Quality evaluation of energy consumed in flow regulation method by speed variation in centrifugal pumps.

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Abstract. Nowadays, energy efficiency and the Electric Power Quality are two inseparable issues in the evaluation of three-phase induction motors, framed within the program of Rational and Efficient Use of Energy (RUE).The use of efficient energy saving devices has been increasing significantly in RUE programs, for example the use of variable frequency drives (VFD) in pumping systems.The overall objective of the project was to evaluate the impact on power quality and energy efficiency in a centrifugal pump driven by an induction three-phase motor, using the flow control method of speed variation by VFD. The fundamental purpose was to test the opinions continuously heard about the use of flow control methods in centrifugal pumps, analyzing the advantages and disadvantages that have been formulated deliberately in order to offer support to the industry in taking correct decisions. The VFD changes the speed of the motor-pump system increasing efficiency compared to the classical methods of regulation. However, the VFD originates conditions that degrade the quality of the electric power supplied to the system and therefore its efficiency, due to the nonlinearity and presence of harmonic currents. It was possible to analyze the power quality, ensuring that the information that comes to the industry is generally biased.

1. Introduction

As development of electronics proceeds electronics and power generation is becoming increasingly expensive, it is necessary to increase efficiency in production processes. This problem is particularly important in the case of applications where pumps are used, since this would allow a reduction in power consumption and more efficiency in the motor and pumping system. The traditional methods used for flow control in pumps are based on the modification of the characteristic curve of the system: Pressure (H) v / s flow rate (Q), which is achieved by using one or more valves, for example, the method of regulating by pressure throttling and bypass flow control method. The use of these methods results in an increase in power consumption, which leads to a significant reduction in efficiency of the motor-pump group [1].

A more efficient way to regulate pump flow is by changing the speed of the electric motor driving the pump, using a three-phase squirrel-cage induction motor, along with a VFD.

Currently, one of the trends in the industry is precisely the use of VFD in pumping systems, as they pertain to special devices lists in Energy Efficiency programs [1-4]. Its principal advantage over the other methods of regulation is that it does not require an intervention in the hydraulic system via

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valves and other electro-mechanical elements. When the device is connected to the electric grid, you can operate the system and achieve the optimal operating point (the most efficient) [5]. However, according to the hydraulic characteristics of the system, its operation can be uneconomical, because VFD are characterized by altering the electric power quality, due to the high magnitudes of harmonic currents that appear in grid side , as a result of the strong distortion suffered by the consumed current [6]. It has been demonstrated that generate harmonics of order 5 and 7 to 63% and 33 % of the fundamental component of the current, respectively, which puts into question the true energy savings provided by the use of VFD in flow regulation in pumps [1, 2, 7]

Additionally, companies that require the application of a flow control method can make wrong decisions because of the technical information provided by the commercial interests of the companies that manufacture VFD, or ignore the requirements or additional costs that must be taken into account in the purchase and implementation of a VFD [1, 2, 4]. In this vein, there is concern of how advisable is the practice of flow control method by speed variation with a VFD from the point of view of its impact on the quality of electric power consumed by the grid.

2. VFD in pumping systems

A VFD system (also called ''frequency converter'') is a device which controls the speed of an AC motor by regulating its voltage input and frequency. This allows the electric motor to reach the optimal operating point (maximum efficiency) and reduce operation costs thanks to energy savings. These devices provide a high degree of control over a pumping system by easily adapting to flow and pressure fluctuations, which is a condition that traditional mechanical methods such as throttling and bypass cannot offer. This causes manufacturers of VFD to offer them as a practical and efficient solution for flow regulation in many industrial applications. However, VFD are not advisable for all applications, for example systems that operate high static head and those that operate for long periods under low flow conditions [8, 9].

Also, as it was stated before, VFD are known to produce conditions that deteriorate the quality of the energy consumed due to non-linearity the presence of high levels of harmonic distortion. In three-phase VFD there are harmonic distortion of 5, 7, 11, 13, 19 and higher odd multiples of the fundamental frequency (60Hz) [8].

