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Full Length Research Paper

Harmonics propagation and distortion caused by a nonlinear load in balance distribution network

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It is very useful to monitor and maintain a good power quality in an electric power system especially on the distribution network. This paper describes a numerical method for calculation the propagation and distortion of harmonics caused by a nonlinear load such as Adjustable Speed Drives (ASD) in a balance distribution network. ASD injects harmonics current into the network, which causes voltage distortion problems. Usually, the harmonics current, harmonics voltage, and Total Harmonics Distortion (THD) are used as indices of power quality in harmonics case. They can be calculated at every buses of a distribution network, as objective of this research. Another aim is to evaluate VTHD in every bus according to its limitation in IEEE Standard 519-1992. This research uses harmonics current spectrum of an ASD as sources and power flow study in ETAP Powerstation. Final conclusion of this work will be compared with the IEEE tests and ETAP Powerstation as a validation. The IEEE Test System 13-buses, a balance industrial system, were used as a case study. This work uses the Matlab software in m-file and the ETAP.

Key words: harmonics, propagation, THD, nonlinear load, balance distribution network.

INTRODUCTION

Quality of electric power in power system can be classified in two categories; there are quality in transient and steady state condition. Quality in transient situation is observed according to the duration of disturbance and it can be categorized in three groups. The first is the *fast transient* such as *switching-surge, spike* (0.5 to 200 microseconds with frequency 0.2 to 5 kHz), *pulse*, and *notch.* The second is over voltage which more than 110% of nominal voltage, or under voltage which it is below of 80 - 85% of nominal voltage, that occurs continuously in 80 millisecond to one second. These disturbances usually called as voltage dip such as *voltage sag, depression, interruption, flicker,* and *fluctuation.* The third is *blackout* or *outage.*

Quality in steady state condition has continued property such as variation of voltage, variation of frequency, phase unbalance and harmonics [Wardhani, 1996].

Numerical analysis and simulations of harmonics are used to quantify the distortion in voltage and current waveforms on a power system distribution network in order to determine the existence and mitigation of resonant conditions.

Ribeiro and Arillaga et al., proposed the models of power system devices for calculating the harmonics propagation caused by a nonlinear loads [Ribeiro,; Arillaga et al., 1985].

Stavros et al. shown the harmonics power flow caused by wind turbine. They use different devices models with Ribeiro's]. This work combines the both models.

This paper presents propagation of harmonics voltage, harmonics current and VTHD (voltage THD) caused by an ASD installed on Bus-9 in a 13 buses balance

industrial IEEE Test system. Result of this research compared with IEEE Standard 519-1992 and the ETAP Powerstation.
The results were obtained from power system analysis formulas that built in m-file of Matlab, but the fundamental load flow study was done in ETAP Powerstation [Abu-hashim et al., 1999].

GENERAL THEORY

Harmonics

Harmonics, in power system engineering, can be defined as a sinusoidal component of a periodic signal (complex waveform) has an integer multiplication of the fundamental power line frequency. One commonly used as index in harmonics problem is total harmonics distortion (THD). THD is affected by effective value of all its components as can be formulated as:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} X_h^2}}{X_1} * 100\% \qquad (1)$$

Where X_1 is root mean square or effective value of the sinusoidal component. X_1 can be as a voltage (VTHD) or current (ITHD).

Generally harmonics in power system caused by non-linear loads used solid state equipment devices, and magnetic circuits. For example electronic ballast lamp, computers (power supplies), PC, mainframe, servers, monitors, video displays, Copiers, scanners, facsimile machines, printers, plotters, lighting controls, dimmers, Electronic ballast, UPS systems, battery chargers, storage systems, etc [Sankaran, 1995; Wagner et al., 1993; http://ecmweb.com/mag/electric_effects_harmonics_power_2/:Effects of harmonics on power systems (28/04/2009); Reactive Power and Harmonic Compensation, 2009].

According to characteristics of solid state power conversion equipment, the harmonics currents will be injected into power system. The harmonics current, through harmonics impedance, will affects the sinusoidal form of fundamental waveform. This condition will disturb the equipments installed on the system that designed to be operated on sinusoidal waveform. This causes additional heating on equipments and failure of isolation either reduce the lifetime of equipments [Sankaran, 1995; Wagner et al., 1993; http://ecmweb.com/mag/electric_effects_harmonics_power_2/:Effects of harmonics on power systems (28/04/2009); Reactive Power and Harmonic Compensation, 2009].

