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AN OVERVIEW OF HARMONIC ANALYSIS DUE TO VARIABLE FREQUECY DRIVE AND MITIGATION TECHNIQUE

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Abstract: Today the use of power electronic devices has increased manifold. Mostly power electronics devices are nonlinear in nature. Harmonics are defined as sinusoidal waveforms having frequencies that are integer multiples of the fundamental frequency (50 or 60 Hz); they may be voltages or currents. The main sources of harmonic sources are power semiconductor devices, electric furnaces, fluorescent lamps, rotating machines, saturated devices like transformer, variable frequency drives (VFDs) in modern industry. High-order harmonics tend to be aggravated by the high-frequency switching operation of power converters, which may trigger the parallel and series resonance in the power system [1]. The processes of cement industry and textile industry with excessive use of nonlinear loads have an impact on the power quality at the connected electric network. Harmonic distortion is one of the most significant phenomena that affect the plant distribution network as well as grid performance. Adjustable speed drives are devices that are used by both paper making machines and ventilators. The processes of cement industry and textile industry with excessive use of nonlinear loads have an impact on the power quality at the connected electric network. Harmonic distortion is one of the most significant phenomena that affect the plant distribution network as well as grid performance. Adjustable speed drives are devices that are used by both paper making machines and ventilators. In this paper, two test systems of IEEE 6 bus system with VFDs and IEEE 9 bus system with VFDs have been used to harmonic analysis. To study the total harmonic distortion produced by ASDs, these have been simulated on two standard test systems, IEEE 6 by system and IEEE 9 bus system with the help of ETAP software.

Keywords – Harmonic analysis, Total harmonic distortion, IEEE 6 Bus system, IEEE 9 Bus system, Variable frequency drive, Adjustable frequency drive.

INTRODUCTION

In the modern power system, the use of power electronic devices is increasing day by day which are non-linear loads that create power quality issues. There have been growing interests in identifying the causes of abnormal harmonics and resonances in the power electronic based power systems.[2].The integration of the power electronic converters into the electric power system has been increased over the last decades because of the extensive usage in different industrial and commercial applications such as renewable energy sources, electric railway systems, variable-speed drivers[3].Various types of disturbances can occur, and among them one of the most important is harmonic distortion; voltage and current waveforms are distorted and consist of different harmonic orders[4].All power electronic devices are the main cause of non-linear loads, which cause many power quality problems in electrical power systems. Non-liner loads produce non - sinusoidal waveform that results in a distorted current waveform and distorted voltage waveform and also draws a large amount of reactive power (VARs). The harmonic pollution has severely degraded the power quality and caused serious dam- ages to facilities working in power system [5]. The electric power systems are operated on frequencies of 50 or 60Hz. Different types of loads produce currents and voltages waveforms with frequencies that are integer multiples of the fundamental frequency (50 or 60 Hz) which produce electrical pollution known as power system harmonics.

HARMONIC SOURCES- Various kind of harmonic sources that are discussed below-

HARMONIC SOURCES: The main source of the harmonics is any non-linear loads that produce the voltage harmonics and current harmonics. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sine wave. So, non-linear device is one in which the current is not proportional to the applied voltage.

2.1 Transformers

A transformer may experience core saturation conditions in one of the following circumstances: Running above rated power can occur during periods of high demand, and working above rated voltage can occur when there is little or no load. This is particularly true when utilities capacitor banks are improperly unplugged, causing the feeder voltage to exceed acceptable levels. Figure depicts the distortion of current when a transformer is saturated. From the illustration, it is obvious that a transformer operating in the saturation region will display a non - linear magnetising current with the third dominant as well as a number of odd harmonics. The impact will become more pronounced as the loading rises [6]. There are no hysteresis losses in a perfect lossless core. But the magnetic flux and the current necessary to generate it, along with the outcomes of a magnetising current of the metal sheet material utilise in the core construction, are linked. If we plot the magnetising current vs. time for every flux value taken into account, even in this scenario the resulting current waveform would not be sinusoidal. Pure sine wave magnetising current is indeed not symmetrical with respect to its maximum value because of the hysteresis effect. The distortion is typically caused by harmonics (odd multiples of three, such as the third, ninth, sixteenth, etc.), although the third harmonic is primarily to blame.

2.2 Rotating Machines

Rotor slots, slight changes in the 3 winding of the a rotating machine, or tiny asymmetry on the machine can all lead to harmonic currents. These harmonics result in an electromotive force (emf) at a frequency matching to the speed/wavelength ratio experienced by the stator windings. Rotating machines are employed in a variety of essential infrastructure and serve as the cornerstone of numerous industries [7]. This section on the behaviour of asymmetrical huge rotating devices [8] has many instances of practical importance, such as the dynamic of rotors with shape faults.The device's magneto motive forces generate harmonics, which depend on speed and are spread as a result. Higher harmonic current can be produced whenever the magnet core is saturated.

2.3 Power Converters

Electronic switching aids in the conversion of 50/60 Hz AC electricity into DC power. For DC applications, the operating range of the electrical switching device is adjusted to change the voltage. Power converters are now the most frequent cause of harmonics in distribution networks due to the increasing use of parameters such voltage and frequency that are changed to adapt to certain industrial and commercial activities. Power converters are frequently thought of as energy-saving technology. In the rectification process, semiconductor devices are only exposed to current for a small portion of the switching frequency cycle. The converter's output must pass via an electrical switching inverter if the energy is to be utilise as AC at a different frequency. The following categories can be used to classify converters:

- Large Power Converters
- Medium-Size Power Converters
- Low-Power Converters
- Variable Frequency Drives

NON-LINEAR LOAD

When the impedance varies, a non-linear load is created; as a result, the current is indeed not proportional to or equal to the voltage. Non-linear loads draw current that is periodic rather than sinusoidal, therefore the current wave is consistent from cycle to cycle and resembles odd harmonics (i.e 3rd, 5th, 7th, 9th, etc.) Power distribution networks now have higher harmonic levels as a result of non-linear loads (NLLs). [9] They require up to three times as much peak value as a load resistance since they have low impedance. [10] Electronic switch power supply and inductive furnace/arc furnace drives are examples of common nonlinear loads.