Harmonic distortion can occur in voltage or current sine waves. In this case, the focus is on distortion in current wave, which is injected to the feed-in network by the users. These harmonic currents flow into the electric network and local electric supply lines and produce negative effects such as overheating of electric conductors, voltage drops, overheating, low efficiency and premature failure of motors and transformers, interference in measurement and communication equipment, etc.

The use of VFD in pumping systems can help to save energy and money because it is an efficient way to regulate flow according to the specific conditions of a process, but the deterioration of the energy consumed can question the its advantages and performance, especially in meeting energy quality standards.

3. Description of the system

The tests were performed on a small scale hydroelectric generation unit composed of Francis and Kaplan turbines. The main components of the system are described below.

3.1. Hydraulic generation and pumping system

The system in which the tests were performed consists of a hydraulic bench containing a unit of small scale Francis and Kaplan turbines for a laboratory. In this case, it was determined that the system would be modeled using the Kaplan turbine which is coupled to an electric generator. Thus, the curve of the system is limited by the pressure drop, due to the transformation that the Kaplan turbine makes of fluid energy into mechanical energy [1, 2]. The scheme of the system operating with the Kaplan turbine is shown in figure 1.
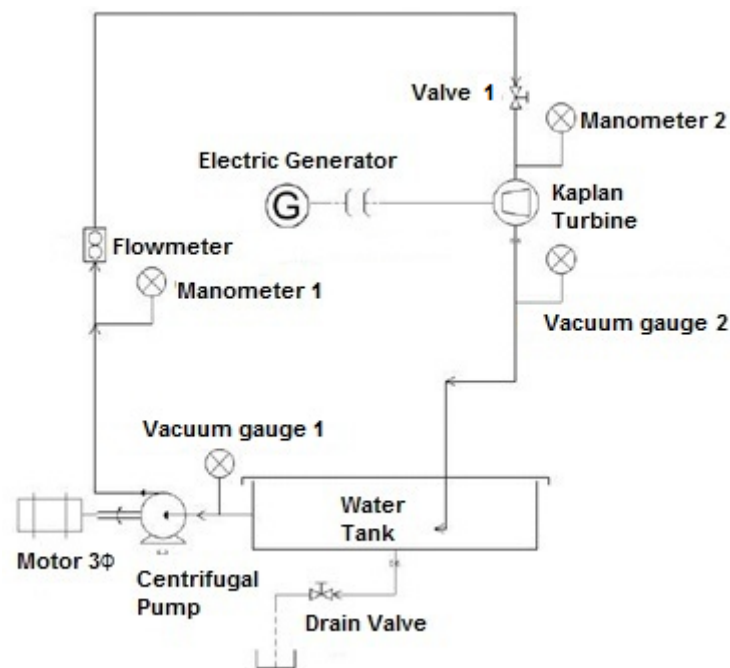

Figure 1. Scheme of the hydraulic generation system operating with Kaplan Turbine [1, 2]

As seen in figure 1, in the suction and the discharge lines there are pressure gauges are available for measuring static pressure or vacuum. Additionally, there is a flowmeter at the pump outlet indicating current flow [1, 2]

3.2 The electric motor

The three-phase induction motor that drives the pump has the following technical characteristics:

- Four poles, Three-phase

- Voltage:220Δ/380Y V.

