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ANALYSIS OF HARMONIC ESTIMATION SYSTEM FOR THREE PHASE SOURCE BASED POWER SYSTEM

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Abstract- In recent years, the traditional power systems' structures have been changed, and the concern over power quality has increased due to the new generation of load equipments. This equipment has been fully automated electronically, so it can be highly sensitive to any power quality disturbances. Indeed, power quality disturbances may cause malfunctions in the equipment, which leads to higher production costs due to decreased production efficiency. Moreover, the electronic converters in these loads produce harmonic currents that increase current distortion. Eventually, the impact of electronic converters on power quality will be increased proportional to the converters lifetime; therefore, maintaining power quality levels above specific baselines will be an essential requirement in future decades.

I. Introduction

The multiple meanings of power quality are the result of defining power quality from different perspectives. Power quality, in generation, relates to the ability to generate electric power at a specific frequency, 50 or 60 Hz, with very little variation; while power quality in transmission can be referred to as the voltage quality. At the distribution level, power quality can be a combination of voltage quality and current quality. From the marketing point of view, electricity is a product and the power quality is the index of the product quality

A. Power Quality Disturbances Classification

In order to be able to classify different types of power quality disturbances, the characteristics of each type must be known. In general, power quality disturbances are classified into two types: steady state and non-steady state. This classification is done in terms of the frequency components which appear in the voltage signals during the disturbance, the duration of the disturbance, and the typical voltage magnitude. These disturbances are mainly caused by:

- External factors to the power system: for example, lightning strikes cause impulsive transients of large magnitude.
- Switching actions in the system: a typical example is capacitor switching, which causes oscillatory transients.
- Faults which can be caused, for example, by lightning (on overhead lines) or insulation failure (in cables). Voltage dips and interruptions are disturbances related to faults.
- Loads which use power electronics and introduce harmonics to the network.

B. Basics of Harmonic Theory:

The term "harmonics" was originated in the field of acoustics, where it was related to the vibration of a string or an air column at a frequency that is a multiple of the base frequency. A harmonic component in an AC power system is defined as a sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple of the fundamental frequency of the system. Harmonics in voltage or current waveforms can then be conceived as perfectly sinusoidal components of frequencies multiple of the fundamental frequency as shown in Eqn.(1.1) and Eqn.(1.2).

fn=(n)*(fundamental frequency) where n is an integer. (1.1)

For example, a fifth harmonic would yield a harmonic component:

fn=(5)*(60)=300Hz and fn=(5)*(50)=250 Hz in 60-Hz and 50-Hz systems. (1.2)

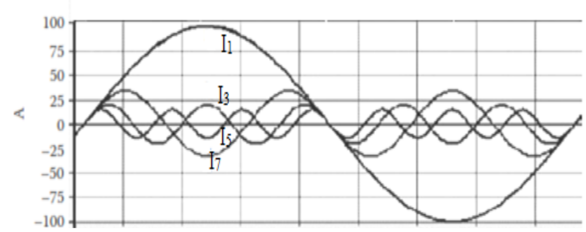


Fig.1.1: Sinusoidal 60-Hz Waveform And 3rd, 5th, 7th Harmonics

Figure 1.1 shows an ideal 60-Hz waveform with a peak value of around 100 A, which can be taken as one per unit (p.u). It also portrays waveforms of amplitudes (1/7), (1/5), and (1/3) per unit and frequencies seven, five, and three times the fundamental frequency, respectively. This behavior of showing harmonic components in decreasing amplitude often follows an inverse law with harmonic order is typical in power systems. These waveforms can be expressed as:

$$i_1 = I_{m1} \sin \omega t$$
$$i_3 = I_{m3} \sin(3\omega t - \delta_3)$$
$$i_5 = I_{m5} \sin(5\omega t - \delta_5)$$
$$i_7 = I_{m7} \sin(7\omega t - \delta_7)$$

Where Imn is the peak RMS value of the harmonic current n.
The resultant distorted waveform can be expressed as:

$\mathbf{I_{total}=i_1+i_3+i_5+i_7}$ **(3.7)**

In this way, a summation of perfectly sinusoidal waveforms can give rise to a distorted waveform. Conversely, a distorted waveform could be represented as the superposition of a fundamental frequency waveform with other waveforms of different harmonic frequencies and amplitudes.

C. Types of Analyses Performed during the Harmonic Analysis:

There are two main types of analyses that could be performed during harmonic analysis:

a. Current and voltage distortion analysis, in which the individual and total current and voltage harmonic distortions are calculated at the various buses then the results are compared with the relevant contractual limits.
b. Impedance versus frequency analysis, in which a plot of the system impedance at various buses is plotted against the frequency. This analysis is important in predicting the system resonances prior to energizing the electrical system. A peak in the impedance plot indicates a parallel resonance while a valley in the impedance plot indicates a series resonance.

