Network Resonance Detection using Harmonic Active Power

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***Abstract*—Resonances in electrical distribution systems can result in amplification of harmonics, which is undesirable in electrical networks. To avoid intrusive measurement techniques, in the majority of the cases network modeling is used to validate if there is an issue with resonance. In this paper a new, innovative but simple, concept is presented which uses relatively basic measurements to segregate the power related to specific harmonics into active and non-active harmonic power. These results are subsequently used in order to find if there is resonance in the electrical network. In this paper the concepts are explained on a theoretical basis and are test cased by numerical modeling. The initial results look promising but additional research is needed to validate the method.**

I. Introduction

With the increased penetration of power electronics, both from electrical loads and generators, the network is additionally strained with harmonic content. When focussing on the problems related to harmonics in networks, they negatively affect the life expectancy of the insulation in the network, generate additional losses in transformers and might damage active capacitor banks [1]–[3]. Because networks consists of inductances, capacitance and some resistance, there is always resonance in the network. Practical problems arise at the moment the resonance amplifies the distortion in either voltage or current. Therefore it is of great concern to determine the network's impedance over frequency characteristic to evaluate if there is an issue related to harmonic resonance. In the majority of the cases this is estimated at the design stage of the network and done via modeling in dedicated software.

In situ monitoring of those impedance over frequency plots is essential for stable operation, but this generally requires intrusive methods. There have been some suggestions of algorithms to try to obtain this data based on measurements using non-intrusive techniques [4], [5]. This proves to be promising, although the long iterative process requires a lot of time. In a practical setting the previous methods are facing practical disadvantages as the network's impedance is varying due to switching actions and reconfiguration of the network by the network operator. In this paper a basic measurement method is suggested to perform a real time detection of resonance phenomena in the network based on the power related to individual harmonics. The basic concept, including its limitations, is mathematically explained in §II and §III. Subsequently, this method is used in a numerical model to testcase the validity §IV and the results validate the suggested method.

Although the results of the modeling indicate that the proposed method has potential, this method does also has constraints. As will be addressed in the paper, the suggested method can bridge the gap to the more complex analysis of the prevailing harmonic phase angle, however this research is specifically focussed on finding a very basic, low level, method for an indication of resonance. As will be discussed in §V, much more validation is needed.

II. Basic analysis of resonance phenomena

In electrical systems, there is a resonance if the reactive power component in the inductor is equal and opposite to the reactive power component in the capacitor. When written in terms of reactances, resonance occurs if:

$$\overline{X_l} = \overline{X_c} \tag{1}$$

With $\overline{X_l}$ the inductive reactance and $\overline{X_c}$ the capacitive reactance. For electrical distribution systems the reactance is depending on the frequency, so resonance occurs for specific resonance frequencies f_r in which:

$$f_r = \frac{1}{2.\pi.\sqrt{L.C}} \tag{2}$$

With L the inductance in [H] and C the capacity in [F]. Two types of resonance can occur, namely parallel resonance and series resonance.

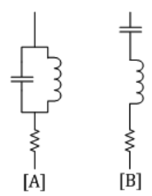

Fig. 1. [A] Parallell resonance with ESR, [B] Series Resonance

In case of parallel resonance the impedance goes from zero to -theoretically- infinite, and then back to zero. Subsequently, in case of series resonance, the impedance goes from highly capacitive to theoretically zero and then back up as an inductor. However, from a practical perspective there is some damping in the electrical network which is modelled by an Equivalent Series Resistor (ESR). Note that in this paper a single measurement location is taken into account. As the resistance only affects the damping, and not the resonance frequencies, dumping all the loss into a single ESR is acceptable for this research. The latter is obviously not allowed for the reactances.

Analyzing the increase of an individual harmonic voltage to current, or visa versa, and claiming that this is solely caused by resonance is too blunt. Due to the attenuation effect, there is a linkage between the voltage and the current distortion. [6], [7] This prohibits modeling the distortion as a single fixed harmonic current or voltage source. Secondly, in a real case there is rarely a situation in which the resonance frequency is exactly tuned to a specific harmonic. All the previous, and including additional damping, illustrate the difficulties for in situ analysis whether or not there is an actual amplification of harmonics due to near-resonance, or just by due to more generated distortion. Therefore this paper suggests another approach, which bypasses nearly all of the previously stated problems.

III. Using Harmonic Active Power to estimate network resonance

The transition of values from the time to the frequency domain is a mathematical decomposition. Consequently, this has resulted in a lot of discussion about the physical interpretation of the concept of electrical power for non sinewave signals [8] [9]. Although this research does not focusses on the physical interpretation of harmonic power, the total power S_h related to each specific harmonic h can be calculated and can provide important insights in the network topology.