- Current: 68.8Δ /39.8Y A

- Power: 20HP-15KW

- Power factor: Cos   0.8

- Frequency: 60Hz

- Nominal speed: 1750 rpm

- Insulation class F and protection IP 54

- Design class B according to NEMA classification.
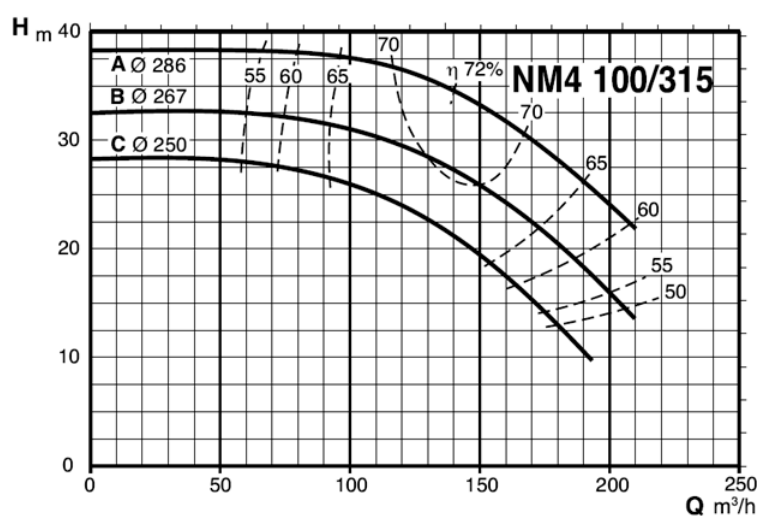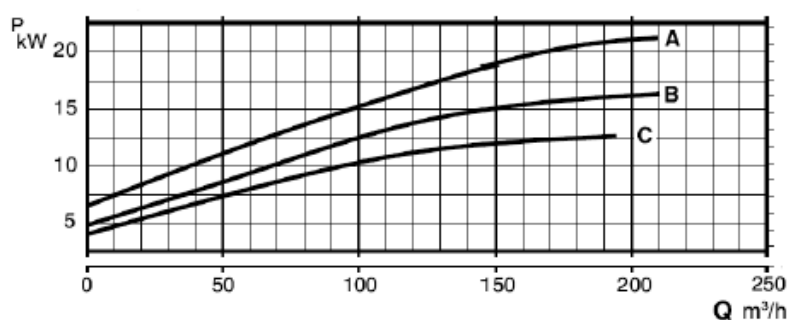
3.3 The centrifugal pump

The centrifugal pump used for the tests has a nominal speed of 1750 rpm. The table 1 shows the nominal characteristics.

Table 1. Pump nominal information [1, 2, 10]

H (m)	Q(m³/h)
Hmax 31,5	Qmin 48
Hmin 14	Qmax 210 m

The pump was manufactured according to the European Standard EN 733 aspiration centrifugal electropumps [1, 10, 11]. The figure 2 shows the pump's characteristic curve supplied by the manufacturer. In this case, the type B pump was used, with a discharge diameter of 267mm.

The figure 3 shows the performace of the pump at a speed of 1750 rpm for the type B pump.

Figure 2. Head vs Flow and Efficiency [1, 2, 10]

Figure 3. Power vs Flow [1, 2, 10]

4. Methodology

For this case, the operation of the motor-pump group was made with the VFD. The measurement of the electric power quality was made taking into account only the emission levels of harmonic currents using a three-phase power quality analyzer. This procedure is regulated according to IEC 61000-3-4, which sets limits for harmonic currents on low and medium voltage equipment consuming more than 16 A per phase and includes all equipment connected to the public network low-voltage alternating current, rated voltage up to 240 V rated voltage single-phase and three-phase to 600 V 50 Hz or 60 Hz [11].

During this test, valve 1 was kept in a fully open position and the tank of the system was kept full to ensure continuous supply of water. In order to obtain enough operating points of the pump, the VFD was programmed to change the rotation speed according to a range of frequencies between 0 Hz and 60 Hz, through a linear potentiometer and consistent monitoring of the frequency output, which corresponds to 21 points of operation in a flow range from 30m^3/h to 127.5 m^3/ h.

For each operating point, the following data was registered [2]:

- Motor speed in revolutions per minute.
- Active, reactive and apparent power and power factor before the VFD.
- Voltages and currents before the VFD.
- Frequency and peak factor.
- Odd harmonics of voltage and current.
- Voltage, current and power output percentage of the drive.
- Output frequency of the inverter.

Data were collected before and after the VFD. Because this device is part of the energy balance, it was necessary to record the parameters that it registers in the output. Considering that there is a derating factor for the VFD, similar to the K factor transformers, which indicates how much to reduce the maximum output power when there are harmonics. It is understood that the useful power received by the motor is the measured active power (KW) and not calculated through the three-phase power formula ($\sqrt{3}$) $V_L I_L$ [1, 2].

