ADVANCED METHODOLOGIES AND NEW TOOL FOR MULTIPHASE POWER QUALITY ANALYSIS & MITIGATION

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INTRODUCTION

For utility network and end-user loads harmonic simulation, a large number of power quality problems show that single phase equivalent circuit and linear model are not suitable to reveal a part of real disturbance events such as unbalance harmonic impedances, asymmetric voltage sag, negative sequence current propagation, and phase to ground harmonic resonance. This paper deals with some particulars aspects of multiphase network harmonic modelling used in ExpertEC©, a new and simple power quality analysis tool developed by Electricité de France (EDF). It makes power quality mitigation easier and it can shorten substantially the studying time of a real power quality problem, compared with a more general simulation software. As ExpertEC uses true multiphase matrix models, it can deal with all the above phenomena by means of its simple and useful industrial loads and sources models. For usual end-user loads such as squirrel cage induction motors, power transformers and lines, full multiphase matrix models are employed in order to characterize positive, negative and zero sequence impedances. These modules make it possible to simulate unbalance voltage impact to an induction machine as it draws important negative sequence currents from the power supply when its input voltage is unbalanced.

The PQ Expert subsystem is a pre-designed element; it can be settled at the point of common coupling of a simulated circuit. Its role is to analyse three-phase power quality problems and give power quality indicators according to the local utility’s limits. If there is violation of the limits, PQ Expert subsystem will propose, design and size an appropriate solution.

The three-phase Norton unit is another useful element for power quality mitigation. It makes it possible to simplify a complex electric grid system to a three-phase steady state active network in which all the impedances and current sources are modelled according to the harmonic frequencies. Harmonic order can be studied up to 256 or unlimitedly when using input data file. In the end, the processing software gives both harmonic spectrum plots and time domain waveform plots.

Other available modules in ExpertEC: user-designed sources, wattmeter, voltage analyser, current analyser, voltage regulator, reactive compensator, protection unit, etc.

The input data of all models are based on either equivalent electric circuit values (R, L, C, E, J, M, etc) or technical data sheet from electric equipment. All the calculations have been validated thanks to a number of on-site power quality mitigations. The studied disturbance mitigation methodologies can be used in different power quality analysis domains: power grids, industrial networks, tertiary power supplies, and embedded electric facilities. The following power problems can be treated with a minimized engineer time:

1. On site harmonic analysis (harmonic, inter harmonic, unbalance harmonic, notched voltage),
2. Electric values calculations such as RMS, Thd, powers, cos(ϕ), energy, motor starting, protection, etc,
3. Harmonic impedance calculation, unbalance impedance measurement and automatic resonance identification,
4. Frequency domain analysis of different types of power transformers (independent flux, forced flux, Scott, etc),
5. Harmonic filter design, sizing and validation, capacitor bank sizing.
6. Unbalance investigation and compensation design,
7. Voltage surge and sag analysis,
8. Protection unit verification.

This software tool was developed for application in “down the meter” power quality services offered by EDF group companies. The detailed multiphase modelling functions of this software will be described in the following paragraphs by different real cases.

METHODOLOGIES FOR MULTIPHASE POWER QUALITY MITIGATION

This part is aimed at describing different methodologies used for multiphase power quality mitigation. As a great part of power grid faults are asymmetrical, the single-phase modelling and symmetrical approaches can’t reveal precisely
disturbance behaviour in real power system. Particularly voltage sags propagation analysis must be studied by true three phase models at different voltage levels. However, the development of three-phase models of all power system equipment was restricted by computer resource. Fortunately, the recent development in computer makes it more and more possible to cope with power quality problem by true three-phase models in a single personal computer.

Asymmetrical components modelling

**Induction motor.** As well known, two thirds of industrial loads is composed of electric motors. Induction motor is a typical asymmetrical load in power quality analysis, because in which the negative sequence impedance is much lower than that of its positive sequence. Based on nodal equations, we can model a passive n-terminal electrical linear load into an admittance matrix referred to nodal equation:

\[
[I] = [Gn] [Vn]
\]

In: vector of nodal current injection
Vn: nodal voltage vector
Gn: load admittance matrix

If the positive sequence impedance is equal to the negative sequence impedance, all up and down triangles elements of G is symmetrical, that is: gi,j = gj,i. i.e. transposable. For asynchronous motor, gij ≠ gj,i, we can’t use a transposable admittance matrix to simulate its harmonic behaviour, and we need to take into account of the asymmetry in the admittance matrix. The same way, the relationships between nodal voltages and currents vectors at motor’s input can be written:

\[
[V] = [Z] [I]
\]

With 
\[
[Z] = \begin{bmatrix}
Zp & 0 & 0 \\
0 & Zn & 0 \\
0 & 0 & Z0
\end{bmatrix}
\]

The above figure shows that an induction machine amplifies greatly unbalance voltage particularly when its slip is lower. The current unbalance may be important even if the voltage unbalance is small. If an end-user load contains a number of induction machines without adjustable speed driver, current unbalance problem caused by voltage unbalance may become critical for thresholds setting of feeder’s protection.

