Scientia et Fides

Level of Harmonics Produced by Variable Frequency Drive Controller Used in Induction Type Water Pump Motor

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ABSTRACT

This study focuses specifically on the determination of electrical noise or harmonic level generated by the variable frequency drive controller in terms of its amplitude and frequency. The central area of concern is the effect of harmonics on the power quality of the electrical supply of Central Philippine University at the point of the pump-motor equipment. Based on the results of the tests, the harmonics of the supply voltage was 2.25%. Running the 5-HP motor directly produced a lower harmonics of 2.10%. When the controller was used to run the motor, the controller in itself produced a significant level of harmonics of 8.42% which interferes with nearby electronic appliances within a very close proximity. A substantial part of the harmonics produced by the controller is filtered from going out of the device itself, so that the harmonic level at the source terminal was about 3.93 %, showing an increase of 1.83% compared to running the motor without the use of the controller. The value is within the acceptable limits of 5% for electronic circuits and systems, but not acceptable for medical and other related highly sensitive instruments, which require a total harmonic distortion (THD) of not more than 3%.

Keywords: *induction type water pump motor, level of harmonics, variable frequency drive (VFD)*

Introduction

Central Philippine University (CPU) is a non-stock, non-profit, Christian, private institution of higher learning founded by American Baptist missionaries in 1905 at Jaro, Iloilo City. Its 24-hectare campus is well laid out with trees, lawns, big fields and several buildings that serve as classrooms, laboratories, libraries, or offices for administration, finance, student services and much more.

The water needed by the school has been supplied by the local water utility Metro Iloilo Water District (MIWD) as well as deep wells within the grounds, to have an ample, continuous supply even when water from the MIWD at times is not available. The university has also put up a 91.13 m^3 water tower that is 21.72 m high. Water is raised to that height by a pump that is driven by a three 3-phase, 5-Hp, 220-V electric motor. It

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is controlled (start and stop) using direct-on-line method.

The central area of the study is the effect of harmonics on the power quality of the electrical supply of CPU at the point of the pump-motor equipment. Harmonics is the occurrence of any “non-linear” current or voltage in an electrical distribution system. The determination of the level of harmonic produced by VFD was a case study conducted at Central Philippine University, Jaro, Iloilo City Philippines to determine the effect of utilizing the VFD for the three-phase induction motor use in the water pumping system of the said institution.

According to the SQUARE D Product data Bulletin, harmonics is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency of 60 Hz (Stephen David Hearn. PE). The total harmonic distortion is the contribution of all the harmonics frequency currents to the fundamental frequency.

Harmonics is the by-product of modern electronics. The common harmonic producing devices include VFDs (Variable Frequency Drive), lighting and computers. It can interfere with the normal operation of an electrical system. High level of harmonics can reduce the efficiency of the facility’s wiring and electrical equipment and increase the amount of interference in the electrical/electronic systems. (Bulletin No 8803PD9402 August 1994 Raleigh, NC, U.S.A)

The presence of this harmonics increases power losses, equipment heating, interference and other related problems. Improve Power Factor and Reduce the Harmonics Distortion of the System (Sandesh, J. et al.), shows that a low power factor entails cost to the community and constitutes additional electrical charges and poor power quality. The major contributor of this problem is the highly inductive load like motors and the in-efficient load. On the other hand, harmonics were generated by active components used in the electronics control system. To address this problem, the system must be capable of correcting the power factor up to unity or adjusting it according to the users’ desire. Another would be for the system not to generate harmonics to reduce losses.

The proposed utilization of the VFD controller specifically GPD515 raises some concerns especially on its effect on the power quality at CPU. The use of a controller, specifically VFDs will produce harmonics because of the nature of the front-end rectifier design the most pulse width modulated VFDs. In addition to that, this will render additional cost since most VFD controllers are expensive. On the other hand, the use of this device to control the induction type motor can reduce energy consumption by controlling its speed. Moreover, it can minimize current surges during the motor start; lessen the wear and tear of the parts specifically the moving and rotating components, prolong the life of the motor, smoothen the response by maintaining the speed and balance the supply voltage. .(http://www.vfds.org/vfd-basic-theory-271552.html).

The said device has been designed to control loads, such as three-phase induction type motors up to 5 Hp. The controller can be programmed for specific applications to smoothen the response of the system.