The other effects of harmonics are [Sankaran, 1995; Wagner et al., 1993; http://ecmweb.com/mag/electric_effects_harmonics_power_2/:Effects of harmonics on power systems (28/04/2009); Reactive Power and Harmonic Compensation, 2009]:

- Reduction of measurement accurateness of induction kWh-meter,
- Losses on electrical machine will be increased and malfunction on electronics equipments, computer systems, and control system,
- Induction motor will *cogging* experienced,
- Protection devices will failure in operation,
- Overheating of neutral conductors, bus bar, lug connections, mercury vapor and fluorescent lighting (electronic ballast), motor control and switchgear, which may affect current interrupting capabilities,
- Circuit breaker nuisance tripping, improper function of on-board breaker electronics, excessive arcing, improper fuse operation or nuisance blown fuse interruption (artificial heating, or “skin effect”),
- AC motor torque pulsation, voltage sags, notching; DC adjustable, speed drives creating high inrush currents,
- Overheating in transformers and cable systems, insulation (dielectric) breakdown,
- Power factor capacitors becoming overloaded, blown fuse, case swelling, insulation failure from excessive peak voltages, overheating due to high RMS currents,
- Effective use of power factor capacitors minimized, increasing costs, potential for resonance conditions,
- Meter, protective relaying, control and other communication and measurement-instrumentation devices (including ground fault detection and digital displays) malfunctioning or providing a faulty reading, missoperation of electronic components and other equipment,
- Communications (telephone, data, video) susceptible to noise, interference in motor controls, control systems, signal distortion.

Harmonics limitation

Harmonics voltage distortion has been regulated on IEEE 519-1992 as in Table 1.

Harmonics propagation

Harmonics propagation at frequency $f_h = h.f_1$ is based on the solution of the set of linear equations:

$$[I_h] = [Y_h][V_h] \qquad (2)$$

Where $[I_h]$ is the vector of the nodal harmonics current injections of each bus, $[V_h]$ the vector of the resulting

Table 1. IEEE standard 519-1992 for voltage distortion limits [IEEE Standard 519-1992].

Bus Voltage at PCC	Individual voltage distortion (%)	VTHD (%)
< 69 kV	3.0	5.0
69.0001 kV - 161 kV	1.5	2.5
> 161.001 kV	1.0	1.5

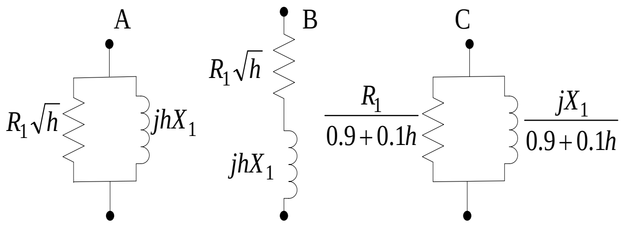

Figure 1. Alternative harmonic models considered for the system load [Stavros et al.,].

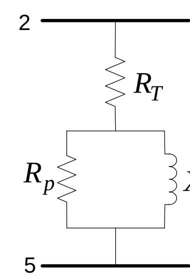

Figure 2. Transformer model [Stavros et al.,

harmonics voltages and $[Y_h]$ the network admittance matrix at frequency f_h.

In practice of standard power system analysis, the admittance matrix of the network $[Y_h]$ is formulated by using the characteristic equations of all network elements such as lines, transformers rotating machines etc, as will be discussed on the next sub-part.

$[Z_h]$ can be obtained by inverting the $[Y_h]$. It is important to seek the harmonics self impedance of the respective buses**,** i.e. the diagonal elements of $[Z_h]$, that is $[Z_{h,ii}]$. The non-diagonal elements $Z_{h,ij}$ are *transfer impedances*, related to the effect on the voltage of bus ***i*** when a harmonics current is injected at bus *j*. *Frequency scan* can be calculated from $[Z_h]$ for varying frequencies $f_h = h.f_1$ which reveals possible *harmonic resonance conditions* of self or transfer impedances.

Modeling of distribution system and its component

For correctly assessing the magnitude of harmonics in power system, it is important to model all system components.

Load model

There are three alternative load models for harmonics analysis. Where in all cases, R_1 and X_1 are the fundamental frequency resistance and reactance, related to the nominal power of the load, where *h* is harmonics order [Figure 1] [Stavros et al.,].

Transformer model

According to [Ribeiro, Ranade and Xu,], it is not important to include capacitance of the transformer. It is caused by that the capacitance of transformer will affect the system on harmonics frequency on 10 kHz. Whereas in practically, the order of harmonics in power system is usually about 100 only. Transformer impedance is equivalent with the *leakage reactance* that linearly with the frequency [Ribeiro ; Arillaga et al., 1985; Dugan et al., 2004; Ranade and Xu,]**.** The Equations (3) to (7) can be used to calculate harmonics impedance of transformer [Figure 2].

$$Z_T = R_T + X_T \quad (3)$$

$$R_S = R_T \quad (4)$$

$$X_p = hX_T \quad (5)$$

$$R_p = 80R_T \quad (6)$$

$$Z_T h_{(25)} = R_1 + \frac{h^2 X_T^2 R_p}{R_p^2 + h^2 X_T^2} + j\frac{hX_T R_p^2}{R_p^2 + h^2 X_T^2} \quad (7)$$

Distribution line model

Distribution line is represented in equivalent circuit exact

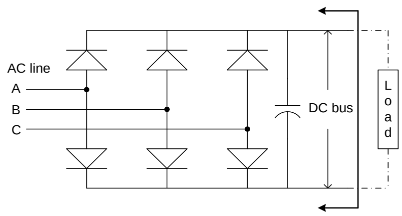

Figure 3. Typical six-pulse front end converter for AC drives [Product Data Bulletin, 1994].

