3-Phase Harmonic Modeling of Unbalanced and Distorted Power System Loads

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Keywords: load modeling, power system harmonics

ABSTRACT

A generic load model for harmonic loads is used in this study. The model consists of resistance, inductance and capacitance connected in parallel with a current source. The modeling technique is based on using actual recorded data and it is particularly suitable for developing aggregate load models. Examples for single and three phase load models are given.

I. INTRODUCTION

There has been an increased interest in recent years in developing aggregate harmonic load models for distribution feeders. This is largely due to the increased presence of non-linear loads (computers, TV sets, variable speed drives, office equipment, electronic ballast, etc.) in customer's facilities and increased sensitivities of modern electronic equipment to harmonic pollution of the network. The non-linear devices produce non-sinusoidal currents even though the applied voltage is perfectly sinusoidal. On the other hand both, linear and non-linear loads (equipment) in a distribution system may be affected by voltage harmonics that exist in the system due to the presence of the non-linear loads at neighboring buses [1]. One of the biggest difficulties associated with the assessment of harmonic propagation in distribution systems is modeling of the system loads. In spite of the small individual powers of various loads commonly encountered in parts of distribution system (e.g., in commercial buildings) a large quantity makes them significant for consideration, and they should not be discarded.

The adequate load modeling is essential for accurate calculations of harmonic current flows. It is however, often impossible to represent all the loads in the system in detailed manner needed to obtain accurate results. There is also a certain level of disagreement regarding the choice of harmonic load models.

Various models have been proposed in the past for modeling loads for harmonic studies [2-10]. A method for modeling distribution system loads as unbalanced three-phase impedance matrix is presented in [2]. The experience has shown that the individual system elements can be modeled by simple equivalent circuits [3]. A part from the adequate modeling of the non-linear loads, representation of linear elements is also very important and it should not be neglected or represented without full consideration of the load characteristics and compositions. A generic load model for harmonic studies proposed in [4] consists of electronic load, resistive load, induction motor load and power factor correction capacitor. Techniques have been developed for identifying the high frequency load characteristics using signal analysis methods [5]. A frequency domain analysis based on the least squares method was used for load modeling in [6,7]. A harmonic load model for representing non-linear loads by a 'crossed frequency' admittance matrix is proposed in [8]. This particular harmonic load model is applicable to passive and stationary electrical loads assuming a constant fundamental frequency voltage. A method based on parallel processing which assumes an unbalanced three-phase system, but neglects the coupling effects that may exist between harmonics of different order is presented in [9]. A time domain load modeling technique based on calculation of the power component is described in [10,11,12]. The proposed method can be used very effectively to isolate the effects of customers with non-linear loads.

The time domain technique proposed in [10,11,12] is used in this study to assess one phase and three phase load parameter It is based on using actual recorded data and therefore suitable for developing aggregate load models without necessary knowing actual load composition.

II. HARMONIC LOAD MODEL

By using current and voltage measurements, a single phase load model for linear, non-linear and general loads models is given in literature [10,11]. In this model, load model parameters are obtained by using time dependent current and voltage expressions. As a result of measurement, voltage applied to single phase load v(t) and load current i(t) can be obtained by harmonic spectrum. These current and voltage's time dependent expressions are given as a function of harmonic order h, as below,

$$v(t) = \sum_{h=0}^{hmak_v} \sqrt{2}.V_h \cos(hwt + \varphi_h) \qquad (1)$$

$$i(t) = \sum_{h=0}^{hmak_i} \sqrt{2}.I_h \cos(hwt + \beta_h) \qquad (2)$$

Here, $\{v(t), i(t)\}$, $\{V_h, I_h\}$, $\{\varphi_h, \beta_h\}$ and $\{hmak_v, hmak_i\}$ parameters are respectively, voltage and current instantaneous values, r.m.s. values of voltage and current harmonics, phase angles of voltage and current harmonics, maximum harmonic degrees of voltage and current. Equivalent circuit for a single phase load is given in Figure 1.