The GDP515 comes with easy to install mounting systems. Each unit comes with a customized program from the factory for maximum performance when used with the C-4 Card Drive, utilizes state-of-the-art 32-bit processing, motor algorithms, auto-tuning, and other benefit-laden technologies creating the cutting edge in AC drive design. It provides flexibility to customers, with a single drive platform offering traditional V/Hz control, sensor less vector, and flux vector control performance.

There is also an issue for current waveform distortion which is Total Harmonic Distortion (THD) versus the actual loading of the equipment power source. As with voltage waveform distortion, the best location to measure current waveform distortion is the power source that feeds the equipment location (i.e., isolation transformer or main service entrance). It gives the best representation of the overall current waveform distortion. “Computers and allied equipment, such as programmable controllers, frequently require AC sources that have no more than 5% harmonic voltage distortion factor, with the largest single harmonic being no more than 3% of the fundamental voltage. Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment that in some cases, have serious consequences. Instruments can be affected similarly, giving erroneous data or otherwise perform unpredictably. Perhaps the most serious of these are malfunctions in medical instruments.” (IEEE Std 519-1992)

To summarize, here are the issues in the use of the GPD515 which include: the degree of harmonics produced by the controller that might cause interference in the public address system of CPU and other related equipment and appliances; the suppressions of current surges; the possibility of significantly conserving energy; and finally, the future development of an assembly system that would be used in the Electrical and Electronics laboratory at CPU College of Engineering.

Methodology

Determining the quality of any given circuit or systems and knowing what is behind any signal power quality is very critical. This will include the measurements of voltage and current and analyze the harmonic content to evaluate whether the controller, the loads, or the external environment produces harmonics. (Bulletin No. 8803PD9402 August 1994 Raleigh, NC, U.S.A).

There are many research studies about harmonics that determine the level and its effect to the electronic and electrical loads. Power system harmonics research: a survey (G.K. Singh), the use of variable frequency speed drives and other nonlinear devices in industrial power systems produces voltage and current distortion called “harmonics.”

The testing of the system included the following: the performance of the system with and without the controller by measuring the energy consumption with a specific fixed load of 3-phase 5-Hp induction type motor and the measurement of the degree of harmonics present in the system.

The block diagram shown in Figure 1 was the set-up needed for the testing of the system. It was composed of eight building blocks which were properly labeled with their corresponding function and operation: The 220 Vac, 60 Hz three-phase line voltage was the main source of the system that supplies power to each of the blocks. Two single-phase kW-Hr meters were used to measure the energy consumption of the entire system. The GPD515 is the VFD controller that can be programmed and reprogrammed to control the operation of the motor. The magnetic contactors were used to switch on and off the system. The selector switch was used to select the mode of operation of the system, with or without the controller. A combiner circuit was used to combine the output of the two magnetic contactors for the specific mode of operation. Lastly, the three-phase AC motor acts as an inductive load of the system.

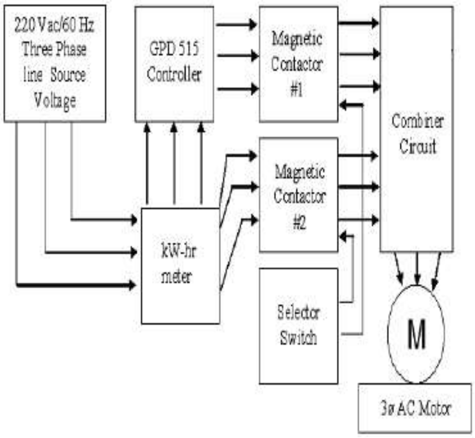


Figure 1. Block diagram for Testing of the System

The system functions as follows: the supply voltage coming out from the source enters into the kW-Hr meter, wherein its output is then connected to the GPD515 controller and on to magnetic contactor one while the other branch circuit is directly connected to the magnetic contactor two. The purpose of this is to select the mode of operation via the selector switch. The selector switch is labeled with the following: bypassed and controller "ON." When the selector switch is set to controller "ON" mode, the controller drives the motor. If the selector switch is in the bypassed mode, the controller cannot be used and the motor is directly connected to the source voltage. The energy consumption was measured. The data will be compared to the testing of the performance of the system with and without the controller. Also, the harmonics produced by the system are measured based on the two modes of operation. Spectrum analyzer was used to plot the harmonics generated by the system, and a number of harmonics produced was determined by using the THD.

