Harmonics & Energy Saving Analysis of VFDs used for HVAC System: A Case Study in Oman

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Abstract

In this paper the methodology for harmonic and energy saving analysis for a laboratory building at the university campus in Oman have been proposed. The harmonics generated by the two variable frequency drives used for heating, ventilating and air conditioning of the building was modelled and simulated using SOLV and ETAP simulation software. The current and voltage distortion levels were measured under different loading scenarios. It is observed that lower order odd harmonics are dominating and can be mitigated using advanced universal harmonic filter to compliance the IEEE519 standard. The simulated results have revealed that about 10% of total energy consumed by induction motors can be saved by using VFDs along with extenuating all prevailing harmonics of the HVAC system.

Keywords Energy Saving, HVAC System, Harmonic Analysis, Harmonic Filters and VFDs

1. INTRODUCTION

Oman is one of middle-east country spread over 309500 square kilometres at Arabian Peninsula. Its climate is hot and dry while costal are hot and humid. To combat with long summer observed in Oman (about 9 months), Heating, and Ventilating and Air Conditioning (HVAC) system is extensively used across the country. The HVAC system alone is consuming about 52% of the total energy consumed by the residential sector [1]. It is also the major source of electricity consumption at the academic organizations and commercial sector. To increase the energy savings, HVAC unit are using the static converter based Variable Frequency Drives (VFDs). These drives act as non-linear loads to supply system.

The VFDs are equipped with solid state converters which control the operation of HVAC system. The VFDs are adjusting the speed of chilled water pump to meet the required comfort cooling. The static converters are consisting of power semiconductor devices which are source of harmonics [2]. The harmonic distortion is measure of the amount of deviation of voltage and current from their pure sinusoidal waveforms, caused by solid state converters in VFDs. The harmonic distortion is eventually polluting the quality of electrical power that adversely affects the power distribution system and connected equipment, if it exceeds certain limits [3]. Therefore, it essential to measure, analysed and limit harmonics in electrical system. There are various national and international standards governing the limits of total harmonic distortion (TDH) like IEEE 519, IEC 61000, EN 50160 and NRS 048-02 [4,5] etc. The recommended practices and harmonic limits prescribed by IEEE519-2014 and IEC 61000-3-4 are widely used by the commercial simulation programs to calculate and analysed the harmonic current, voltage and Total Demand Distortion (TDD). The commercial HVAC market in USA, Canada and other North American counties has adopted the IEEE519 standard.

The most common rectifier circuit in 3-phase VFD is 6-pulse diode rectifiers. It is robust, cost effective and extensively used in HVAC system to reduce its capital cost [6]. The shortcoming of 6-pulse rectifier is, it contains low order odd harmonics. There are various practices available to mitigate the harmonics problem in various applications [7, 8]. Also, VFDs analysis using machine learning tools seems to be more fruitful for extended operation in a complex industrial environment for high computational dependency [9-10]. For instance, based on the configuration of the input rectifier bridge, a 3-phase VFDs can use higher pulse techniques. Other than that, various types of passive filters can be used to alleviate the harmonics [11, 12]. The latter option is expensive and increases the installation cost of HVAC system.

At academic organization several nonlinear loads are connected to the supply system and many scholars had conducted the harmonic studies [13, 14]. In this paper, a case study to analyse the harmonics and energy savings of VFDs based HVAC system at university laboratory building have been proposed. Three scenarios are taken into consideration to simulate each situation. Simulations are carried using SOLV and Electrical Transient Analyser Program (ETAP) software and results are compared to compliance with IEEE519 standard.

The paper has organised in 6 sections. The section 1 describes the introductory part while data collected for the case study is presented in section 2. The simulations carried out by simulator program under three scenarios are described in section 3. The results and conclusions are presented in section 4 &5 respectively. The references are listed in section 6.

