Proceedings of the Ninth IASTED European Conference
Power and Energy Systems (EuroPES 2009)
September 7 - 9, 2009 Palma de Mallorca, Spain

HARMONIC CURRENTS CIRCULATION IN ELECTRICAL NETWORKS SIMULATION AND ANALYSIS

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ABSTRACT

In this paper, we propose a detailed harmonic flow analysis for the test system consists of 13 buses Balanced Industrial Distribution System (BIDS) to illustrates that the exist of harmonic source in any branch of the system will affect the voltage and current waveforms in most of the system buses before they create problems on the utility supply system. This approach will be useful in arriving at equitable ways of settling customer complaints, sharing the cost of waveform distortion through rate structures, penalties, etc.

The study used the current harmonic contents of an adjustable speed drive (ASD) as an example of a harmonic produced load connected at different locations at the (BIDS) and with different loading conditions illustrated using No.18 cases example loads.

We used the simulink tool box of the Matlab program for the simulation and analysis of the test system.

KEY WORDS

Harmonics, Modeling, Simulation, Test Systems, electric Networks

1. Introduction

A harmonic-producing load can affect other loads if significant voltage distortion is caused. The voltage distortion caused by the harmonic-producing load is a function of both the system impedance and the amount of harmonic current injected.

Therefore, power quality has become one of the most important issues in power systems lately. Harmonic producing loads include fluorescent lamps, switching power supplies, AC/DC converters, adjustable speed drives and power electronic equipment. The harmonic spectrums of` these harmonic loads are studied in [1].

Harmonic problems usually show up within the customer's electrical power networks before they create problems on the utility supply system [2].

Therefore, several regulations limit the percentage of current and voltage harmonics for electrical devices and systems. Electrical and electronic device manufacturers have to use different harmonic mitigation methods to comply with these regulations.

Harmonic studies have become an important aspect of power system analysis and design in recent years. Harmonic simulations are used to quantify the distortion in voltage and current waveforms in a power system and to determine the existence and mitigation of harmonic distortions.

Statistical analyses of measurements of harmonics are presented in [3]. Other paper shows real measurements on commercial building electrical networks [4]. However, for any scheme to be effective, the portion of the distortion caused by an individual customer has to be isolated.

Many techniques are being developed using digital computer programs are available for harmonic analysis and modeling.

Paper [5] presents harmonic simulation for three test systems as the most common harmonic study scenarios encountered in industry. The purpose was to simulate test system harmonic to demonstrate guidelines for the preparation and analysis of harmonic problems through case studies and simulation examples. The study was useful for the development of new harmonic simulation methods and for the evaluation of existing harmonic analysis software.

In this paper we simulate the test system on the simulink tool box of the Matlab program with the same parameters and configuration used in [6] as standard study test system approved and published by IEEE Transaction on power delivery.

The goal of the study was to illustrate many of the important considerations in evaluating harmonic current circulations for an industrial facility. These include:

- Multiple sources harmonic effects
- Monitor voltage distortion on the different buses.
- Choose the best design of harmonic filters to control harmonic levels
- Evaluating the time varying nature of the harmonic levels.

2. Test System

The test system used consists of 13 buses Balanced Industrial Distribution System (BIDS) as shown in Fig. 1 and is representative of a medium-sized industrial plant.

The system is extracted from a common system that is being used in many of the calculations and examples in the IEEE Color Book series [6]. Due to the balanced nature of this example, only positive sequence data is provided, Capacitance of the short overhead line and all cables are neglected.

Table 1 shows the line and cable impedance data.

Table 1 System Line and Cable Impedance

from	To	Voltage Kv	R	X
100	01	69:13.8	0.00139	0.00296
03	50	13.8:0.48	0.00122	0.00243
03	05	13.8:0.48	0.00075	0.00063
03	26	13.8:4.16	0.00157	0.00131
03	06	13.8:0.48	0.00109	0.00091

Also table 2 presents transformers data for the 13 buses (BIDS) shown in Fig. 1 [5].

