Electronic Improvements made for Industrial Valve

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Abstract

The paper puts in perspective the aspects of classic valve construction and the use of off-the-shelf products in order to improve the valve's features in terms of user interface, valve status in operating conditions and control interface to classic standardized communication protocols, such as EtherCAT®, ProfiBUS®. Because the resulting products are meant to be functional prototypes, most parts used for implementing new features will not be fully developed as for a sellable product, but only to the stage of proof-of-concept. To fully develop the used equipment will imply a dedicated study, which would allow the shift from general purpose use development boards and breakout sensor boards to application-specific equipment designed for assembly line manufacturing. The same study includes the use of Internet-of-Things in industrial environment and will be the subject of separate and dedicated article. The paper only mentions the possibilities and ways of achieving future design ideas.

Keywords: Optical limit switches, position feedback, temperature and humidity data, redundancy communication protocol, devices fault signalling

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1. Introduction

In this paper, the research project, entitled "Competitive equipment used for actuating valves used in transport and distribution networks of flammable gases", presents electronic improvements made to the prototype made in conjunction with the project partners, Icpe, INCDT "Comoti" and Aerofina. The prototype is an ATEX valve with features equal or greater than what can be found on the market.

Aerofina is in charge of making the housing and the mechanical system of the valve.

Icpe has to research and develop a competitive motor to power the valve, as well as suggesting and developing improvements to electromechanical subsystems used.

Comoti, as the main partner, offers guidance and support in developing the prototype in this knowledge transfer type of project. The improvements focus on three main aspects: ease of build, improved feedback and reliability, issues that occur in present valves. This includes using optical switches instead of mechanical ones, having better heat dissipation for moisture prevention system and conditional use of it, feedback for motor winding temperature, temperature and humidity, real-time feedback of the valve's butterfly position in increments of percentage.

Furthermore, this paper will present the possibilities of improving the classic construction by adding to the control box of the valve EtherCAT® and WiFi™ features by the use of inexpensive and off-the-shelf electronics.

Being an undergoing project, the prototype will be presented in its existing state and mention future changes that will occur or are considered to be studied for implementation, as a result to present configuration and tests made.

A great attention is given to the mechanical limit switches used, because of the difficulty of setting them up during assembly and difficult manufacturing of the contacting cams.

A limit switch is a device that operates one or more contacts based on its position set by an object. In most basic motor operating valve (MOV) actuator applications, that use traditional mechanical switches, a cam fastened to a shaft driven by a gearbox opens or closes an electrical connection. This way, a monitoring system can easily determine if a specific position of the valve is reached. This position is regularly the end position, but intermediary position contacts can also be implemented in some cases.

Other limit switch types include (but they are not limited) lever, roller plunger or whisker, varying in size and contact arrangement [1], [2]. Normally, limit switches for basic valve actuators contain at least 4 contacts.

Two are used for breaking the electric motor circuit when the valve reaches either one of the end positions (open or closed). The other two are used for signalling the position to the control system (Figure 1).

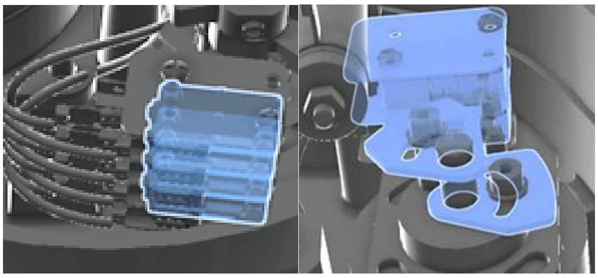

Figure 1. Limit switches (left), torque switches (right), actuated by camshaft

Such an example can be seen in Figure 1 on the left. Two torque switches can also be seen in Figure 1 on the right. They are used to prevent physical overloads, mostly, but not limited to, as a backup for a malfunctioning limit switch. They are tripped by the lateral displacement of the actuator's worm that turns and compresses a spring.

According to [3], mechanical switches can be vulnerable to breakdowns due to vibration. Other environmental factors, such as liquids, debris or fumes, can also cause malfunction, but in a MOV actuator casing these are limited. Another disadvantage shown in [4-google books] is in the design of the moving parts with problems such as over travel, travel speed and direction. The cams are rather challenging to develop and setup, in order to actuate the switch with adequate amount of force. This is one of the leading causes of limit switch failures.