2. HVAC AND POWER DISTRIBUTION SYSTEM

This study has carried out to analyse the harmonic analysis of the VFDs used for the HVAC system. This is providing the comfort cooling to engineering laboratories building at university campus. A segment of the schematic diagram of HVAC system where VFDs are driving to Chilled Water Pump (CWP) associated with Air Handling Unit (AHU) is shown in figure 2.1.

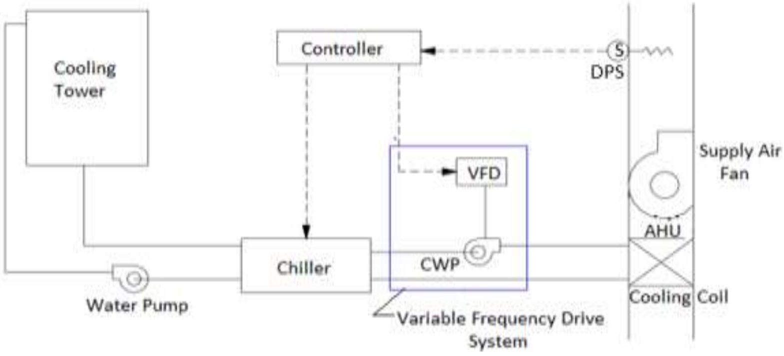

Figure 2.1.Schematic diagram of a segment of HVAC system and location of CWP [15]

Three induction motors, each 15 kW ratings are installed out of them two motors are operating the pumps to circulate the chilled water according to desired cooling. One motor is kept spare to meet any emergency. The discharge of the CWP is controlled by VFD system through Differential Pressure Sensors (DPS) connected to valves. A single line diagram of the electrical power distribution is shown in figure 2.2

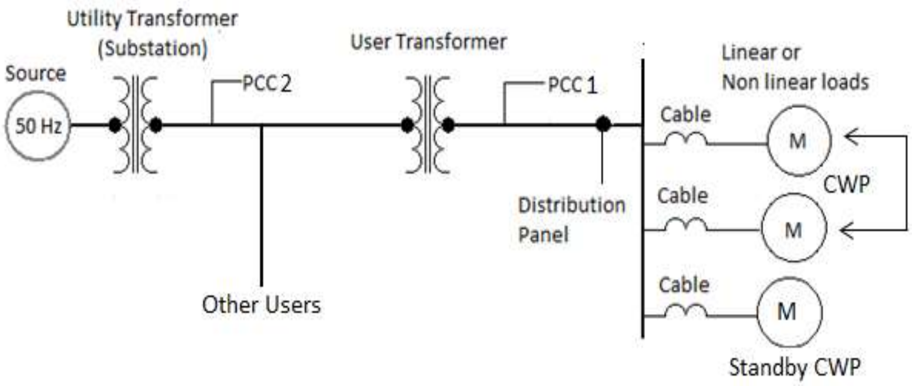

Figure 2.2.Single line diagram showing power distribution system

Point of Common Coupling (PCC) is the important location where power quality parameters are measured for harmonic analysis. As per IEEE 519 standard, it is preferred to be in the secondary side of utility and user's transformer. The specifications of other major components of distribution system are given below in table 2.1.

Table 2.1: Major components and their specifications

Components	Specifications
Utility Transformer	33/11 kV, 15 MVA, 50 Hz, %Z 5.5
User Transformer	11/0.440 kV, 1 MVA, 50 Hz, %Z 5.0
VFD: Induction Motors	3-phase, 0.440 kV, 15 kW, 50 Hz
Operating Information of HVAC System	Tariff: US$0.06 per kWh, Operating hour/day: 9 hrs, Operating days per year: 221 days

3. SIMULATION OF VFDS

Computer simulation program is used to simulate the existing VFDs. The simulator uses nodal analysis by expressing nodal matrix and evaluating the set of differential equations. The backward Euler and Fourier series are the major mathematical tools used by computer to analyse the periodic waveform like sinusoidal wave of integer multiple of 50 Hz frequency. The nonlinear loads are substituted by equivalent linear circuit models to get converge to final solution. To analyse the VFDs application following three scenarios are taken into consideration.

