Harmonics Analysis and Calculation in Power System Networks

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Abstract- The harmonic distortion in the power system is increasing with wide use of nonlinear loads such as wave rectifiers, static VAR compensator, and solid-state controlled devices.Thus, it is important to analyze and evaluate the various harmonic problems in the power system prior to their occurrence. This paper presents a technique to analyze propagation of harmonic current and voltage in power system networks, and determine the location and magnitude of the maximum harmonic current and voltage in the network .Frequency dependent models of a power system elements and loads have been developed for the appropriate range of frequency. The harmonic source representation is described. The location of harmonic source, and the system loads are all found to be factors in determining the magnitude of harmonic currents and voltages flow in the system.

Key words: Harmonic, Nonlinear load, Harmonic power flow

حساب وتحليل التوافقيات في شبكات نظم القدرة

الخلاصة –يزداد تشويه التوافقيات في منظومة القدرةالكهربائية مع زيادة استخدام الاحمـال اللاخطيـة كمقومات الموجة،المعوضات غير الفعالة للقدرة واجهزة السيطرة التي تستخدم الثايرستورات ومـا شـابهها، لذالك فأنه من الضروري تحليل و تقييم مختلف مشاكل التوافقيات في منظومة القدرة قبل حدوثها.
يقدم هذا البحث تقنية لتحليل انتشار فولتيات وتيارات التوافقيات في شـبكات منظومـة القـدرة الكهربائيـة وحساب موقع وقيمة اعلى توافقية بالنسبة للتيار و الفولتيه في الشبكة،وكذلك ايجاد نموذج لعناصر منظومـة القدرة و احمالها يعتمد على التردد لمدى مناسب من الترددات،كما تم وصف تمثيل مصدر التوافقيات.
لقد وجد بانه موقع مصدر التوافقيات،واحمال المنظومة هي عوامل مؤثر في تحديد قيمة التوافقيات للفولتيـة والتيار في المنظومة.

List of symbols

B: Susceptance(S)
f: Fundamental frequency (Hz)
G: Conductance(S)
h: Harmonic order number
I_h: Harmonic injected current (A)
I_{jk}: Harmonic current flowing on link between nodes j and k (A)
$P_{3\Phi}$: Three phase active power (KW)
$Q_{3\Phi}$: Three phase reactive power (KVAR)
R: Resistance at fundamental frequency (Ω)
V_j: Harmonic voltage at node j (KV)
V_k: Harmonic voltage at node k (KV)
V_L: RMS line voltage (KV)
X_C: Capacitive reactance at fundamental frequency (Ω)
X_d'': Generator sub transient reactance (Ω)
X_L: Inductive reactance at fundamental frequency (Ω)
Y': Shunt harmonic admittance of transmission line(S)
Y_1, Y_2: Harmonic admittance of long transmission Line(S)
Y_h: Harmonic admittance(S)
Z': Series harmonic impedance of transmission line(Ω)
Z_h: Harmonic impedance (Ω)
Z_{im}: Harmonic impedance between node i and node m (Ω)
Z_{jk}: Harmonic impedance of link between node j and k (Ω)
Z_o: Characteristics impedance of transmission line (Ω)
Z_t: Harmonic impedance of transformer (Ω)
ω: Angular velocity (rad/sec)
γ : Propagation constant
l: Length of transmission line (Km)
θ: Fundamental voltage angle (degree)

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Introduction

The problems of power system harmonics are not a new. It is as old as power network itself, at past time the major concerns were the effects of harmonics on a synchronous and induction motors, communication equipment interface and shunt capacitor failure .Number of precaution was taken by the manufactures such as the designing of the equipment more tolerable to the effect of the harmonic [1] .Utilities were able to eliminate or reduce the harmonics flowing in the power system by means of harmonic filters. Recently, the problem of harmonics is becoming again a current concern with the widespread use of solid state power electronics devices. The most common devices being introduced into industrial plants include variable speed ac motor drive, variable speed dc motor drive. There are a number of advantages when using these new devices. The advantages are normally a reduced cost of operation in the form of lower energy costs, better efficiency, less maintenance, and dependable operation .Each of these devices inject a nonsinusoidal current waveform into the plant distribution system and transmission network depending upon the size of the device and the system parameters. Other sources of harmonics include static var system (SVS) which have largely replaced conventional synchronous condenser [2]. The linear nature of the loads has shown a trend to change to highly nonlinear characteristics with a significant increase in primarily current harmonics. It should be recommended practice to analyze an electrical system before addition of large power electronic devices to determine the effect on the other parts of the power system After the wave shape of both the current and voltage have been determined, the harmonic content can be easily analyzed. The analysis to determine the magnitude and the order of the harmonics included in the waveform is based on Fourier transform theory.

Concept of Distortion Waveforms

To understand the distortion phenomena, it is necessary to analyze the distorted waveform by a process called harmonic analysis .It allows us to express the distorted waveform as a sum of dc component, fundamental sine wave of the distorted waveform and series of pure sine waves .These sine waves have different magnitudes and their frequencies are integer multiple of the fundamental distorted waveform. This expression is called Fourier series representation. A distorted waveform can be analyzed using Fourier series representation applies following equations [3]

$$X(t) = a_o + \sum_{n=1} a_n \cos(n\omega t) + b_n \sin(n\omega t) \quad (1)$$

Where

$$a_o = \frac{1}{T}\int_0^T X(t)d(t)$$

$$a_n = \frac{2}{T}\int_0^T X(t)\cos(n\omega t)d(t)$$

$$b_n = \frac{2}{T}\int_0^T X(t)\sin(n\omega t)d(t)$$

n=1, 2, 3 …

Fourier series can be expresed in another form given in equation

$$(2)\ X(t) = \sum_{n=-\infty}^{n=\infty} C_n e^{j2n\pi ft}$$

Where

$C_n=(a_n-jb_n)/2$.

when the positive and negative half cycles of a waveform have identical shapes with respect to the vertical axis and the average value of its period equal to zero(dc component equal zero),the Fourier series contains only odd harmonic component .These waveforms are called symmetrical waveform. The harmonic component can be plotted using time domain. Figure (1) shows the summation of the fundamental (50Hz) and third harmonic (150Hz) [2, 3].

Development of Frequency Dependent Model for Network Elements

To assemble the elements of a system into a bus impedance matrix at each harmonic, frequency dependent model for each element must be developed.

1-PassiveElements

All passive elements are considered to behave linearly with frequency, such as resistor, inductor and capacitor .The following characteristics are observed by these elements [2]:

R=constant

$$X_L(h) = jhX_L \quad (3)$$

$$X_C(h) = -jX_C / h \quad (4)$$

Where X_L and X_C are the fundamental frequency inductive and capacitive reactances respectively.

2-Generators

For the purpose of determining the network harmonic admittance, the generators can be modeled as series combination of resistance and inductive reactance [3]:

$$Z = R\sqrt{h} + jX_d^{"}h \quad (5)$$

Where R is derived from the machines power losses and $X_d^{"}$ is the generator's sub transient reactance. negative sequence fundamental frequency stator current produce flux rotate at twice synchronous speed .The resultant flux is forced into paths flow permeability which do not link any rotor circuit. These paths are characterized by the sub transient reactance [4].When harmonic currents flow from network into the stator windings of a generator, they create a flux rotating at a speed greater than the speed of the rotor .This is very similar to the action of negative sequence currents in a synchronous machines [5], therefore use sub transient reactance for generator.