3.1VARIABLE FREQUENCY DRIVE

Total harmonic distortion (THD) is the ratio of the signal's distorted power to its fundamental power. Disrupted voltage is also referred to as distorted current harmonics and distorted current as voltage harmonics. The phrase is most frequently used to describe how much a digital signal has been distorted.

As more PV systems are integrated into grid systems, THD has grown to be a significant issue [16]. When performing multilevel voltage waveform analysis in time series, THD is a possibility [17]. Technique used to reduce voltages total harmonic distortion (THD) - the harmonics that are not as readily covered up by the fundamental (desired signal) when they emerge at a great distance in frequency from it. For contrast, crossover distortion is substantially more noticeable at a given THD.

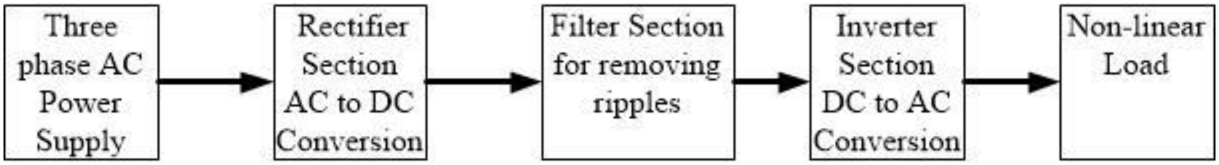
$$N_s = 120f / p$$

Any **Variable Frequency Drive** or VFD incorporates following three stages for controlling a *three phase induction motor.*

a) Rectifier stage: A full-wave, solid-state rectifier converts three-phase 60 Hz power from a standard or higher utility supply to either fixed or adjustable DC voltage.

b) Inverter stage: Electronic switches power transistors or thyristors - switch the rectified DC on and off, and produce a current or voltage waveform at the desired new frequency. The amount of distortion depends on the design of the inverter and filter.

c) Control system: Its function is to control output voltage i.e. voltage vector of inverter being fed to motor and maintain a constant ratio of voltage to frequency (V/Hz).



3.2TOTAL HARMONIC DISTORTION

Total harmonic distortion (THD) is the ratio of the signal's distorted power to its fundamental power. Distorted voltage is also referred to as distorted current harmonics and distorted current as voltage harmonics. The phrase is most frequently used to describe how much a digital signal has been distorted.

As more PV systems are integrated into grid systems, THD has grown to be a significant issue [16]. When performing multilayer voltage waveform analysis in time domain, THD is a possibility [17]. Technique used to reduce voltage total harmonic distortion (THD) - the harmonics that are not as readily covered up by the fundamental (desired signal) when they emerge at a great distance in frequency from it. For instance, crossover distortion is substantially more noticeable at a given THD.

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}$$

Where, n = nth order harmonic components of current waveform.

V_1= Root Mean Square (RMS) value of fundamental voltage

V_n = nth order harmonic components of voltage respectively

4.1TECHNIQUE OF HARMONIC USING SINGLE TUNED FILTER

Harmonics can be reduced using passive filters, a standard technique that is well understood. The majority of passive filters require special design due to the unique system impedances, load current harmonics, background voltage distortion, interactions with nearby sources and loads, and background voltage distortion.

An RLC filter, which often has a low harmonic impedance characteristic, is a series RLC circuit set to a single harmonic frequency. Its total impedance, which is the total of the electrical conditions modulated by each harmonic oscillator, is determined by that impedance.

$$Z_n = R_n + j(\omega L_n - 1/\omega C_n)$$

At a resonance frequency

$$1/\omega L\, C_n\, n = \omega$$

$$Z_n = R$$

The frequency at which an ideal single-tuned filter is tuned is said to make both its inductive and capacitive reactance equal[19]. This filter is shunt-connected to the distribution system and provides low current impedance, which encourages harmonic current to flow in a different direction across the system [20]

4.1.1Harmonic Analysis 6 Bus System

Table 1 Bus input data for 6 bus system

Bus ID	KV	MVA	Mvar	VTHD	VIHD
1	4.160	0.00	0.00	2.50	1.50
2	4.160	13.00	0.00	2.50	1.50
3	4.160	13.00	5.00	2.50	1.50
4	4.160	0.357	0.152	2.50	1.50
5	4.160	0.357	0.152	2.50	1.50
6	4.160	0.357	0.152	2.50	1.50

IEEE 6 Bus system consists of five transformers T1-T5 for which transformer primary and secondary voltage ratings are given in Table 1

Table 2 Transformer input data for 6-bus system

Transformer ID	MVA	Primary KV	Secondary KV
T1	2.00	4.160	4.160
T2	2.00	4.160	4.160
T3	2.00	4.160	4.160
T4	2.00	4.160	4.160
T5	2.00	4.160	4.160