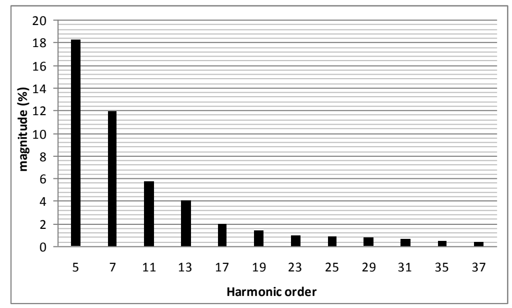

Figure 4. Spectrum of harmonic current caused by 6- Pulse ASD [Product Data Bulletin, 1994].

Table 2. Current harmonic source data [Product Data Bulletin, 1994].

Harmonic #	%	Relative angle
1	100.00	0.00
5	18.24	-55.68
7	11.90	-84.11
11	5.73	-143.56
13	4.01	-175.58
17	1.93	111.39
19	1.39	68.30
23	0.94	-24.61
25	0.86	-67.64
29	0.71	-145.46
31	0.62	176.83
35	0.44	97.40
37	0.38	54.36

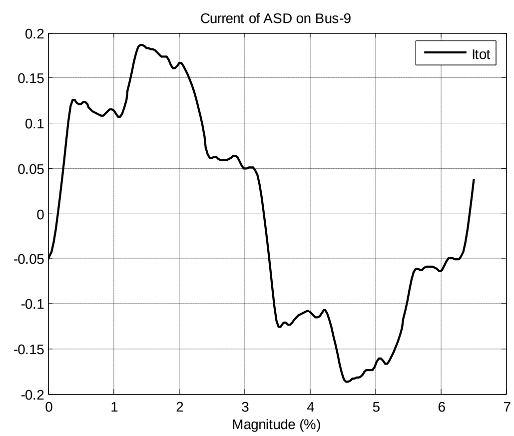

Figure 5. Waveform of harmonics current caused by 6-Pulse ASD.

pi. Correction factor for *skin effect* applied by replaced the value of line resistance with [Arillaga et al., 1985]:

$$R = R\left(1+\frac{0.646h^2}{192+0.518h^2}\right) \quad (8)$$

Non-linear loads

Generally, the harmonic in power system analysis is caused by nonlinear loads, such as fluorescent lamp, solid state power conversion equipment like ASD [Arillaga et al., 1985]. The terms "linear" and "non-linear" define the relationship of current to the voltage waveform. A linear relationship exists between the voltage and current, which is typical of an across-the-line load. A non-linear load has a discontinuous current relationship that does not correspond to the applied voltage waveform [Figure 3 and Table 2] [Product Data Bulletin, 1994].

One example of nonlinear loads is ASD. The characteristics of harmonics on it are based on the number of rectifiers (pulse number) used in a circuit and can be determined by the following equation:

$$h = (n \times p) \pm 1 \quad (9)$$

Where:
n = an integer (1, 2, 3, 4, 5 …)
p = number of pulses or rectifiers

For example, using a 6 pulse rectifier, the characteristic harmonics will be:

$h = (1 \times 6) \pm 1 \Rightarrow$ 5th & 7th harmonics
$h = (2 \times 6) \pm 1 \Rightarrow$ 11th & 13th harmonics
$h = (3 \times 6) \pm 1 \Rightarrow$ 17th & 19th harmonics
$h = (4 \times 6) \pm 1 \Rightarrow$ 23rd & 25th harmonics [Product Data Bulletin, 1994]

Spectrum of harmonics current caused by six pulses ASD is described on Figure 4, where its ITHD is 23.06%.

Signal of harmonics current caused by six pulses ASD is plotted on Figure 5. Admittance matrices of system [Grainger and dan Stevenson, 1994; Gungor, 1988] can

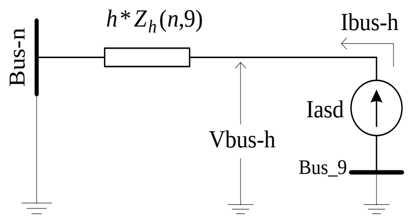

Figure 6. *Circuit for* calculating the harmonics voltage, harmonics currents, VTHD, and ITHD [Stavros et al., ????].

