ASSESSING OF IMPACT OF DISTURBING LOAD ON POWER QUALITY

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INTRODUCTION

This report reflects theoretical and practical experience, gained by authors in the area of power quality (PQ) control and analysis. Such factors as actualization of Russian standard [1] directed to the application of IEC norms and PQ measurement methods and appearance on the domestic market the means for PQ factor measurements show the necessity to change existing approaches of PQ measurements and analysis. The PQ analysis is the determining the causes of mismatches between actual distortion levels in electric network and admissible ones.

The papers published by CIGRE and CIRED [2] resulted in working out such new methods of PQ analysis when electrical power supply system is divided into subsystems depending on network configuration and distortion power flow directions. Specific factor of mismatching (matching) is the correlation between partial (admissible) impact and actual (measured) one at the node (point) of PQ control. The advantage of these methods is that they are based on actual measurements of distortion factors which allows their “online” application and, hence, make it possible to compute partial impacts from each subsystem in harmonic and unbalance distortions at control node (point) of power system, for specified time interval.

The method has been verified for networks of 0.4, 6, 10, 220 kV. For these purposes long-term measurements (more than 7 days running) of voltage, current and power flows of distortions were carried out by apparatus designed in Moscow Power Engineering Institute.

The necessity to measure subsystem actual impact in control point is related to solving such problem as:

a) determining consumer with electrical devices which distort voltage at control point,
b) controlling operation of electrical devices by introducing the means for PQ improving,
c) regulating contract relations between power supply system and consumer concerning their influences on PQ at the point of common coupling (PCC).

The above problems aim at ensuring PQ, i.e. at reducing the level of conductive disturbances in electrical networks generated usually by nonlinear and unbalanced loads (industrial and household). The absence of regular PQ control resulted in serious problems related to electromagnetic compatibility. Distortions caused by electrical devices were also uncontrolled. As a result the PQ at PCC in the network of 6, 10 and 0.4 kV do not comply with standard requirements. Fig. 1 shows the values of such mismatches. The diagram presents the results of measurements made for 1.5 year period at dozens of control point of electrical networks of different towns with 50 – 150 thousands population. Control PQ factors are placed at horizontal axis and the number of cases when standard norms were exceeded (in per cent of all the measurements) – on the vertical one. The violation of the standard is detected if during seven days measurements while results the standard value of PQ factor has been exceeded at least in one day.

It is obvious, that at the border point of two subsystems (or PCC) PQ should satisfy standard requirements. Such subsystems can be electrical utilities, power systems of city or big industrial plant. In the simplest case those are electrical power system and consumer. Electrical power supply requirements in this case are determined by a contract. This contract should also included mutual duties at PCC. Influence of each subsystem on PQ is evaluated at this point. Hence, just here the impacts of those subsystems should be limited in such way that their sum is less than admissible standard value. Such an impact is considered as admissible. At the node (point), which is usually substation, several subsystems can be connected.

It is known, that PQ is specified by voltage characteristics: in special cases, total harmonic distortion factor and n-th harmonic voltage, negative and zero sequences voltages. As voltage distortion are caused by currents and power distortions in subsystem elements, the admissible impact can be limited by this parameters too.

Thus admissible impact is such a distortion level, which is allowed to each of the subsystems. The value of the admissible impact should be defined in power supply contract for each side. Operating condition of each subsystem is not constant but changes during the time depending on network circuit, electrical devices structure, thus influencing PQ. This influence is estimated by actual impact, which should be measured. While changing in time it can become greater or less than admissible one. The value of PQ for a given node is considered admissible one if the sum of actual impacts of each subsystem is less than standard value.

The aim of PQ analysis is to determine actual impact and, after comparison with the norm, to find voltage distortion causes. When the cause is known, it is possible to influence it by working out means of decreasing negative impact on PQ. Such actions, for example, can be regulated in according with power supply contract making distortion source owner to use technical devices for limiting injected distortions or to compensate the damage to other subsystems.
1. PROBLEM DESCRIPTION (INITIAL CONDITIONS)

Subsystem influence on PQ at control point depends on power of distortion sources, their location with relation to control point and power supply sources, network circuit and presence of compensation devices.

