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HARMONIC POWER FLOW ANALYSIS

دراسة تحليلية لحساب سريان القدرة الكهربية تحت تأثير التوافقيات

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الخلاصة: يقدم هذا البحث طريقة جديدة لحساب أنسياب القدرة الكهربية فى منظومة القوى الكهربائية تحت تأثير التوافقيات ، معتمدة على طريقة نيوتن - رافسون مع تحسين درجة أدائها ، كذلك يمكن من خلال هذه الطريقة ايجاد مركبات الجهد للتوافقيات المختلفة ، مركبات القدرة الكهربية (القدرة الفعالة ، الغير فعالة ، القدرة الظاهرية) ، وحساب معامل القدرة عند كل نقطة تحميل على منظومة القوى الكهربائية تحت تأثير التوافقيات . والنموذج المقترح يمكنه من تناول الانواع المختلفة للاحمال الغير خطية وذلك بمعلومية العلاقة بين الجهد والتيار لهذه الاحمال .

Abstract : In this paper a developed technique based on Newton-Raphson algorithm with improved convergence characteristic is derived for the harmonic analysis of system containing nonlinear loads. This technique is able to calculate voltage spectra, power components (P, Q, S) and power factor at each load point under harmonic distortion. Additionally, the proposed technique can handle all types of nonlinear loads assuming that V-I characteristic is known for these loads.

1. INTRODUCTION

Waveform distortion has always been present to some extent in electric power systems. However, there is a growing concern for this problem because of the increasing numbers and sizes of the nonlinear electronic devices used in the control of power apparatus and systems. Harmonics superimpose themselves on the fundamental waveform, distorting it and changing its magnitude. The distortion caused by superimposing harmonics to the fundamental is determined not only by their frequency, but also by their amplitude and phase relationship to the fundamental.

The distorted waveforms are usually composed of harmonics and cause bad effects on the power circuits. These effects are summarized as, series and parallel resonances, failure of the power factor improving capacitor, interference to control circuits and communication systems, metering error, and malfunction of harmonic sensitive electronic equipment.

The harmonic analysis methods can be grouped in two general categories : Frequency Domain Analysis methods and Time Domain Analysis methods. In Time Domain methods, the system model is in the form of differential equations. Solution is obtained by assuming a set of initial conditions and integrating the system equations over time. After the system has reached steady state, the voltage and current waveforms of interest are subjected to Fourier Analysis in order to derive the harmonic spectrum [1-2]. The method is capable of simulating power system nonlinearities. However, it is computationally demanding and practically limited to the study of small systems.

The most widely used method for harmonic analysis in power systems is the Linear Frequency Domain Analysis method [3]. This method is based on the assumption that the harmonic current generated by any nonlinear devices, are independent of the voltage waveform and the system harmonic impedances. Thus, the converter is modelled as an ideal harmonic current generator. The power system is represented with an admittance matrix equation at each harmonic of interest. The above method can deal with a large power system due to its computational efficiency. However, modeling the converter as a constant harmonic current source introduces inaccuracies. A method that overcomes the above limitations is the Nonlinear Frequency Domain Analysis method. This method couples a nonlinear converter model with a linear model of the power system [4-7]. The solution is found using Gauss method. Another papers [8-9] extends the Newton-Raphson power flow technique to include harmonics by increasing the number of algebraic nonlinear equations to reflect the power and volt amperes mismatches. When this is done, the Jacobian matrix is considerably large.

The Nonlinear Frequency Domain Analysis is a promising method from the computational and accuracy point of view. This paper extends the principle of Nonlinear Frequency Domain Analysis with a developed technique based on Newton-Raphson algorithm. The proposed technique has improved convergence characteristic and can handle all types of nonlinear loads assuming that V-I characteristic is known for these loads.

2. PROBLEM FORMULATION

2.1. System Components Models

In this section, models of arc furnaces and converters are presented. Others such as transmission lines, transformers, synchronous and induction machines are described in [6].