During testing, the following data were collected: voltage per phase, current per phase, the energy consumed per hour and the harmonics' amplitude and frequency, both with and without the controller.

The percent total harmonic distortion (%THD) of the harmonics with and without the controller. The percent total harmonic distortion (%THD) is computed using the formula:

$$\%\mathrm{THD} = \sqrt{\frac{V_2^2}{V_1^2} + \frac{V_3^2}{V_1^2} + \frac{V_4^2}{V_1^2} + \ldots \frac{V_n^2}{V_1^2}} \text{ X } 100\%$$

Where: V_1 = fundamental signal
V_2 = second harmonics
V_3 = third harmonics
Vn = the nth harmonics

Moreover, tests were applied to determine if there were additional harmonics present in the electrical system (before the GPD515 controller is used). Should there be such distortions in the quality of power, it will then be determined if it is within the permissible levels, and if the use of the device would either add or reduce system harmonics.

Results

The specifications of each component were determined based on the ratings of the three-phase induction motor that is currently being used in the water pumping station of CPU. The pump motor being used is a 5-Hp, 220 V AC, three phase induction type. Based on these ratings, the following components were used; 3-phase 30-A circuit breaker, 30-A magnetic contactor with over current protection for direct-in-line connection without the controller, and 20-A magnetic contactor with over current protection at the output of the controller. The line current was measured using the current transformer with a 50/5 ratio. The panel board layout of the system is shown in Figure 2 above. As can be seen, power can be supplied to a motor load either through direct starting via the 30-A contactor or using the controller passing the 20-A contractor.

The next illustration shows the entire set-up of the testing measuring and testing. In measuring the circuit parameters, there were two conditions considered; the motor was directly connected to source (direct-in-line), and when the motor was controlled by the GPD515 controller.Before the system was tested the voltage in each line was measured and the reading was 232.3 VAC and 8.6-A respectively. This test was used to determine whether the source supplied the desired voltage to the system and the current measurement was used to determine the normal operation of the induction motor. The other phase voltage was 232.5 V, the system supply voltage is almost balanced, indicating that the supply voltage was ideal for testing.

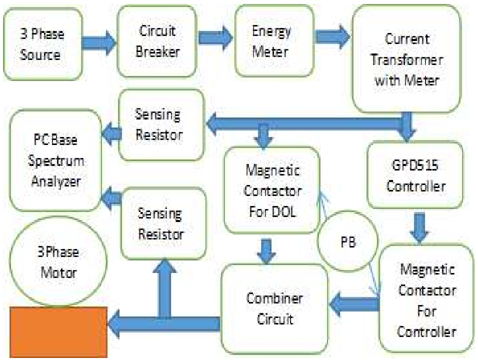


Figure 2. Panel Board

System Testing with GPD 515 Controller.

Figure 3. The complete Set-Up of the System

The result of the source voltage reading was almost similar to that of DIL testing, as the output voltage using the controller was 233.7 VAC with 9.52-A at 60.00 Hz. This will indicate that the system operated normally and was ideal for performance testing and determination of the degree of harmonics produced.

Testing the Harmonic Content of the System.

In testing the harmonic content of the system, there were two conditions considered; (1) test the harmonics with direct-on-line connection with the motor directly connected to the source, (2) test the harmonics content with the motor controlled by the GPD515 controller. The harmonics were measured using the PC based spectrum analyzer.

Testing the Harmonic Content of the System Using Direct-On-Line Method.

Before testing the harmonics produced by the system, that of the source voltage was determined first, and these served as the reference data in determining the harmonics content at the source are shown below in Figure 4.

Initially, with the load OFF, there were some significant harmonics present at the source terminal. The highest peak was the fundamental frequency which was the line frequency of 60.55 Hz, 0.7126 V. The second peak was the first significant harmonics or the dominant harmonics, with a frequency of 301.8 Hz, and the amplitude of 0.01486V and the third peak was the second harmonics present with frequency of 422.9 Hz, 0.006037 V. and the rest of the peaks were insignificant because the amplitudes were very low.