II. STEPS OF PERFORMING A HARMONIC ANALYSIS STUDY

If a harmonic analysis study is required to be performed due to any of the cases described in section (II), the following steps should be followed:

a. Obtain the electrical system one-line diagram and highlight the available nonlinear loads, capacitor banks and medium voltage cables of long length within the industrial system.
b. Highlight the point of common coupling (PCC) which is the point that connects the industrial network with the utility or with the neighboring plant.
c. Highlight the in-plant system buses that are expected to be affected from harmonic distortions.
d. Gather the harmonics-related data of all nonlinear loads within the plant.
e. Obtain, from the utility company, the relevant data of current and voltage harmonics at the contractual PCC including the minimum and maximum short circuit fault levels and the permissible limits on voltage and current harmonics because the allowable harmonic limits vary from country to country.
f. Model the electrical network using any of the commercially available softwares such as the electrical transient analyzer program (ETAP).
g. Perform the harmonic analysis for the electrical network at the various possible operating scenarios.
h. Check the individual and total voltage and current distortion levels at the interested system buses and at the PCC.
i. Check the harmonic frequency spectrum, which is a plot of each individual harmonic value with respect to the fundamental value versus frequency.
j. If the harmonic distortion results exceed the allowable limits, select an appropriate harmonic mitigation solution and the optimum insertion point for that solution. Further details about this point are introduced in section (V).
k. Re-perform the harmonic analysis study after adding the harmonic mitigation technique to ensure compliance with the contractual / international harmonic limits.

III. USE OF PRONY METHODS

The Prony analysis (P.A) is a parametric method of large complexity. This method outperformed its Fourier transform (F.T) counterpart in the accuracy of signal modeling and analysis for many practical signal processing situations.

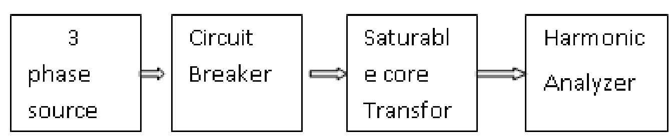
The advantages of LS Prony's method includes precise estimation of frequency, amplitudes and phases, in addition to the ability to compute damping coefficients for the signal components, which can be used for transient analysis.

IV. METHODOLOGY

In saturable core Transformer, during the rise in the current the developed flux does not increases proportionally but it saturate over the particular limit. Due to this, however, current is sinusoidal but the developed flux is non-sinusoidal i.e. it consist harmonics. This developed flux induced a voltage in the Transformer winding that voltage also consists of harmonics.

Whenever, a Transformer is connected to the source by a circuit breaker the Transformer winding get energized suddenly and a large amount of current is induced due to sudden start of Transformer. This current is called 'Inrush current'. Since, this current is developing of flux and this flux will consist of saturation futures so this will cause generation of harmonics in the Transformer voltage. After some instant, the inrush current is decayed out hence, these harmonics are also get minimized.

In this way, the harmonic present during the Transformer energizing due to saturable core features has different frequencies and has different damping coefficient. So, we cannot predict about damping coefficient from Fourier analysis. Hence, we are using 'Prony analysis' to estimate not only the harmonic frequencies content but their decay rates. For this purpose, we have used a 3 phase source connected saturable core Transformer model as sown in following block diagram-



The three phase saturable transformer is energized through a circuit barker closing from a 500(kv) source. The rating of transformer source are giving below-

1. Source-
   a. Phase to phase rms voltage (V) =500kv, 3 phase.
   b. Phase A angle=0.
   c. Frequency=60 Hz.
   d. Source resistance (Rs) =5.55Ω
   e. Source inductance (Ls) =0.22H.
2. Transformer-
   a. Winding 1 and winding 2 are start connected.
   b. Winding 3 is delta connected.

c. Core type-saturable with initial flux.
d. Nominal Power=450 MVA.
e. Winding 1 rating=500kV (phase to phase)
f. Winding 2 rating=230kV (phase to phase)
g. Winding 3 rating=60kV (phase to phase).
h. Magnetizing resistance (Rm) =500pu.
i. Magnetizing inductance (Lm) =500pu.
j. Initial flux (ϕ_A) =0.8pu.
k. Initial flux (ϕ_B) =-0.4pu.
l. Initial flux (ϕ_C) =+0.4pu.

3. Saturation characteristics-

I	Flux
0	0
0.001	1.2
1	1.52

The circuit breaker is located in between source and the Transformer. Initially, the c.b.is open and it is closed at t=0.05 sec. and having frequency 60 Hz i.e. after 3 cycle circuit breaker is turned on. Hence, the inrush current will be observed at the 3rd cycle.