In case of parallel circuit, a specific current harmonic will translate into a high voltage harmonic. As harmonic sources are mostly modeled as a current source, the power S_h can be calculated based on the Norton Equivalent:

$$\overline{S_h} = \overline{R_{ESR}.I_h^2} + \frac{\overline{U_{X_c}}}{X_c} + \frac{\overline{U_{X_l}}}{X_l} \tag{3}$$

With U_{X_l} the voltage over the inducance which is equal to U_{X_c} the voltage drop over the capacitance. Subsequently, in case of series circuit:

$$\overline{S_h} = \overline{R_{ESR}.I_h^2} + \overline{I_h^2.X_c} + \overline{I_h^2 X_l} \tag{4}$$

In case of perfect resonance, the reactive power dissipated in the inductor is equal but opposite to the reactive power in the capacitor. This simplifies both Eq.3 and Eq.4 to:

$$\overline{S_h} = \overline{R_{ESR}.I_h^2} \tag{5}$$

Whereas S_h only consists of an part with real power, so Eq.5 simplifies to

$$S_h = P_h = \frac{1}{T}\int_0^T u_t.i_t.dt \tag{6}$$

In analogy to the evaluation of powers in sinewave condition, in case of the abscence of resonance, there is also a nonreactive part Q_h of order h. Note that in this research there no physical interpretation to the value of Q_h is given, nor needed.

$$Q_h = U_{h\_RMS} * I_{h\_RMS} * \sin(\phi_h) \tag{7}$$

In case of perfect resonance, the reactive power dissipated in the inductor is equal but the conjugate of the reactive power in the capacitor. So, the conclusion is that in case of resonance, the only power transposed from outside to the resonance circuit is active harmonic power. Therefore the proposed method states:

- if the power related to the harmonics only contains a minor fraction of active power, there is no clear indication of resonance.
- if the power related to a specific harmonic does contain a significant fraction of active power, there is a possible risk of resonance.

In this specific analysis the goal is to evaluate the possibility of resonance. A basic network harmonic analysis gives the levels of individual RMS voltages and currents for each harmonic frequency. Straightforward multiplication of the voltage and current RMS values result in the apparant power. Simply adding Eq.6 to the analysis enables a quick evaluation of possible resonance.

As a consequence of the simplification of Eq.3 and 4 to Eq.5 the type of resonance (either series or parallel) is lost. Although this is a drawback of the proposed strategy, it is of less importance to understand the nature of the resonance. This method is ideal to quickly evaluate if there is a risk to resonance based on relatively low level measurements. Additionally, the ratio between the active and the non active component can be evaluated, resulting in a indication of the phase angle, which then makes the link to the prevailing harmonic angle [10]. This is no longer a part of the current research question but should be included in future research.

IV. Modeling

A. Introduction

In order to evaluate the harmonic active power related to resonance, the CIRED-CIGRE C4-109 model is being used as a base line. The lumped model presented in Fig.2 is made in Matlab Simulink and the parameters were extracted from a real LV network, with a 400kVA transformer and approximately 600m of low voltage cable. The network is modeled in such a way that the background distortion can be modeled as a voltage source. The load is represented by 2 current sources: one for the fundamental component with nominal load at

50Hz and; one with 6% of nominal amplitude and variable frequency representing the distortion component of the load. Resonance is created by adding capacitance parallel to the MV/LV transformer, which results in this specific case in a resonance between the upstream network and transformer and the parallel capacitance. Damping is provided by adding some resistance in all of the reactive components. At this stage the actual value is of less significance.

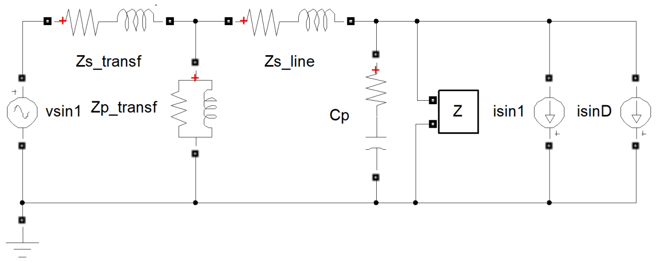

Fig. 2. Basic lumped model layout based on the CIGRE C4-104.

In the modeling enviroment there is a possibility to add an impedance measurement in order to validate the network impedance in relation to the frequency. The magnitude and the phase angle of the impedance is measured outside of the resonating circuit, and in this case at the LV side of the transformer. The results for the specific model are given in Fig.3.