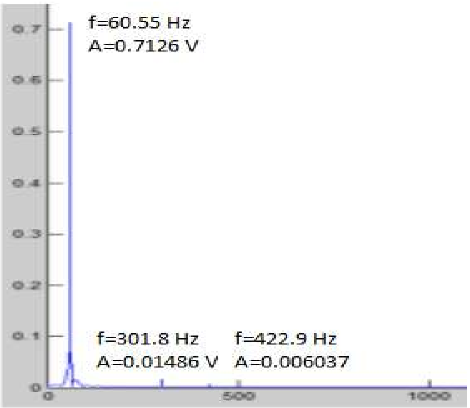


Figure 4. Frequency Spectrum of the Source Voltage with Load OFF.

of frequency at the higher frequency range. Figure 5 is the zoomed version of Figure 4, used for a more unobstructed view of the small peaks shown in the previous figure.

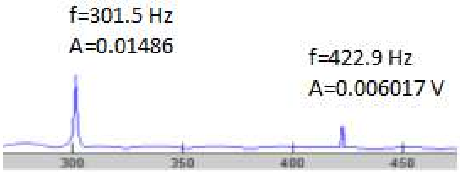


Figure 5. Frequency spectrum of the source voltage with load OFF, zoomed-in version.

The percent total harmonics distortion (%THD) was calculated to be equal to 2.25% which was below the required limit of the IEEE standard of 5%. It means that the source noise is an acceptable level and therefore a good power source.

In turning on the system which enables the direct-on-line connection, the motor was connected directly to the source terminal without the controller. To measure the harmonics content at the source terminal, the Spectrum Analyzer was connected to the sensing resistor installed at one of the phases of the source. The instruments automatically plotted the harmonics and saved the data, as shown in the graph of Figure 6. The same procedure was followed to get the data to the load side terminal.

Figure 6 shows the frequency spectrum of the source and load terminal. The highest peak still was the fundamental frequency of 60.55 Hz with amplitude of 0.6445 V, the next peak was the second highest significant harmonics in the system with frequency of 301.8 Hz, 0.01251 V while the third highest was at 421.9 Hz, 0.00522 V. The other harmonics were insignificant. This showed that the three-phase, 5 Hp, 220 V AC induction motor did not produce significant harmonics when it was in use. This was not a harmonically generated load. Based on the data shown from the frequency spectrum the %THD is 2.10% which was lesser than the previous values without load.

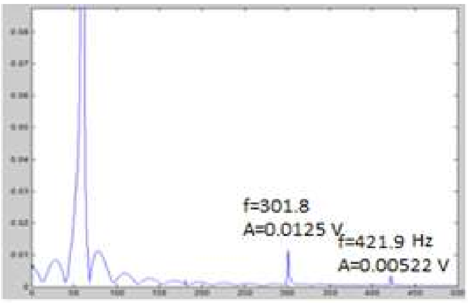


Figure 6.Frequency spectrum of the source voltage with load OFF.

Testing the Harmonic Generated by a GPD515 Controller.

The harmonics were measured first at the load side with the same procedure followed by the measurements of harmonics at the source side. The result was shown in Figure 7.

In Figure 7, the highest peak is at 59.57 Hz with amplitude of 0.5402 V, followed by the 299.8 Hz at 0.04303 V, many smaller peaks were produced within the band of 500 Hz - to - 4000 Hz. The data show that when the controller was used it generated a % THD of 8.42%, The value is much higher compared to the standard limits sets by IEEE.

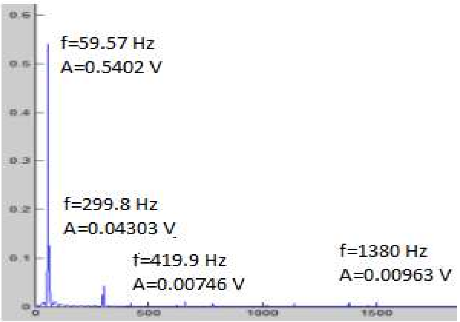


Figure 7. Frequency Spectrum of the Load Voltage of the Controller.

This indicates that the output of the controller produces significant number of unwanted signals. These harmonics may interfere with electronic appliances, equipment, and systems if not properly shielded and grounded. The harmonic or noise coming from the output of the controller was caused by the following: the output of the controller was not pure sine wave; and the controller utilizes active devices to regulate the load which generates harmonics. These harmonics generated by this controller do not pose a problem with induction type motors because such harmonics have very small amplitudes.