3.1. Scenario 1: CWP operated by 6-pulse VFDs

In this scenario, two induction motors of 20 hp each are coupled to chilled water pumps are operating. The speed of the motor is controlled by VFD which is using 6-pulse rectifier circuit to convert AC in to DC and Pulse Width Modulation (PWM) technique to convert DC into AC at desire voltage and frequency. The single line diagram of this scenario is shown in figure 3.1

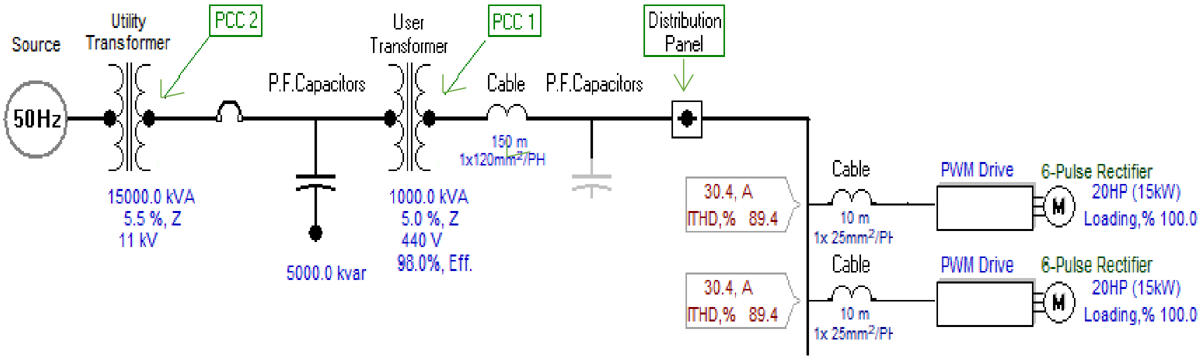

Figure 3.1.Single line configuration for simulating scenario-1

3.2. Scenario 2: CWP operated by 12-pulse VFDs

In this scenario, the speed of the chilled water pump is controlled by VFD. The 12-pulse rectifier circuit and inverter is supplied through a phase shifting transformer. To prevent the harmonics flow into upstream line, 2% reactor impedance at AC input reactor and 3% reactor impedance at DC link reactor are considered to simulate the scenario. The voltage to frequency ratio in all scenarios is kept constant to maintain the rated torque of the motor. The single line diagram of this scenario is shown in figure 3.2

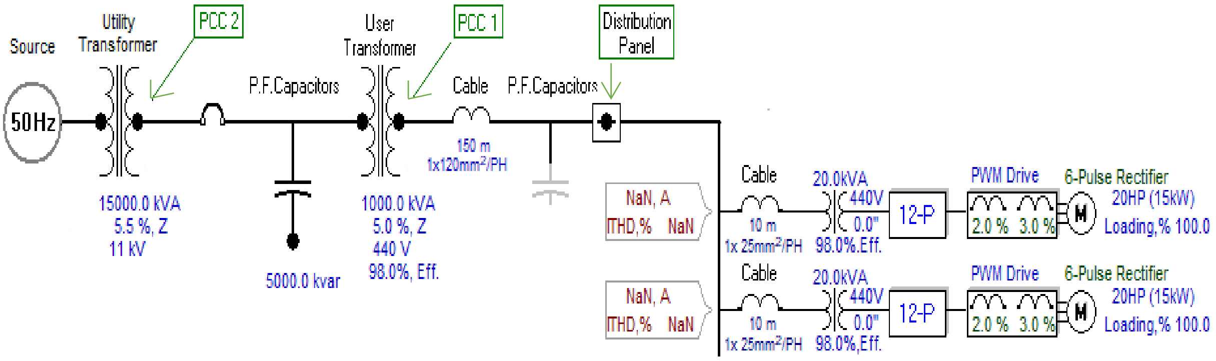

Figure 3.2.Single line configuration for simulating scenario 2

3.3. Scenario 3: CWP operated by VFDs along with Passive Filter

This topology is similar to scenario1. To reduce the impact of harmonics, the passive harmonic filters like Advanced Universal Harmonic Filter (AUHF) are considered to simulate the scenario. The single line diagram of this scenario is shown in figure 3.3