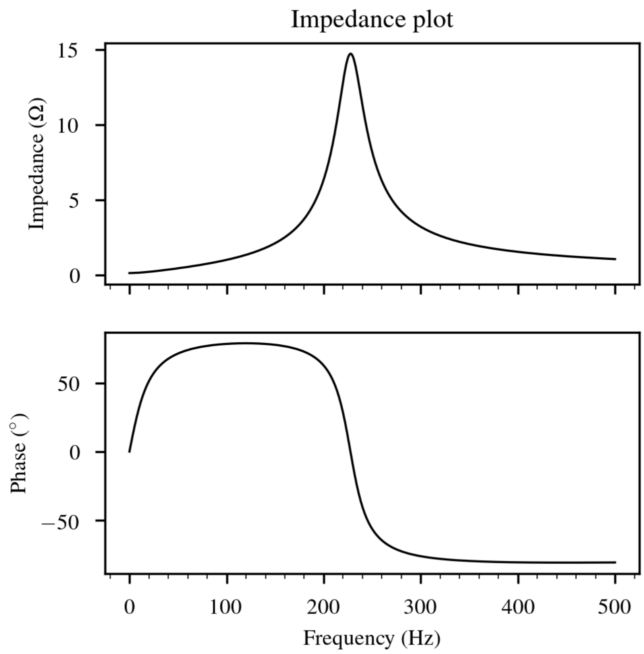

Fig. 3. Impedance plot of the model represented in Fig.2, as observed from the harmonic load

It is seen in Fig.3 that resonance doesn't manifest itself only in a single frequency but it has a certain bandwidth due to the resistive damping in the circuit. This means that the effect of resonance can be measured also when there is an harmonic current in a near resonance frequency.

B. Simulations at fixed resonance frequency and variable harmonic current frequency

In a first simulation, the network resonance frequency is fixed at 250Hz and the harmonic current distortion component has a constant magnitude of 6 % of the fundamental current. The current is sweeped in frequency and is incrementally increased with 1Hz. The harmonic measurements are done using simple preset single FFT-blocks in Matlab and the reactive power is being calculated according to Eq. 6.

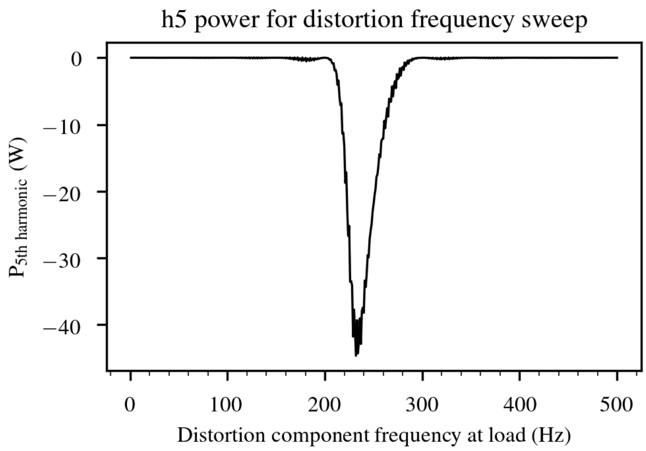

Fig. 4. Harmonic active power at h5, with a resonance circuit at 230Hz, with fixed harmonic load current magnitude and variable harmonic frequency, measured at the load

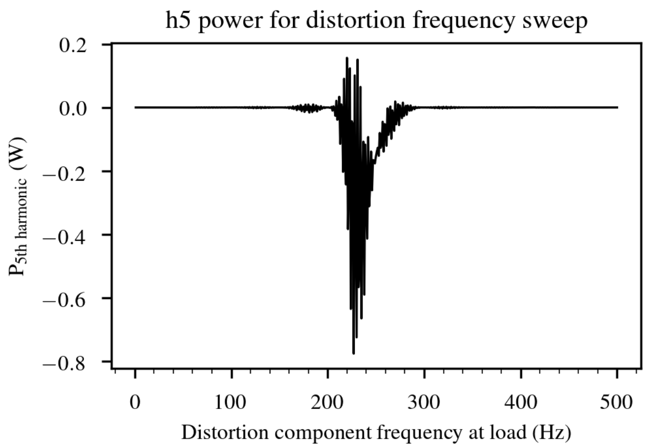

Fig. 5. Harmonic active power at h5, with a resonance circuit at 250Hz, with fixed harmonic magnitude and variable harmonic frequency, measured at the source

C. Simulations at variable resonance frequency and fixed distortion component

In the second simulation, the network's resonance is altered by changing the network capacitance. This approach facilitates the comparison of the results, as the circuit's inductance remains high for variable resonance. frequency of the distortion component of the current is fixed at 250Hz.