However, the presence of these may cause interference with the nearby equipment specifically audio and other related appliances, equipment, and systems if these are not properly installed and are in very close proximity with the controller. Figures 8 and 9 are the zoomed-in versions of Figure 7 to highlight the smaller peaks from 300 Hz-to-2000 Hz.

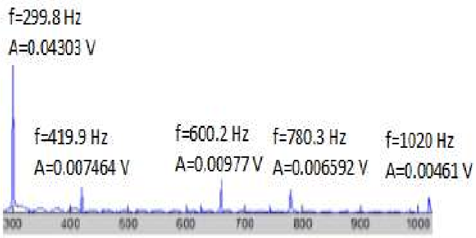


Figure 8. Magnified frequency spectrum of the load voltage of the controller at 100 Hz-to-1000 Hz

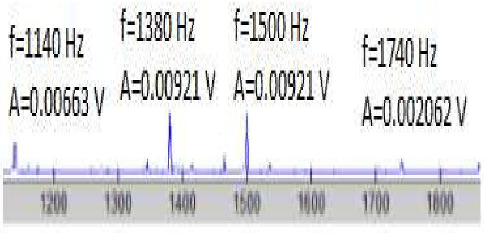


Figure 9. Frequency spectrum of the Load Voltage of the Controller from 1000 Hz –to- 1900 Hz.

The resulting Figure 10, shows the frequency spectrum at the source side, with the highest peak at 60.55 Hz having an amplitude of 0.5331 V, which was the source frequency. The next highest peak was the 300.8 Hz, with 0.01681 V which was the first significant harmonics present followed by the 420.9 Hz, with 0.007966 V. The other peaks of very low amplitude were not considered significant.

Based on Figure 10 the total harmonics distortion (THD) of the system with controller is 3.93%. It was shown that there were significant increases in the number of harmonics and the amplitude, but the harmonic content was still within the acceptable level. It only shows that the harmonics at the output of the controller were also present at the source terminal. However, the bigger harmonics at the output side of the controller were significantly reduced because the controller has a built-in mechanism that suppresses the harmonics, thereby, minimizing these electronic noises induced that would otherwise revert to the system. Figure 11 shows the clearer view of the small peaks in Figure 10.

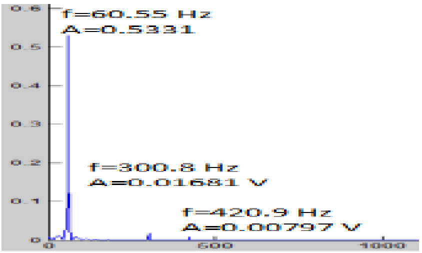


Figure 10. Frequency Spectrum of the Source Voltage of the Controller Load "ON"

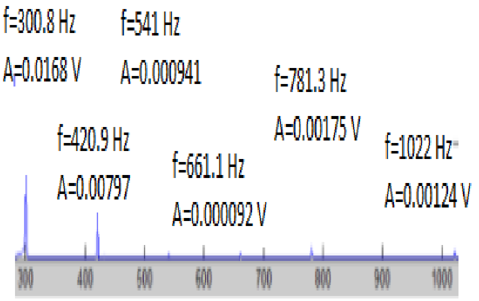


Figure 11.The Magnified Frequency Spectrum of the Source Voltage of the GPD515 Controller.

Figure 12 shows the output waveform of the controller in the time domain. The waveform is a modified sine wave, which is an acceptable supply voltage for the operation of the system. This waveform consists of harmonics, which was the integral multiple of fundamental frequency from 300.8 Hz, 420.9 Hz, 541 Hz, 661.1 Hz, 781.3 Hz and 1022 Hz as shown in Figure 16b. The harmonics shown were the ones that can be viewed significantly by the spectrum analyzer.

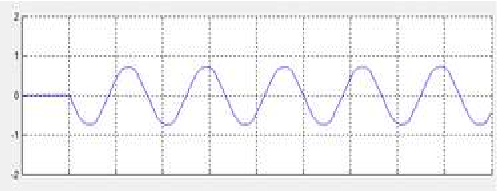


Figure 12. The Output Waveform of the GPD515 c

Figure 13 shows the smooth sine wave signal coming from the electrical power supply. This is an ideal signal for the source to run the load smoothly.