Arc Furnace

An arc furnace has a continuous harmonic spectral. It present two harmonic band widths:

- sub harmonics (0 - 25) hz
- harmonics (50 - 1000) hz

In this paper, only harmonics are considered and therefore the model shown in fig. 1 is used as in [7]. The ratio r of the harmonic current of order h, $I^{(h)}$, to fundamental, $I^{(1)}$, is given by:

$$r = 0.15 + 3.5\, e^{-0.4(h-2)} \qquad h \text{ even} \qquad (1)$$

$$r = 0.15 + 7.5\, e^{-0.45(h-3)} \qquad h \text{ odd} \qquad (2)$$

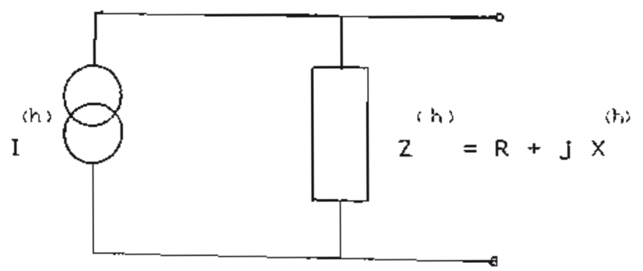

fig. 1 Arc Furnace Model

Converter

The experimental converter model used represents the converter as in [7]. The ratio rc of harmonic current of order h, $I^{(h)}$, to fundamental, $I^{(1)}$, is given by

$$rc = \frac{1}{(h - 5/h)^{1.2}} \qquad h= 5,7,11,13,.... \qquad (3)$$

2.2. Harmonic Load Flow Equations

Consider a power system of N busses. Let bus 1 to be a slack bus, busses 2 through NL are conventional load busses (Linear loads), busses NL+1 through N as nonlinear load busses. Busses 1 through NL are handled in usual way. For busses NL+1 through N , the injected harmonic currents at these busses are required. The injected harmonic current at a nonlinear bus is dependent on the nature of nonlinear load at this bus. In this paper, we consider the source of harmonic is a converter although other nonlinear loads of known characteristics are also analyzed in the same way. The injected harmonic current at bus i can be written as

$$I_i = V_i \, (Y_{ii} + y_{NLi}) + \sum_{\substack{j=NL+1 \\ i \neq j}}^{N} Y_{ij} \, . \, V_j \qquad (4)$$

where

Y_{ij} : (i-j) bus admittance element evaluated at h harmonic order.

y_{NLi} : the equivalent admittance of nonlinear load at bus i at h harmonic order.

I_i : injected harmonic current at bus i.

In polar form,

$$V_i = |V_i| \, e^{j\theta_i} \qquad (5)$$

$$Y_{ij} = |Y_{ij}| \, e^{j\phi_{ij}} \qquad (6)$$

$$y_{NLi} = |Y_{NLi}| \, e^{j\phi_{NLi}} \qquad (7)$$

$$I_i = |I_i| \, e^{j\delta_i} \qquad (8)$$

Substituting in equation (4), then,

$$I_i = |V_i||Y_{ii}| \, e^{j(\theta_i + \phi_{ii})} + |V_i||y_{NLi}| \, e^{j(\theta_i + \phi_{NLi})} + \sum_{\substack{j=NL+1 \\ i \neq j}}^{N} |Y_{ij}||V_j| \, e^{j(\theta_j + \phi_{ij})} \qquad (9)$$

The current I_i can be resolved into active component Ia_i and reactive component Ir_i.

$$Ia_i = |V_i||Y_{ii}|COS(\theta_i + \phi_{ii}) + |V_i||y_{NLi}| COS(\theta_i + \phi_{NLi}) + \sum_{\substack{j=NL+1 \\ i \neq j}}^{N} |Y_{ij}||V_j| COS(\theta_j + \phi_{ij}) \qquad (10)$$

$$Ir_i = |V_i||Y_{ii}|Sin(\theta_i + \phi_{ii}) + |V_i||y_{NLi}| Sin(\theta_i + \phi_{NLi}) + \sum_{\substack{j=NL+1 \\ i \neq j}}^{N} |Y_{ij}||V_j| Sin(\theta_j + \phi_{ij}) \qquad (11)$$