3-Transformers

These are considered to be liner elements and modeled as series impedance of resistance and inductive reactance with resistance R adjusted for skin effects. The series harmonic impedance is [2, 3]:

$$Z_t = R\sqrt{h} + jX_t h \quad (6)$$

Where R derived from the transformer power losses. The transformer's saturation effect could be represented by means of a harmonic current injection source**.**

4-Transmission Lines

A transmission line consist of distributed inductance and capacitance, which affect the magnetic and electrostatic condition of the line ,and resistance and conductance which affect the losses .These electrical parameter are calculated from line geometry and conductor data. The calculated parameters are expressed as a series impedance and shunt admittance per unit length .A representation of the line include the line total inductance, resistance and conductance as lumped parameter by (nominal π model) as shown in figure (2)[3] .Where the series harmonic impedance is:

$$Z' = R + jh\omega L \quad (7)$$

And shunt harmonic admittance is:

$$Y' = G + jB \quad (8)$$

Where

$B = \omega C$

For long transmission line the series impedance and shunt admittance modified to [6, 7]:

$$Z = Z_o \sinh(\gamma l) \quad (9)$$

$$Y_1 = \frac{1}{Z_o}\tanh(\gamma l/2) \quad (10)$$

$$Y_2 = \frac{1}{Z_o}\tanh(\gamma l/2) \quad (11)$$

$Y_1 = Y_2$

Where

$$Z_o = \sqrt{Z'/Y'} \quad (12)$$

And

$$\gamma = \sqrt{Z'Y'} \quad (13)$$

And the representation of long transmission line includes modified series impedance and shunt capacitance by an (equivalent π model) derived from (nominal π model) as shown in figure (3) [6, 7].

5- Capacitors Bank

These are considered to be passive elements [2, 3], where

$$X_C(h) = -jV_L^2 / hQ_{3\Phi} \quad (14)$$

Where

The magnitude of V_L obtained from fundamental frequency information of conventional power flow solution.

6-Linear load

There are no generally acceptable load equivalent for harmonic analysis .in each case the derivation of equivalent impedance harmonic bandwidths from P (active) and Q (reactive) power flows will need extra information on the actual composition of the load .The aggregate nature of the load makes it difficult to establish models based purely on theoretical analysis .Attempts to deduce models from measurements have been made. There are three type loads model as below [2, 3]:

(i) Parallel R-X_L equivalent, where

$$R = V_L^{\ 2} / P_{3\Phi} \quad (15)$$

And

$$X_L(h) = jhV^2{}_L / Q_{3\Phi} \quad (16)$$

(ii) Parallel R-X_L, with

$$R(h) = V_L^2 / kP_{3\Phi} \quad (17)$$

And

$$X_L(h) = jhV_L^2 / kQ_{3\Phi} \quad (18)$$

$$k = 0.1h + 0.9 \quad (19)$$

(iii) Parallel R-X_L in series with X_S,

Where

$$R = V_L^{\ 2} / P_{3\Phi} \quad (20)$$

And

$$X_L(h) = jhR / 6.7(Q_{3\Phi} / P_{3\Phi} - 0.74) \quad (21)$$

$$X_S(h) = j0.073hR \quad (22)$$

Models (ii) and (iii) with a coefficients are derived from measurements on medium voltage.

Where the magnitude of V_L obtained from fundamental frequency information of conventional power flow solution.

7-Non-linear load

These are represented by either a harmonic current injection source or by harmonic voltage source .Harmonic current source are used to represent the harmonic contribution of static var compensator (SVC), rectifier and electronic appliance .A static var compensator is represented by harmonic current injection given by I_h= (%h) $I_{1\Phi}$, where (%h) is a percentage of fundamental SVC current, the SVC current at fundamental frequency given by [2, 8]:

$$I_{1\Phi} = Q_{3\Phi} / \sqrt{3} V_L e^{j(\theta \pm \pi/2)} \quad (23)$$

Where θ and V_L obtained from information of conventional power flow solution , and π/2 is required phase shift since the current leads or lags the voltage by 90.Therefor the need to solve the conventional fundamental frequency power flow to use the information in determine the harmonic current injected by source of harmonic ($I_{1\Phi}$), and determine the linear load parameter (R, X_L, and X_S) .Therefore the results of fundamental frequency power flow solution effect on the magnitude of harmonic source current. The harmonic voltage sources are arc furnaces, and pulse width modulation (PWM) converter [3].

Harmonic Voltage and Current Flow in Power System Networks

The magnitude of the currents generated and impedance matrices for various frequencies present are obtained from system and source of harmonics data which are normally known. For these harmonics, the reference node for the impedance matrix will be at ground potential, so the system is solved at each frequency of interest using [2, 5]

$$[I_h] = [Y_h][V_h] \quad (24)$$

$$[V_h] = [Z_h][I_h] \quad (25)$$

$$Z_h = Y_h^{-1}$$

If a source of harmonic were placed at node m of an n node system, the matrix for harmonic voltage would be [5]

$$\begin{bmatrix} V_1 \\ \bullet \\ \bullet \\ V_m \\ \bullet \\ \bullet \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{11}Z_{12} \bullet\bullet\bullet\bullet\bullet Z_{1n} \\ \bullet \\ \bullet \\ Z_{m1}Z_{m2} \bullet\bullet\bullet\bullet\bullet Z_{mn} \\ \bullet \\ \bullet \\ Z_{n1}Z_{n2} \bullet\bullet\bullet\bullet\bullet Z_{nn} \end{bmatrix} * \begin{bmatrix} \bullet \\ \bullet \\ \bullet \\ I_h \\ \bullet \\ \bullet \\ \bullet \end{bmatrix} \quad (26)$$

Where
I_h=magnitude of harmonic current entering the system at node m
Therefore the harmonic voltages are

$$(27) \quad V_i = I_h Z_{im}$$

Where i is an integer from one to n. Since the impedance matrix and I_h change for each frequency, the harmonic voltages will also vary. Knowing the harmonic voltages at every node, it is possible to determine the harmonic current flow on any link

$$(28) \quad I_{jk} = (V_j - V_k) / Z_{jk}$$

If there is more than one harmonic source in the system, the harmonic current in each element is calculated for each source separately .All the currents associated with particular elements are then summed vectorially [5, 9].

Block Diagram of Harmonic Analysis

Figure (4) show the processes used to analyze and determine the harmonic voltages and currents at all nodes and transmission lines in the power system networks. The harmonic analysis approach proceeds along the following steps.

step1: enter the transmission lines parameters(R, X, and B), active and reactive power for each load bus, the voltage for generation bus, and the generators' impedance.

Step2: A conventional power flow solution is carried out for the system under study to drive fundamental frequency information for the voltage magnitudes and angles at all nodes of the network for use this information to calculate the parameters of linear loads impedance (R, X_L, and X_S), and use this information for calculate the fundamental frequency current of harmonic source (TCR) from equation (20).

Step3: develop the harmonics models for each component of network (transmission lines, linear loads, generators, transformer, and harmonic source).

Step4: form the harmonic admittance matrices [Y_h] and harmonic impedance matrix [Z_h] for system under study.

Step5: determine the harmonic voltages for all buses and harmonics currents flowing in all transmission lines in network by using the equations from (24) to (28).

Step 6: plot the results

System under Study

Figure (5) shows a one line diagram of the system under study, buses one through five are 138 KV and the buses six through twelve are 69 KV .the transmission line and branch data are given in table (1),all base on (100MVA).

The harmonics source current was static var compensator simulated by thyristor controlled reactor (TCR) as shown in figure(6)[9,10] ,and the maximum amplitude of harmonic current at full conduction angle as a percentage of the fundamental frequency current for delta connection of TCR are listed in table(2) [8,10].The (TCR) is used in load compensation in electrical power system ,load compensation is the management of reactive power to improvement the power factor, and voltage regulation of power system, the compensating equipment usually being installed near to the load. It is also used in compensation of transmission system in order to increase its power transmission capacity [2, 8]. TCR can be represented as a constant reactive power load in conventional power flow solution and a source of harmonic in harmonic analysis [9].

The loads (load3, load4, load5, load7, load8, load9, load10, load11, and load 12) in figure (5) are modeled by using the linear load model type (i), (ii), and (iii).