Table 2 Transformers Data

Trans	from	To	Voltage Kv	Tap	KVA	%R	%X
T1	01	03	69:13.8	69	15000	0.4698	7.9862
T2	50	51	13.8:0.48	13.45	1500	9593	5.6694
T3	05	49	13.8:0.48	13.45	1250	0.7398	4.4388
T4	05	39	13.8:4.16	13.11	1725	0.7442	5.9537
T5	26	29	13.8:0.48	13.45	1500	0.8743	5.6831
T6	06	11	13.8:0.48	13.8	1500	0.8363	5.436
T7	06	19	13.8:2.4	13.11	3750	0.4568	5.481

The load and power flow for the generation, load, and bus voltage data as presented by [5] shown at table 3.

Table 3 The Load and Power Flow Study

Bus	Vmag (p.u.)	δ (deg)	Pgen (Kw)	Qgen (Kvar)	Pload (Kw)	Qload (Kvar)
100	1.000	0.00	7,450	540	-	-
01	0.999	-0.13	-	-	-	-
03	0.994	-24.00	-	-	2,240	2,000
50	0.995	-2.39	2,000	1,910	-	-
51	0.995	-3.53	-	-	600	530
05	0.994	-2.40	-	-	-	-
49	0.980	-4.72	-	-	1,150	290
39	0.996	-4.85	-	-	1,310	1,130
26	0.994	-2.40	-	-	-	-
06	0.994	-2.40	-	-	-	-
11	0.979	-3.08	-	-	370	330
19	1.001	-4.69	-	-	2,800	2,500
29	0.981	-4.16	-	-	810	800

We choose the point of common coupling (PCC) in this study to be at the secondary side of the transformer connected to bus 29 and the point of connection to the linear load, which will be monitored.

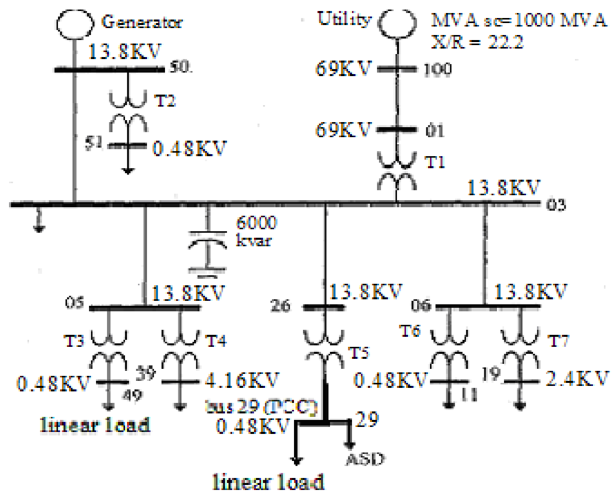

Fig. 1 The modified 13 buses (BIDS) Test system presented at [5]

Also Fig. 1 shows the modified 13 buses Balanced Industrial Distribution Test system with the connection of the linear load at bus 29 which choose to be the PCC as it is the medial branch of the system and also the ASD controlling a number of parallel motors in some of study cases.

In this study we removed the ASD at bus 49 as presented by [5] with a linear load presented by large motor with the same power rating as shown in Fig. 1.

An adjustable speed drive controlling number of electrical three phase motors has been modeled by harmonic current sources. Each harmonics content modeled by a current source with frequency multiple integers of the fundamental frequency and magnitude, phase angle related to the fundamental current as shown in the Table 4 [7].

Table 4 Current Injection Model for ASD

Load Level	100%		75%		50%	
h-order	Mag.	Angle	Mag.	Angle	Mag.	Angle
1	100.0	0	100.0	0	100.0	0
3	0.35	-159	0.59	-44	0.54	-96
5	60.82	-175	69.75	-174	75.09	-174
7	33.42	-172	47.03	-171	54.61	-171
9	0.50	158	0.32	-96	0.24	-102
11	3.84	166	6.86	17	14.65	16
13	7.74	-177	4.52	-178	1.95	71
15	0.41	135	0.37	-124	0.32	28
17	1.27	32	7.56	9	9.61	10
19	1.54	179	3.81	9	7.66	16
21	0.32	110	0.43	-163	0.43	95
23	1.08	38	2.59	11	0.94	-8
25	0.16	49	3.70	10	3.78	7

3. Study Cases for the Test System

We connect the harmonic sources to 3 buses from the system. These buses were (B29, B11 & B51) which have the same voltage level 480V 3 phase.

By using different combinations from the harmonic sources distributed on the three Buses (B29, B11 & B51) separately or combined and with different loading conditions 50%, 75% &100% for the ASD controlling the induction motors we get a No.18 different cases from the test system as shown at table 5.