As shown in figure, we can observe the 3 phase inrush current in the Transformer after closing of circuit breaker initially-

I_A=2.8amp. (Yellow line)

I_B=-1.6amp. (Blue line)

I_C=-0.5amp (Green line)

Hence, the phase A has an enormously high inrush current during the transformer energizing (See in fig. 4.1).The voltage is measured for phase A because it has highest inrush current.

$$V_A(pu) = V_A/(500 * 10^3 * \sqrt{2})$$

We can see that upto the 3rd cycle i.e. 0.05sec. the voltage is purely sinusoidal but after 3rd cycle as inrush current introduced we can observed that harmonics are introduced in the V_A.We can observed that the irush current I_A(yellow line) , (top) is getting decayed gradually and it become almost 1/3rd after 0.5 sec. and parallel the harmonic distortion in our voltage is also varying and these distortion are also getting reduced as time reaches to 0.5sec..

We have also observed the developed flux in our phase a winding in secondary side. This flux is obtained as-

$$V_a = \frac{d\phi}{dt}$$

$$\phi = \int Va\, dt$$

Hence, by inserting integrator box i.e. (1/s) in the path of voltage V_{a2} we can observed the flux ϕ_a(Pu) at the transformer secondary side.

We have used a multi meter base measurement for observing the current passing through the circuit breaker named as ($I_{c.b.}$) and transformer flux or primary side. Circuit breaker and the primary winding flux alone with flux induced in the secondary side of phase a winding.

We can observe that at 0.5sec., a large flux is generated specially in the phase a winding of the primary side of magnitude about 2.3pu. In that flux decayed to 1.5pu at t=0.5sec. Same flux is also observed in secondary side winding a flux.

V. RESULT ANALYSIS

We have developed a Matlab based algorithm to observed the short time cycle of the phase A voltage one by one sequentially using Prony analysis algorithm. This algorithm selects a particular cycle as per the user input and using Prony algorithm it develops the transfer function of the Prony harmonic analyzer system. This transfer function is simplified by algorithm to obtain the residue and poles of the developed harmonic Prony transfer function. For the selected voltage cycle, the residues and poles are further processed using mathematical formation to obtain the magnitude, phase, time content and frequencies of the various harmonic component present in the selected cycle of the voltage(Va (pu)). The order of transfer function for Prony analysis i.e. N=20 is taken. In this way, we get 20 different values of frequencies that represent the harmonic content of the selected cycle. In this way, we can get the information of about 10 harmonic frequency contents in a voltage cycle because our algorithm represents the results in +ve and –ve frequencies.

Using these results, we have calculated the energy ad total harmonic distortion of each cycle before and after generation of inrush current. Our approach consists of three steps. Initially we run our simulink model for generation of the inrush current by the transformer energizing phenomenon. In this step, the voltage ie generated by simulink model is export to the workspace of Matlab environment. In next step, we generated the FFT analysis report using Powergui tool of the simulink block. Using the response obtained by Fourier analysis Powergui tool we have obtain the value of percentage magnitude of the fundamental and harmonic content. In the last step, we applet the Prony analysis Matlab based algorithm to investigate the harmonic content of voltage signal Va pu for each cycle sequentially.

We have tabulated the harmonic frequencies and their magnitude observed by the Fourier analysis along with the results obtained by Prony analysis. The table of Prony analysis also displays the time consent of the harmonic content along with their magnitude for each cycle. The observation that has been generated from the analysis of the both the tables shows that before closing the circuit breaker there are no harmonics present here and both Fourier and Prony methods only represents the fundamental component but after closing the circuit brake, we observed the presence of several harmonic frequencies of voltage obtain from the to 20th cycle.

At the 4th cycle, since inrush current is at its maximum intensity the Prony analysis shows that this cycle consist of 4th harmonic as the most significant component after the fundamental frequency. After 4th, th harmonic is more significant. The decay consent of 4th harmonic is7.2*10^-3 and for the 20th harmonic the time constant is 0.34*10^-3. The decay constant shows the sustainability of the harmonic component. Longer the decay consent smaller will be damping factor of the waveform. It has been observed that both fundamental and 4th harmonic have near about some decay consent and it indicates that 4th order harmonic will damped very slowly as compare to the 20th and other higher order harmonics.

The Fourier analysis also justify that the 4th harmonic has highest percent magnitude and after 4th harmonic the significant of 3rd and 5th harmonics are found, total harmonic distortion obtain is 27.8%. Similarly, we have observed the decay constant and percent magnitude of each harmonics in each cycle.

VI. Conclusion

It has been concluded as both Fourier and Prony confirms the presences of 4th harmonic as the most affective frequency constant that causes the distortion in voltage waveform. As the number of cycles increases the % magnitude of 4th harmonic is found to be increases and after the 8th cycle the magnitude of 4th harmonic is suddenly decreases and it decays to the range of 10.5v upto the 13th cycle and after the cycle the harmonic again start raising and present as a most affective harmonic content in each cycle. In this way out of 17 cycles in almost 9 cycles, 4th harmonic is present with largest magnitude. Thus conclusions are also verified by the Fourier analysis results.

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