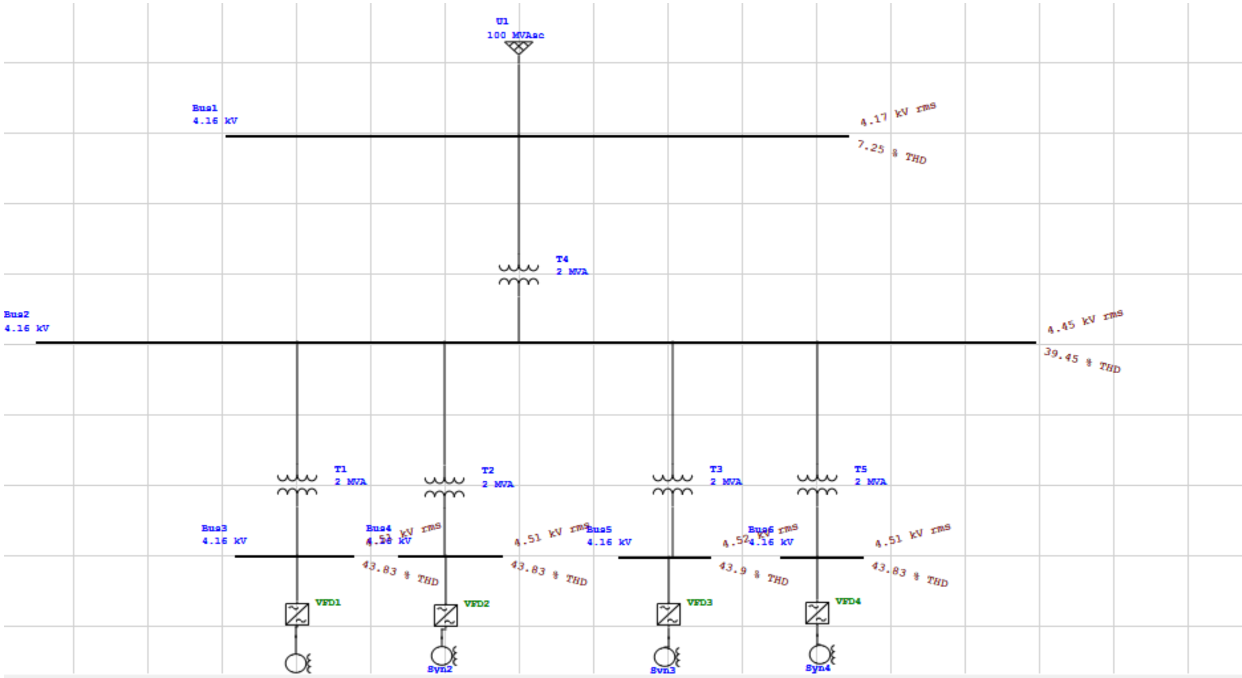
Machine input data consists of power grid, synchronous machine data, and bus id is shown below

Table 3 Machine input data for 6 bus system

Machine ID	Bus ID	MVA	KV	RPM
U1	Bus 1	100	4.160	0.00
Motor 1	Bus 3	0.388	4.160	1000
Motor 2	Bus 4	0.388	4.160	1500
Motor 3	Bus 5	0.388	4.160	1500
Motor 4	Bus 6	0.388	4.160	1500

4.1.2Simulation and harmonic analysis without VFDs for 6 bus system of 6,12 and 18 pulse system

Simulation Diagram for IEEE 6 Bus System with VFDs is shown in fig that is consists of 6 buses, transformers and synchronous machines.



Simulation diagram with VFDs for 6 bus system of 6 pulse system

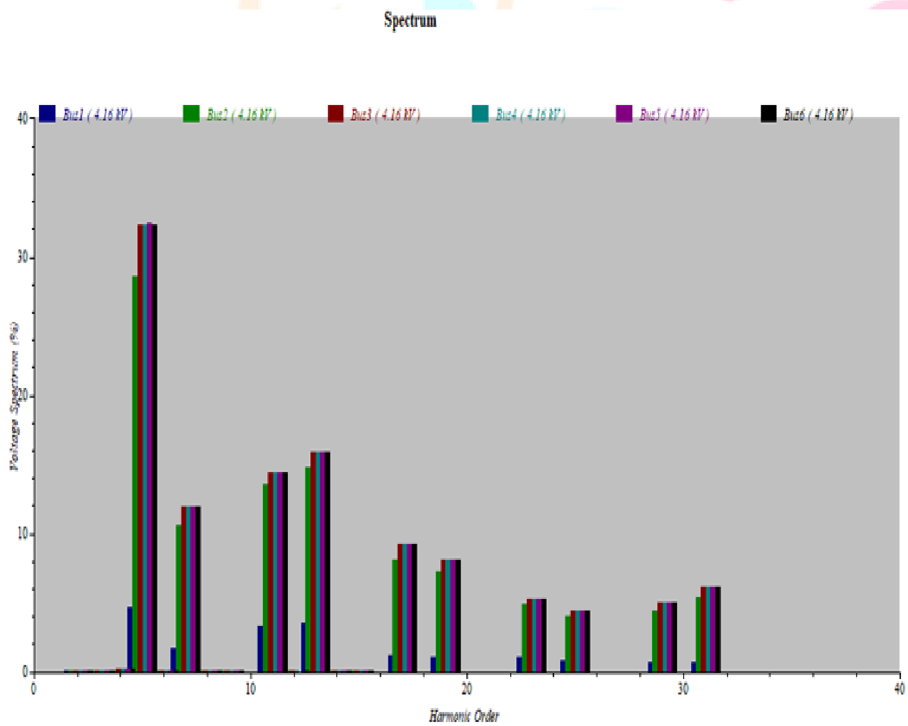
Harmonic analysis performed on the under consideration entire power system with voltage waveform and its harmonic spectrum captured at all the buses are shown in figure 1.4 & 1.3 respectively. Variable frequency drives are produced more harmonic distortion. Such as, harmonic distortion are 7.25%,39.45%,43.83%,43.83%,43.83%,43.83%,at bus 1,2,3,4,5 and bus 6 in pulse system respectively. Whereas, these devices are produced higher order harmonics like as,5,7.11,13,17,19,23,25,29, and 31 respectively. In 12 pulse system harmonic distortion such as 6.71%,28.86%,30.95% etc. whereas these devices are produced higher order harmonics like as 5,7,11,25,29and 29 respectively. In 18 pulse system harmonic distortion are 1.65%,7.79%,8.46% etc. whereas these devices are produced THD like 5,7.11,13,1719,23,25,and 31 respectively