We monitored the effect of the 30 hp PWM-type ASD as a harmonic source serving a number of parallel 20 hp induction motor on the linear load connected to Bus 29 as our concerned bus to this study. All the other loads in the system are linear electrical loads.

Table 5 Input Cases at Different Locations with Different Loading Conditions

	Bus 29		**Bus 51**		**Bus 11**		**Linear Load Bus**	
Case	Motors equiv-alent hp	ASD load level %	Motors equiv-alent hp	ASD load level %	Motors equiv-alent hp	ASD load level %	KW	KVAr
1	800	57	-	-	1200	50	700	200
2	800	75	400	100	800	100	600	400
3	800	50	800	75	800	100	600	600
4	800, 600	50, 100	-	-	-	-	200	200
5	800, 400	75, 50	-	-	-	-	600	200
6	800, 400, 400	50, 100, 75	-	-	-	-	300	0
7	600	100	600	100	800	100	600	600
8	800, 400	100, 75	-	-	-	-	300	100
9	400, 400, 400	100, 75, 50	-	-	-	-	400	200
10	1200	75	800	50	-	-	400	100
11	400, 800	100, 50	800	50	-	-	500	200
12	1200	50	-	-	800	50	700	300
13	400 ,1200	75, 50	-	-	800	50	500	100
14	400	50	800	75	800	50	1200	300
15	-	-	800	75	1200	50	1000	600
16	1200	100	-	-	-	-	200	100
17	400	75	400	75	400	75	800	800
18	800	100	1200	50	1200	50	300	300

3.1 Voltage THD results for all system buses

At each case we monitor the voltage wave form for all the system buses and also we measure the voltage total harmonic distortion (THDv) to indicate the effect of the nonlinear load in all buses voltages and spatially bus 29, which is the point of connection to the linear as shown in tables 6 to 8.

We find that the THDv at bus 29 (PCC) is varying from case to other according to harmonic source rating and location in the system. The THDv reaches in some cases 52.6% as in case No. 18 which could be seen as the wrest case from point of view of the THDv at bus 29.

While in other case the THDv may reach a very small percentage 9.2% as in case 15.

Table 6 THDv at all the System Buses for Case 1 to 6

Bus	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
100	0.748	0.869	0.936	0.614	0.548	0.688
01	1.497	1.785	1.941	1.163	0.991	1.349
03	8.040	9.668	10.560	6.137	5.139	7.195
50	7.786	9.363	10.220	5.944	4.977	6.968
51	8.068	11.490	15.090	5.961	5.206	6.933
05	8.039	9.667	10.550	6.136	5.138	7.194
49	6.664	8.055	8.783	5.097	4.258	5.974
39	7.495	9.037	9.864	5.719	4.785	6.707
26	8.035	9.666	10.550	6.135	5.133	7.191
06	8.036	10.020	10.560	6.137	5.139	7.195
11	14.300	15.610	16.010	6.195	5.410	7.206
19	7.537	10.910	9.926	5.754	4.814	6.748
29	12.790	14.760	13.330	18.100	15.760	21.120

Table 7 THDv at all the System Buses for Case 7 to 12

Bus	**Case 7**	**Case 8**	**Case 9**	**Case 10**	**Case 11**	**Case 12**
100	0.876	0.603	0.566	0.785	0.718	0.684
01	1.799	1.136	1.039	1.583	1.423	1.339
03	9.758	5.976	5.417	8.525	7.622	7.146
50	9.452	5.788	5.247	8.248	7.374	6.920
51	13.680	5.894	5.357	11.400	10.890	7.160
05	9.757	5.975	5.417	8.524	7.622	7.145
49	8.147	4.971	4.497	7.073	6.324	5.916
39	9.129	5.572	5.047	7.951	7.107	6.656
26	9.761	5.978	5.415	8.519	7.618	7.138
06	9.761	5.976	5.418	8.525	7.623	7.143
11	15.900	6.125	55.670	8.867	7.928	10.33
19	9.187	5.606	4.849	8.000	7.150	6.694
29	13.930	18.390	16.210	18.270	15.320	13.77