The Newton-Raphson method is used to solve the harmonic load flow:

$$X^{\mu+1} = X^{\mu} + \Delta X \qquad (12)$$

$$F(x) = -J.\Delta X \qquad (13)$$

or

$$X^{\mu+1} = X^{\mu} - J^{-1}.F(x) \qquad (14)$$

where μ is the iteration number, J the jacobian, and,

$$F(x) = [\Delta P, \Delta Q, \Delta Ia^{(2)}, \Delta Ir^{(2)}, \ldots\ldots, \Delta Ia^{(h)}, \Delta Ir^{(h)}]^T \qquad (15)$$

$$\Delta X = [\Delta V^{(1)}, \Delta\theta^{(1)}, \ldots\ldots\ldots\ldots, \Delta V^{(h)}, \Delta\theta^{(h)}]^T \qquad (16)$$

and where, Δp, ΔQ, are the fundamental active and reactive power mismatch, $\Delta Ia^{(h)}$, $\Delta Ir^{(h)}$,are the active and reactive current mismatch at h harmonic order due to injected harmonic current at nonlinear busses. To enhance the convergence of the scheme, an adaptive factor α can be added to (14) as,

$$X^{\mu+1} = X^{\mu} - \alpha J^{-1}.F(x) \qquad (17)$$

the value of α is

$$0 < \alpha < 1 \qquad (18)$$

2.3. Power Calculations

The solution of (17) gives the bus voltages, currents flow and power flow at each harmonic order. The non-sinusoidal bus voltage V_i and current I_i are

$$V_i = \sum_{h=1}^{H} V_i^{(h)} . \tag{19}$$

$$I_i^{(h)} = \sum_{\substack{j=1 \\ i \neq j}}^{N} I_{ij}^{(h)} \quad , h=1,2,3,4,\ldots\ldots\ldots,H \tag{20}$$

or.

$$I_i = \sum_{h=1}^{H} I_i^{(h)} \tag{21}$$

where, H is highest harmonic order of interest. The bus voltage $V_i(t)$ and current $I_i(t)$ expressed in terms of its rms harmonic components are

$$V_i(t) = \sum_{h=1}^{H} V_i^{(h)} \sin(hwt + \alpha_i^{(h)}) \tag{22}$$

$$I_i(t) = \sum_{h=1}^{H} I_i^{(h)} \sin(hwt + \beta_i^{(h)}) \tag{23}$$

The active power P_i (average power) at bus i,

$$P_i = \sum_{h=1}^{H} V_i^{(h)} . I_i^{(h)} . \cos(\alpha_i^{(h)} - \beta_i^{(h)}) \tag{24}$$

The term reactive volt ampere ' Q ' is used for a mathematical quantity which should not be confused with power. This quantity does not possess the conservation property of P. The reactive volt ampere Q_i at bus i,

$$Q_i = \sum_{h=1}^{H} V_i^{(h)} . I_i^{(h)} . \sin(\alpha_i^{(h)} - \beta_i^{(h)}) \tag{25}$$

also the apparent volt ampere S_i at bus i ,

$$S_i = \sqrt{\left[\sum_{h=1}^{H} (V_i^{(h)})^2\right]\left[\sum_{h=1}^{H} (I_i^{(h)})^2\right]} \tag{26}$$

In the case of sinusoidal voltage and current,

$$S^2 = P^2 + Q^2 \quad (27)$$

In the non-sinusoidal case equation (27) does not hold. A term D_i called a distortion volt ampere at bus i is given by

$$D_i = \sqrt{S_i^2 - P_i^2 - Q_i^2} \quad (28)$$

also, the power factor PF_i at bus i with non-sinusoidal voltages and currents is,

$$PF_i = P_i / S_i \quad (29)$$

3. SOLUTION TECHNIQUE

The steps used to solve the harmonic load flow of the power system subject to harmonic sources will be as follows:

1) Load flow calculations of the power system subject to power sources at fundamental frequency.
2) Load flow calculations of the power system subject to harmonic source.
3) Power calculations in system with non-sinusoidal voltages and currents.

4. APPLICATIONS

4.1. Test System

The proposed technique has been tested on 7- bus system [10] which is given in fig. 2. Tables 1 and 2 illustrates the main data of the test system. A 18 MW converter has been used as source of harmonic at bus 5 to analyze the voltage harmonic spectra.