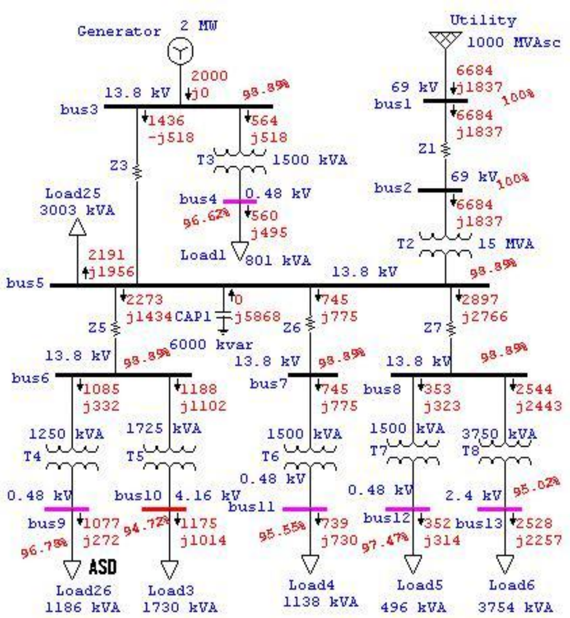

Figure 7. Load flow study of IEEE Test System 13 buses – a balanced industrial system [Abu-hashim et al., 1999].

be formed as:

$$Y_h = \begin{bmatrix} Y_h(1,1) & Y_h(1,2) & \dots & Y_h(1,13) \\ Y_h(2,1) & Y_h(2,2) & \dots & Y_h(1,13) \\ \dots & \dots & \dots & \dots \\ Y_h(13,1) & Y_h(13,2) & \dots & Y_h(n,n) \end{bmatrix} \quad (10)$$

Impedance matrices of Equation (10) is [3]

$$Y_h = Y_h^{-1} \quad (11)$$

Furthermore, circuit on Figure 6 can be used to calculate the harmonics voltage, harmonics currents, VTHD, and ITHD in every bus. Formula for voltage harmonics calculation is as follows.

Table 3. Per-Unit Line and Cable Impedance Data (base values: 13.8 kV; 10,000 kVA) [Abu-hashim et al., 1999].

From	To	R	X	R/X
1	2	0.00139	0.00296	0.516
5	3	0.00122	0.00243	0.502
5	6	0.00075	0.00063	1.19
5	7	0.00157	0.00131	1.198
5	8	0.00109	0.00091	1.19

$$V_{bus-h} = hxZ_h(n,9)xI_{bus-h} \quad (12)$$

STUDY CASE

The IEEE Test System 13-buses, a balance industrial system, is used as a study case as shown in Figure 7. The data of the system can be seen on Tables 2, 3, 4, 5 and Figure 7 [Abu-hashim et al., 1999].

Additional data used for this research are:

- The system impedance of the system in Figure 6 was determined from the fault MVA and X/R ratio at the utility connection point. These values are 1000 MVA and 22.2, respectively. This data was used for obtaining system equivalent impedance of the system.
- The local (in-plant) generator was represented as a simple Thevenin equivalent. The internal voltage, determined from the converged power flow solution, is 13.98/-1.52° kV. The equivalent impedance is the sub-transient impedance which is 0.0366 + j1.3651 ohm.
- The plant power factor correction capacitors are rated at 6000 kvar.

Flow chart of this research is shown in Figure 8.

RESULTS

The result of this research includes impedance diagram, harmonics voltage spectrum, harmonics current spectrum, impedance scan and validation of VTHD as mentioned as follows.

Harmonic impedance diagram

One of the results of this research is diagram of harmonics impedance. It can be calculated by using the Equations (3) to (8), and the results are shown in Figure 9. The data in Tables 5 and 6 will be used in this step [Abu-hashim et al., 1999].

Harmonics voltage spectrum

On Figure 10, the 7th harmonics voltage on Bus-1 can be

Table 4. Transformer Data [Abu-hashim et al., 1999].

From	To	Voltage	Tap	kVA	%R	%X
2	5	69:13.8	69	15000	0.4698	7.9862
3	4	13.8:0.48	13.45	1500	0.9593	5.6694
6	9	13.8:0.48	13.45	1250	0.7398	4.4388
6	10	13.8:4.16	13.11	1725	0.7442	5.9537
7	11	13.8:0.48	13.45	1500	0.8743	5.6831
8	12	13.8:0.48	13.8	1500	0.8363	5.4360
8	13	13.8:2.4	13.11	3750	0.4568	5.4810

Table 5. Generation, Load, and Bus Voltage Data (from power flow study results) [Abu-hashim et al., 1999].