Result

Case 1:

In this case (TCR) located at bus3 and the system's loads model type (iii). It is observed from data listed in table (3), that the bus3 and buses connected directly and near bus 3 carry the largest harmonic voltages and currents. The harmonic bus voltage are equal to harmonic injected current product with impedance line between the bus and the bus that the harmonic source connect to it, the voltage harmonic at bus3 equal to product of harmonic injected current with driving point impedance of bus3,it is the largest impedance of other buses, therefore bus3 carry the largest harmonic voltages in network .The current injected to the system at fifth harmonic it is larger than other harmonic order, therefore the maximum harmonic voltage for all buses occur at the fifth harmonic order. The figures (7) to (10) show the spectrum of four largest harmonic voltages, and figures (15) to (18) show the distortion waveform in time domain for four largest harmonic voltages in the System at buses (3, 5, 2, and 4). It is observed from data listed in table (4) that the highest harmonic current flowing in the transmission line directly connected at the bus 3 and the lines near it because these lines carry largest harmonic voltage, figures from (11) to (14) show spectrum of four largest harmonic currents in system lines4-5, 2-3, 3-4, and 2-4, and the figures from (19) to (22) show the distorted waveforms of these currents in time domain. Since the current flowing on a line is a function of the impedance of that line and the voltage across that impedance, then it is important to observe the voltages across these lines and their series impedances change with harmonic order, therefore the peak of harmonics currents do not appear at the same harmonic order for all lines. Table (4) shows that the largest harmonic currents occur at fifth harmonic order, because the largest harmonic voltages occur at fifth harmonic.

Case2:

In this case (TCR) located at bus12 and the system's loads model type (iii). It is observe from data in table (5) that the highest harmonic voltages occur at bus12 directly connected to the TCR and the buses directly connected to bus 12 at 7, and 11 as shown in figures (23), and (24), also it is shows that the maximum harmonic voltage occurs at fifth harmonic order for all buses. Table (6) shows that the largest harmonic currents flowing on the transmission lines direct connected to bus 12 were placed the TCR, figures (25), and (26) show the spectrum of maximum harmonic current flowing on lines12-7, and 12-11.

Case3:

In this case (TCR) located at bus3 and the system's loads model type (ii).It is observed from table (7), bus3 and buses directly connected and near it carry largest harmonics voltages, also it is observed that the maximum harmonic voltage for all buses occur at the fifth harmonic, the data listed in table (8) explain that the highest harmonic current flowing in line directly connected to bus3.

Case4:

In this case (TCR) located at bus12 and the system's loads model type (ii). It is observed from table (9)that the largest harmonic voltage occurs at the bus12 directly connected to the TCR ,and the buses directly connected to bus12 .Table (10)shows the largest harmonic current flowing in line 12-7 and 12-11,lines connected to bus 12.

Case5:

In this case (TCR) located at bus3 and the system's loads model type (i).It is observed from table (11) and (12) that the highest harmonic voltages occur at bus3 and the bus directly connected near to bus3, and the largest current flowing on lines directly connected and near to bus3 lines4-5, 2-3, 3-4, and line 2-4.

Case6:

In this case (TCR) located at bus12 and the system's loads model type (i). It is observed from table (13) that the largest harmonic voltage occurs at the bus12 directly connected to the TCR, and the buses directly connected and near of bus12.Table (14) shows the largest harmonic current flowing in lines connected to bus 12, lines 12-7 and 12-11.

Conclusion

From the results of the six cases studied, it appears that the harmonic current flows on system transmission lines can exceed the current injected by a harmonic source at any frequency, if this frequency causes large harmonic voltage magnitude. The maximum harmonic voltages and currents flowing in transmission lines occur at the bus directly connected to (TCR) and the lines and buses directly connected to this bus.The highest injected harmonic current at fifth harmonic order for all cases study, therefore the highest harmonic voltage and harmonic current occur at fifth harmonic. As the harmonics frequencies increase, the magnitude of the harmonic injected current decrease therefore, in order to obtain a large harmonic current flow at the higher orders, the amplification of injected for a line would have to be very large .It was found that this happens when a transmission line reaches a resonant frequency. The harmonic injected current in case of TCR connected to bus12 larger than TCR connected to bus 3, therefore the highest harmonic voltage and current for TCR located at bus12 larger than highest harmonic voltage and current in case TCR located at bus3 for all types of loads.

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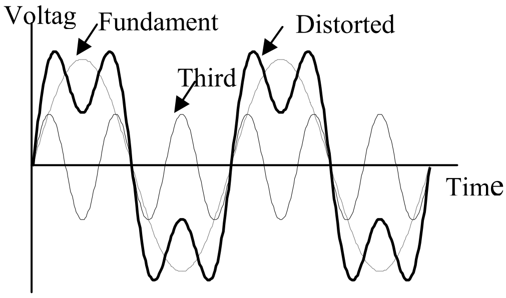


Figure (1) fundamental plus third harmonic

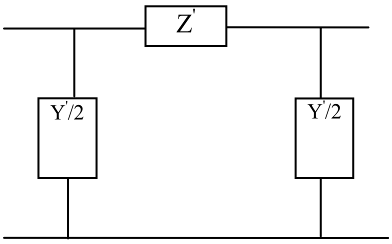


Figure (2) nominal π model of transmission line

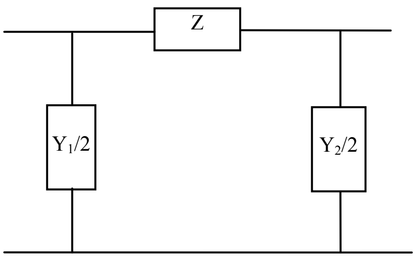


Figure (3) equivalent π model for long transmission line

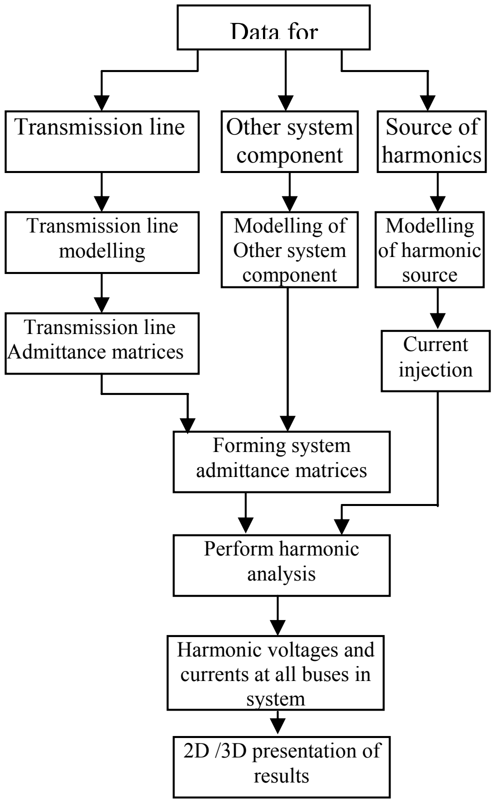


Figure (4) block diagram of harmonics analysis

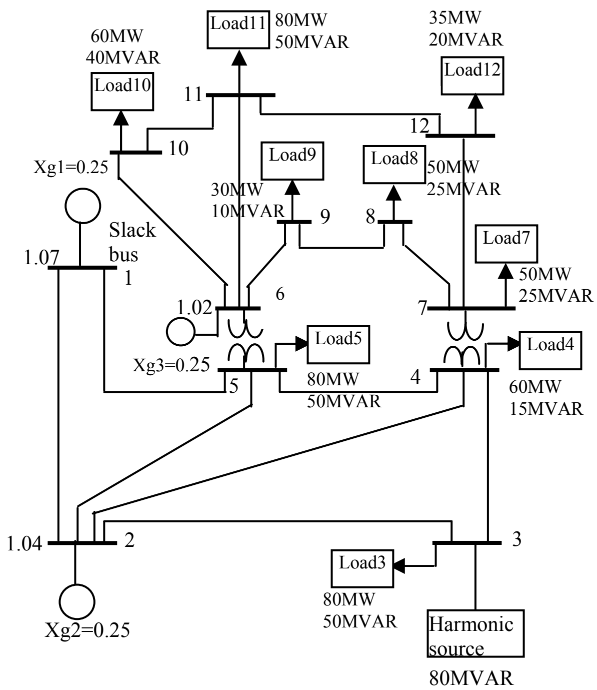


Figure (5) one line diagram of system under study

Brach type	Bus number		R(pu)	X(pu)	B(pu)
	From	to			
Line	1	2	0.08827	0.18553	0.04970
Line	2	3	0.13732	0.29126	0.07731
Line	3	4	0.07847	0.16492	0.04418
Line	4	5	0.08837	0.17523	0.04684
Line	1	5	0.07847	0.16492	0.04418
line	2	4	0.15694	0.32984	0.08836
line	2	5	0.09808	0.20615	0.05522
Trasf	5	6	0.0000	0.20000	0.00000
Trasf	4	7	0.0000	0.20000	0.00000
Line	6	9	0.05885	0.12369	0.0000
Line	6	10	0.11768	0.24733	0.0000
Line	6	11	0.19617	0.4123	0.0000
Line	7	8	0.07062	0.14843	0.0000
Line	7	12	0.09808	0.20615	0.0000
Line	8	9	0.07454	0.15667	0.0000
Line	10	11	0.07454	0.15667	0.0000
Line	11	12	0.27464	0.57723	0.0000