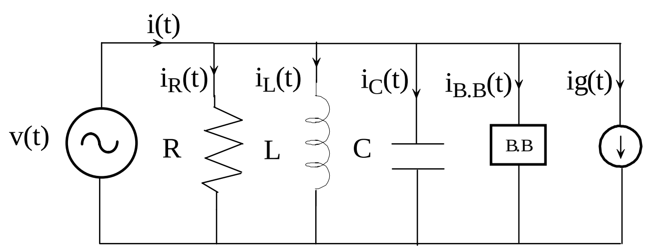


Figure 1. General equivalent circuit of single phase load

Here, $i(t)$ is the load current, $i_R(t)$, $i_L(t)$ and $i_C(t)$ are the current of R, L, and C, $i_g^+(t)$ error current of load model, $i_{B.B}(t)$ total harmonic currents with order that is other than these of voltage. The equivalent values of R, L, and C are calculated as follows:

$$R = \frac{(V)^2}{P} \qquad (3)$$

$$C = \frac{\frac{1}{T}\int_0^T i(t).\frac{d\,v(t)}{dt}.dt}{\frac{1}{T}\int_0^T \left[\frac{d\,v(t)}{dt}\right]^2 dt} \qquad (4)$$

$$L = \frac{\frac{1}{T}\int_0^T [w(t)]^2 dt}{\frac{1}{T}\int_0^T i(t)w(t)dt} \qquad (5)$$

Here P is the active power and V is the rms value of voltage applied to load. C shows capacitance, L reflects inductance and T denotes the period. In Equation 5, w(t) is defined as,

$$w(t) = \int_0^t v(t)dt \qquad (6)$$

which is 90^0 phase shifted fundamental component of single-phase load voltage.

Current drawn by R, L and C components are calculated as follows respectively,

$$i_R(t) = \frac{v(t)}{R} \qquad (7)$$

$$i_L(t) = \frac{1}{L}\int v(t)dt \qquad (8)$$

$$i_C(t) = C\frac{d\,v(t)}{dt} \qquad (9)$$

Here negative values of R, L and C have physical meanings. Negative values indicate that these elements are not in the equivalent circuit and currents of these elements aren't calculated.

$i_g^+(t)$ is the sum of load currents whose harmonic degrees are different from voltage harmonic degrees.

Error current related to load model is shown as a current source in load model, and calculated as,

$$i_{B.B}(t) = i(t) - i_R(t) - i_L(t) - i_C(t) - i_g(t) \qquad (10)$$

Here, a suitable load model for linear, non-linear and general loads is defined. By this approach, using load model parameters, harmonic dependent mathematical model (Figure 2) of two-terminal component can be obtained for each harmonic.

$$\mathbf{I}_h = \mathbf{Y}_h.\mathbf{V}_h + \mathbf{J}_h \qquad (11)$$

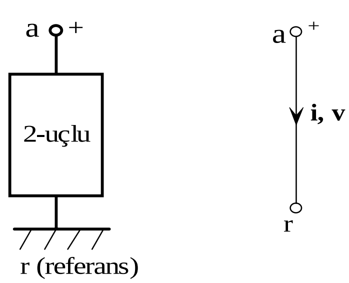


Figure 2. Two-node single phase load and its mathematical model

Y_h and J_h are given as below,

$$\mathbf{Y}_h = \left(\frac{1}{R}\right) + i\left(2.\pi.f_1.h.C - \frac{1}{2.\pi.f_1.h.L}\right) \quad (12)$$

$$\mathbf{J}_h = \mathbf{I}_{B.Bh} + \mathbf{I}_{g_h} \quad (13)$$

The algorithm given above for obtaining single phase load model can be used in single phase symmetrical component circuits. As a result, mathematical models for 3 phase nonlinear and asymmetrical loads can be obtained.

In order to obtain three-phase load model, line and phase voltage harmonics are measured at first. Then, the procedure is applied as given in Figure 5, with the orders described with numbers. These numbers reflect the following properties,

1. Time depending functions of voltage and current's positive, negative and zero components are obtained by using measured harmonic spectrum of phase voltages and currents.

In 2,3, and 4 operation blocks, mathematical models of positive, negative and zero order component circuits are developed by the proposed single phase load model algorithm.

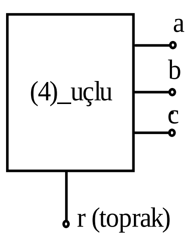
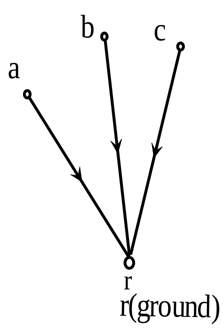