Alternatives such as valve switches or proximity switches are also to be considered. Valve switches encapsulate their components within a metal enclosure.

However, this does not add much value to a switch that is already encapsulated in an enclosure that is itself certified for specific environments.

Among some of the newer technologies, Hall Effect sensors use a moving permanent magnet to create induction (electric current), sensed by the device. This eliminates the contact problems of mechanical limit switches, but they are susceptible to high magnetic fields [5]-[7]. Optical sensors use a light emitter to generate light and a light receiver to detect the presence of an object without physical contact [8].

In order to have this improvement to be more of an implementation than a new concept development, we took a look into the working principle of incremental encoders and apply it to our application [9].

Another issue addressed is the temperature inside the motor. Most induction motors have a fan mounted on the shaft ensuring air flow for cooling [10], but in this particular case the motor is in a confined space which renders the fan useless. As preventive measure, most of these motors have a thermal switch that disconnects the star/delta connection once a temperature limit is reached, but this solution is a fail-safe for preventing damaging the windings. Despite several achievements in numerous design aspects of electric machines, it is generally agreed that thermal design methodologies development lags [11]. A direct consequence of temperature rise is increased losses due to heat and decreased efficiency [12].

Permanent monitoring of the winding temperature [13] would not only ensure efficient use of the motor, but also would improve reliability and prepare the possible future product for Industry 4.0 implementation [14]. Although, the solution seems simple at first by simply introducing a thermal sensor inside the winding, data collection and communication imply difficult setup.

Because of thermal fluctuations of environmental air, moisture phenomena might occur. To address this issue, most valves have a heating system inside based on an always-on ceramic resistance connected to 220-240 V AC.

Reviewing older designs, it has come to attention that this part is one that often fails.

For the prototype, we address this issue in order to improve both reliability and power consumption.

Most valves work in closed or open position of the butterfly, but there are manufacturers who allow intermediate positions such as 25 %, 50 % and 75 % open/closed, by adding intermediary limit switches. In order to improve this, we decided to use an absolute encoder, to achieve increments of 10 % on opening or closing the valve.

There are several types of communication between devices and system control unit, of which most used are EtherCAT and Profibus. In order to be a competitive product we have to include at least these two into the product to a certain level.

2. Valve electronics

The butterfly of the valve has an extending shaft connected to it which, in classic construction has cams mounted which contact the switches see Figure 1 above.

Mechanical switches were replaced with optical switches mainly for reliability purposes and easier construction. Mechanical switches require complicated cams with special profile machined making them hard to manufacture. What is more, these cams need to be placed very precisely in order to make contact with the roller mounted of the cantilever of the switch and the worker who assembles it must also take into consideration the length of the cantilever and possible deflection of it while it is pressed.

Taking into consideration that any system of this kind is made up at least four switches, there is a considerable amount of time spent on adjusting during assembly phase.

To address the above issues, we turned to the use of optical switches which simplifies both construction and assembly.

According to their construction optical switches can function and be utilized in different modes. The switches have an infrared light source and a receiver in the form of a phototransistor sensitive only to infrared light. Detection is made in two ways: one involves having the emitter and the receiver facing each other and an obturator obstructs the beam of light; the other one implies having the emitter and receiver mounted at angle facing flat surface, such as the receiver catches the reflected beam of the emitter if the surface is white or has reflective properties.

In order to reduce costs, we opted for off-the-self sensors which come in different variants, in terms of the signal level (LOW, HIGH) they send once the beam is interrupted or not reflected. The sensors we used were beam interruption type which sends HIGH if the beam is interrupted.

An alternate method was to use magnetic sensors and circular discs with magnets mounted on the butterfly shaft. This was discarded because not only required in-house electronics to be developed, but also the discs with magnets involved both undesired manufacturing and magnet costs.

Because the optical sensors only work with 5 V DC, it was required to add 5 V relays driven by these sensors. These are also off-the-shelf parts, complete break-out boards, which function on a 5 V power supply with their inputs having pull-up resistors. Because of this, if the optical sensors are directly connected to the relay boards, as soon as they had power they would switch the relay on, while the beam was not interrupted.

At first, an additional electronics board made from optocouplers was developed to inverse the signal, but because of space considerations, it was removed and the obturator was replaced with a disc which had a slot machined on the side to let the beam pass and detect a limit position (see Figure 2).