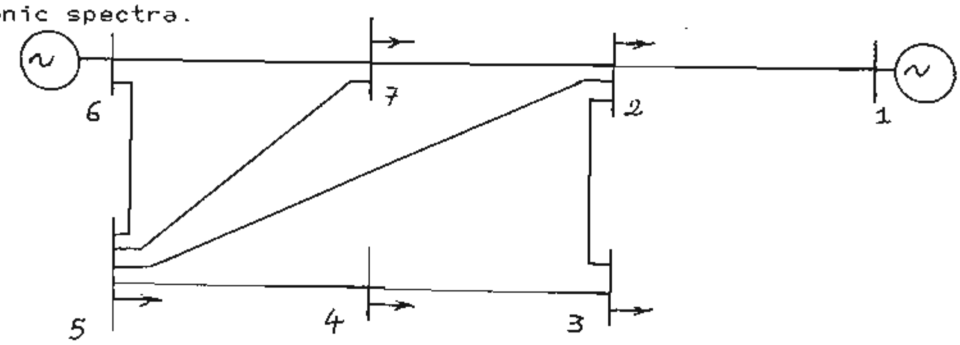

Fig. 2 The sample 7-bus power system

Table 1. Impedance and line charging for the sample 7-bus system on 100 MVA base

Bus code	Impedance Z_{ij} (p.u)	Line charging $y_p/2$ (p.u)
1-2	0.082 + j0.192	0.0000
2-3	0.067 + j0.171	0.0173
2-5	0.058 + j0.176	0.0187
2-7	0.013 + j0.042	0.0064
3-4	0.024 + j0.100	0.0100
4-5	0.024 + j0.100	0.0100
5-6	0.019 + j0.059	0.0260
5-7	0.057 + j0.174	0.0170
6-7	0.054 + j0.223	0.0250

Table 2. Scheduled generation and loads

bus code	Generation (p.u)		Load (p.u)	
	P	Q	P	Q
1	0.9	0.3	0.000	0.000
2	0.0	0.0	0.478	0.039
3	0.0	0.0	0.942	0.190
4	0.0	0.0	0.135	0.058
5	0.0	0.0	0.180	0.120
6	-	-	0.000	0.000
7	0.0	0.0	0.076	0.016

4.2. Results and Discussions

The obtained results using the proposed technique are illustrated in Fig. 3 and Table 3. Figure 3 shows the harmonic spectra at each load bus with the presence of converter at bus 5. The magnitudes of the harmonic voltages are given in percent of the fundamental. Table 3 illustrates the power components (P, Q, S, D) and the power factor at each bus under the effect of harmonic distortion.

The following remarks are regarded while dealing with this test system:

- Using the proposed technique, convergence towards a minimum with a mismatch varying between 0.0001 and 0.001 is obtained.
- The number of iterations varies between (3- 10).
- The maximum distortion of the voltage occurs at the nonlinear load bus.
- The harmonic voltage distortion generated by a nearby customer could produce, to another customer, a low power factor operating problem.

Table 3. Power components and PF at each load point under harmonic distortion

bus no.	P(p.u)	Q(p.u)	S(p.u)	D(p.u)	PF	
1	0.8919	0.2980	0.9415	0.0399	0.947	lag.
2	0.4776	0.0334	0.4789	0.0093	0.973	lead
3	0.9396	0.1909	0.9592	0.0291	0.795	lag.
4	0.1386	0.0583	0.1505	0.0065	0.208	lag.
5	0.1920	0.1254	0.2364	0.0574	0.102	lag.
6	1.0596	0.1911	1.0789	0.0700	0.820	lead
7	0.0758	0.0144	0.0773	0.0029	0.815	lag.

5. CONCLUSIONS

A developed technique based on Newton-Raphson algorithm with improved convergence characteristic is successfully extended and implemented to analyze harmonic spectra and calculate all power components and power factor at each bus under harmonic distortion in a power system. The proposed technique is general enough to be used with power system of any size, any type of harmonic sources as well as any number of generated harmonic signals. Finally harmonic power flow calculations, which can assist in locating harmonic sources are easily carried out for a test system.