Table 8 THDv at all the System Buses for Case 13 to 18

Bus	**Case 13**	**Case 14**	**Case 15**	**Case 16**	**Case 17**	**Case 18**
100	0.820	0.744	0.756	0.617	0.583	1.095
01	1.667	1.487	1.516	1.171	1.085	2.308
03	8.998	7.990	8.164	6.179	5.695	12.59
50	8.714	7.727	7.896	5.984	5.511	12.18
51	9.045	13.090	13.20	6.020	7.594	17.33
05	8.997	7.990	8.163	6.178	5.694	12.59
49	7.461	6.618	6.764	5.148	4.720	10.48
39	8.392	7.447	7.609	5.765	5.303	11.77
26	8.989	7.987	8.163	6.184	5.693	12.59
06	8.995	7.987	8.159	6.179	5.694	12.58
11	11.65	10.900	14.32	6.256	7.618	17.26
19	8.440	7.490	7.651	5.800	5.335	11.84
29	19.41	7.972	8.122	19.57	7.684	17.77

Comparing the results in tables (6 to 8) with the THDv allowable limit at IEEE 519-1992 [8] we find that at bus 29 all the results exceeds the allowable limit even in case 15 which is the lowest percentage of THDv.

3.2 Current THD results for bus 51, 11 &29

Also at each case we monitor the current wave forms at bus 51, bus 29 and bus 11 and we measure the current total demand distortion at these buses.

The (THDi) at bus 51, 29 and 11 are shown in tables 9 to11 due to the circulation of the harmonic currents at the linear load is also indicated at the same tables.

Table 9 THDi from Bus 51, Bus 29 and Bus 11 for Case 1 to 6

Bus	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
51	1.970	21.750	34.790	1.505	1.302	1.732
11	50.980	42.040	42.060	1.554	1.344	1.789
29	35.890	36.570	28.950	60.530	46.300	66.260
29:LL	7.209	4.852	3.461	4.721	7.641	21.120
29:HL	85.070	85.070	94.900	78.810	87.420	82.330

Table 10 THDi from Bus 51, Bus 29 and Bus 11 for Case 7 to 12

Bus	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
51	28.230	1.502	1.355	30.080	30.090	1.748
11	42.020	1.551	1.399	2.162	1.944	41.490
29	27.340	55.660	51.450	56.440	46.460	39.290
29:LL	3.771	9.471	6.275	10.920	7.067	5.704
29:HL	69.600	73.490	79.740	85.070	81.330	94.900

Table 11 THDi from Bus 51, Bus 29 and Bus 11 for Case 13 to 18

Bus	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18
51	2.201	34.880	34.890	1.549	22.000	38.860
11	41.440	41.500	51.030	1.600	31.320	50.920
29	56.080	11.880	2.486	57.660	16.790	44.290
29:LL	12.820	4.792	2.486	7.689	2.048	4.775
29:HL	91.500	94.900	0.000	69.600	85.070	69.600

From tables 9 to 11 we find that the THDi at bus 29:LL linear load is varying from case to other according to harmonic source rating and location in the system. The THDi reaches in some cases 41.6% as in case No. 6 which could be seen as the wrest case from point of view of the THDi at bus 29:LL. While in other case the THDi can reach a very small percentage 2.82% as in case 15.

Comparing the results in tables 9 to 11 with the THDi allowable limit at IEEE 519-1992 [8] we find that at bus 29:LL at some of the results exceeds the allowable limit while in some other cases do not exceed the limits but there a circulation of the harmonic currents due to the harmonic sources exist in the system at some of the buses. This will have a harmful effect in the linear load without containing any harmonic source itself.

In the next section we will discuss in details the cases with the special results from the point of view of THDv at bus 29 and THDi at bus 29:LL (linear load) required to be analyzed.

4. Discuss for the cases with the special results

4.1 Case No. 6

In this case the nonlinear loads applied as shown in table 5 to the test system presented in Fig. 1. While the linear load at Bus 29 was 300kW.

Figs. 2 to 5 shows the current and voltage curves for phase A of case 6 at Bus51, Bus11 and Bus29.