Figure 3. Four-node notation of 3 phase load



$$\begin{bmatrix} \hat{\mathbf{E}}^a \\ \hat{\mathbf{E}}^b \\ \hat{\mathbf{E}}^c \end{bmatrix}_h = \begin{bmatrix} \mathbf{Y}^{aa} & \mathbf{Y}^{ab} & \mathbf{Y}^{ca} \\ \mathbf{Y}^{ab} & \mathbf{Y}^{bb} & \mathbf{Y}^{bc} \\ \mathbf{Y}^{ca} & \mathbf{Y}^{bc} & \mathbf{Y}^{cc} \end{bmatrix}_h . \begin{bmatrix} \mathbf{V}^a \\ \mathbf{V}^b \\ \mathbf{V}^c \end{bmatrix}_h + \begin{bmatrix} \mathbf{J}^a \\ \mathbf{J}^b \\ \mathbf{J}^c \end{bmatrix}_h$$

Figure 4. Mathematical model of 4-terminal component representing 3 phase load

By reverse transformation of mathematical models of symmetrical component circuits, 4 terminal element's harmonic dependent mathematical model is obtained as in Figure 4.

In electric distribution networks, certain number of loads are placed close to each other and supplied from a main distribution point. Because of this structure, these loads are accepted as a single load and this "total load composed of different type of individual loads" are expressed as general load [12]. By this proposed method, problems in modeling single phase and three phase loads in electric distribution systems, are solved and mathematical models of linear and/or nonlinear, single phase and three phase loads can be obtained not related to its connection group.

