HARMONIC MODELLING OF DISTORTING LOADS ON DISTRIBUTION FEEDERS AND IN A LARGE POWER SYSTEM

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Abstract

In most of frequency response type program, it is common to assume that all harmonic sources have the same phase angle. In this paper this assumption is investigated for distorting loads with diode rectifier front ends. Based on these investigation correct equivalent models of distorting loads are proposed firstly on one distribution feeder and secondly for distribution feeders in different subsystems of a large network. For the purpose of these investigations a Power Electronic Simulator (PES) with Time Domain solution has been used.

1. INTRODUCTION

Proposed installations of harmonic sources can be checked to see if they will meet standards by means of harmonic analysis computer programs(1-2). Most cases can be conveniently and easily examined by a frequency response type program where harmonic sources are represented by a parallel connection of ideal ac current sources at each harmonic frequency. Due to lack of data, it is common to assume that all harmonic sources have the same phase angle (normally zero). This gives a worst case result in most cases.

In an attempt at more realistic results, some studies have assumed a random distribution of phase angles(3-4). This may be applicable where most of the sources are SCR rectifiers (e.g DC drives) where the firing angle vary independently. However, it is expected in future that most harmonic sources will have diode rectifier front ends where the variations in the phase angle is much more restricted.

The assumption of equal phase angle might seem reasonable for harmonic sources with diode rectifiers such as AC derives but deserves closer investigation. In this paper this assumption is investigated first for representation of loads on one distribution feeder and secondly for distribution feeders in different subsystems. The first investigation is useful when harmonics analysis of a single feeder is made by the frequency domain computer program. The second case is for calculation of harmonic distortion level in a large interconnected network.

2. METHODOLOGY

For investigation of the assumption of equal phase angle of loads on one distribution feeder, the phase angle at each harmonic order and variation of the phase angle of the harmonic current injected by the rectifier is obtained with respect to the size of the rectifier and the condition of its connection to the system (sensitivity analysis). If this variation is not significant, then this assumption can be correct provided correct equal phase angle is assumed. For the purpose of the sensitivity analysis a Power Electronic Simulator (PES)[5] has been used.

The results of obtained sensitivity analysis is verified by studying a typical distribution feeder with two rectifiers. In this study first the harmonic current and voltage distortion level of a feeder with two rectifiers for different system conditions are obtained by PES. Then the rectifiers are replaced with two equivalent harmonic sources with equal phase angles as obtained before and harmonic current and voltage distortion levels are obtained for the same system conditions. Comparison between the two cases gives the accuracy of the assumption of equal phase angles for the harmonic sources with rectifiers.

For representation of distribution feeders in different subsystem with ideal current sources, the results obtained from the first case is used to give the required phase angles of the equivalent harmonic current sources.

3.POWER ELECTRONIC SIMULATION PROGRAM

In all of system studies in this paper, Power Electronic Simulation Program [5] has been used to obtain current and voltage in time domain. By the aide of spectrum analysis which is part of the simulator, harmonic current and voltage can be calculated. Generally (PES) calculates circuits in which electronic devices are used as switches. It has some advantages over existing methods in harmonic studies. The main features of PES are :

1)The circuit input is by means of a circuit schematic drawn on the screen.

2)The built in models have been chosen to give a lot of flexibility in constructing models for complex devices. These models include switched mode power supplies, power converters,ac and dc motors.

3)The output is shown on the screen graphically . A harmonic spectrum facility is available.

4. INVESTIGATION ON THE ACCURACY OF ASSUMPTION OF EQUAL PHASE ANGLE FOR HARMONIC SOURCES

The assumption of equal phase angle is investigated first for representation of loads on one distribution feeder and secondly for distribution feeders in different subsystems.

4.1 Loads On One Distribution Feeder

Assume a distribution feeder supplies "n" harmonic sources connected at different locations as shown in Figure 1. The phase angle of the nth harmonic current source is assumed to be $(\theta n)_h$ for harmonic order h with respect to absolute reference. The harmonic sources can be modelled with equal phase angle for harmonic current only if the difference of the phase angle of the sources are negligible. One method to investigate is to find the variation of the harmonic current phase angle of one diode rectifier with respect to system parameters at each harmonic order .

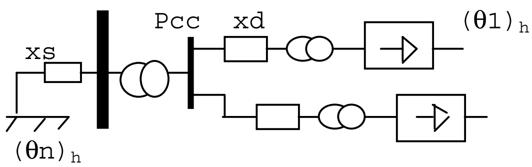

Figure 1: A Typical Distribution Feeder

4.1.1 Sensitivity Analysis

For sensitivity analysis first it is assumed that only one rectifier has been connected to the system. With this condition the effect of the following system parameters on the phase angle is investigated.

-Size of the rectifier
-Fault level at the PCC
-Reactance of distribution line
-Combination of above cases.