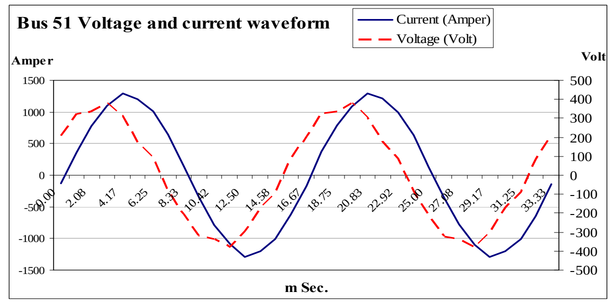

Fig. 2 Current and Voltage waveform at Bus 51

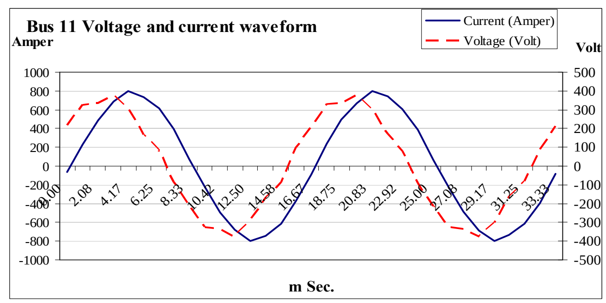

Fig. 3 Current and Voltage waveform at Bus 11

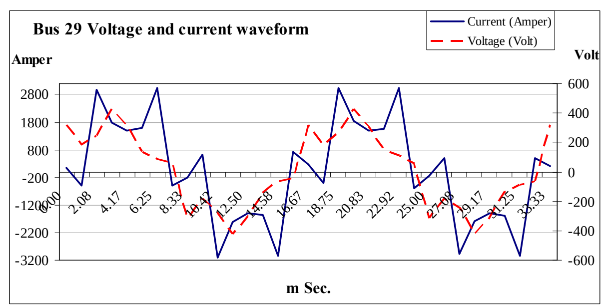

Fig. 4 Current and Voltage waveform at Bus 29

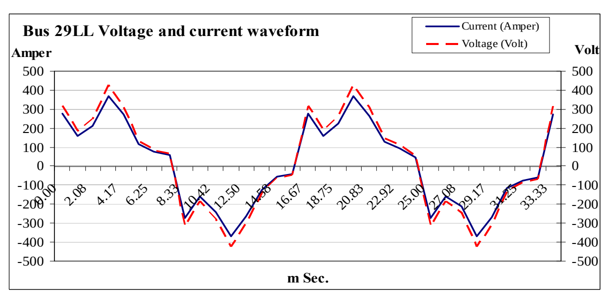

Fig. 5 Current and Voltage waveform at Bus 29:LL (Linear Load)

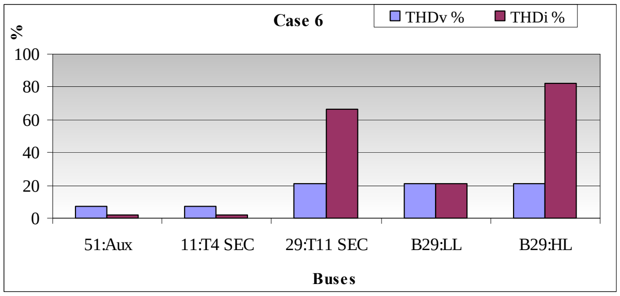

Fig. 6 Voltage and Current Total Harmonic Distortion at Buse51, 11 &29

We notice from Fig. 6 That at bus 29 (THDi) is 31.61% and (THDv) is 21.120% which exceeds the IEEE 519-1992 [8] allowable limit. While the THDi was 21.120% at the point of connection of the linear load.

4.2 Case No.15

In this case the nonlinear loads applied as shown in table 5 to the test system presented in Fig. 1. While the linear load at Bus 29 was 1000kW & 600kVAr.

Figs. 7 to 10 below shows the current and voltage curves for phase A of case 15 at Bus51, Bus11 and Bus29.