Considering control point as substation bus, it is possible to divide power supply system into several subsystems connected to this bus (Fig. 2).

Each of subsystems \( S_1, S_2, S_3 \) carries to the common bus its actual impact. This impact can be considered as positive, if subsystem contains distortion sources, and negative, if distortion sources are absent. In the last case such subsystem compensates distortions at the common bus. Impact of each subsystem is individual with respect to the others. Therefore while estimating the impact of e.g. subsystem \( S_4 \), all the other subsystems should be combined (Fig. 2).

Peculiarity of the method of determining the influence of distortion loads on PQ is that the impact is continuously determined by measured voltages, currents and powers. Therefore there is no necessity in combining subsystems. This makes solutions procedures for operational and design problems different.

The system as a whole (Fig. 2) can be represented as an equivalent circuit (Fig. 3).

For this circuit impact of each subsystem \( S_\Sigma \) or \( S_C \) can be determined in the following way:

- for voltage:
  \[
  \hat{U}_\Sigma = \frac{\hat{U}_c - \hat{I}_T}{Z_c} \frac{Z_c Z_\Sigma}{Z_\Sigma + Z_c} = \frac{\hat{U}_c - \hat{I}_T Z_c}{Z_\Sigma + Z_c}, \tag{1}
  \]
  \[
  \hat{U}_C = \frac{\hat{U}_c + \hat{I}_T}{Z_c} \frac{Z_c Z_\Sigma}{Z_\Sigma + Z_c} = \frac{\hat{U}_c + \hat{I}_T Z_c}{Z_\Sigma + Z_c}, \tag{2}
  \]

here \( \hat{U}_T \) and \( I_T \) - voltages and currents of distortions measured at the coupling point (a and b nodes in fig. 3.).
The values of input impedances can be determined provided
\[ Z_i = \frac{\Delta U_{T_i}}{\Delta I_{T_i}} \]    \hspace{1cm} (7)
where \( \Delta U_{T_i} = U_{T_i} - U_{T_{i-1}} \) and \( \Delta I_{T_i} = I_{T_i} - I_{T_{i-1}} \).

All measured values are represented as complex numbers. Depending on the signs of \( \Delta U_{T_i} \) and \( \Delta I_{T_i} \) real parts of complexes can be positive or negative. If \( \text{Re}(Z) > 0 \) measured impedance \( Z_i \) characterizes input impedance \( Z_c \), and in opposite case (\( \text{Re}(Z) < 0 \)) – input impedance \( Z_S \). Based on the long-term measurements arrays of values \( U_{T_i}, I_{T_i}, Z_i \), \( Z_c \) are accumulated. Further it is possible to calculate actual impacts of each subsystem by using expressions (1) – (6).

Practical calculations revealed a drawback of the method. The \( \Delta U_{T_i} \) and \( \Delta I_{T_i} \) are caused by occasional changes of operating condition in subsystem \( S_X \) or subsystem \( S_C \). Within \( \Delta t = 3 \) sec \( U_{T_i} \) and \( I_{T_i} \) usually do not change significantly (less than the measurement error). Hence the resistance \( Z_i \) can be determined provided \( \Delta U_{T_i} \) and \( \Delta I_{T_i} \) increase greater than the measurement error. Therefore time interval should be increased so that \( \Delta U_{T_i} \) and \( \Delta I_{T_i} \) exceed instrument error. However this increases the error of \( Z_i \) calculation.