Table 4 THD and Harmonic Order of 6 bus system with VFD of 6,12 and 18 pulse system

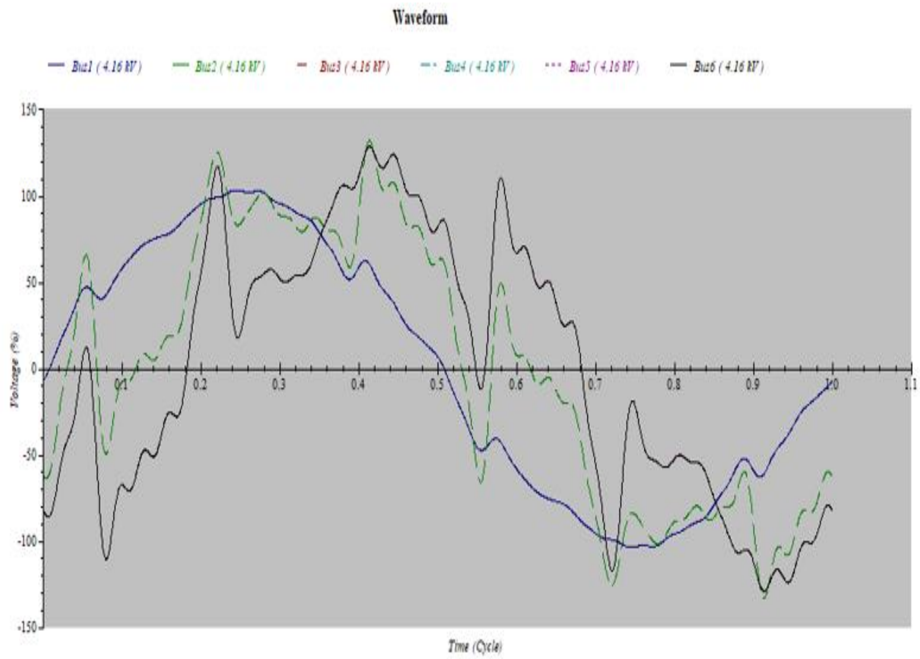
Bus No.	**Harmonic analysis**			
	Percentage & Harmonic order	**6 Pulse VFDs**	**12 Pulse VFDs**	**18 Pulse VFDs**
1	**THD%**	7.25%	6.71%	1.65%
	Harmonic order	5,7,11,13	11,13,25	
2	**THD%**	39.45%	28.86%	7.79%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5,7,11,13,17, 19,23,25	5,7,11,13,19 ,23,25
3	**THD%**	43.83%	30.95%	8.46%
	Harmonic order	5,7,11,13,17, 19,23,25,29,31	5,7,11,13,17,19, 23,25,31	5,7,11,13,17,19, 23,25,31

4	**THD%**	43.83%	30.95%	8.46%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5,7,11,13,17,19, 23,25,31	5,7,11,13,17,19 ,23,25,31
5	**THD%**	43.83%	30.95%	8.46%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5,7,11,13,17,19, 23,25,31	5,7,11,13,17,19, 23,25,31
6	**THD%**	43.83%	30.95%	8.46%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5,7,11,13,17,19, 23,25,31	5,7,11,13,17,19, 23,25,31

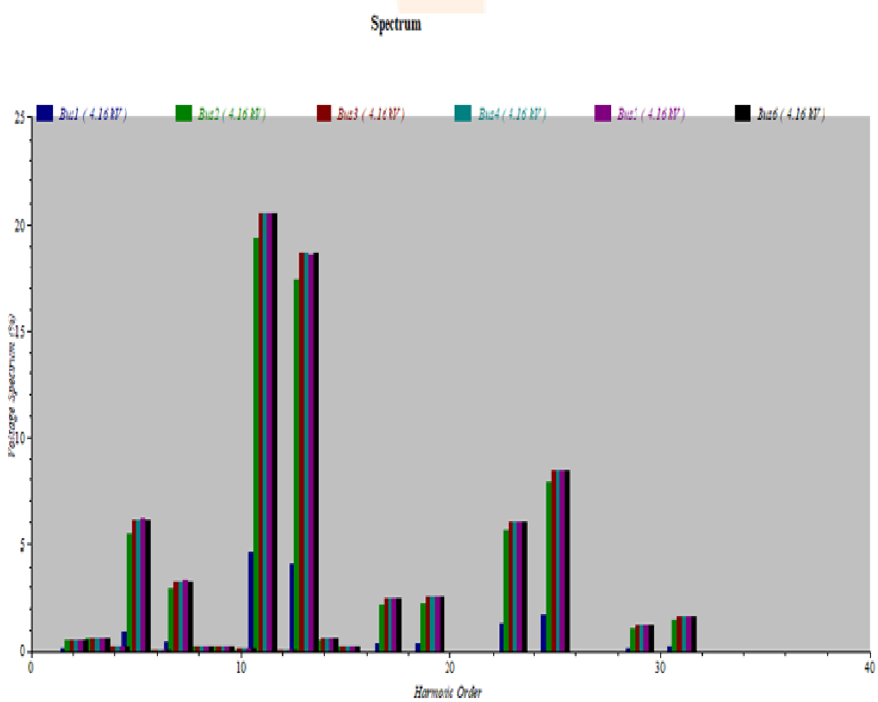
Voltage spectrum with 6 pulse VFD for 6 bus system of 6 pulse system