Nevertheless, there were still small amounts of peaks or irregular shapes caused by electronic noise or electromagnetic interference.

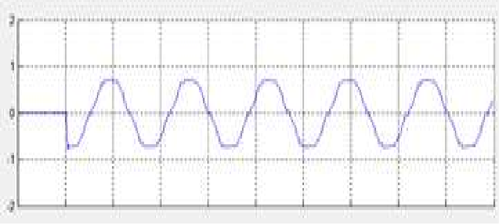


Figure 13. The waveform of the output Voltage without controller

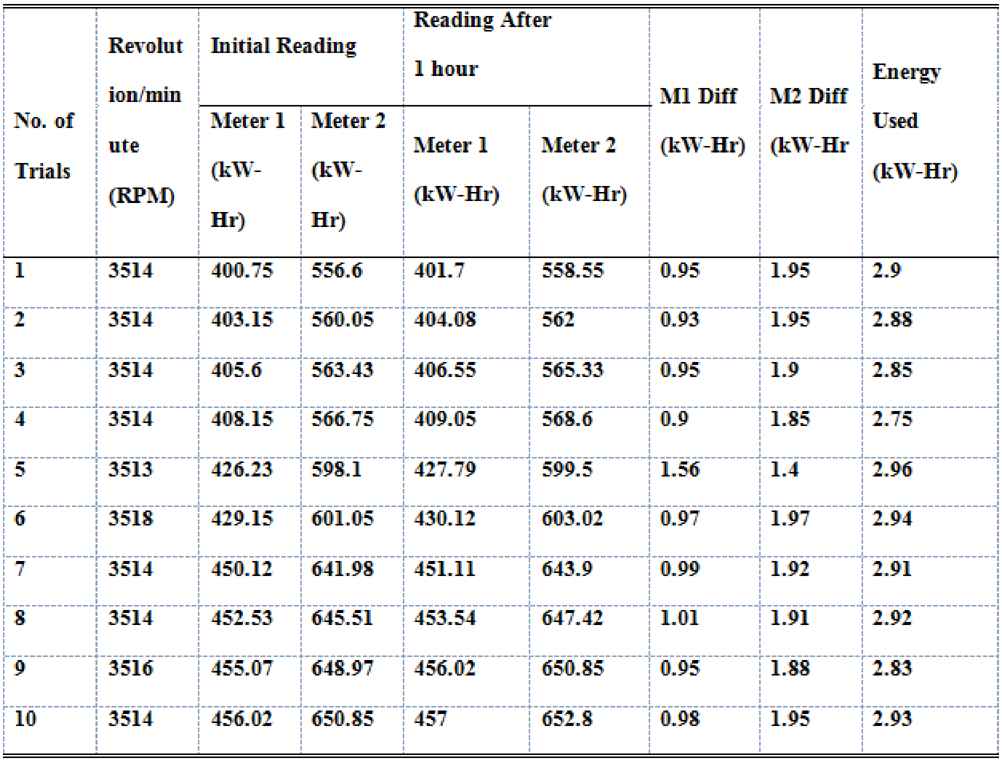
Testing the Energy Consumption of the System

The two-watt meter method of measuring the energy consumption utilized two single phase energy meters. The readings of the two meters were added to obtain the total energy consumed by the three-phase system. The initial readings of the meters were recorded before the actual testing.

The actual energy consumption is the sum of the differences between the initial readings and the readings after one-hour. The reading of the meter was calculated by subtracting the initial reading of the meter and the reading after an hour.

The average energy consumed is the sum of the usage in kW-Hr divided by the number of trials. Table 1 show that M1 average reading was 1.019 kW-Hr while M2 was 1.868 kW-Hr, giving the overall average difference of the two meters of 0.849 kW-Hr. The average difference in readings between the meters was about 0.849 kW-Hr and this value shows that the system using the DIL was unbalanced. The energy consumed per line had a large discrepancy; therefore, the power delivered per line was not equal. This will affect the performance of the motor as well as its mechanical parts and components.