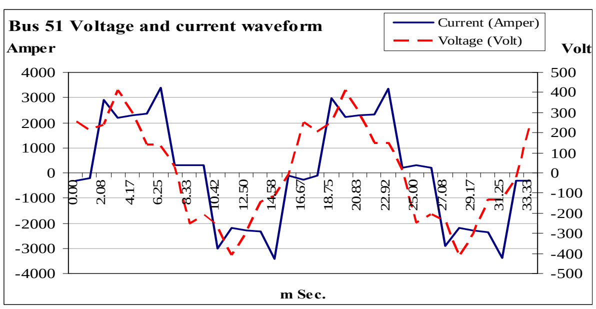

Fig. 7 Current and Voltage waveform at Bus 51

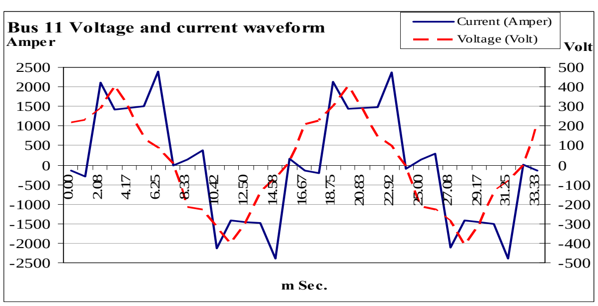

Fig. 8 Current and Voltage waveform at Bus 11

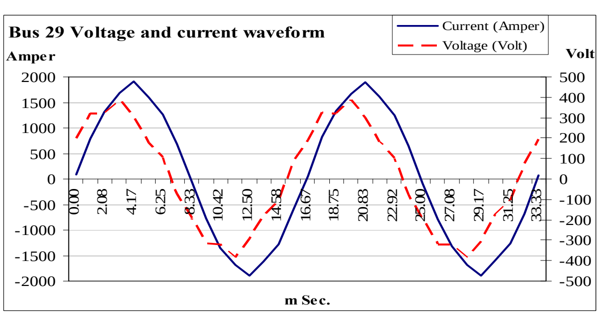

Fig. 9 Current and Voltage waveform at Bus 29

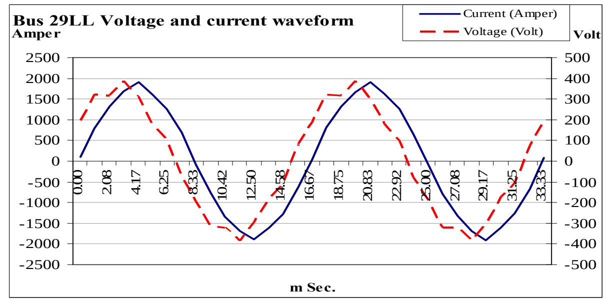

Fig. 10 Current and Voltage waveform at Bus 29:LL (Linear Load)

We notice from the current and voltage waveforms and chart presented on Fig. 11. That the (THDi) is 2.486% at the PCC (bus 29) whoever there is no harmonic source connected to this bus and the nonlinear loads were on the neighbor buses in the system. While the (THDv) is 8.122% which exceeds the IEEE 519-1992 [8] the voltage allowable limit due to the neighbor nonlinear loads at bus 51 and bus 11.

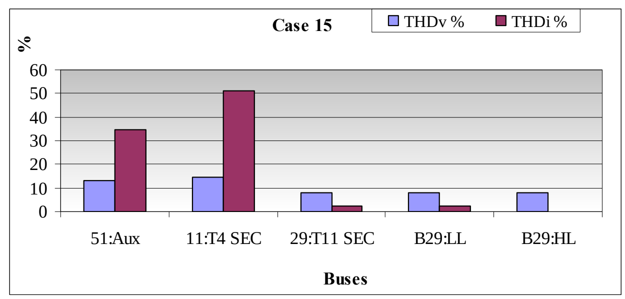

Fig. 11 Voltage and Current THD at Buse51, 11 & 29

5. Effect of Harmonic Sources at Different Locations on the whole system

The following chart bars show the effect of connecting harmonic sources on different locations in the system on (THDv) and (THDi) of bus 51, 11&29 as summarized in tables 6 to 11.

5.1 Effect of Harmonics at Different Locations on bus 51

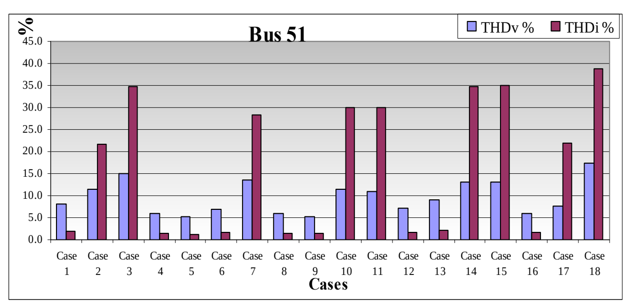

Fig. 12 Comparison for THDv and THDi at Bus 51 on different cases

Fig. 12 shows that there is no harmonic source connected directly to bus51 in some cases as the following case 1,4,5,6,8,9,12,13&16 however the voltage total harmonic distortion (THDv) in most of these study cases exceeds 5% allowable by IEEE519-1992 [8].