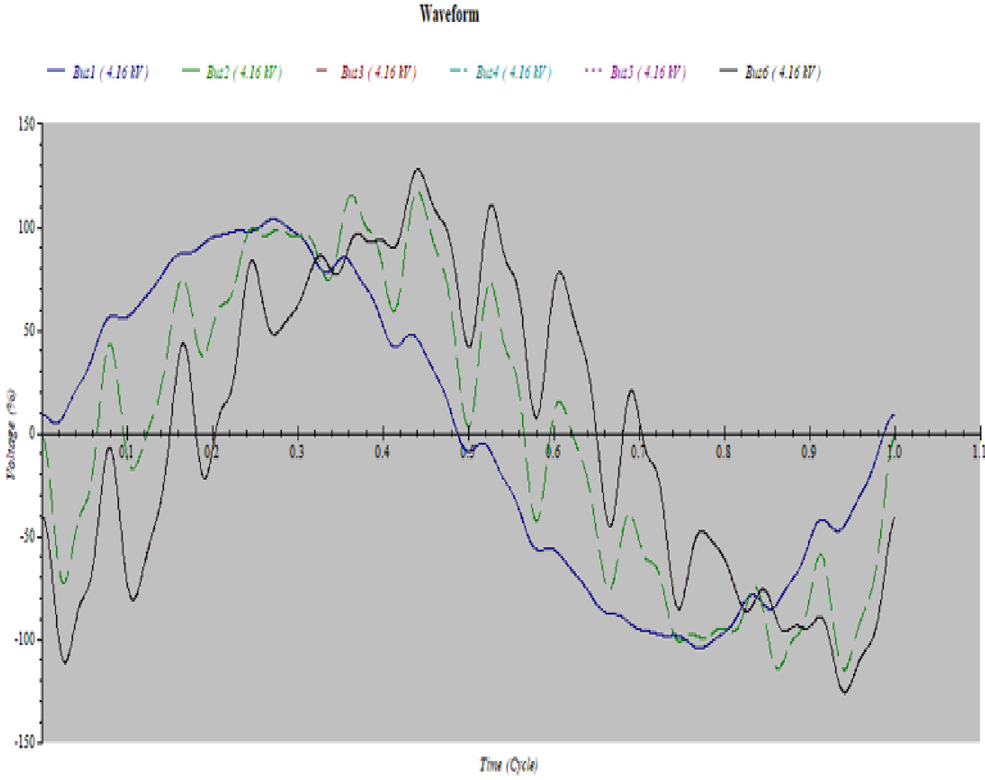
voltage spectrum with 6 pulse VFD for 6 bus system



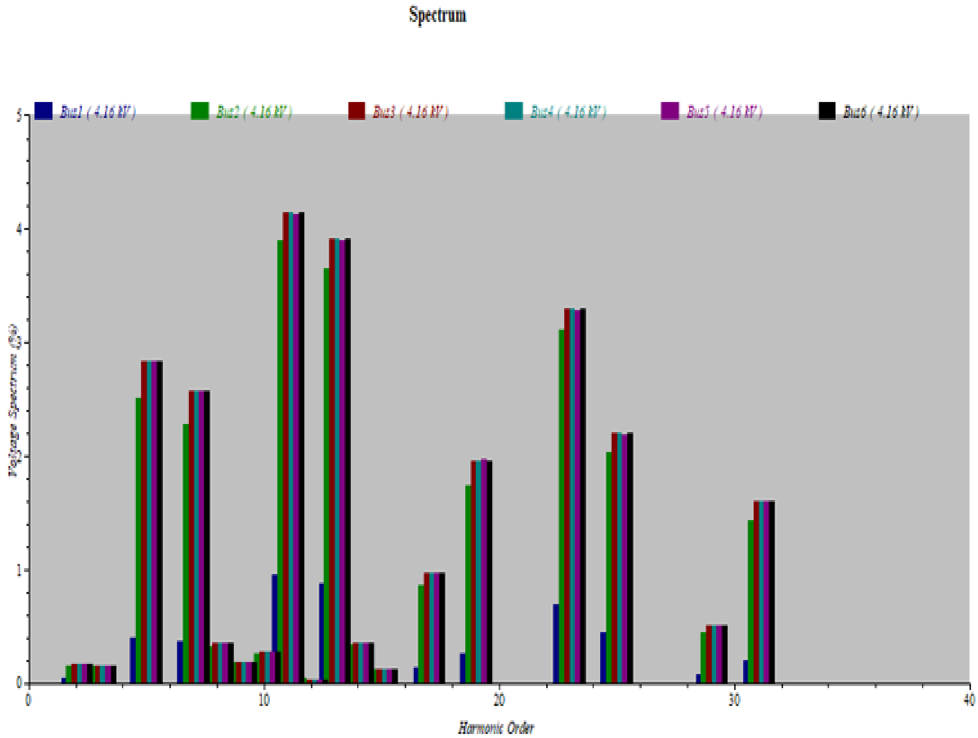
voltage waveform with 6 pulse VFD for 6 bus system