According to IEC 61000-3-4 standard, the evaluation method of harmonic currents can be performed with direct measurement of the emission or calculating the emission by simulation [13]. If direct measurement is made, it must be done in normal operation conditions for a week, where 95% of the RMS values of each harmonic voltage averaged in 10 minutes should not exceed the indicated values. However, for this test, the measurement period was limited to the time needed to take the information from different points of flow.

The connection between the device under test and its power supply is direct. But in this case, the electric feed-in of the hydraulic generation system comes from a circuit that has other loads of the building connected in parallel. Therefore, it cannot be ensured that there is immediate connection to the point of common coupling and isolated from other loads. The system was connected to a voltage of 220V and a frequency of 60 Hz [2].

In Colombia, in the mid-nineties the generating and distribution companies addressed the subject of the Power Quality, in view of technological developments through microelectronics that arrived to the country. The Energy and Gas Regulatory Commission (CREG), adopted the guidance of the Institute of Electrical and Electronics Engineers - IEEE 519-1992 about harmonic limits, through its Resolution 070 of 1998 [11]. Therefore, the harmonic current limits on which this article is based are set in IEEE 519 and IEC 61000-3-4 standards. Tables 2 and 3 present the harmonic current limits established in the standards IEE5519-1992 and IEC 61000-3-4 and respectively.

Table 2. Maximum harmonic distortion of current in percentage according to IEEE 519 [2, 4, 13, 14].

	Odd harmonics of orders 3rd to 11th	Total Harmonic Distortion in Current (THDi)
Limit of current distortion for general Distribution systems (120V to 69000V).	4,0	5,0
Limit of current distortion for general sub-transmission systems (69001V to 161000V).	2,0	2,5
Limit of current distortion for general transmission systems (69001V to 161000V), dispersed generation and cogeneration.	2,0	2,5

According to table 2, the maximum limit of DTH (%) taken as reference in this case is 5%, for general distribution systems 120V to 69000V. For limits of individual harmonic currents, the values of reference in this case are set out in table 3.

Table 3. Maximum distortion of individual harmonics according to IEC 61000-3-4 [2, 13, 15]

Harmonics non multiple of 3		Harmonics multiple of 3	
Harmonic order (n)	Maximum current I_n/I_1 (%)	Harmonic order (n)	Maximum current I_n/I_1 (%)
5	10,7	3	21,6
7	7,2	9	3,8
11	3,1	15	0,7
13	2,0	21	≤ 0,6
17	1,2	27	≤ 0,6
19	1,1	≥ 33	≤ 0,6
23	0,9		
25	0,8		
29	0,7		

5. Results and analysis

Table 4 shows the results obtained during the test for 21 operation points regarding the power quality in terms of harmonic distortion. The harmonics correspond to the average obtained from the three line currents.

As seen in Table 4, the levels of total and individual harmonic distortion decrease as the frequency is about to reach to 60 Hz, which is the nominal frequency of operation of the equipment and the power grid.

Table 4. Results of current harmonics due to the VFD [2]