Table 1 shows different cases for the performance of the sensitivity analysis. The studied cases represent weak and strong power systems, light and heavy loaded feeder. In all cases a capacitor filtered diode rectifier as shown in Figure 2 has been considered. Each rectifier capacitor in the model has been connected in series with a DC voltage (equal to L-L voltage of the transformer secondary (5.6KV) for initial capacitor charging and the damping of the initial transient waveshapes. The current in Table 1 is the magnitude of the current source IA as shown in Figure 2. It is assumed that the system primary voltage is 13.8KV line-line and the rectifier is connected to the system by delta-delta transformer with a ratio of 3.3. The other parameters on Table 1 have been defined in Figure 1.

Table 2 gives the magnitude of the harmonic current and voltage distortion level. Note that PES gives peak current and voltage.

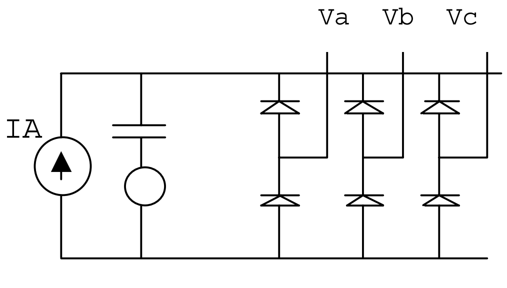

Figure 2 :Distorting Load Model

Table 1 :System Parameters

Sys param	Base case	Case (i)	Case (ii)	Case (iii)
IA	0.014	0.036	0.036	0.072
(xd)	0.047	0.047	0.047	0.148
(xs)	0.28	0.28	0.84	0.28

All values in PU on 100MVA, 13.8KV

Table 2 : Harmonic level at PCC

Harmonic order	Harmonic Current(A)	Harmonic Voltage(V)
1	73.4	19480
5	49	231
7	31.3	207
11	7	62
13	5.4	61
17	3.3	58
19	1.9	38
23	1.5	30
25	0.9	23

4.1.2 Calculation of the Harmonic Current Phase Angle of the Rectifier at Each Harmonic Order

To obtain the phase angle of the rectifier, the rectifier is replaced by a two phase equivalent harmonic current source as shown in Figure 3. A two phase equivalent source is sufficient to represent three phase system under balanced system conditions. Each harmonic current source is controlled by a voltage probe. The voltage probe is connected across a series of harmonic voltage sources.

In order to obtain the same system condition with the equivalent harmonic source as the rectifier, two factors should be considered. First the harmonic current injection level by the equivalent current source should be the same as the replaced rectifier. This is achieved with a suitable selection

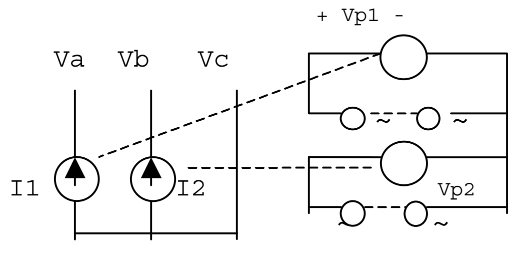

Figure 3 : Harmonic source as modelled in PES

of voltage magnitude at each harmonic in harmonic voltage source circuit. Secondly the waveshape of the harmonic current distortion level at the PCC should be the same for the two cases. This is achieved by adjustment of the phase angles of the harmonic voltage source at each harmonic. Table 3 gives the required phase angles for equivalent harmonic source at each harmonic. Hence the obtained phase angles are with respect to the fundamental system voltage at the PCC (zero for phase "a").

Table 3 : phase angle and Magnitude of the harmonic current

Harmonic order	Angle (phase a)	Mag(A)
1	-10	73.4
5	120	49
7	-90	31.3
11	-120	7
13	60	5.4
17	90	3.3
19	30	1.9
23	180	1.5
25	180	0.9

Similar procedure was performed to obtain the phase angle of the rectifier for other cases as shown in Table 1. It was found that the variation of the phase angle up to the 13^{th} harmonic is less than 15% as compared with the base case. This indicated that harmonic sources with diode rectifier can be represented with ideal current sources and equal phase angles in computer programs for harmonic order up to 13^{th} provided the assumed phase angle for each harmonic order to be according to Table 3. It is important to notice that the assumption of equal zero phase angle (normal practice) gives significant error.

In the next section this conclusion is verified for a typical distribution feeder with two harmonic sources with diode rectifiers.

4.1.3 : Accuracy on the Assumption of Equal Phase Angle on A Distribution Feeder with Two Rectifiers

The distribution feeder selected for investigation of the assumption of equal phase angle for harmonic sources is as shown in Figure 1 but with only two rectifiers connected to the system. The power system is assumed to be balanced and is modelled by its equivalent Thevenin model reactance derived from short circuit studies. The system voltage level and other parameters are the same as in Section 4.