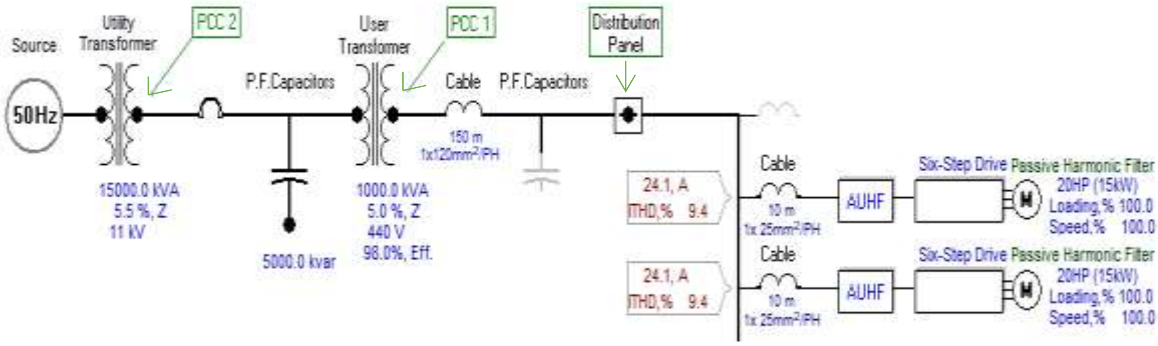

Figure 3.3.Single line configuration for simulating scenario 3

4. RESULTS

4.1 Voltage and Current Harmonics

It can be depicted from the figure 4.1 that, the VFDs consist of 6-pulse bridge rectifier along with PWM inverter generate the highest total harmonic distortion at PCC1. The waveform distortion reduces by using a 12-pulse bridge rectifier. More effectively the current wave and becomes near to sinusoidal in 3rd scenario which is using advanced universal harmonic filter.

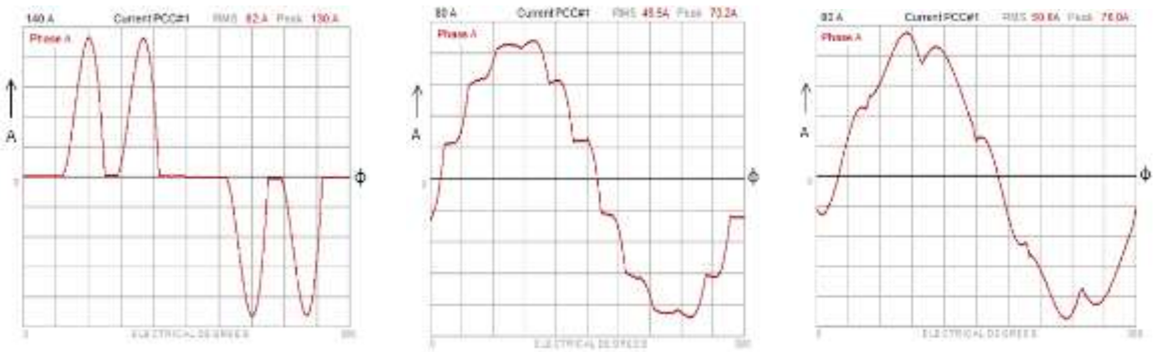

Figure 4.1.Total harmonic current waveforms of scenarios1, 2 &3 respectively

It can be seen from table 4.1, the total harmonic distortion and maximum individual harmonics of voltage in all scenarios have not exceeded the level of 1.1 and 0.7 % respectively. This is well below the recommended values of IEEE519-2014 standard.