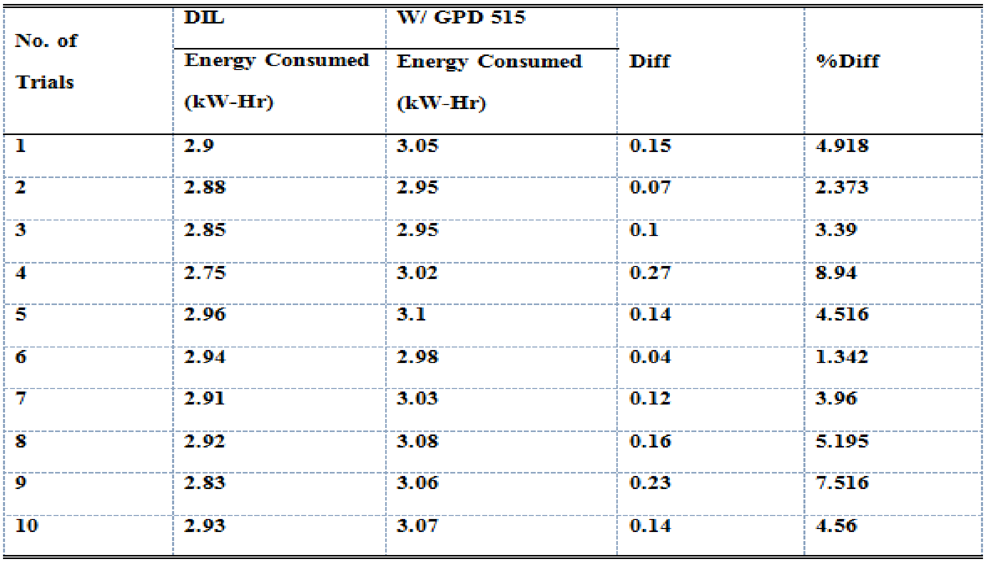
Table 1.
System Data Using Direct-On-Line (DOL)



No. of Trials	Revolution/minute (RPM)	Initial Reading		Reading After 1 hour		M1 Diff (kW-Hr)	M2 Diff (kW-Hr	Energy Used (kW-Hr)
		Meter 1 (kW-Hr)	Meter 2 (kW-Hr)	Meter 1 (kW-Hr)	Meter 2 (kW-Hr)			
1	3514	400.75	556.6	401.7	558.55	0.95	1.95	2.9
2	3514	403.15	560.05	404.08	562	0.93	1.95	2.88
3	3514	405.6	563.43	406.55	565.33	0.95	1.9	2.85
4	3514	408.15	566.75	409.05	568.6	0.9	1.85	2.75
5	3513	426.23	598.1	427.79	599.5	1.56	1.4	2.96
6	3518	429.15	601.05	430.12	603.02	0.97	1.97	2.94
7	3514	450.12	641.98	451.11	643.9	0.99	1.92	2.91
8	3514	452.53	645.51	453.54	647.42	1.01	1.91	2.92
9	3516	455.07	648.97	456.02	650.85	0.95	1.88	2.83
10	3514	456.02	650.85	457	652.8	0.98	1.95	2.93

The same procedure was used to acquire the data in Table 2. The average energy consumed by the system after ten (10) trials is about 3.029 kW-Hr with GPD51 controller. This means that the system with controller will consume an average energy of 3.029 kW-Hr in one hour of continuous operation while the DIL will consume around 2.887 kW-Hr. In addition to that, the average difference between meter 1 (M1) and meter 2 (M2) was about 0.007 indicating that the system was almost balanced in terms of the energy consumption per line. This means that the controller deliver almost the same power per line and these will further improve the performance of the motor.

Table 2.
Percent Difference of the Energy Consumed Between DOL and with GPD 515



No. of Trials	DIL	W/ GPD 515	Diff	%Diff
	Energy Consumed (kW-Hr)	Energy Consumed (kW-Hr)		
1	2.9	3.05	0.15	4.918
2	2.88	2.95	0.07	2.373
3	2.85	2.95	0.1	3.39
4	2.75	3.02	0.27	8.94
5	2.96	3.1	0.14	4.516
6	2.94	2.98	0.04	1.342
7	2.91	3.03	0.12	3.96
8	2.92	3.08	0.16	5.195
9	2.83	3.06	0.23	7.516
10	2.93	3.07	0.14	4.56

The percent difference between the consumption of the two systems is shown in Table 3. There was a 4.67% difference in energy consumption which shows that there was a 4.671 % of power consumed in excess when using the controller as compared to using without it. This means that there were no significant powersavings in using the controller, however, the effect of using it is the balanced power consumption of the motor, which in effect, makes the motor more efficient and minimizes the wear and tear of the mechanical components of the motor.