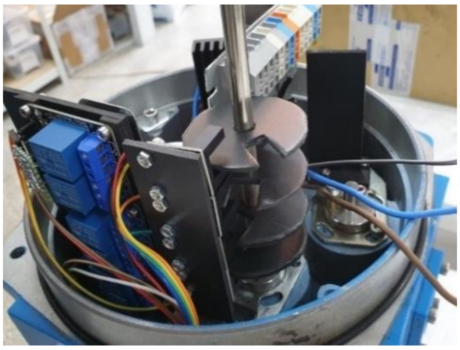

Figure 2. Experimental model of valve.

This configuration was used only for four out of six switches. For the two used for torque limiting, there was not enough room for the disc.

In order to improve reliability, besides the classical thermocouple used in the motor winding which disconnects the star/delta connection in case of temperature reaching 130 °C, we inserted a temperature sensor into the winding to have continuous feedback.

The fact is that being a PT1000 sensor, which has a temperature dependent resistance, there was a need to make it easily read by the controlling PLC of the valve.

The problem was that the PLC controlling the valve might be up to 100 meters away, the added cable length to the thermal sensor would induce differences in measurements and a software adjustment. PLCs do in turn measure either a difference of voltage (0-10), or a variation of current (4-20 mA). For this, we found an adaptor (see Figure 3) to which you can connect several types of thermal sensors: PT1000/PT100/NI100 and it can be programmed via mobile phone through RF.

Figure 3. PT1000 adaptor

This adaptor translates the change in resistance into current variation.

Because of thermal variations, either induced by the fluid temperature in the pipes connected to the valve, or induced by environmental temperature, moisture phenomena occur inside the valve, which is detrimental to both electronics and mechanical parts alike.

To address this, instead of using a usual ceramic resistor, we installed a resistor with an aluminium shell which was mounted onto a radiator (Figure 4).

Figure 4. Anti-moisture resistor

Between the resistor housing and the radiator, we applied CPU-grade thermal paste, to improve heat transfer from the resistor to the radiator and in turn, to the air inside the valve.

Another feature addressed is that of real-time position of the butterfly-shaft. Most valves have the working principle of a valve, with closed or open position.

For this reason, they have limit switches at both ends of the butterfly stroke, doubled by other two for safety, as there are some cases when the fluid in the pipe forces beyond the intended stops. Depending on their size and constructions, some valves also have a pair of switches for detecting the torque inside the worm gear, which engages the butterfly, the play of the worm being transformed into rotation of a shaft which can then be detected by the switches.

Real-time position of the shaft would provide further functionality of the valve.

To accomplish this, it was proposed at first an incremental quadrature encoder with 1024 pulses per channel, but after further considerations, it was rejected as it implied additional electronics for gathering the 5V signal it uses and translate it to the PLC alongside the disadvantages of it being incremental and not absolute.

We turned to the use of an angular absolute encoder based on a potentiometer. This could be easily used with the PLC as it would divide a 10V source as it rotated.

Again, disadvantages outweighed the advantages, as implementation involved additional electronics and mechanical adaptation parts and initial positioning during assembly.

The solution came in the form of an absolute encoder with 16 bits of resolution, redesigned for 90 ° rotation with overstepping of 27 ° in both directions. This would not only provide information about position in increments of 9 ° (10 %), but also would be a redundant system for the limiting switches.

For the first iteration of the prototype, communication with the valve relies solely onto the capabilities and features of the PLC used for controlling the system, as most of the attention was focused onto achieving a working basic prototype. Despite this, we also took a short look into how we would implement EtherCAT® and Profibus. WiFi™ was also studied as a possibility, either just for relaying information about that status of the valve to the user, or to provide full communication and control. This is subjected to furthermore research in order to be implemented.

3. Testing and results

The replacement of mechanical switches with a system developed on the use of optical switches and relay boards did solve manufacturing issues, but created other issues: volume occupied, price and reliability.

It is observed looking at Figure 1 and Figure 2, that there is a massive difference in volume between the boards with electronics and the simple mechanical switches (in blue).

There is also a matter of a slight price increase, as the electronics do cost more, but it is a fair trade as manufacturing time and price decreases when referring to the special cams production time and assembly mounting time used in conjunction with the switches.