Table 4.1: Total harmonic distortion of voltage at PCC1 under different scenarios

Total Harmonic Distortion under Different scenarios	Calculated Value%{h}	IEEE-519:2014 Limits	Remarks
Scenario 1			
Voltage Total Harmonic Distortion (THD_v)	1.1	8.0	Pass
Max Individual Voltage Harmonic	0.7{5th}	5.0	Pass
Scenario 2			
Voltage Total Harmonic Distortion (THD_v)	0.2	8.0	Pass
Max Individual Voltage Harmonic	0.2{11th}	5.0	Pass
Scenario 3			
Voltage Total Harmonic Distortion (THD_v)	0.2{7th}	8.0	Pass
Max Individual Voltage Harmonic	0.1	5.0	Pass

The current harmonics are more concern for any distribution system and are shown in table 4.2. It can be observed from table 4.2, the total harmonic distortion and low order harmonics except 17th are higher than the prescribed limits of international standard. Therefore, it is vital to mitigate harmonics to avoid their adverse effects on distribution system and connected devices. In scenario 2, a 12-pulse converter has used to operate the

VFD which is able to mitigate most of current harmonics except 11th order. To optimally mitigate all low order current harmonic, scenario 3 is more effective where an advanced universal passive harmonic filter has used to keep the total distortion less than IEEE519-2014 limit.

Table 4.2: Total harmonic distortion of current at PCC1 under different scenarios

Total Harmonic Distortion under Different scenarios	**Calculated Value%{h}**	**IEEE-519:2014 Limits**	**Remarks**
Scenario 1			
Current Total Demand Distortion (THD_i)	86.8	12.0	*Fail*
Max Individual Current Harmonic<11	70{5th}	10.0	*Fail*
11 to 16	12.6{11th}	4.5	*Fail*
17 to 22	0.1{17th}	4.0	Pass
23 to 34	3{23rd}	1.5	*Fail*
>35	1.1{35th}	0.7	*Fail*
Scenario 2			
Current Total Demand Distortion (THD_i)	9.1	12.0	Pass
Max Individual Current Harmonic<11	2.2{5th}	10.0	Pass
11 to 16	7.1{11th}	4.5	*Fail*
17 to 22	0.0{17th}	4.0	Pass
23 to 34	1.1{23rd}	1.5	Pass
>35	0.5{35th}	0.7	Pass
Scenario 3			
Current Total Demand Distortion (THD_i)	8.9	12.0	Pass
Max Individual Current Harmonic<11	8.1{7th}	10.0	Pass
11 to 16	2.5{11th}	4.5	Pass
17 to 22	0.0{17th}	4.0	Pass
23 to 34	0.8{23rd}	1.5	Pass
>35	0.4{35th}	0.7	Pass

4.2 Energy Saving

The energy consumed by motors at rated load have simulated by considering two situations, one when motors are operating without any control and second when these are controlled by the VFD system. It is observed that VFD system is able to reduce about 10% of total energy consumed by the motors. Further it is noted VFDs consist of higher pulse converters and harmonic filters are used, the energy consumption is slightly increases. For instance, the use of harmonic filters, compared to 6-pulse converter will increase about 0.75% energy consumption of the motors.

Though VFDs are responsible to generate the harmonics and theses harmonics flowing through the power system increase losses and energy consumption, but the total energy consumption of the motors equipped with VFDs consuming lesser power compared to operating the motors without control.

5. CONCLUSION

Following are the conclusions based on the harmonic analysis and energy savings of this study:

- The use VFDs for CWP in the HVAC system is useful. It is able to reduce about 10% energy consumption. It is beneficial to increase the system efficiency and to diminish the electricity bills.
- The advanced universal passive harmonic filters are capable to mitigate lower order prevailing harmonics to the compliance level of IEEE 519-2014 standard.
- The VFDs are generating the harmonics but these can be reduced by using phase shifting transformer, higher order bridge converters and harmonic filters.

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