Bus Name	Bus #	V_{mag} (p.u.)	θ (deg)	P_{gen} kW	Q_{gen} kvar	P_{load} kW	Q_{load} kvar
100:UTIL-69	1	1.000	0.00	7450	540	-	-
01:69-1	2	0.999	-0.13	-	-	-	-
03:MILL-1	5	0.994	-2.40	-	-	2240	2000
50:GEN1	3	0.995	-2.39	2000	1910	-	-
51:Aux	4	0.995	-3.53	-	-	600	530
05:FDR F	6	0.994	-2.40	-	-	-	-
49:RECT	9	0.980	-4.72	-	-	1150	290
39:T3 SEC	10	0.996	-4.85			1310	1130
26:FDR G	7	0.994	-2.40	-	-	-	-
06:FDR H	8	0.994	-2.40	-	-	-	-
11:T4 SEC	12	0.979	-3.08	-	-	370	330
19: T7 SEC	13	1.001	-4.69	-	-	2800	2500
29:T11 SEC	11	0.981	-4.16	-	-	810	800

calculated as follows:

$V_{7(1)} = (1.8)(10^{-5})(69kV) = 1.242$ volt.

$V_{7(2)} = (0.3)(10^{-5})(69kV) = 0.207$ volt.

It can be clearly seen that V_7 on Bus-1 is higher than Bus-2. In Figure 11, the harmonics voltage on Bus-3 is more higher than Bus 5, 6, 7 and 8, and it is more higher on Bus 9 than Bus-4,11, and 12.

$V_{11(7)} = (3.5)(10^{-4})(13.8kV) = 4.8$ volt.

$V_{11(8)} = (2.1)(10^{-4})(13.8kV) = 2.89$ volt.

Harmonic current spectrum

In Figure 12, the harmonics current on Bus-1 is higher than Bus 2, and it is higher on Bus 13 than in Bus-10. The 7^{th} harmonics current on Bus-1 can be calculated as follows:

$I_{7(1)} = (4.3)(10^{-3})(83.67A) = 0.36$ ampere.

In Figure 13, the harmonics current on Bus-7 is higher than Bus 3, 5, 6, 8 and it is higher on Bus 11 than on Bus-4, 9, 12.

In Figure 14, for overall value, the ITHD is higher than VTHD. It can be clearly seen that the VTHD on Bus-9 and Bus-10 in this work were 10.61 and 10.63% respectively.

Whereas the ITHD is dispersed. ITHD on Bus 11 is higher than others. Five the biggest ITHD are on Bus-11, 13, 7, 8 and 12. VTHD on Bus 9 and 10 are higher than on the others Buses.

Validation and comparison of VTHD

For comparison purposes as has been shown on Figure 15, the IEEE test results, this work Matlab), and ETAP Powerstation results are presented.

Dominant VTHD of IEEE result, that is 8.02%, was occurred in one bus that is the Bus-9. This work shows that the dominant VTHD were occurred on two buses, the Bus-9 and Bus-10, there are is 10.61% and 10.63% respectively. VTHD on ETAP result is 11.73% on Bus-9.

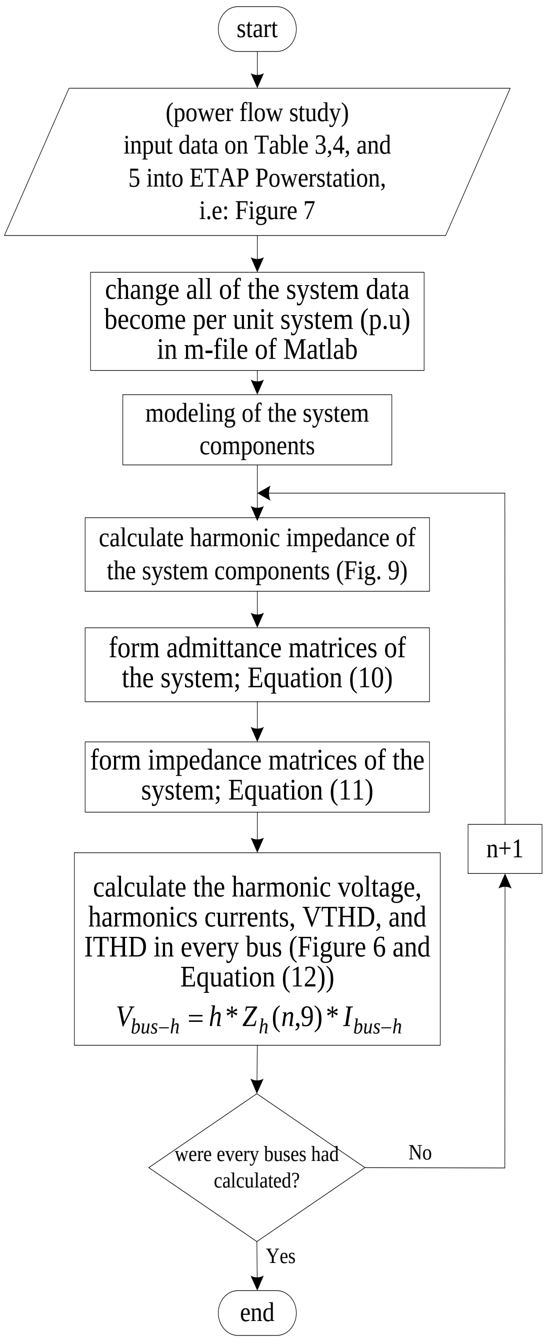

Figure 8. Research flow chart.