However the (THDi) was less than 5% in these cases which could be acceptable from the IEEE519-1992 standard [8] point of view but still have a harmful effect on the linear loads may be connected at this bus.

5.2 Effect of System Harmonics on bus 11

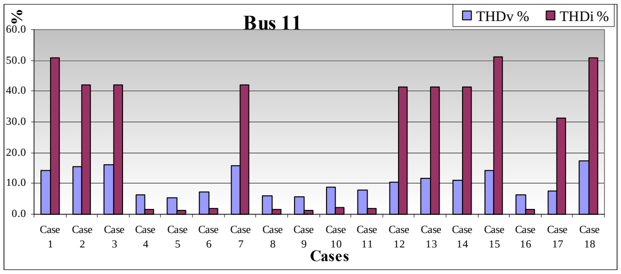

Fig. 13 Comparison for THDv and THDi at Bus 11 on different cases

Fig. 13 shows that there is no harmonic source connected directly to bus11 in some cases as following case 4,5,6,8,9,10,11&16 however the (THDv) was found between 5% and 10% which exceeds 5% allowable by IEEE519-1992 [8]. While the (THDi) was less than 5% in these cases which is acceptable by IEEE519-1992 [8] but still have a harmful effect on the other linear loads.

5.3 Effect of System Harmonics on bus 29

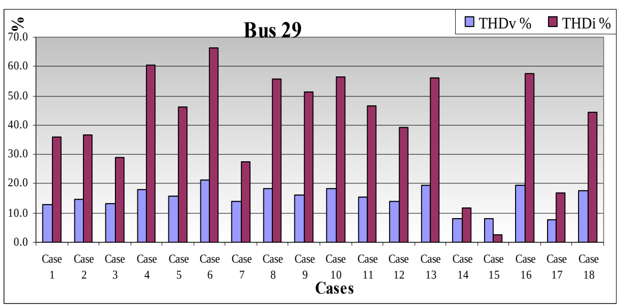

Fig. 14 Comparison for THDv and THDi at Bus 29 on different cases

Fig. 14 shows that when there is no harmonic source connected directly to bus29 in case 15 the (THDv) is 8.122% which exceeds allowable 5% by IEEE519-1992 [8] and the (THDi) is 2.486%. Accordingly the connection of the harmonic sources on bus51 and bus11 affect the power quality on bus 29.

Also connection of the harmonic source to bus29 affects the quality of the voltage and current for the linear load on the same bus.

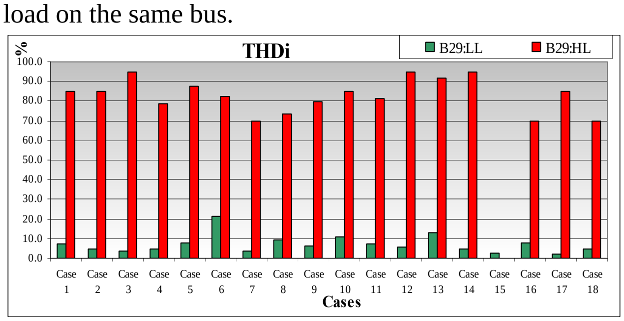

Fig. 15 Comparison THDi at linear load and nonlinear load of Bus 29 for different cases

Fig. 15 Shows that the THDi in most of the cases was between 2.486% at case 15 (no source of harmonic connected at bus29) and 21.120% at case 6 when the linear load is very small and the nonlinear load is very big at different loading conditions.

Also the (THDv) and (THDi) at the linear load in most of the cases exceeds the allowable limits accepted by the IEEE 519-1992.

6. Conclusion

As a general rule from this simulation and analysis based on industrial distribution system, the exist of the harmonic producing loads such as an adjustable speed drive (ASD) in an industrial distribution system will circulate harmonic currents in all the system braches which accordingly affect all the system buses voltages. However there is no harmonic source connected directly to these buses. This in many cases may exceed the allowable voltage total harmonic distortion (THDv) and/or the current total harmonic distortion (THDi) by the standards such as IEEE519-1992 [8].

Accordingly the nonlinear loads should forced by rules to apply some sort of harmonic suppression such as active harmonic filters to avoid the harmful effects of harmonic currents circulations at the different buses on the neighbor loads in the system.

References

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