![Fig. 2. Unbalance amplification curve](image)

The following simulation curve reproduces the relation between \( \frac{\delta i}{\delta v} \) and slip of a low voltage 3-phase squirrel-cage induction machine.

\[
\delta i/\delta v \quad \text{Unbalance amplification by an AC motor}
\]

If we decompose three-phase values into positive sequence (Vp, Ip, Zp), negative sequence (Vn, In, Zn) and zero sequence (Vo, Io, Zo), the above schema can be drawn as the sum of following equivalent circuits:

\[
\begin{align*}
Vp &= Vp(0^\circ) + Vp(-120^\circ) + Vp(240^\circ) \\
Vn &= Vn(0^\circ) + Vn(120^\circ) + Vn(240^\circ) \\
Vo &= Vo(0^\circ) + Vo(120^\circ) + Vo(240^\circ)
\end{align*}
\]

All these values are in complex, with \( a = e^{j120^\circ} \):
In the other hand, asynchronous induction machines can compensate slightly upstream unbalanced voltage sags, because its negative impedance is lower than its positive one. Therefore, the main drawback of this kind of load is current unbalanced amplification during voltage sag (Fig. 3). When fault direction analysis is performed, this phenomenon must be taken into account because an up-stream voltage sag can also provoke serious over current.

Three-phase transformer. Three-phase power transformer considered as a balanced device is justified in the majority of practical situations. However, it has an asymmetrical component behaviour, particularly, in fault analysis. We have modelled three-phase transformer in phase coordinates, so no more assumptions are necessary for the global model, even though it is possible to make physical assumption of each phase in order to simplify the three-phase-model. We construct a twelve dimensions complex matrix to represent all 6 windings, mutual inductances, and magnetic circuit reluctance. The next flow chart shows the steps of true three phase transformer modelling.

Simulated Norton network is a 4-terminal element that can be built by both modelling and site measurement. It contains current sources and impedances. A typical three-phase Norton network is modelled by 7 series data sheet: 1 frequency, 3 currents and 3 impedances. Each phase of Norton network is constructed by frequency $f$, impedance $Z_f$ and current source $J_f$ shown in following figure.

For a given large scale simulated circuit, ExpertEC can build automatically an equivalent steady-state Norton network by frequency scan in two steps at each frequency: short circuit and open circuit simulations in order to define $Z_f$ and $J_f$ values.

Three phase impedance measurement and automatic resonance frequency identification

At a point of common coupling of three phase power system, impedance is suggested to be calculated by a three phase current source set by positive, negative and zero sequences components according to scanned frequency. The typical elements that affect three-phase impedance calculation are induction machine, network neutral system, three-legged power transformer, etc. Frequency impedance scans give all phase-phase and phase-neutral impedances represented in magnitude & angle via frequency.

The following curves show the impedances calculated at the secondary of two types of transformers simulated by true three-phase model (1 MVA, 50Hz). $Z_1$ is the impedance calculated by a single-phase impedance meter, and $Z_{tr}$ is the phase impedance measured by a three-phase impedance meter. For a three-legged power transformer, the error from single-phase impedance calculation is very important. In this case, a three-phase impedance calculation must be used.
The automatic resonance frequency identification function is a useful tool for harmonic mitigation. The principle of automatic harmonic resonance identification is to analyse $dZ/df$ values. If $dZ/df=0$ at $f = f_{r1}$, there is a harmonic resonance at the measuring point. If the impedance gets maximum value at frequency $f_{r1}$, the resonance is a parallel harmonic resonance and it will amplify mainly downstream harmonic current at this frequency. If the impedance gets minimum value at $f_{r2}$, there is a series resonance. In this case, the downstream harmonic current will be filtered. If the resonance elements (R,L,C) are located in front of the analysis point, ie, load side, upstream harmonic voltage of this frequency could provoke downstream harmonic current.

At each identified resonance frequency, the amplifying coefficient is estimated by impedance module.

**Power quality indication and PQ expert subsystem**

**Power quality indicators.** The power quality indication is one of the power quality expert functions, which gives the levels of power quality parameters compared with local utility standards:

- Total voltage harmonic distortion (Thd_V),
- Total current harmonic distortion (Thd_I),
- Reactive power / active power (Tan),
- Voltage unbalance (UnB.V),
- Current unbalance (UnB.I).