Operation Point	Q (m^3/h)	F (Hz)	Total Harmonic Distortion and Individual Odd Harmonics							
			THD(%)	H3(%)	H5(%)	H7(%)	H9(%)	H11(%)	H13(%)	H15(%)
1	30	16,3	175,93	23,03	93,23	87,03	17,93	71,80	62,37	10,80
2	35	18,4	169,27	18,60	92,40	85,33	14,13	67,93	57,63	8,30
3	40	20,5	162,30	23,03	91,73	84,27	16,87	66,00	55,30	8,93
4	45	22,7	147,20	14,77	90,27	81,27	10,30	59,27	40,50	5,37
5	50	25,1	146,33	15,17	89,57	80,13	10,37	38,90	44,97	5,23
6	55	27,2	137,13	13,43	87,90	77,07	8,43	51,30	38,27	4,03
7	60	29,3	136,47	16,23	87,67	76,67	9,87	50,77	37,67	4,40
8	65	31,6	127,50	13,10	85,63	73,07	7,77	44,53	31,07	3,57
9	70	33,1	125,53	12,73	85,20	72,17	7,13	42,83	29,27	3,30
10	75	35,7	115,40	12,63	82,83	68,20	6,10	36,53	23,13	3,00
11	80	38,1	112,80	10,43	80,87	64,57	5,33	31,20	18,27	2,80
12	85	40,3	107,93	8,83	79,63	62,70	4,10	28,73	16,20	2,17
13	90	42,4	102,27	13,50	77,23	58,43	5,50	23,10	11,93	3,37
14	95	44,8	98,70	14,17	75,50	55,67	4,87	19,53	9,37	3,03
15	100	46,6	95,50	13,33	74,17	53,67	4,33	17,37	8,23	2,73
16	105	48,8	91,23	12,50	72,40	50,93	3,93	14,60	7,10	2,37
17	110	50,9	90,50	4,67	72,50	50,93	1,80	14,10	5,63	0,90
18	115	52,9	89,43	4,90	72,03	50,20	1,73	13,27	4,63	0,77
19	120	55,5	85,60	4,23	69,93	47,07	1,40	10,33	3,97	0,63
20	125	58,1	82,60	3,83	68,53	45,07	1,13	8,70	3,73	0,43
21	127,5	60	80,80	3,77	67,53	43,63	1,43	7,63	3,67	0,53

Figure 4 shows a comparison of the measurement results of THD and individual odd currents with the maximum limits established in IEEE 519 and IEC 61000-3-4 standards.

According to the results presented in figure 4, it shows that VFD devices inject large amounts of harmonics in the electrical network. The values of THD express the large amount of harmonic current flowing in the network, for example, the operating point of 30 m^3/ h has a THD of 180%, which means that the harmonic currents are almost two times higher than the fundamental current [2]. This also reflects not only the size of disturbances in the grid, but also that the VFD is characterized for having large energy losses represented in the power dissipated by harmonic currents that do not contribute to the useful power.

Also, a tendency to lower the current harmonics as the flow increases was identified. This means that the quality of the power improves as it approaches the nominal operating conditions, at a frequency of 60 Hz. Likewise, the values of the harmonic multiples of 3 are lower than the amounts registered in the other orders. The high levels of harmonics multiples of 3 indicate that the electric motor is suffering pro and against torque forces, which causes it to lose power and overheat when it is operated using the VFD [2].