Table (1) branch data for system under study

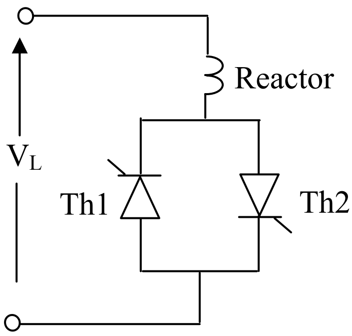


Figure (6) harmonic source thyristor controlled reactor (TCR)

Harmonic order	Percentage of fundamental current
5	5.05
7	2.59
11	1.05
13	0.75
17	0.44
19	0.35
23	0.24
25	0.2
29	0.15
31	0.13

Table (2) maximum amplitude of harmonic current in (TCR).

Harmonic order / Busvoltage	1 fundanental	5	7	11	13	17	19	23	25	29	31
V_1	1.0700	0.005792	0.0045124	0.0034024	0.0031075	0.0021449	0.0026272	0.00040158	0.00011502	0.000006	0.0000017
V_2	1.0400	0.0071777	0.0054405	0.0032025	0.0022304	0.00049126	0.0004185	0.00011908	0.0000456	0.000017	0.000012
V_3	0.9703	0.013202	0.0081566	0.0065388	0.008053	0.0040828	0.0023564	0.0013211	0.001167	0.0006197	0.000467
V_4	0.9854	0.0084957	0.0047932	0.0009719	0.0022266	0.0023329	0.0021601	0.0013918	0.0010222	0.0002393	0.0001347
V_5	1.0173	0.0087342	0.0060512	0.0032662	0.0023007	0.0005924	0.0005577	0.00057438	0.00027791	0.0000386	0.0000179
V_6	1.0200	0.0037118	0.0022276	0.0009315	0.0005537	0.0000422	0.0002571	0.0001137	0.0000416	0.0000041	0.0000023
V_7	0.9758	0.0047166	0.0023842	0.0002223	0.00066478	0.00076966	0.00074734	0.00042471	0.00031603	0.00007428	0.0000418
V_8	0.9690	0.0040053	0.0020618	0.0004143	0.00011529	0.00026339	0.00033634	0.00011211	0.00009819	0.0000249	0.0000143
V_9	0.9810	0.0038896	0.00220399	0.00045356	0.0001023	0.00023464	0.00034691	0.0001075	0.00008948	0.0000233	0.0000134
V_{10}	0.9428	0.0027327	0.0012883	0.00036595	0.00017728	0.0000162	0.00010616	0.0000291	0.00000000	0.0000029	0.0000018
V_{11}	1.0641	0.0028041	0.0013013	0.0003593	0.00017044	0.0000197	0.00010752	0.0000286	0.0000000	0.000003	0.0000019
V_{12}	0.9457	0.0035623	0.0016315	0.00011052	0.00030353	0.00036458	0.00035878	0.00018607	0.00013868	0.0000323	0.0000181