If there is violation of the limits, PQ Expert subsystem will propose, design and size an appropriate solution such as filter, unbalance compensator. The following example shows harmonic mitigation performed by PQ Expert subsystem for a foundry. At the 20 kV feeder, there are two disturbance loads: induction heating ovens equipped with 12-pulse rectifiers. On basis of voltage and current measurements from the site, the whole associated network is modelled and a PQ Expert subsystem is inserted at secondary of the 20 MVA transformer.

**Active filter design.** The above figure shows that total voltage harmonic distortion exceed the normalized limits. Based on this technical information, PQ Expert subsystem can automatically design an appropriate passive filter or size a suitable active filter. The active filter size takes account of busbar voltage and harmonic currents. For this site, an active filter is sized by the following parameters:

- Rated filter power = 810 kVA without reactive power compensation or 5.4 MVA with reactive compensation,
- Compensated frequencies = 150 to 1500 Hz
- Compensation phase current is evaluated and shown in following figure (without reactive power compensation).

**Passive filter design.** As the tangent value of this site exceeds the normalized limits, passive filter solution has been selected. PQ Expert sub system automatically designs a set of appropriate passive filters whose roles are to compensate the most important harmonic current and to correct power factor at the point of common coupling. The filter design takes account not only of theoretical calculations but also engineering parameters that can make it easier to contact a filter manufacturer. The automatic filter design is done in the following steps:
- Spectrum analysis with site measuring data,
- Reactive power compensation at fundamental frequency,
- Choice of type of filter,
- Calculation of filter elements RLC,
- Rated voltages and currents calculation,
- Establishment of data sheet for filter manufacturer.

According to the analysis of the above site data, the first harmonic current to be filtered is order 11 (550Hz for 50Hz fundamental). In order to avoid low harmonic parallel resonance with network impedance, the filters are designed from 250 Hz with the following engineering restrictions:

- Upstream transformer short-circuit power = 130 MVA,
- Rated line voltage = 20 kV,
- Reactive power compensation = -5.4 MVar,
- Fundamental frequency = 50Hz,
- Shunt filter frequencies = 250, 350, 550, 650 Hz,
- Quality factor = 30 to 45.

The fundamental reactive power and the quality factor are two important aspects to ensure filter stability. When filter power is 50% greater than that of the upstream power transformer, it is recommended to take necessary precautions in order to mitigate over voltage caused by passive filter. If there is important transient load (frequent motor starting), damped filter structure must be used. Based on the above site parameters, 4 shunt passive filters are designed by PQ Expert subsystem:

<table>
<thead>
<tr>
<th>Filter 250 Hz</th>
<th>Filter 350 Hz</th>
<th>Filter 550Hz</th>
<th>Filter 650 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (Ohm)</td>
<td>2.86</td>
<td>2.01</td>
<td>0.46</td>
</tr>
<tr>
<td>L (mH)</td>
<td>54.87</td>
<td>27.36</td>
<td>7.35</td>
</tr>
<tr>
<td>C (µF)</td>
<td>7.45</td>
<td>7.59</td>
<td>17.09</td>
</tr>
</tbody>
</table>

With these four filters, the impedance at the point of common coupling is modified. They have shifted parallel resonance points to less harmful frequencies. The first parallel resonance frequency is moved to 197 Hz, which is lower than that of the lowest existing harmonic current.

All the filter components are calculated and verified by both RMS values and arithmetic sum values. With the designed filters, phase currents have been “cleaned” and complied with utilities power quality standards. After put into service of these four filters, a series of site measurements has shown that the voltage Thd was reduced from 9.8% to 2.1%.

CONCLUSIONS

This paper presents useful approaches for three-phase power quality analysis using full matrix modelling methods, which give truthful results for multi frequency calculation, particularly for power transformers, power lines and induction machines. The harmonic-unbalanced components make it inadequate to use single-phase model for harmonic analysis. Even in voltage dip investigation, symmetric model is insufficient to examine fault attenuation through a three-legged power transformers. For an industrial network harmonic diagnosis, it is recommended to use three-phase impedance calculation in order to reveal unbalance harmonic resonance.

A pre-designed power quality expert unit in the software can give directly relative power quality levels compared with local utility standards. This function makes it easy to design and size an appropriate filter, compensator, etc.

Frequency domain Norton network can be used for steady state power quality mitigation. It makes possible to simplify a studied complex electric grid system to a three-phase active component.

REFERENCES