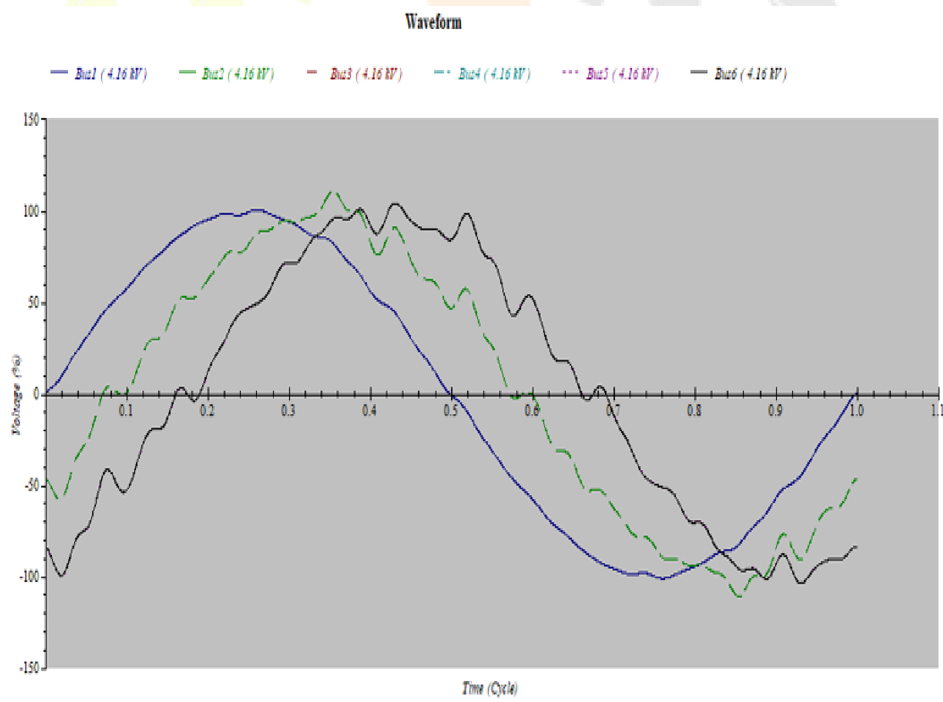
voltage spectrum with 12 pulse VFD for 6 bus system