Out of the box, the electronics are not waterproof; as mentioned above, moisture phenomena might occur. To make them waterproof they need to be potted with an insulating material or sprayed with enamel for electronics.

A basic test of functionality was undergone to verify the system of optical switches and relay boards. The shaft with four discs with cut-outs was rotated and we checked the engagement of the relays.

What is more, each optical sensor and each relay has optical feedback in the form of a red led which relates its state.

Lacking the availability of a PLC, the subassembly used for measuring the temperature inside the motor composed of a PT1000 temperature sensor and PT1000 adaptor was not verified through a specific test, as the functionality of the adaptor was not in question. We did measured instead the temperature inside the motor during qualification test, as the motor was designed to work in S4 conditions [15].

The PT1000 sensor was connected to a temperature module of the LabView setup made for the S4 duty cycle test and the evolution in time of the temperature was recorded.

The accuracy of the measurement was verified once the temperature reached the plateau value and compared to the measured value of temperature via a handheld device with temperature probe which was in contact with the motor housing.

The evolution inside the valve of the temperature and humidity, while the anti-moisture resistor was under power, was measured by using a setup composed of a microcontroller based development board connected to a laptop, a calibrated humidity and temperature sensor module, a RTC (Real Time Clock) module and a SD card reader/writer module.

The software was written in a C++ IDE.

The microcontroller took the time and date from the RTC, verified if 10 seconds had passed; when 10 seconds were registered, it then acquired temperature and humidity data which was then written in a .txt log file on a SD card installed in the SD module and also showed the values onto the laptop screen.

Temperature verification was made by the use of a thermal camera (Figure 5), which also showed that the anti-moisture resistor plateaued at around 88 °C and it was powered by 230 V 50 Hz Ac; the temperature of the resistor was measured via a dedicated device with contact temperature probe.

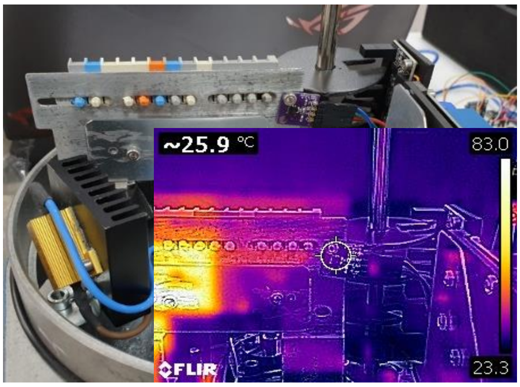

Figure 5. Temperature verification

During the test, which took about one hour, the temperature and humidity stabilized after about 45 minutes.

At first, the temperature and humidity module was used for testing purposes only, but it was considered at a later time to be an important addition to feedback elements for the valve as a product and a strategy of including it in the final product was studied.

Another test made, outside the valve, was for determining the influence of 100 meters length of terminals for the PT1000 sensor. For the test, two PT1000 sensors were glued onto a metal plate, one sensor with 30cm terminals and the other with 30 cm plus 100 meters. The metal plate as heated with an industrial heater-blower and a table of measurements was made; different temperatures were measured by a dedicated device and were noted in column one of the table, which corresponded to measured resistance values of the two PT1000 sensors (the values for the sensor with short terminals were noted in column two, and the for the other sensor in column 3). The resistances were measured using a dedicated RLC meter. The formula used to convert the resistance to temperature was (for 0 °C to 850 °C range) [16]:

$$R_t = R_0(1 + At + Bt^2)$$

$$A = 3.9083 * 10^{-3} {}^{\circ}C^{-1}$$

$$B = -5.775 * 10^{-7} {}^{\circ}C^{-2}$$

A graphical interpretation of the data collected led us to the conclusion that the temperature of both PT1000 sensors had the same evolution with the difference that the one with longer terminals had an offset corresponding to the resistance of the terminals in conditions of constant environmental temperature.

For making these tests, a software algorithm was developed for each and every breakout module, testing their functionality. After determining that they could be used, a breadboard made from all of them was made and a testing software was made to include all.

4. Discussion (changes)

During mounting of the Infra-Red U-shaped sensors of the travel and torque limiting systems, we observed that installing both relay boards and sensors, the space inside the valve is greatly reduced. In order to resolve this issue, in the following months of the project we will mount a sealed box outside the valve in which all electronics will be mounted. By installing this box outside the valve and placing most of the electronics inside, greatly reduces the risk of corrosion of the printed circuit boards.