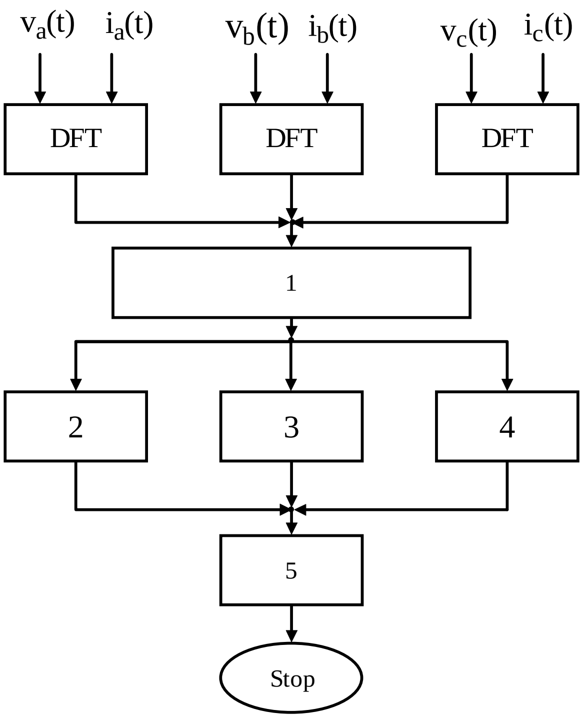


Figure 5. Flow diagram of three phase load model

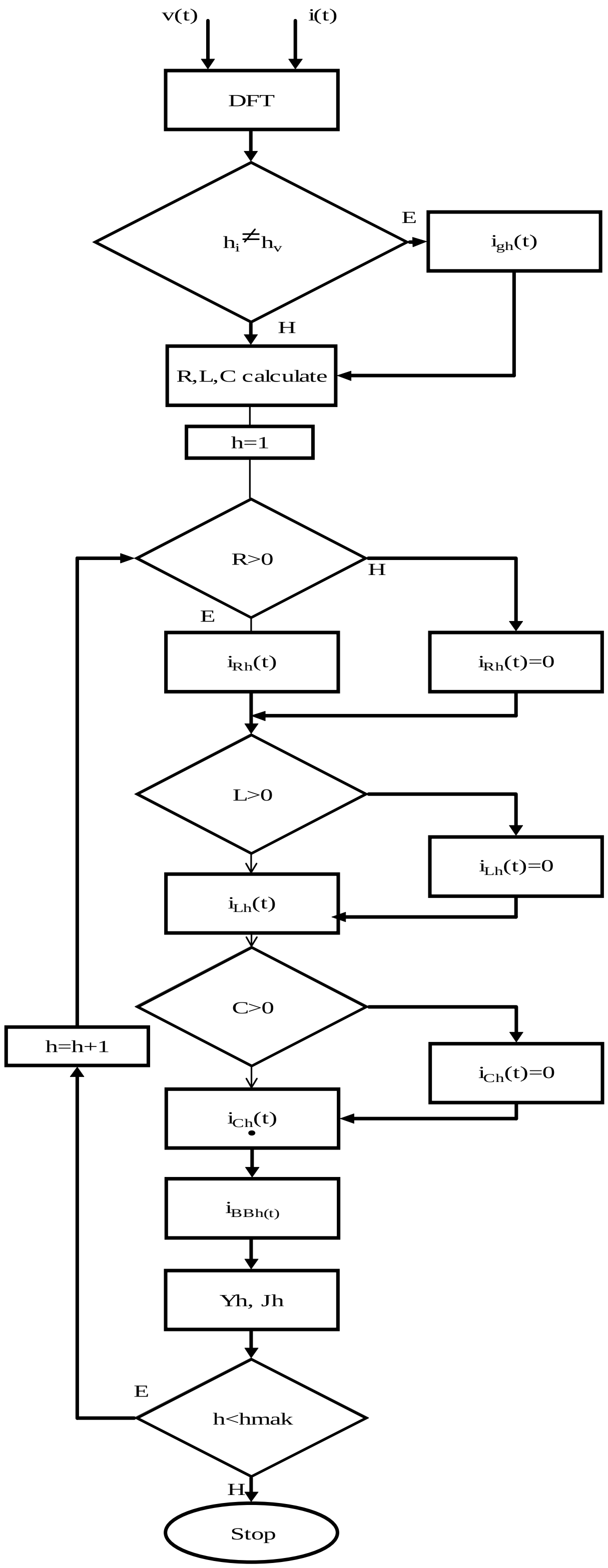


Figure 6. Flow diagram of single phase load model

III. EXAMPLES

Here are the single phase and three phase, linear and nonlinear load models by the proposed method for various operational cases.

Table 1. Harmonic spectrum and load model of single phase linear load

	Harmonic spectrum of voltage and current					
	1		3		5	
	Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)
V	1	0	-	-	-	-
I	1	-30	-	-	-	-
	Load model					
Ig	-	-	-	-	-	-
Ib.b	0	0	-	-	-	-
R	1,1547 p.u					
L	0,0053 p.u					
C	-					

Table 2. Harmonic spectrum and load model of three phase linear and symmetrical load

		Harmonic spectrum of voltage and current					
		1		3		5	
		Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)
A	V	1	0			-	-
	I	1	-30			-	-
B	V	1	-120				
	I	1	-150				
C	V	1	120				
	I	1	90				
		Load Model					
0	Ig	-	-	-	-	-	-
	Ib.b	-	-	-	-	-	-
	R	-					
	L	-					
	C	-					
1	Ig	-	-	-	-	-	-
	Ib.b	0	0	-	-	-	-
	R	1.1547 p.u					
	L	0.0053					
	C	-					
2	Ig	-	-	-	-	-	-
	Ib.b	-	-	-	-	-	-
	R	-					
	L	-					
	C	-					

Table 3. Harmonic spectrum and load model of single phase nonlinear load

	Harmonic spectrum of voltage and current					
	1		3		5	
	Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)
V	1	0	0,6	0	-	-
I	1	-30	0,6	30	0.05	30
	Load model					
Ig	-	-	-	-	0.05	30
Ib.b	0,0864	90	0.3676	90	-	-
R	1.1547 p.u					
L	0.0063 p.u					
C	25.10^{-6} p.u					

Table 4. Harmonic spectrum and load model of three phase nonlinear load

		Harmonic spectrum of voltage and current					
		1		3		5	
		Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)	Magnitude (pu)	Angle (°)
A	V	1	0	0.6	0	-	-
	I	1	-30	0.6	30	0.05	30
B	V	1	-120	0.6	0	-	-
	I	1	-150	0.6	30	0.05	-210
C	V	1	120	0.6	0	-	-
	I	1	90	0.6	30	0.05	170
		Load model					
0	Ig	-	-	-	-	-	-
	Ib.b	-	-	-	-	-	-
	R	1,1547 p.u					
	L	-					
	C	$4,421.10^{-4}$ p.u					
1	Ig	-	-	-	-	-	-
	Ib.b	0	0	0	0	-	-
	R	1.1547 p.u					
	L	0,0053 p.u					
	C	-					
2	Ig	-	-	-	-	0.05	30
	Ib.b	0	0	0	0	-	-
	R	-					
	L	-					
	C	-					

IV. CONCLUSION

In this paper, a load model is developed for single and three-phase, linear and nonlinear and general loads, by using the measure of voltage and current of load terminals. Three-phase load models are independent of their connection group. By using these load models, effects of general loads to harmonic power flow and resonance frequency studies in distribution systems can be studied. Also, compensation requirements of loads can be obtained more accurately.

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