2. DOMINANT FACTOR OF INFLUENCE

The practice shows, that almost all subsystems influence distortion level at control point. Therefore considering impacts from each of subsystems (Fig. 3) in time, it is possible to illustrate current values PQ as it is shown in Fig. 4. As is shown in Fig. 5, actual impact of consumer can be both less than admissible level (the requirements of contract are met) and greater. In [3] it is shown, that subsystem \( S_C \) which is analyzed, impacts smaller or greater than subsystem \( S_X \). Thus combined influence from both subsystems depends on greater subsystem impact. Directions of active (\( P_{\text{dist}} \)) and reactive power (\( Q_{\text{dist}} \)) flows determined for each of harmonics or symmetrical components are signs of dominant influences [2,3]. It is obvious, if the power of distortion flows out from subsystem \( S_C \) (the sign of \( P_{\text{dist}} \) is positive) the dominant distortion sources are there. This condition is valid for active power, in the case of the reactive power it is necessary to take into account the location of control point and presence of reactive compensation devices. For example, if capacitor bank is connected to consumer bus, there reactive power of main frequency can be negative (excessive compensation), but reactive power of \( n \)-th harmonic will be consumed by the bank. That is \( Q_{\text{dist}} > 0 \) and \( Q_{\text{load}} < 0 \). During the measurements in the network of high nominal voltage (110 kV and greater) it is necessary to take into account line susceptance.

Dominant factor varies in time depending on the system operating condition. In other worlds, distortion level at control point changes in time depending on correlation of impacts of \( S_C \) and \( S_X \). To estimate the total impact means to find the impact during the confidence time interval, where dominant factor is systematic. Just for this conditions it is advisable to work out and use different technical actions directed to reducing dominant subsystem influence on PQ. Systematicity of dominant factor can be estimated by correlation factor (\( \rho \)) between controlled distortion voltage and load power consumed by analyzed subsystem. Numerous measurements of these parameters showed that there may by three possible cases:

- \( \rho \rightarrow 1 \), there is direct correlation between consumer load and distortion voltage changes; in other words, with the increase of consumer load, the distortion level increases too;
- \( \rho \rightarrow -1 \), the distortion voltage decreases when load increases; the load compensates distortion at control point and improves PQ;
- \( \rho \rightarrow 0 \), there is no clear dependence between considered values due to the absence or unimportant changes in one of them.
3. METHOD OF DETERMINING THE ACTUAL IMPACT

If periodic measurements show that PQ exceeds standard values, than it is necessary to estimate actual impact of each subsystem, compare it with admissible one, and define the sources of PQ deterioration. To estimate actual impact at control point, distortion voltage and corresponding currents, active and reactive powers are measured. During time interval, for which confidence samples of measured parameters can be obtained, the signs of active and reactive distortion powers and correlation factor between distortion voltage and powers transmitted from subsystem $S_\Sigma$ to subsystem $S_C$ are determined.

The actual impact is evaluated as the most probable one from measurement results depending on dominant influence of subsystem (sign Pdist) and on correlations between distortion voltage and power consumed by subsystem. Depending on the sign of Pdist and $\rho$ the following cases are possible:

a). $\text{Pdist} < 0$ and $\rho \to 1$. In this case dominant distortion source is situated in subsystem $S_C$ and according to (7) it is possible to determine input impedance $Z_C$ only. Expressions (1)-(6) cannot be used. The type of the function $U_T = f(S_C)$ is determined by applying least-squares method to the stored values array. When function coefficients are determined, the value of $U_T$ is calculated for $S_C = 0$, giving the constant component $U_T(0)$ in distortion voltage. Actual impact of subsystem $S_C$ is equal to $U_{C_i} = U_{T_i} - U_T(0)$.

b). $\text{Pdist} < 0$ or $\text{Pdist} > 0$ with $\rho \to 0$. In this case there are distortion sources in both subsystems and their influences are the same. To evaluate actual impact, expressions (1) – (6) should be used, as input impedance $Z_i$ can be determined for each subsystem.

c). $\text{Pdist} < 0$ and $\rho \to -1$. The actual impact of subsystem $S_C$ is unimportant and distortion source is located inside of subsystem $S_C$ connected in parallel with compensating load. The actual impact of subsystem $S_C$ relatively to control point can be considered as equal to $U_{C_i} = U_{T_i}$ with $U_{S_i} = 0$.