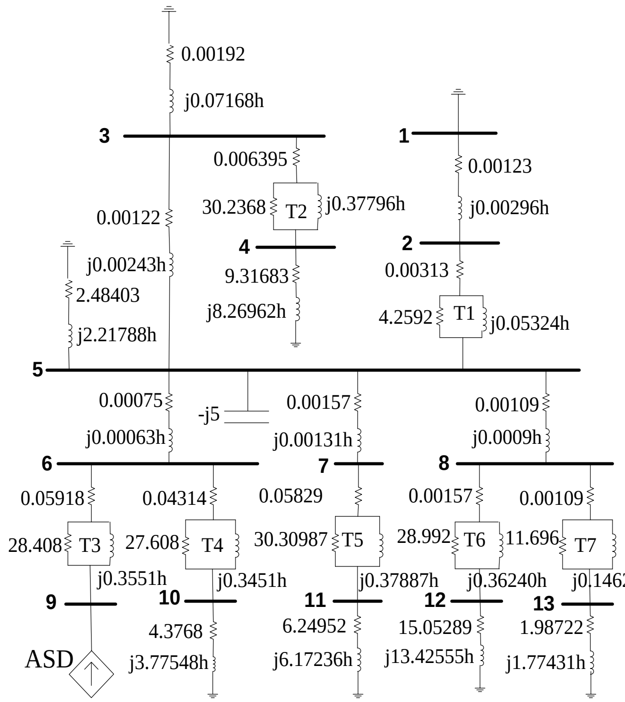

Figure 9. Harmonics impedance diagram (in p.u.) system of Figure 7.

Harmonics frequency scan

Harmonic Frequency scans or “driving point impedance” plots are generally used in harmonic analysis to gain physical insight into the response of the network.

It can be seen that on Figure 16, 17, 19, there are no resonance. Property of the lines is inductive, that is that their impedance is increase as $2\pi f L$ according to the frequency of the harmonics current. In the Figure 18, the results of frequency scan show the resonance occurrence between harmonics 25 and 30.

The characteristics of driving point impedance, that resulted through frequency scan in Figure 16, 17, 18, 19, were same on the some buses, but it shows resonance in two buses, that is Bus 12 and 13.

For comparison between Figures 14 and 15, VTHD on the Bus 9 and 10 are relatively high, but the ITHD is 2.8% on Bus 9 and it is 0% on the Bus 10.

Conclusions

The propagation and distortion of harmonics from an ASD to the others are presented. Comparison between numeric results in the Matlab file, IEEE test result, and standard software such as the ETAP Powerstation are presented and discussed. Main conclusions are:

1. The modeling and formulation of system devices affect the result accurateness in m-file of Matlab. VTHD on the Matlab occurs in two buses, but in the ETAP and IEEE only in one bus.
2. VTHD in every software (IEEE test, Matlab, and ETAP) exceeding the limitation of IEEE Standard 519-1992.
3. The high ITHD are dispersed on many buses according to the frequency scan.
4. Result of frequency scan shows that, generally, property of the lines in the system are inductive.

Table 6. Plant Voltage Harmonic Summary [Abu-hashim et al., 1999].

Bus Name	Bus #	V_1 (V_{LN})	V_5 (V_{LN})	V_7 (V_{LN})	THD_V (%)
100:UTIL-69	1	39645.70	40.37	104.23	0.28
01:69-1	2	39538.00	52.36	135.14	0.37
03:MILL-1	5	7712.77	53.51	138.13	1.93
50:GEN1	3	7726.55	51.72	133.51	1.87
51:Aux	4	262.74	1.72	4.40	1.81
05:FDR F	6	7709.24	54.07	138.35	1.94
49:RECT	9	269.89	12.79	12.83	8.02
39:T3 SEC	10	2240.05	14.83	37.21	1.80
26:FDR G	7	7709.07	53.48	138.04	1.93
06:FDR H	8	7703.35	53.43	137.91	1.93
11:T4 SEC	12	260.40	1.78	4.59	1.90
19: T7 SEC	13	1302.74	8.58	21.78	1.81
29:T11 SEC	11	256.29	1.71	4.36	1.84