Table (3) harmonic bus voltages in per unit

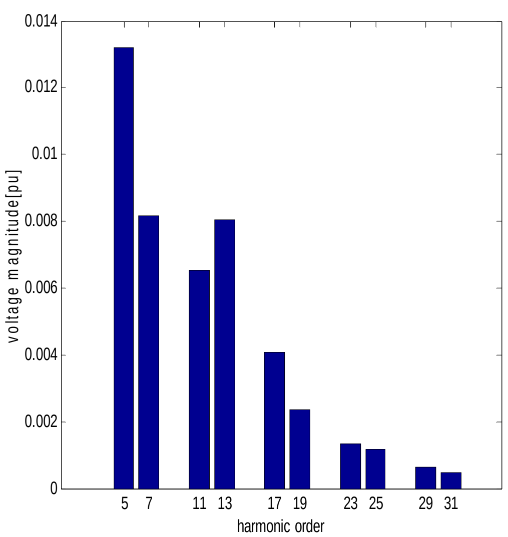


Figure (7) harmonic voltage spectrum in per unit at bus 3

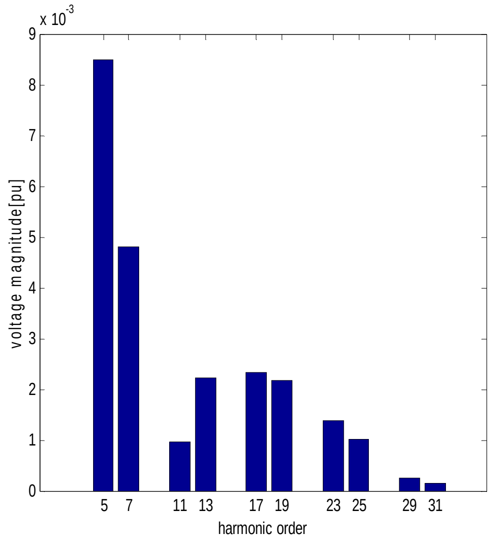


Figure (9) harmonic voltage spectrum in per unit at bus 4

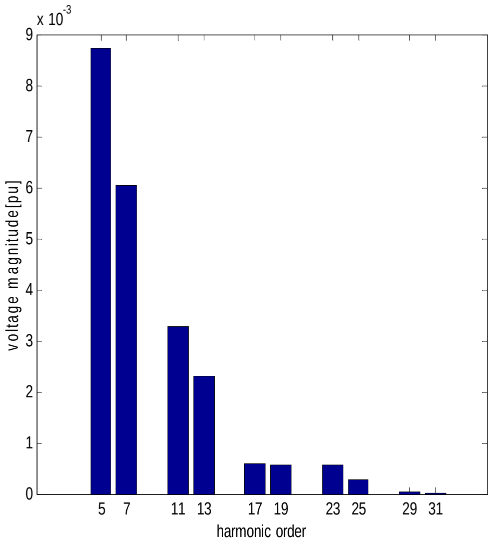


Figure (8) harmonic voltage spectrum in per unit at bus 5

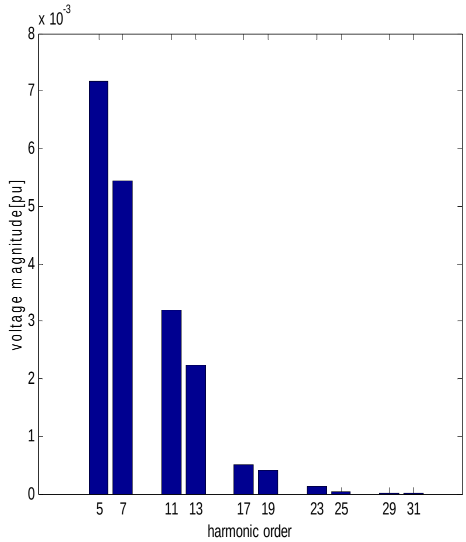


Figure (10) harmonic voltage spectrum in per unit at bus 2

Harmonic order / Line current(pu)	5	7	11	13	17	19	23	25	29	31
I_{1-2}	0.0085386	0.0039764	0.001568	0.0014764	0.0022226	0.0031055	0.002235	0.00095876	0.00019707	0.0002159
I_{1-5}	0.010084	0.0041895	0.002153	0.0040216	0.00083162	0.00092307	0.0011846	0.00072328	0.00022645	0.0001429
I_{2-3}	0.033412	0.0171399	0.014536	0.01633	0.019169	0.010755	0.013623	0.025153	0.026693	0.025278
I_{2-4}	0.0052764	0.0016521	0.0054065	0.0063247	0.0052467	0.0077268	0.014101	0.010037	0.0053369	0.004119
I_{2-5}	0.013716	0.0064564	0.0022231	0.0011936	0.00068665	0.00095213	0.0069198	0.0078412	0.0023752	0.0015199
I_{3-4}	0.030891	0.019925	0.030824	0.0097588	0.0021423	0.0017952	0.00153928	0.0018764	0.0025417	0.002756
I_{4-5}	0.0093826	0.006525	0.012938	0.03967	0.0046389	0.0052383	0.0013076	0.0011692	0.00090838	0.0007898
I_{6-9}	0.002456	0.0015747	0.0014437	0.001231	0.00072557	0.00020709	0.00034779	0.00019342	0.0000331	0.0000166
I_{6-10}	0.013214	0.0075678	0.0026266	0.0014085	0.00021838	0.00051703	0.00024298	0.0000842	0.000000	0.000000
I_{6-11}	0.01364	0.0077837	0.002699	0.0014494	0.00023508	0.00052445	0.0002483	0.0000862	0.000000	0.000000
I_{7-8}	0.0059514	0.0027441	0.0010972	0.0014127	0.0011068	0.0007118	0.00055113	0.00041586	0.0000782	0.0000401
I_{7-12}	0.0074724	0.0034405	0.00038048	0.00074392	0.00076806	0.00064963	0.00035056	0.00029803	0.000100	0.000000
I_{8-9}	0.00041938	0.0001091	0.0000607	0.00005903	0.00002719	0.000013515	0.00000974	0.0000056	0.000000	0.000000
I_{10-11}	0.00019062	0.00004965	0.000010909	0.000009278	0.0000040376	0.0000017	0.0000013	0.000000	0.000000	0.000000
I_{11-12}	0.009601	0.0042773	0.001698	0.0023586	0.0017977	0.0011825	0.00088845	0.00056893	0.000111	0.000100
Harmonic current(pu)	0.02424	0.012432	0.00504	0.0036	0.002112	0.00168	0.001152	0.00096	0.00072	0.000624

Table (4) harmonic current in per unit flowing on transmission lines

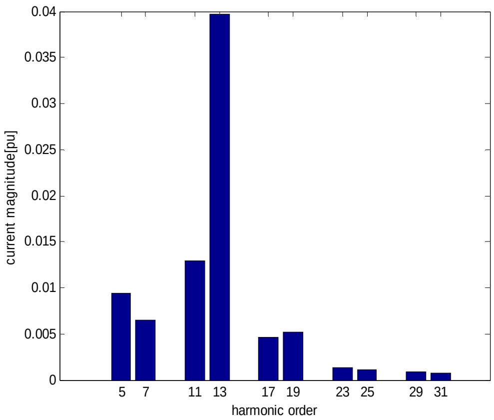


Figure (11) harmonic current spectrum in per unit flowing in line 4-5

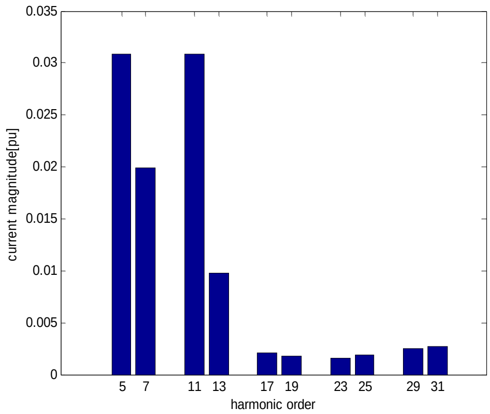


Figure (13) harmonic current spectrum in per unit flowing in line3-4

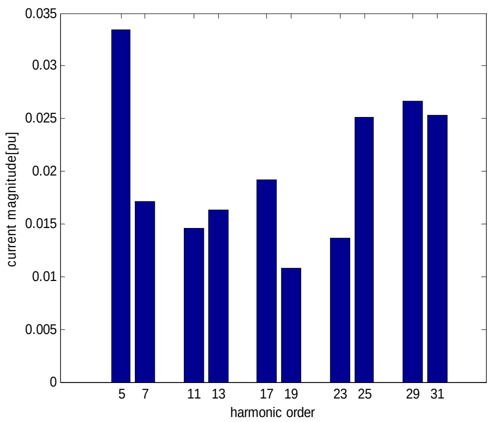


Figure (12) harmonic current spectrum in per unit flowing in line 2-3

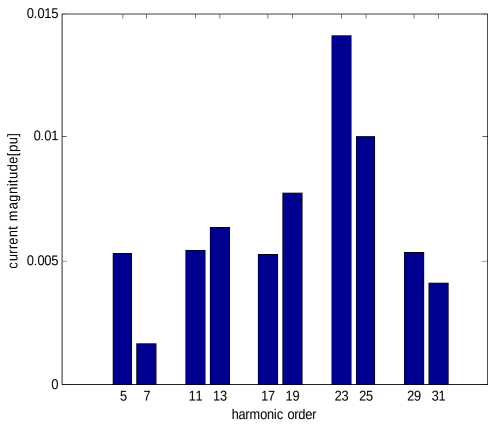


Figure (14) harmonic current spectrum in per unit flowing in line 2-4

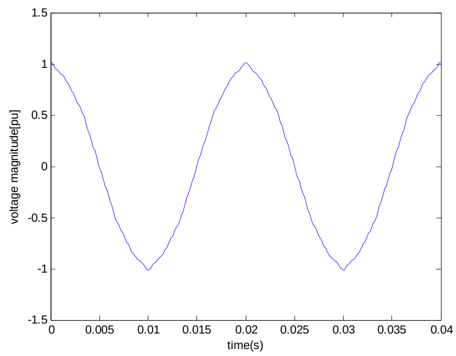
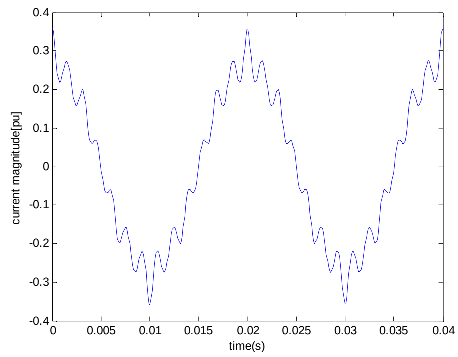


Figure (15) voltage waveform at bus (3)



Figure(19)current waveform flowing in line4-5

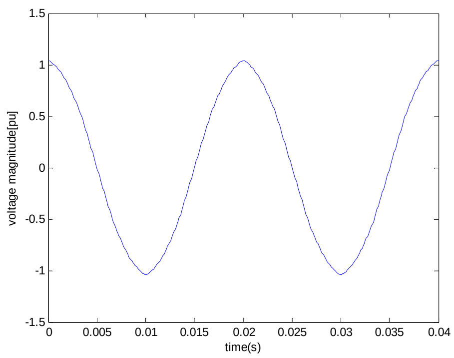
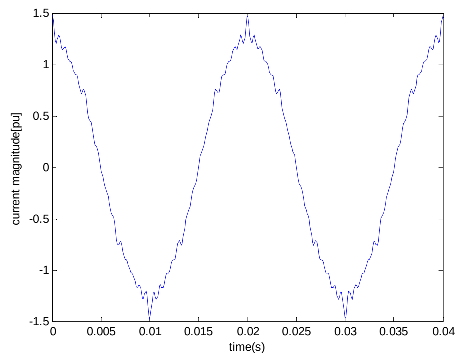
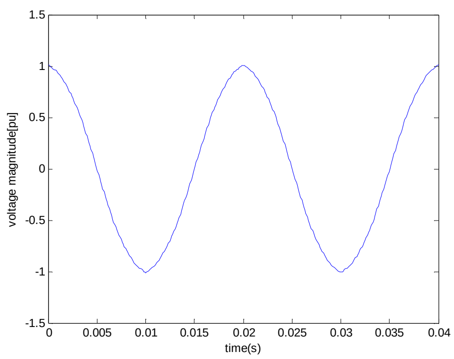