The red dots in the figure 4 represent the harmonic emission limits established in IEEE 519 and IEC 61000-3-4 standards. It can be observed that THD limits established by the IEEE 519 Standard were not accomplished in any operation point.
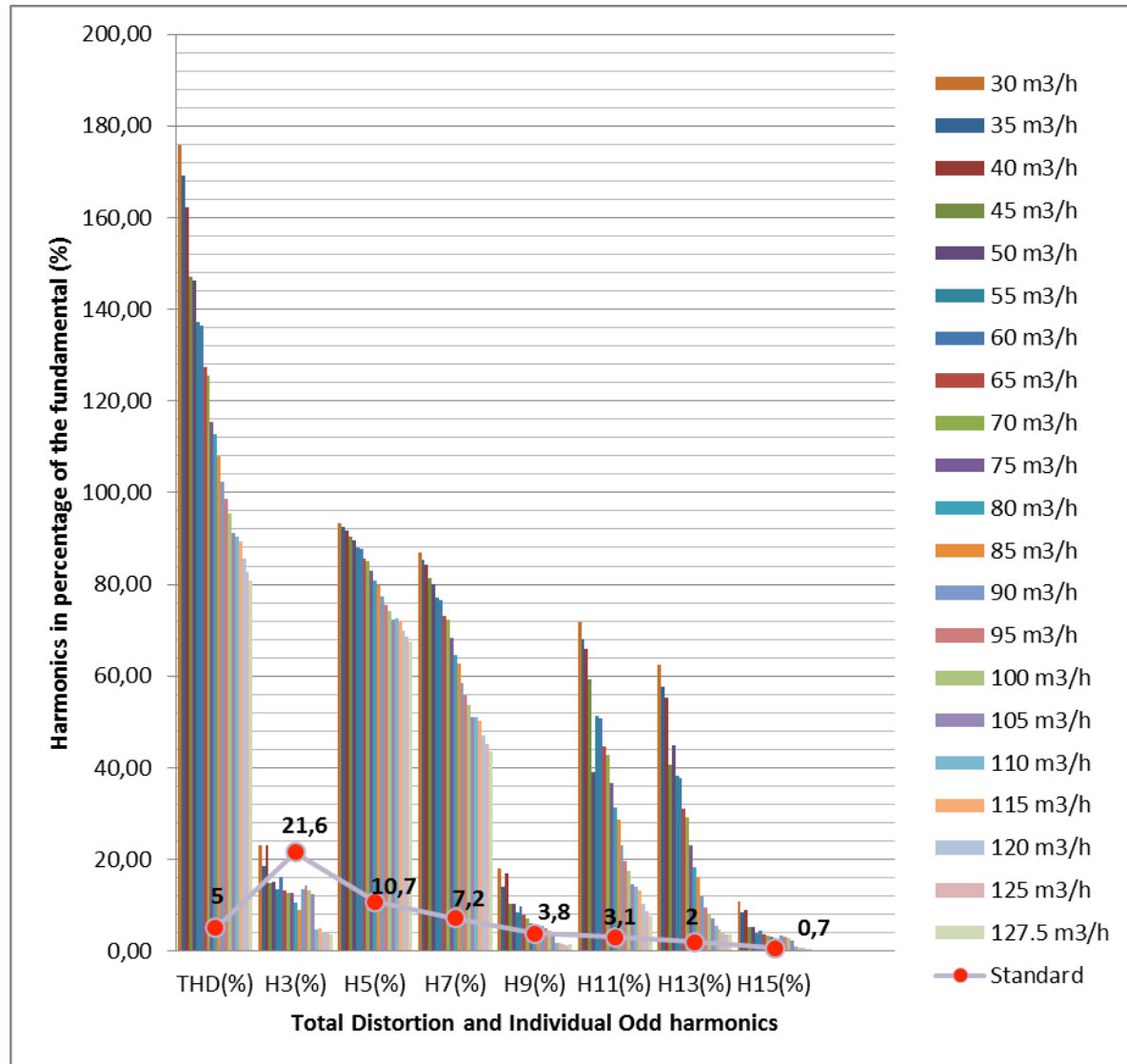

Figure 4. Comparison of THD and individual odd harmonic levels with IEEE 519 and IEC 61000-3-4 Standards [2]

The limits of individual harmonic currents of order 5-15 and at some points of order 3 were massively unaccomplished according to IEC 61000-3-4 Standard. As a particular case, it is recommended a prior diagnosis of the system's grid, which can be done by connecting a purely resistive load to identify and evaluate the harmonic currents that may be circulating and are unrelated to the pumping system [2].

6. Conclusions

With the development of this project, it was possible to put into question the effects that bring the use of VFD on the electric power quality. The use of VFD for flow regulation in pumping systems has as the main advantage, the energy savings, but the emission of large amounts of harmonics deteriorates its performance.

According to the information gathered, it was shown that VFD distorts the voltage sine wave and produces harmonic currents. In order to mitigate these problems, it is necessary to acquire additional devices such as filters for the elimination of harmonics or the use of shielded cables to conserve electromagnetic compatibility, which increases operation costs.

In terms of electromagnetic compatibility standards, it was found that the conditions established in the IEC 61000-3-4 standard in its execution to ensure its validity contains requirements that are very difficult to meet completely because of their stringency.

Finally, it was possible to identify that there is a need to consider additional costs that companies have to assume in order to ensure the quality of electric power when using a VFD. This must be done before purchasing and installing the VFD, since solving the problems caused by the presence of harmonics after having installed the machine usually consumes more time and money.

Acknowledgements

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