Moreover, even if there were no power savings with the use of controller, the revolution- per-minute (rpm) of the motor is higher compared to without the use of controller as shown in Table 2 and 3. This indicates that the efficiency of the motor increases with the use of the controller.

There were no significant energy savings when the controller was used in the system. Nevertheless, with the aid of a controller, the energy consumed by both meters was nearly balanced as indicated by a 0.007 average “meter reading difference” which was better as compared to running the pump motor without the controller, where the readings were more unbalanced as evidenced by a 0.849 average meter reading difference.

Furthermore, the use of the controller regulates the starting current to rise gradually until full load current is achieved which negates a high starting current found in using DOL control. This prevents current spikes that could otherwise damage the connections of contactors, thereby prolonging their use. High starting torque is also minimized which contributes to the protection of the motor from wear and tear and results in extended life of the mechanical parts.

Summary, Conclusion and Recommendation

Summary

The determination of the level of harmonics produced by the variable frequency drive controller used to control the induction type water pump motor at the water pumping station of Central Philippine University was explicitly determined by the electrical noise or harmonic level generated by the controller. Also, the researchers tested whether or not the use of the controller could reduce the power consumption of the system. The test system was constructed with its specific components along with its needed tools and instruments for testing. The PC virtual spectrum analyzer was utilized to test the harmonics of the system which include the initial reading of the harmonics without and with the aid of a controller. The DMM was used to measure the voltage, while a clamp ammeter was used to measure the operating current of the motor and two single-phase kW-Hr meters were used to measure the power consumption of the system. To determine the degree of harmonics present in the system the researchers used the equation given by the percent total harmonics distortion (%THD) and the reference data was based on the IEEE standard of not more than 5% allowable total harmonic distortion for the normal operation of the system. The reduction of the power consumption was calculated using the difference between the power consumption of the motor, first with the controller and then without the controller. This showed that the controller produced a significant level of harmonics that can cause interference to nearby electronic appliances which are sensitive to electrical noise specifically computers, radios, public address systems and other related electronic circuits and systems if they are within very close proximity. However, this noise or harmonic generated was not significantly induced at the source terminal because the controller has a built-in filter circuit that will substantially reduce its amplitude and the number of harmonic components within the acceptable range at the source terminal. Thus, there was acceptable “throwback” of significant harmonics to the power system. Lastly, there was no significant reduction in the energy consumption with the use of the controller over the DOL using open loop control mode.

Conclusion

The determination of the level of harmonics produced by the variable frequency drive controller used to control the induction type water pump motor at the water pumping station of Central Philippine University was successfully conducted by designing the block diagram for testing of the system. The researchers were able to construct, and test the function and operation of the system for harmonics content. The level of harmonics content was also evaluated using THD and it was found out that there was an increase of 1.83% in the THD of the system when using the controller as compared to without using it. There was no significant reduction in the energy consumption of the system when using the controller, but there were significant increases in amplitude and the number of harmonics produced in the system. The harmonics produced at the source terminal was within the acceptable level but at the load terminal, it was above the maximum allowable value. However, this will only affect nearby sensitive electronic appliances, system and circuits, but, not on the system which are connected far from the same peak-off point. The controller provides a balanced supply voltage, which improved the motor performance.

Recommendation

It is recommended that when installing this system, it should be located far from noise sensitive electronic devices or systems. When installing the controller and load, the wiring must be as short as possible and must be shielded to minimize electromagnetic induction or interference.

To further improve the installation of the system, an input filter, and reactor circuit must be installed at the source terminal to reduce further the noise or harmonics induced by the controller. In spite of a significant number of harmonics produced by the controller, it is recommended that this controller must be installed with an induction type motor for the reduction of wear and tear of the mechanical component of the motor, thereby prolonging the life of the mechanical devices specifically the mechanical motor and improvement of its performance.

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