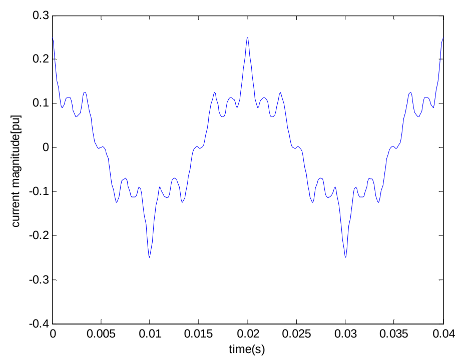
Figure (16) voltage waveform at bus (5)



Figure(20)current waveform flowing in line2-3



Figure(17)voltage waveform at bus(4)



Figure(21)current waveform flowing in line3-4

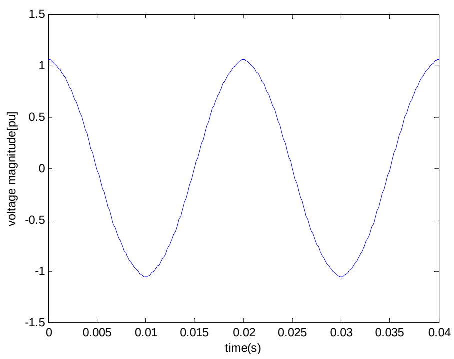
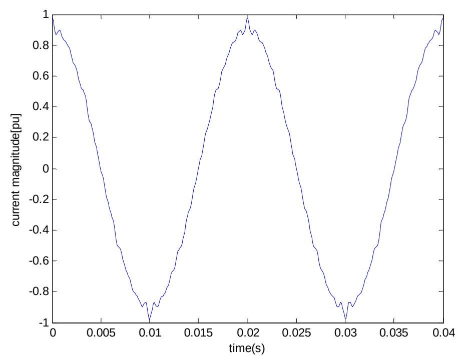


Figure (18) voltage waveform at bus (2)



Figure(22)current waveform flowing in line2-4

Harmonic order / Busvoltage	5	7	11	13	17	19	23	25	29	31
V_1	0.0031084	0.0017513	0.0006468	0.0034302	0.0003937	0.0007051	0.0001825	0.0000651	0.000000	0.0000000
V_2	0.0034624	0.0020172	0.0008731	0.0006232	0.0002698	0.0001169	0.0000000	0.0000000	0.000000	0.0000
V_3	0.0036546	0.0016738	0.0001133	0.0003114	0.0003740	0.0003680	0.0001909	0.0001422	0.0000313	0.0000000
V_4	0.0035205	0.0013239	0.00045778	0.0006188	0.0002983	0.0004548	0.0005603	0.0005480	0.0001979	0.0001328
V_5	0.0042456	0.0020065	0.00026647	0.0001323	0.0003614	0.0001061	0.0002735	0.0001391	0.000000	0.0000000
V_6	0.0025832	0.0012123	0.0005600	0.0005111	0.0002205	0.0002592	0.0001248	0.0001446	0.0001283	0.0001174
V_7	0.0067617	0.0042096	0.002392	0.0018969	0.0012016	0.0010877	0.0008287	0.0006005	0.0005340	0.0005036
V_8	0.0041912	0.002306	0.0011799	0.0009279	0.0005107	0.0004805	0.0003309	0.0002573	0.0002248	0.0002093
V_9	0.003656	0.0020252	0.0010733	0.0008584	0.0004724	0.0004518	0.0003119	0.0002459	0.0002158	0.0002013
V_{10}	0.0037736	0.0019256	0.0008752	0.0006671	0.0003794	0.0003435	0.0002449	0.0002216	0.0001877	0.0001715
V_{11}	0.0042563	0.0021641	0.00096527	0.0007276	0.0004137	0.0003699	0.0002627	0.0002359	0.0001983	0.0001807
V_{12}	0.020256	0.013128	0.0072525	0.0057711	0.0040664	0.0035385	0.0028106	0.0024638	0.0021321	0.0019674

Table (5) harmonic bus voltages in per unit

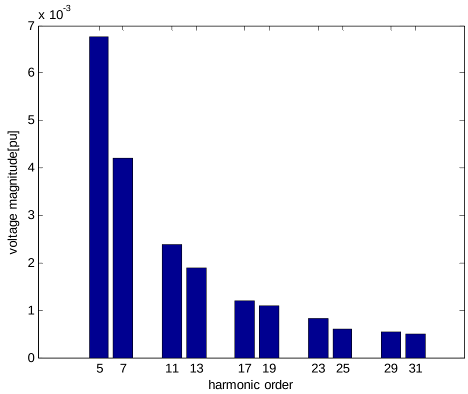


Figure (23) harmonic voltage spectrum in per unit at bus 7

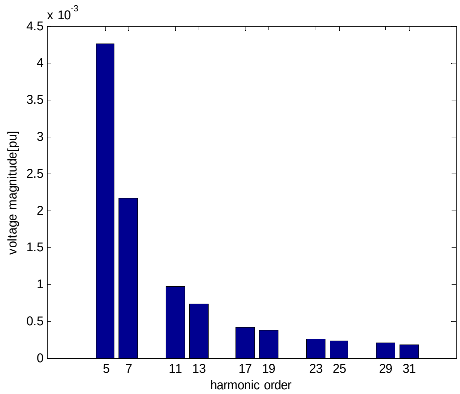


Figure (24) harmonic voltage spectrum in per unit at bus 11

Harmonic order / Line current(pu)	5	7	11	13	17	19	23	25	29	31
I_{1-2}	0.0014034	0.0006396	0.0003092	0.0003013	0.0006840	0.0008388	0.0007991	0.0005283	0.0001447	0.0000914
I_{1-5}	0.003728	0.0005893	0.0008529	0.001565	0.0000537	0.0002166	0.0005393	0.0003697	0.0001116	0.0000611
I_{2-3}	0.0021036	0.0011062	0.0012058	0.0013721	0.0027332	0.0019247	0.0017053	0.002694	0.0011944	0.0008240
I_{2-4}	0.0030422	0.0023133	0.0021209	0.0018848	0.0008109	0.0012596	0.0055284	0.005552	0.0048391	0.0045359
I_{2-5}	0.0024724	0.0001256	0.0007421	0.0007329	0.0005519	0.0001741	0.003809	0.0035884	0.0005986	0.0002898
I_{3-4}	0.0044476	0.0026261	0.0028259	0.0007986	0.0004713	0.0006107	0.0006135	0.0006414	0.0006889	0.0006953
I_{4-5}	0.0038089	0.0023743	0.0023902	0.0042986	0.0007927	0.0012599	0.0005425	0.0006093	0.0006929	0.0007089
I_{6-9}	0.0088678	0.0046608	0.0015549	0.0008629	0.0007001	0.0003928	0.0003762	0.0001901	0.0001294	0.000161
I_{6-10}	0.0076869	0.0039832	0.0013087	0.0005847	0.0006275	0.0002564	0.0003539	0.0002194	0.0001377	0.0001173
I_{6-11}	0.010992	0.0054223	0.0016782	0.0007920	0.0007701	0.0003418	0.0004106	0.0002592	0.000164	0.0001387
I_{7-8}	0.014928	0.0084001	0.0033272	0.0022901	0.0015677	0.0011406	0.0008711	0.0006455	0.0004910	0.0004305
I_{7-12}	0.051884	0.027689	0.010639	0.0076846	0.0052127	0.0039418	0.0028877	0.0030978	0.0022011	0.0018515
I_{8-9}	0.0015492	0.0005535	0.0001310	0.0000742	0.0000350	0.0000231	0.0000137	0.0000000	0.0000000	0.0000000
I_{10-11}	0.0011826	0.0004834	0.0001365	0.0000834	0.0000401	0.0000280	0.0000163	0.0000122	0.0000080	0.0000065
I_{11-12}	0.10574	0.069538	0.034814	0.02632	0.019372	0.01493	0.011475	0.0093079	0.0071691	0.0063173
Harmonic current(pu)	0.024745	0.012691	0.005145	0.003675	0.002156	0.001715	0.001176	0.00098	0.000735	0.000637