For investigation of the assumption of equal phase angle of two rectifiers, two stages are considered. In Stage 1 the magnitude of the harmonic current and voltage distortion level of a feeder with two rectifiers are obtained for different system conditions. Then in Stage 2 the rectifiers are replaced with two harmonic sources with equal phase angles with the same system conditions as the two rectifiers. The assumed equal phase angle at each harmonic order is according to phase angles as shown on Table 3. The comparison between the results of the two stages gives the accuracy of the assumption of the equal phase angles. Different cases regarding to the size of rectifier and system parameters as shown in Table 4 have been considered. Table 5 shows the harmonic current and voltage distortion level for Case (i). Similar results were obtained for other cases. The results are the bench-mark for the subsequent comparisons.

Table 4 : System Parameters

Sys-param	Base case	Case (i)	Case (ii)	Case (iii)	Case (iv)
(IA)1	0.014	0.036	0.014	0.014	0.036
(IA)2	0.021	0.072	0.021	0.021	0.072
xs	0.28	0.28	0.28	0.84	0.28
xd	0.047	0.047	0.148	0.047	0.148

All values in PU on 100 MVA and 13.8 KV base

Table 5 :Harmonics for case (i)

Harm-order	I1(A)	I2(A)	Ipcc(A)	Vpcc(V)
1	166	331	498	19460
5	65	98	164	765
7	25	30	49	330
11	13	22	33	335
13	6	13	15	192
17	6	9	12	176
19	3	8	8	139
23	3	5	5	101
25	2	5	4	99

In order to validate the assumption of equal phase angle, the two rectifiers are replaced with two equivalent harmonic sources and equal phase angles. The harmonic current is obtained for various cases as shown in Table 4. Table 6 shows the error of the magnitude of harmonic current at the PCC if rectifiers are replaced with equivalent harmonic sources. It is observed that up to 13the harmonic the error is less than 15%. This is consistent with results obtained in Section 4.

Table 6: % Error for Cases

Harm-order	Case (i)	Case (ii)	Case (iii)	Case (iv)
1	0	0	0	0
5	0	0	2	0.8
7	12	3	3	20
11	6	9	8	13
13	25	10	9	50
17	23	18	20	50
19	31	21	20	64
23	69	28	28	160
25	56	34	33	130

5. MODELLING OF THE DISTRIBUTION FEEDERS IN DIFFERENT SUBSYSTEMS

In Section 4, it has been shown that the harmonic sources with diode rectifiers in one distribution feeder can be represented by ideal current source with equal phase angles for only low order harmonics. In this section this assumption is investigated for distribution feeders in different subsystems. Based on this investigation the required phase angle of the ideal ac current source for representation of distribution feeders in the computer programs are given.

Assume that the phase angles of the fundamental system voltage at the PCCs(where the distribution feeders are connected) with respect to the system common reference are $\theta 1, \theta 2$, ..,θr...and θn. These angles can be obtained from normal load flow. Let us assume the distribution feeders are represented as harmonic current sources at different buses(PCCs) for each harmonic by $I1\angle\alpha 1$, $I2\angle\alpha 2$... $Ir\angle\alpha r$...and $In\angle\alpha n$ where αr is the phase angle with respect to the phase angle of the fundamental system voltages at the PCC. If the feeders supply only harmonic sources with diode rectifiers, then all angles of the harmonic current sources at each harmonic with respect to the fundamental system voltages can be assumed equal to 'α' for example :

$$\alpha 1=\alpha 2=.....=\alpha n=\alpha$$

The phase angle of each harmonic source with respect to common reference for each harmonic source is obtained as: $\phi r=\theta r-\alpha$. The harmonic voltage distortion level is calculated from :

$$\mathbf{V}_h=\mathbf{Z}_h.\mathbf{I}_h$$

By writing the equation in terms of the magnitude and the phase angle , it can be shown that the magnitude of the harmonic voltage is independent of the phase angle 'α'. Consequently each harmonic source (distribution feeder) can be modelled as an ideal current source with the phase angle equal to the phase angle of the fundamental system voltages at its PCC.

6. CONCLUSIONS

In most of the frequency domain harmonic analysis program, it is common to represent all harmonic current sources with ideal ac current sources and zero phase angle with respect to the absolute reference. This is due to lack of sufficient data regarding the phase angles. In this paper this assumption was investigated firstly for the loads on one distribution feeder and secondly for distribution feeders in different subsystems. It has been assumed that the loads have diode rectifier front ends.

For modelling of harmonic sources on one distribution feeder it has been found that the assumption of

equal phase angle for harmonic sources can be used only for harmonics up to the 13th provided the correct phase angle is assumed
at each harmonic order(e.g 120° for 5th harmonic).

For modelling of distribution feeders in different subsystems with ideal current sources, it was found that the phase angle of the equivalent source should be equal to the phase angle of the fundamental system voltage at the PCC where the distribution feeder has been connected otherwise an error of up to 20% may occur.

The obtained results in this paper can be used in the frequency domain computer program for harmonic modelling of distorting loads.

7. REFERNCES

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