The voltage THD of residential, official and commercial loads is more than industrial one but industrial harmonic voltage orders 7, 11 and 13 were more than others.

**Indices proposed based on combining of all PCC single indices on each points**

These indices reflect the overall situation of power quality disturbances in each sample’s points. Two indices proposed were as follow: improved UPQI and K<sub>margin</sub>.

**Improved UPQI**

The UPQI index ignore the values that are less than permissible values. To resolve this problem, a neighborhood of permissible limitation was introduced and the indices were rated. An example is provided in table 2.

**Fig 2** Comparison of sample point THDs and proposed system indices

Unbalanced voltage SI and voltage THD of sample network were compared by SI<sub>max</sub>, TOP<sub>max</sub> and Average<sub>max</sub> (Fig3). The unbalanced voltage index was acceptable but THD SI was not in range especially for the 5<sup>th</sup> order harmonic. THD<sub>50</sub> of 3.61 which is out of the range (120%).

**Case study**

The border indices were defined, measured and calculated to make the power quality qualification of each point comparable. They were denoted by PQI<sub>TOP</sub>, PQI<sub>50</sub> and UPQI.

To calculate harmonic index, first, all impermissible single index were considered and then were normalized to the permissible level. The value larger than one was chosen. It’s called H<sub>i</sub> and is given by:

\[
H_i = 1 + \left( \text{THD}_i - 1 \right)^2 + \sum_{r=1}^{13} \left( V_{hi} - 1 \right)^2
\]

(7)

From the two flicker indicators, short term and long term indices, maximum value of them was selected. The difference between nominal and effective voltages is voltage deviation index which is denoted by ΔV<sub>max</sub>. Fig. 5 shows the maximum value and 95% of normalized single and system indices for a chosen point. All indices were
normalized so the values more than one were excluded. The bar graph shows harmonic and flicker indices that are out of range. The value of UPQI is equal to 1.99; therefore the power quality of sample point is not acceptable. Now, it is possible to compare all chosen points in terms of power quality based on PQI_{Top}, PQI_{av}, and UPQI.

The bar graph shows harmonic and flicker indices that are normalized so the values more than one were excluded. The value of UPQI is equal to 1.99; therefore the power quality of sample point is not acceptable. Now, it is possible to compare all chosen points in terms of power quality based on PQI_{Top}, PQI_{av}, and UPQI.

SI based on standard permissible or impermissible indices (K_{margin})
Some GPQI such as UPQI and I_{Top} are based on permissible indices; so they are not suitable for representing global power quality situation. Given permissible and impermissible indices UPQI_{Top} and UPQI_{Av} were defined in previous section, another index is presented which is named K_{margin}. It is a paragon of permissible value and indices margin.

\[ k_{margin} = \frac{\sum_{i=1}^{N'} k_i \Delta l_i}{N'}, \quad \Delta l_i = 1 - l_{in} \]  

I_{in} represents normalized value of single indices (P.U in terms of permissible value), K_i is weighted factor, and N’ shows the number of permissible indices. K_{margin} is calculated based on permissible indices and denotes average of indices and permissible margin. If UPQI and K_{margin} are considered simultaneously, the power quality state of network will be shown completely according to permissible and impermissible indices.

SOFTWARE INTRODUCTION
For the purpose of quick and easy calculation, plot curve and analysis, software designed in MATLAB/GUI was designed in two consecutive processes.
Fig 11 a sample of software output (normalized system indices for residential-commercial station based on single index maximum values) Based on network information and control variables, the first part generates output which lists the measurement points. According to the list, in each measurement step, the results will be used as the input data of second process. Finally, it provides outputs like table, plot and etc. to show individual, systematic and unified indices of network’s power quality. Different scenarios could be defined in this software based on different control variables. The software is able to match future network changes. Figs. 10 and 11 show the software overview and outputs, respectively.

CONCLUSION

This paper presents a new algorithm to select sample points in order to prioritize measurement of power quality indices. Then, it proposed global power quality indices to compare power quality qualification of points. This purpose was achieved by two strategies: combining of single indices on each PQ disturbance and combining of all PCC single indices on each sample’s points. First one shows the power quality of each disturbance in sample region and the second concerns global power quality of each point. Finally, a software was designed to improve the calculation speed and accuracy. This algorithm was considered in Gilan electric power distribution network. This algorithm can provide the power quality perspective to the utility company's managers to help them decide better to improve the network problems. The most important result of this paper is introducing of a method to make the power distribution system observable by limited measurement and proposing of global indices to compare different points, which enable continuous monitoring of power quality.

Results showed that the harmonic injection of residential and commercial loads was more than industrial so that the PQ monitoring of industrial loads isn't enough.

It is necessary to define new PQ monitoring method according to spread and penetration of these loads. As further work, this algorithm could be evaluated in other networks and be improved. Besides, it is necessary to determine standard level for each GPQI. And finally, to reduce harmonic loss and useless occupied capacity of network present, new method to filtering according to new load pattern could be developed.

REFERENCES