voltage waveform with 12 pulse VFD for 6 bus system

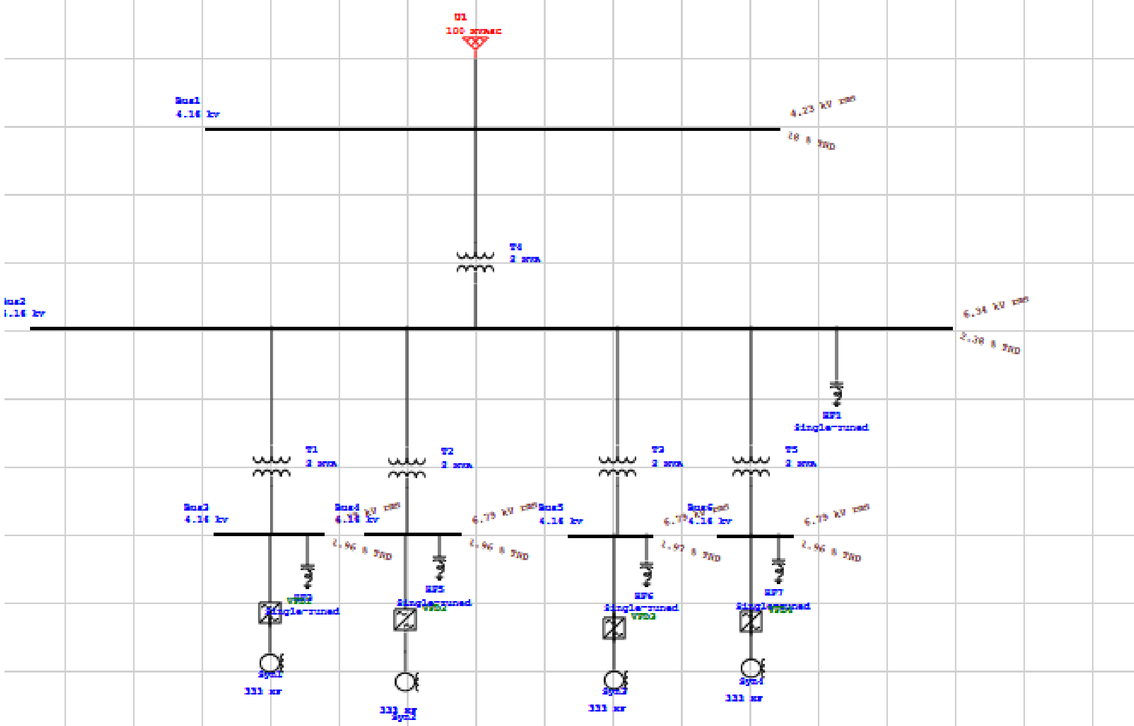


voltage spectrum with 18 pulse VFD for 6 bus system

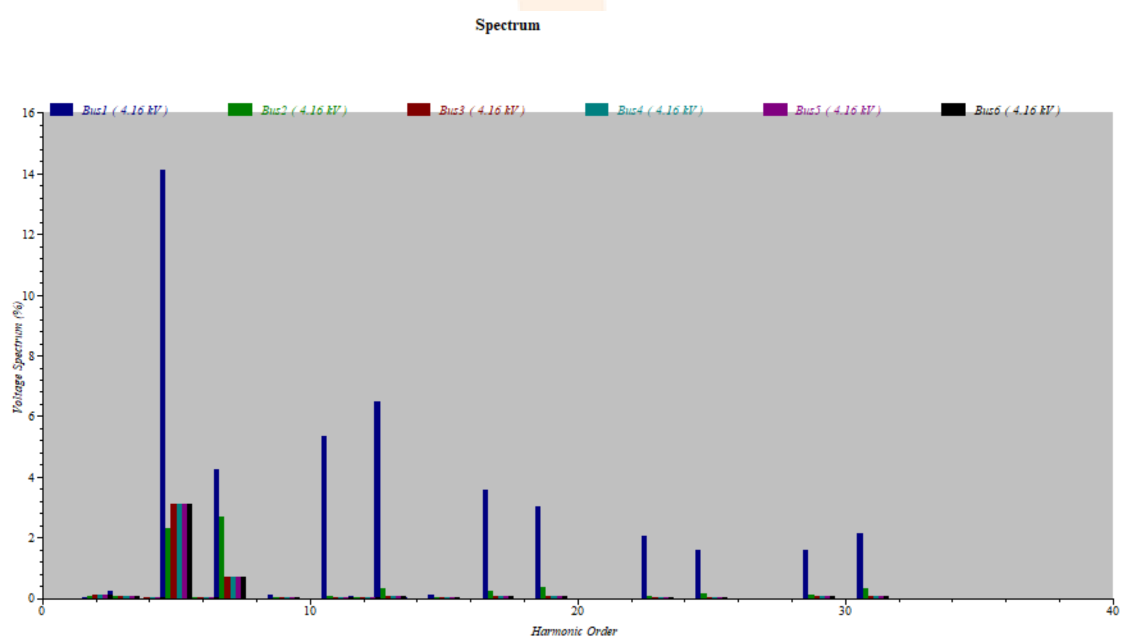


voltage waveform with 18 pulse VFD for 6 bus system

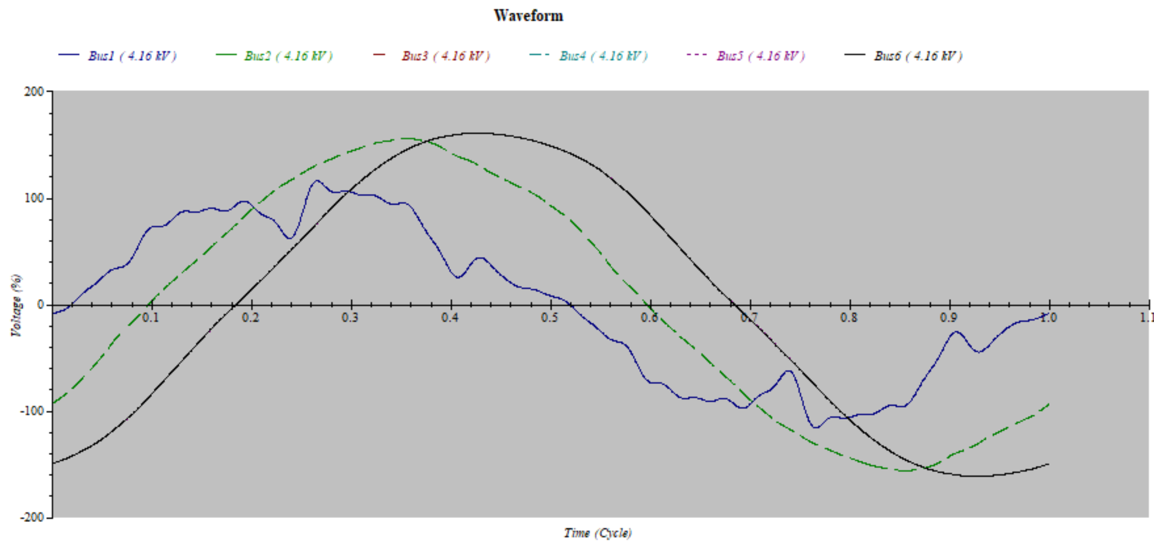
Table 5 Simulation and harmonic analysis with VFDs for 6 bus system with filter



Simulation diagram of 6 pulse with vfd for 6 bus system with filter



Spectrum diagram of 6 pulse with vfd for 6 bus system with filter



WAVEFORM DIAGRAM OF 6 PULSE WITH VFD FOR 6 BUS SYSTEM WITH FILTER

Table 6 Comparison of 6 Pulse system of 6 bus system with and without filter

Bus No.	**Harmonic analysis**		
	Percentage & Harmonic order	**6 Pulse VFDs without filter**	**6 pulse VFD with 11th order filter**
1	**THD%**	7.25%	18%
	Harmonic order	5,7,11,13	5,7,11,13, 17,19,23,25,29,31
2	**THD%**	39.45%	2.38%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5,7
3	**THD%**	43.83%	1.96%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5
4	**THD%**	43.83%	1.96%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5
5	**THD%**	43.83%	1.96%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5
6	**THD%**	43.83%	1.96%
	Harmonic order	5,7,11,13,17,19, 23,25,29,31	5

From the table 6 observed that the total harmonic distortion as well as higher harmonic order such as 7,11th, 17th 19th, 23rd ,25th ,29th ,31st harmonic order has been reduced without variable frequency drives.

Table 7 Comparison of 12 Pulse system of 6 bus system with and without filter

Bus No.	Harmonic analysis		
	Percentage & Harmonic order	**12 Pulse VFDs without filter**	**12 pulse VFD with 11th order filter**
1	**THD%**	6.71%	12.12%
	Harmonic order	11,13,25	
2	**THD%**	28.86%	0.86%
	Harmonic order	5,7,11,13,17,19, 23,25	
3	**THD%**	30.95%	0.66%
	Harmonic order	5,7,11,13,17,19, 23,25,31	
4	**THD%**	30.95%	0.66%
	Harmonic order	5,7,11,13,17,19, 23,25,31	
5	**THD%**	30.95%	0.66%
	Harmonic order	5,7,11,13,17,19, 23,25,31	
6	**THD%**	30.95%	0.66%
	Harmonic order	5,7,11,13,17,19, 23,25,31	

From the table 7 observed that the total harmonic distortion as well as higher harmonic order such as 5th ,7th ,11th, 17th 19th, 23rd ,25th ,29th ,31st harmonic order has been reduced without variable frequency drives.