Table (6) harmonic current in per unit flowing on transmission lines

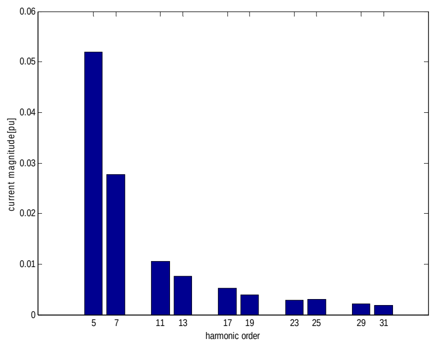


Figure (25) harmonic current spectrum flowing in line 12-7

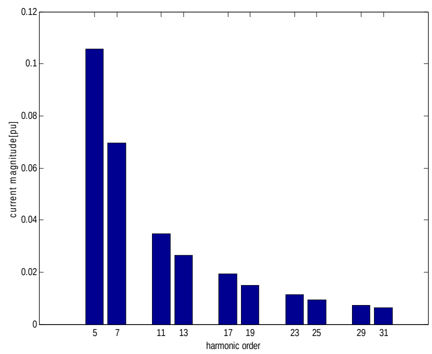


Figure (26) harmonic current spectrum flowing in line 12-11

h / Busvoltage	5	7	11	13	17	19	23	25	29	31
V_1	0.0059	0.0033	0.0017	0.0010	0.0005	0.0007	0.0000338	0.0000136	0.0000034	0.0000019
V_2	0.0073	0.0041	0.0021	0.0010	0.0002	0.0002	0.0000476	0.0000286	0.0000127	0.0000088
V_3	0.0130	0.0070	0.0031	0.0025	0.0014	0.0011	0.0006548	0.0005136	0.0003426	0.0002808
V_4	0.0081	0.0035	0.0006	0.0005	0.0003	0.0002	0.0000814	0.0000563	0.0000295	0.0000215
V_5	0.0077	0.0039	0.0014	0.0005	0.0001	0.0001	0.0000102	0.0000061	0.0000025	0.0000016
V_6	0.0028	0.0012	0.0003	0.0001	0.0000	0.0000	0.0000028	0.0000016	0.0000006	0.0000004
V_7	0.0037	0.0013	0.0001	0.0001	0.0000	0.0000	0.0000111	0.0000069	0.0000030	0.0000020
V_8	0.0028	0.0010	0.0001	0.0000	0.0000	0.0000	0.0000018	0.0000009	0.0000003	0.0000002
V_9	0.0027	0.0010	0.0001	0.0000	0.0000	0.0000	0.0000017	0.0000008	0.0000003	0.0000002
V_{10}	0.0013	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000002	0.0000001	0.0000000	0.0000
V_{11}	0.0014	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000002	0.0000001	0.0000000	0.0000
V_{12}	0.0024	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000013	0.0000009	0.0000003	0.0000002

Table (7) harmonic bus voltages in per unit

h / Busvoltage	5	7	11	13	17	19	23	25	29	31
V_1	0.0022	0.0009	0.0002	0.0001	0.0000	0.0000	0.0000012	0.0000004	0.0000001	0.0000
V_2	0.0025	0.0010	0.0003	0.0001	0.0000	0.0000	0.0000007	0.0000003	0.0000001	0.0000001
V_3	0.0024	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000016	0.0000009	0.0000003	0.0000002
V_4	0.0029	0.0008	0.0002	0.0001	0.0000	0.0000	0.0000105	0.0000066	0.0000029	0.0000020
V_5	0.0030	0.0010	0.0001	0.0000	0.0000	0.0000	0.0000020	0.0000010	0.0000003	0.0000002
V_6	0.0019	0.0006	0.0001	0.0001	0.0000	0.0000	0.0000066	0.0000043	0.0000020	0.0000014
V_7	0.0055	0.0029	0.0010	0.0006	0.0003	0.0002	0.0001000	0.0000722	0.0000410	0.0000311
V_8	0.0031	0.0013	0.0004	0.0002	0.0001	0.0000	0.0000148	0.0000095	0.0000043	0.0000029
V_9	0.0026	0.0011	0.0003	0.0002	0.0001	0.0000	0.0000128	0.0000081	0.0000037	0.0000025
V_{10}	0.0020	0.0008	0.0002	0.0001	0.0000	0.0000	0.0000088	0.0000060	0.0000031	0.0000023
V_{11}	0.0024	0.0009	0.0002	0.0001	0.0000	0.0000	0.0000125	0.0000087	0.0000047	0.0000035
V_{12}	0.0167	0.0099	0.0042	0.0029	0.0016	0.0012	0.0007606	0.0006051	0.0004146	0.0003440

Table (9) harmonic bus voltages in per unit

h / Line current(pu)	5	7	11	13	17	19	23	25	29	31
I_{1-2}	0.0062	0.0031	0.0008	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002
I_{1-5}	0.0063	0.0028	0.0018	0.0045	0.0005	0.0003	0.0001	0.0001	0.0001	0.0000
I_{2-3}	0.0268	0.0164	0.0105	0.0122	0.0209	0.0093	0.0169	0.0181	0.0200	0.0203
I_{2-4}	0.0039	0.0021	0.0033	0.0036	0.0041	0.0049	0.0033	0.0030	0.0024	0.0022
I_{2-5}	0.0087	0.0052	0.0020	0.0012	0.0005	0.0007	0.0024	0.0012	0.0007	0.0006
I_{3-4}	0.0259	0.0209	0.0282	0.0178	0.0103	0.0097	0.0091	0.0087	0.0084	0.0082
I_{4-5}	0.0067	0.0053	0.0078	0.0747	0.0052	0.0018	0.0014	0.0012	0.0009	0.0008
I_{6-9}	0.0027	0.0020	0.0010	0.0005	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
I_{6-10}	0.0160	0.0091	0.0035	0.0013	0.0003	0.0003	0.0000	0.0000	0.0000	0.0000
I_{6-11}	0.0166	0.0096	0.0037	0.0014	0.0003	0.0003	0.0001	0.0000	0.0000	0.0000
I_{7-8}	0.0060	0.0028	0.0008	0.0006	0.0003	0.0002	0.0001	0.0001	0.0000	0.0000
I_{7-12}	0.0079	0.0035	0.0005	0.0004	0.0003	0.0002	0.0001	0.0001	0.0000	0.0000
I_{8-9}	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{10-11}	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{11-12}	0.0118	0.0051	0.0011	0.0012	0.0006	0.0003	0.0001	0.0001	0.0000	0.0000