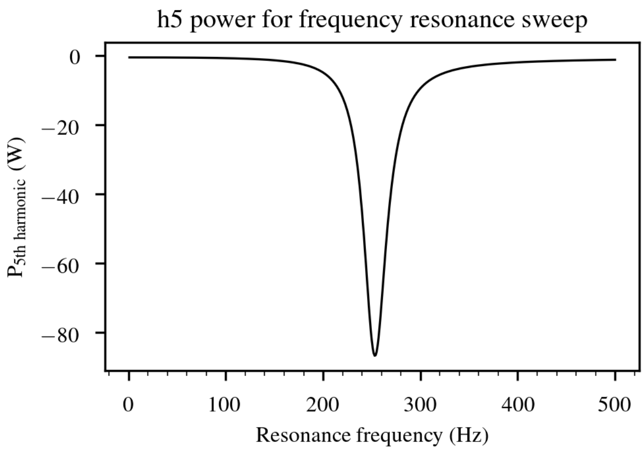

Fig. 6. Harmonic active power at h5, with fixed harmonic magnitude and variable network resonance, measured at the load

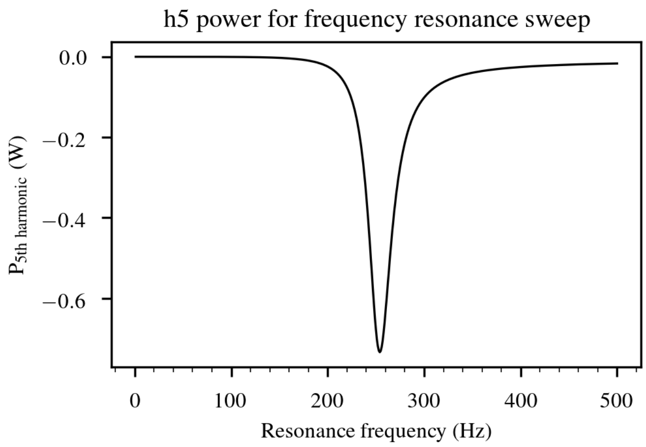

Fig. 7. Harmonic active power at h5, with fixed harmonic magnitude and variable network resonance, measured at the load

D. Analysis of the simulation results

In the simulation presented in §IV-B the harmonic frequency in incrementally increased with 1Hz/step. Although this does not represent a realistic distortion consisting of mainly odd - and in specific cases even harmonics - this simulation validates the assumptions in the paper: if the injected harmonic is in the near resonance or resonance, there is a significant increase of harmonic active power. In the simulations, there has been no reference made to the reactive power related to harmonics, as this is a topic of much discussion [9] which has no added value to the presented research goals in this paper. Although the harmonic active power does have a sign, indicating injection or extraction of harmonic active power, this has also not yet been taken under consideration as the goal was to meerly evaluate if there is active harmonic power in case of resonance. Both subjects, namely the reactive power and the sign of the harmonic active power, are topic which will be included in future research.

In the second simulation, the harmonic power is evaluated for a varing resonance frequency. As the parallell capacitance value is shifted, not only the frequency of the resonance is affected but also its bandwidth. This also implies that the fixed network impedance plot presented in Fig.3 changes with the parallel capacitance value in center frequency and bandwidth. The measurements also confirm the assumptions of the paper, i.e. that there is harmonic active power in case of near-resonance or resonance.

V. Conclusions and Future Research

As loads are fluctuating over time, so is the harmonic content in the network. As resonances may impose an actual problem in the network, a fast algorithm to evaluate the possibilty of a resonance is highly valuable. In this paper it is suggested that the concept of harmonic active power can be used to evaluate if there is a possibility of resonance. Although the suggested method has been validated by numerical modeling, the authors do not yet claim any statements regarding the practical validity of the proposed analysis, as much more research is needed. The first step should be to validate the method using network modeling tools on a more theoretical basis and subsequently using more data from practical case studies.

The authors assume that this method would be particularly suitable for network analysis at medium and high voltage. Finding resonances in the low voltage network might impose some problems as the R/X ratio of a low voltage installation is very high in relation to MV and HV networks. However, the advantage of this method is that it can be done in nearly real time, with low computation effort and gives fast results.

As hinted, the ratio of P_h/Q_h is related to the phase angle between the harmonic current and voltage. So, future research will include the link between the presented research and the concept of prevailing harmonic phase angles, which is much more validated and studied in scientific literature. An extensive validation comparing measurements with models should back up the statements. If there is validity to the previous claims, logging the prevailing harmonic phase angle in combination with the actual values of P_h could results in an in situ algorithm which detects resonances and alert the network operator of resonance, even at low values of distortion.

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