Table 8 Comparison of 18 Pulse system of 6 bus system with and without filter

Bus No.	Harmonic analysis		
	Percentage & Harmonic order	**18 Pulse VFDs without filter**	**18 pulse VFD with 11th order filter**
1	**THD%**	1.65%	3.35%
	Harmonic order		
2	**THD%**	7.79%	0.46%
	Harmonic order	5,7,11,13,19,23, 25	
3	**THD%**	8.46%	0.26%

	Harmonic order	5,7,11,13,17,19, 23,25,31	
4	**THD%**	8.46%	0.26%
	Harmonic order	5,7,11,13,17,19, 23,25,31	
5	**THD%**	8.46%	0.26%
	Harmonic order	5,7,11,13,17,19, 23,25,31	
6	**THD%**	8.46%	0.26%
	Harmonic order	5,7,11,13,17,19, 23,25,31	

From the table 8 observed that the total harmonic distortion as well as higher harmonic order such as 5th ,7th ,11th,13th, 17th, 19th, 23rd ,25th ,29th ,31st harmonic order has been reduced without variable frequency drives.

Table 9 Comparison of 6 Pulse system of 9 bus system with and without filter

Bus No.	**Harmonic analysis**		
	Percentage & Harmonic order	**6 Pulse VFDs without filter**	**6 pulse VFD with 11th order filter**
Bus 1	**THD%**	5.77%	4.5%
	Harmonic order	5,7,11,13,17,19	5,7,11,13
Bus 2	**THD%**	39.35%	15.11%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5
Bus 3	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7
Bus 4	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7
Bus 5	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7
Bus 6	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7
Bus 7	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7
Bus 8	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7
Bus 9	**THD%**	53.71%	10.99%
	Harmonic order	5,7,11,13,17,19 ,23,25,29,31	5,7

From the table 9 observed that the total harmonic distortion as well as higher harmonic order such as 5th ,7th ,11th,13th, 17th, 19th, 23rd ,25th ,29th ,31st harmonic order has been reduced without variable frequency drives.

Table 10 Comparison of 12 Pulse system of 9 bus system with and without filter

Bus No.	Harmonic analysis		
	Percentage & Harmonic order	12 Pulse VFDs without filter	12 pulse VFD with 11th order filter
Bus 1	THD%	4.49%	3.67%
	Harmonic order	11,13	11,13
Bus 2	THD%	27.59%	3.33%
	Harmonic order	5,11,13,17,19,23,25,31	5
Bus 3	THD%	37.43%	3.29%
	Harmonic order	5,11,13,17,19,23,25,29,31	2,5
Bus 4	THD%	37.43%	3.29%
	Harmonic order	3,5,11,13,17,19,23,25,29,31	2,5
Bus 5	THD%	37.43%	3.29%
	Harmonic order	3,5,11,13,17,19,23,25,29,31	2,5
Bus 6	THD%	37.43%	3.29%
	Harmonic order	3,5,11,13,17,19,23,25,29,31	2,5
Bus 7	THD%	37.43%	3.29%
	Harmonic order	3,5,11,13,17,19,23,25,29,31	2,5
Bus 8	THD%	37.43%	3.29%
	Harmonic order	3,5,11,13,17,19,23,25,29,31	2,5
Bus 9	THD%	37.43%	3.29%
	Harmonic order	3,5,11,13,17,19,23,25,29,31	2,5

From the table 10 observed that the total harmonic distortion as well as higher harmonic order such as 3th, 5th ,11th,13th, 17th, 19th, 23rd ,25th ,29th ,31st harmonic order has been reduced without variable frequency drives.

Table 12 Comparison of 18 Pulse system of 9 bus system with and without filter

Bus No.	Harmonic analysis		
	Percentage & Harmonic order	18 Pulse VFDs without filter	6 pulse VFD with 11th Order filter
Bus 1	THD%	1.19%	0.953%
	Harmonic order		
Bus 2	THD%	7.59%	1.46%
	Harmonic order	5,11,19,23,25,31	
Bus 3	THD%	10.27%	1.39%
	Harmonic order	5,11,13,17,19,23,25,29,31	

Bus 4	**THD%**	10.27%	1.39%
	Harmonic order	5,11,13,17,19, 23,25,31	
Bus 5	**THD%**	10.27%	1.39%
	Harmonic order	5,11,13,17,19, 23,25,31	
Bus 6	**THD%**	10.27%	1.39%
	Harmonic order	5,11,13,17,19, 23,25,31	
Bus 7	**THD%**	10.27%	1.39%
	Harmonic order	5,11,13,17,19, 23,25,31	
Bus 8	**THD%**	10.27%	1.39%
	Harmonic order	5,11,13,17,19, 23,25,31	
Bus 9	**THD%**	10.27%	1.39%
	Harmonic order	5,11,13,17,19, 23,25,31	

From the table 12 observed that the total harmonic distortion as well as higher harmonic order such as 5th ,11^{th},13^{th}, 17^{th}, 19^{th}, 23^{rd} ,25^{th} ,31^{st} harmonic order has been reduced without variable frequency drives.

CONCLUSION

In this research paper, Harmonic Analysis has been analyzed at both the IEEE 6 and 9 bus systems by using ETAP software. Total harmonic distortion and harmonic order has analyzed with or without filter. The total harmonic distortion and harmonic order are calculated before the single tuned filter and after the 11^{th} harmonic order filter installed. In this research paper. Total harmonic distortion and harmonic order has been highly reduced in case of 18 Pulse as compared to 6 and 12 Pulse system with and without filter.

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