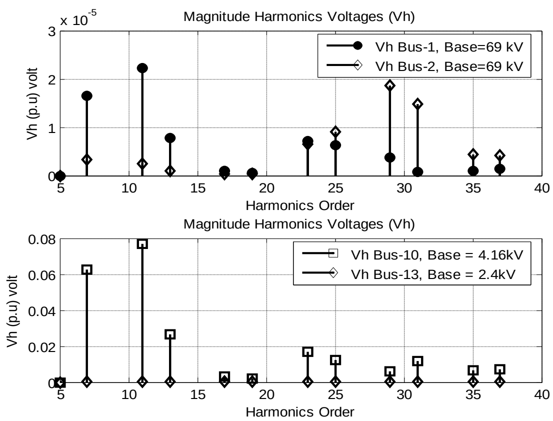

Figure 10. Harmonics voltage spectrum on Buses-1, 2, 10, 13.

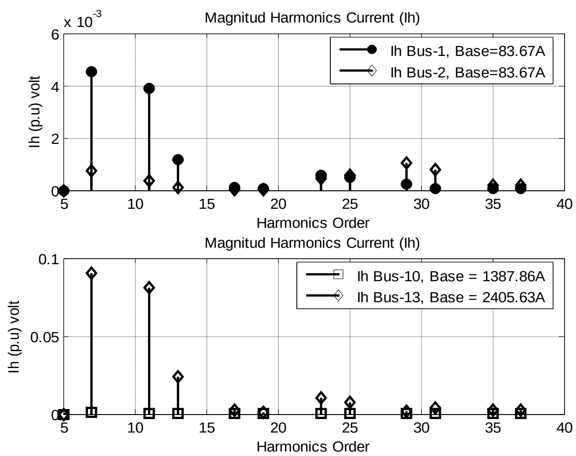

Figure 12. Harmonics current spectrum on Buses -1, 2, 5, 3, 4, 6.

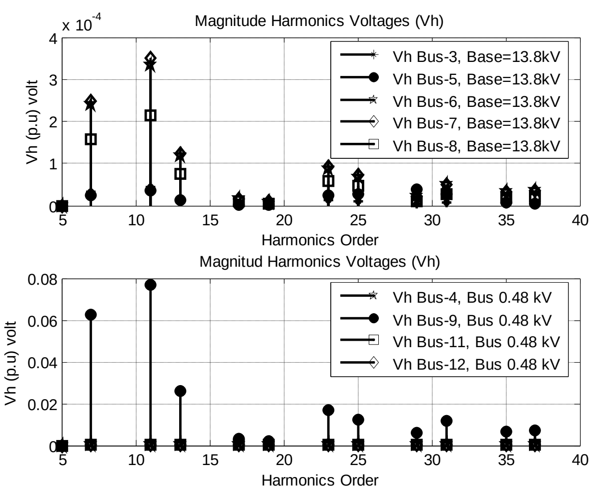

Figure 11. Harmonics voltage spectrum on Buses-7, 8, 11, 9, 10, 12, 13.

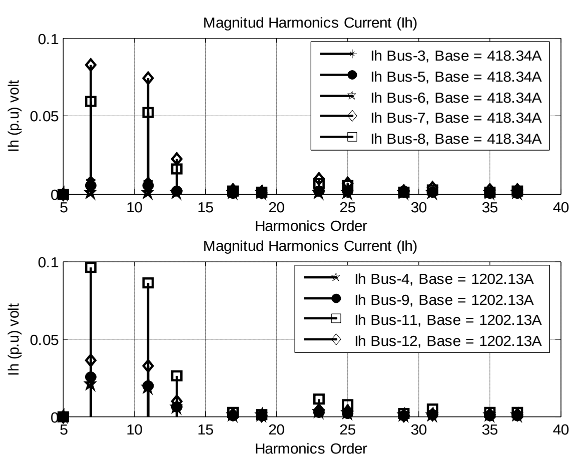

Figure 13. Harmonics current spectrum on Buses-7, 8, 9, 10, 11, 12, 13.

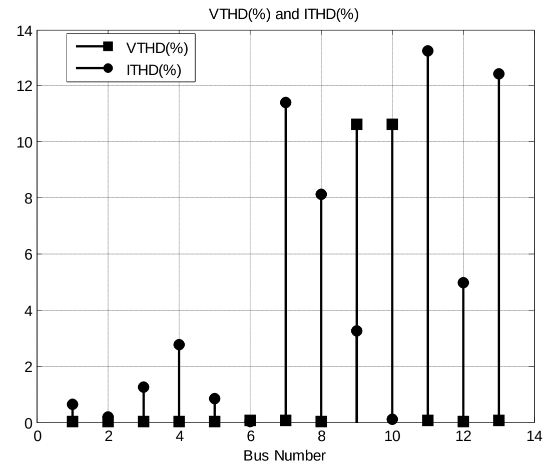

Figure 14. VTHD and ITHD on every bus.