d). $\text{Pdist} > 0$ and $\rho \to 1$. This shows that the dominant source is in subsystem $S_\Sigma$. In this case with the increase of subsystem $S_C$ load the distortion voltage decreases. Thus subsystem $S_C$ compensates distortion at control point and $U_{C_i} = 0$, $U_{S_i} = U_{T_i}$.

e). $\text{Pdist} > 0$ with $\rho \to 1$. The distortion source is in subsystem $S_\Sigma$. But in this case with the increase in the subsystem $S_C$ load the distortion voltage decreases. Then, as in previous case $U_{C_i} = 0$, $U_{S_i} = U_{T_i}$.

4. THE EXAMPLE OF REAL IMPACT ESTIMATION

Fig. 6 shows how the value of total harmonic distortion changes during seven days. The graph is based on measurement results in feeding cable line at distribution substation (nominal voltage 10 kV). Half-hour average values are used. Maximum and average values are presented. Long term measurements of voltage harmonic spectrum show that 13-th harmonic voltage does not comply with standard.

The harmonic source in consumer networks is trolleybus traction substation and the source in power supply network is railway traction substation with 12-pulse converters. The 11- and 13-th harmonics are characteristic of 12-pulse converter. Correlation factor between consumer load power and 13-th harmonic voltage was equal to $\rho \approx 0,11$. Active power of the 13-th harmonic in measurement range was both positive and negative. Using the technique described above and expression (7), input impedances of power supply network ($S_\Sigma$) and consumer load ($S_C$) relatively to control point were calculated for 13-th harmonic (Fig. 7). The distribution of input impedances pictured in the complex plane show that $\text{Re}(Z_\Sigma) < 0$ and $\text{Re}(Z_C) > 0$. Average values of impedances during measurement interval are...
equal to 

\[ Z_C = 21.17 + j64.615 = 67.99 \angle 72^\circ \]  

and 

\[ Z_C = 10.35 - j96.018 = 96.57 \angle 84^\circ \]  

Fig. 6. Graph of voltage total harmonic distortion for seven-day period

Now by using the impedances thus obtained it is possible to determine actual impact in measured voltage of 13-th harmonic from each sides by (1)-(6) expressions. As a result 13-th harmonic voltage is presented as sum of two components (Fig. 8).

As is show in Fig. 8, the actual impact of power supply system at 13-th harmonic component of voltage is significantly greater than the consumer one. As actual impacts are vectors, the their sum of modules is not equal to the voltage measured. Due to phase shift there is slight compensation of the harmonic components.

CONCLUSION

The method has been developed for estimating influence of voltage distortion sources on PQ at power system nodes. In this case the node is considered as a border between two subsystems, the influence of each of them is to be estimated. In general case this influence is of stochastic character, and therefore the estimation of the subsystem impact is performed by probabilistic methods.

The method is based on the results of continuous measurements with the duration of more than 24 hours, that is according to PQ standard. The measurements are executed by programmable devices, which can register voltage, current and power each 3 sec.

Within chosen time interval, which guarantees forming confidence sample, the correlation factor between controlled parameter and power (load) of subsystem as well as distortion power \( (P_{\text{dist}}) \) sign are estimated. According to this criterion the dominant subsystem is determined. The reliability of estimation increases for larger values of correlation factor.

Measurements performed in actual power supply system confirm practical usefulness of the suggested method. The influence is estimated by the difference between actual measured impact and admissible one established preliminary for each subsystem. Positive sign of the difference for a subsystem means that it is necessary to use special means of decreasing distortion level injected by subsystem.

The method can be used for estimating the influence of nonsinusoidal and unbalanced operating conditions.

REFERENCES


[2] REVIEW: Methods for measurement and evaluation of the harmonic emission level from an individual distorting load, CIGRE 36.05/CIRED 2 joint WG CCO2 (Voltage quality), 1999.