Table (8) harmonic current in per unit flowing on transmission lines

h / Line current(pu)	5	7	11	13	17	19	23	25	29	31
I_{1-2}	0.0009	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{1-5}	0.0021	0.0003	0.0002	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{2-3}	0.0014	0.0010	0.0006	0.0004	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
I_{2-4}	0.0025	0.0015	0.0009	0.0007	0.0007	0.0005	0.0004	0.0003	0.0002	0.0002
I_{2-5}	0.0014	0.0002	0.0002	0.0002	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000
I_{3-4}	0.0036	0.0021	0.0018	0.0010	0.0003	0.0003	0.0001	0.0001	0.0001	0.0001
I_{4-5}	0.0026	0.0018	0.0014	0.0091	0.0006	0.0003	0.0002	0.0001	0.0001	0.0001
I_{6-9}	0.0060	0.0031	0.0008	0.0004	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
I_{6-10}	0.0032	0.0018	0.0004	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
I_{6-11}	0.0069	0.0036	0.0010	0.0005	0.0003	0.0002	0.0001	0.0001	0.0001	0.0001
I_{7-8}	0.0145	0.0089	0.0040	0.0029	0.0018	0.0015	0.0010	0.0008	0.0006	0.0006
I_{7-12}	0.0515	0.0311	0.0158	0.0132	0.0101	0.0091	0.0079	0.0073	0.0067	0.0064
I_{8-9}	0.0013	0.0005	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{10-11}	0.0015	0.0007	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
I_{11-12}	0.1528	0.1244	0.0935	0.0864	0.0778	0.0738	0.0688	0.0656	0.0627	0.0607

Table (10) harmonic current in per unit flowing on transmission lines

h / Busvoltage	5	7	11	13	17	19	23	25	29	31
V_1	0.0081	0.0051	0.0030	0.0020	0.0011	0.0014	0.0001	0.0000236	0.0000036	0.0017
V_2	0.0093	0.0055	0.0025	0.0014	0.0003	0.0004	0.0001	0.0000379	0.0000157	0.0107
V_3	0.0143	0.0078	0.0063	0.0051	0.0024	0.0018	0.0010	0.0007691	0.0004758	0.3783
V_4	0.0107	0.0049	0.0013	0.0016	0.0011	0.0008	0.0003	0.0002210	0.0000981	0.0666
V_5	0.0111	0.0066	0.0031	0.0017	0.0004	0.0002	0.0001	0.0000414	0.0000125	0.0073
V_6	0.0047	0.0023	0.0008	0.0004	0.0001	0.0000	0.0000	0.0000140	0.0000046	0.0028
V_7	0.0061	0.0025	0.0003	0.0005	0.0004	0.0003	0.0001	0.0000604	0.0000255	0.0169
V_8	0.0051	0.0023	0.0004	0.0001	0.0001	0.0001	0.0000	0.0000211	0.0000083	0.0053
V_9	0.0050	0.0023	0.0005	0.0001	0.0001	0.0001	0.0000	0.0000199	0.0000078	0.0050
V_{10}	0.0036	0.0014	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000035	0.0000011	0.0006
V_{11}	0.0037	0.0015	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000035	0.0000011	0.0006
V_{12}	0.0047	0.0018	0.0001	0.0002	0.0002	0.0001	0.0000	0.0000240	0.0000092	0.0058

Table (11) harmonic bus voltages in per unit

h / Line current(pu)	5	7	11	13	17	19	23	25	29	31
I_{1-2}	0.0071	0.0041	0.0019	0.0011	0.0010	0.0010	0.0005	0.0004	0.0003	0.0002
I_{1-5}	0.0095	0.0046	0.0018	0.0026	0.0006	0.0005	0.0003	0.0002	0.0001	0.0001
I_{2-3}	0.0247	0.0178	0.0163	0.0161	0.0171	0.0100	0.0184	0.0203	0.0223	0.0225
I_{2-4}	0.0043	0.0015	0.0043	0.0038	0.0053	0.0055	0.0058	0.0050	0.0036	0.0030
I_{2-5}	0.0109	0.0068	0.0027	0.0013	0.0009	0.0007	0.0033	0.0020	0.0011	0.0009
I_{3-4}	0.0236	0.0201	0.0222	0.0092	0.0042	0.0043	0.0040	0.0039	0.0040	0.0040
I_{4-5}	0.0072	0.0070	0.0139	0.0305	0.0049	0.0029	0.0013	0.0012	0.0009	0.0008
I_{6-9}	0.0033	0.0018	0.0012	0.0008	0.0004	0.0002	0.0000	0.0000	0.0000	0.0000
I_{6-10}	0.0184	0.0097	0.0034	0.0016	0.0003	0.0002	0.0001	0.0001	0.0000	0.0000
I_{6-11}	0.0189	0.0099	0.0034	0.0016	0.0003	0.0002	0.0001	0.0001	0.0000	0.0000
I_{7-8}	0.0071	0.0027	0.0012	0.0011	0.0006	0.0004	0.0002	0.0001	0.0000	0.0000
I_{7-12}	0.0098	0.0037	0.0005	0.0006	0.0005	0.0004	0.0001	0.0001	0.0000	0.0000
I_{8-9}	0.0005	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{10-11}	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{11-12}	0.0131	0.0053	0.0021	0.0022	0.0014	0.0009	0.0004	0.0002	0.0001	0.0001

Table (12) harmonic current in per unit flowing on transmission lines

h / Busvoltage	5	7	11	13	17	19	23	25	29	31
V_1	0.0039	0.0019	0.0007	0.0003	0.0002	0.0004	0.0000	0.0000	0.0000	0.0000
V_2	0.0044	0.0021	0.0009	0.0007	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
V_3	0.0047	0.0018	0.0001	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000
V_4	0.0045	0.0012	0.0006	0.0006	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
V_5	0.0053	0.0022	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000
V_6	0.0029	0.0013	0.0006	0.0005	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
V_7	0.0065	0.0044	0.0026	0.0019	0.0011	0.0009	0.0006	0.0005	0.0004	0.0003
V_8	0.0041	0.0025	0.0014	0.0010	0.0005	0.0004	0.0002	0.0002	0.0001	0.0001
V_9	0.0036	0.0022	0.0013	0.0009	0.0005	0.0004	0.0002	0.0002	0.0001	0.0001
V_{10}	0.0038	0.0021	0.0009	0.0006	0.0003	0.0002	0.0001	0.0001	0.0001	0.0001
V_{11}	0.0042	0.0023	0.0009	0.0006	0.0003	0.0002	0.0001	0.0001	0.0001	0.0001
V_{12}	0.0198	0.0136	0.0074	0.0057	0.0038	0.0031	0.0023	0.0020	0.0015	0.0013

Table (13) harmonic bus voltages in per unit

h / Line current(pu)	5	7	11	13	17	19	23	25	29	31
I_{1-2}	0.0015	0.0007	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
I_{1-5}	0.0038	0.0007	0.0007	0.0015	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001
I_{2-3}	0.0023	0.0014	0.0016	0.0020	0.0019	0.0008	0.0006	0.0005	0.0004	0.0003
I_{2-4}	0.0024	0.0027	0.0026	0.0021	0.0016	0.0020	0.0031	0.0031	0.0028	0.0026
I_{2-5}	0.0023	0.0001	0.0007	0.0007	0.0004	0.0001	0.0023	0.0011	0.0005	0.0004
I_{3-4}	0.0040	0.0031	0.0026	0.0014	0.0008	0.0008	0.0007	0.0006	0.0006	0.0005
I_{4-5}	0.0030	0.0027	0.0032	0.0045	0.0014	0.0011	0.0007	0.0007	0.0006	0.0006
I_{6-9}	0.0091	0.0056	0.0021	0.0011	0.0007	0.0004	0.0003	0.0002	0.0001	0.0001
I_{6-10}	0.0064	0.0040	0.0015	0.0006	0.0003	0.0001	0.0001	0.0001	0.0000	0.0000
I_{6-11}	0.0097	0.0053	0.0016	0.0006	0.0004	0.0001	0.0001	0.0001	0.0000	0.0000
I_{7-8}	0.0148	0.0087	0.0035	0.0025	0.0017	0.0013	0.0009	0.0008	0.0006	0.0005
I_{7-12}	0.0526	0.0264	0.0099	0.0078	0.0054	0.0047	0.0035	0.0030	0.0024	0.0021
I_{8-9}	0.0015	0.0006	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{10-11}	0.0012	0.0005	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I_{11-12}	0.1056	0.0698	0.0394	0.0335	0.0272	0.0242	0.0200	0.0182	0.0160	0.0149

Table (14) harmonic current in per unit flowing on transmission lines