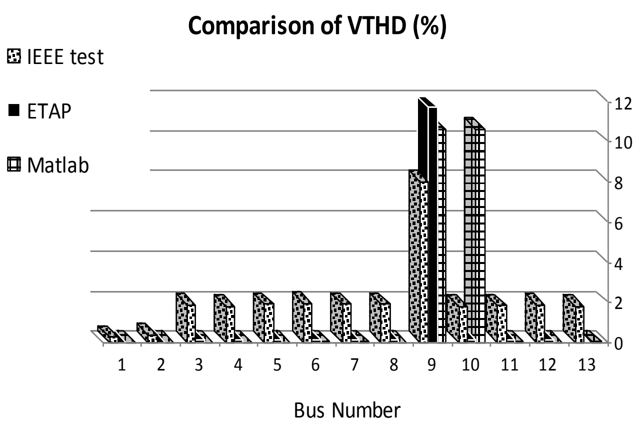

Figure 15. Comparison of VTHD on every bus in IEEE test [Abu-hashim et al., 1999], Matlab and the ETAP.

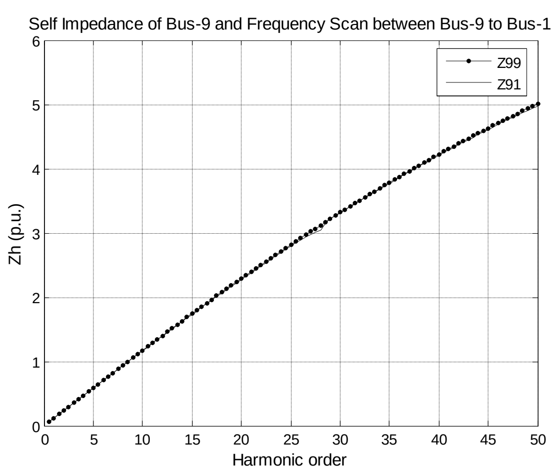

Figure 16

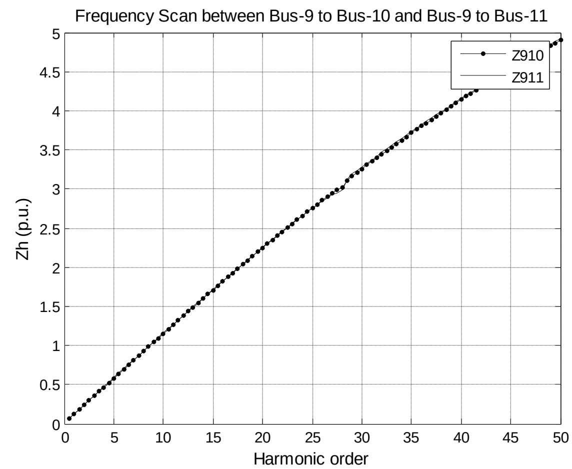

Figure 17

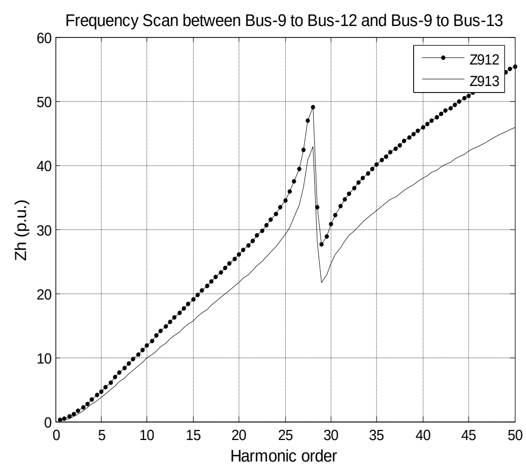

Figure 18

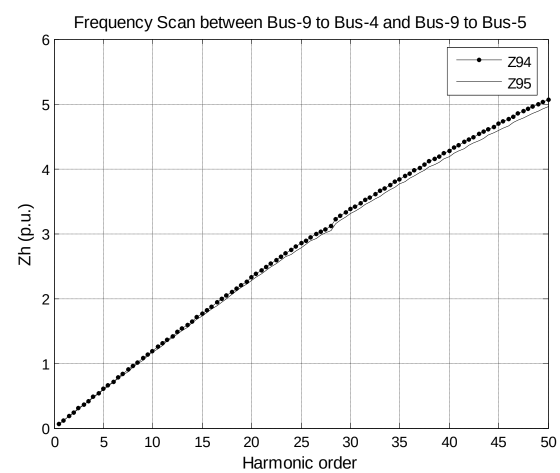

Figure 19

FURTHER WORK

According to the exceeding of the limitation of VTHD as shown on IEEE Standard 519-1992, it is needed a solution for reducing the VTHD. The active or passive filter or combination of them can be used in these purposes.

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