We also observed that the height of the stacked U-shaped sensors was higher than the stack of normal limit switches and we looked into how we can make it more compact. We concluded that it is better to replace the interruption type IR sensors with reflective type, mainly because we can mount more sensors of this type in a smaller space and the detection markers can be easily printed onto a cylinder.

There are two types of IR reflective sensors:

- analogue (RA);
- so-called digital (RC).

The differences are at the level of their output; the analogue one has the phototransistor connected to V CC via a pull-up resistor and the output varies according to the amount of light it receives, while the digital one has an RC circuit above it connected to V CC and requires a microcontroller for measurement, because of the way it functions. For the digital type, the output alternates to an input as the capacitor is firstly charged (input) and then the microcontroller measures the time it takes for the capacitor to discharge via the phototransistor, which corresponds to the amount of light it receives.

We chose two sensor boards, one with 2 sensors and one with 9 sensors of RC type IR reflective sensors. Four of these 9 and the 2 sensor board were converted to analogue type sensors and their signal passed through a 74HC14 hex inverter Schmidt trigger in order to pass the signal directly to the relay boards, not passing them through a microcontroller. The hex inverter Schmidt trigger is required to change the analogue signal received from the sensors to a digital signal, the thresholds at which this happens being very close to logic level thresholds. For example, if the input voltage is greater than 2 V, the output is LOW (inverting) and if the voltage is less than 0.6 V the output goes HIGH.

The other five sensors are going to be used as an encoder with 4 bits of resolution (4 sensors), the fifth sensor being used to indicate the exact position for the valve being opened 50 %. The encoder is based on any typical 4 bit encoder in terms of function. It is important to mention that the encoder will have a Grey code [17], [18] type reflective area and the pattern will not be radially distributed, but axially reducing the required space for mounting and the encoder works only on 144°, not 360 ° as any other encoder, giving the possibility of mounting a second row of sensors in mirrored position for redundancy (some additional signal processing would be required, such as introducing OR gates). The grey code is usually used for encoder applications mainly because only one bit changes at a time and there are fewer detection slots/reflective slots required.

Four bits of resolution translates to 16 detectable positions and they are distributed in the following manner: 10 positions between 0 ° and 90 ° (the working angle of the valve's butterfly, 3 positions between -27 ° and 0 °, 3 positions between 90 ° and 117 °. Only 10 position were chosen for the working angle in order to command the valve to open in increments of 10% percentages, while the other 6 can be used to detect faults such as moving past the close/full open positions. The signal going directly to relay boards will also be sent to the microcontroller.

The positioning of the valve's butterfly will be done with respect to its direction of movement. For example if the valve is at 0°and a command is given to open 20%, the butterfly will start and rotate, the encoder reads position 0-10 %, then 10 %-20 % and it will stop as soon as the reading is 20 %-30 %; also, if the command is given to close to 10 %, the motor will start turning the butterfly and the encoder will measure 20 %-30 %, then 10 %-20 % and the microcontroller will give command to stop as soon as the encoder reads position 0-10 %.

In Figure 6, below you can see the breadboard grey code used to test the sensors in unravelled form (of the cylinder side), with dimensions of 62.832x36 mm corresponding to an angle of 144 ° of a Ø 50 mm cylinder.

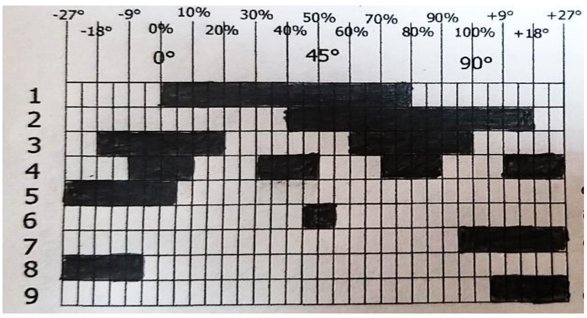

Figure 6. Grey code reflective strip pattern

The first 4 rows are for the 4 bits; the 5th row is for 0 ° position (signal for PLC), the 6th row is for 50 % open (45 °), the 7th row is for closed position(signal for PLC) and 8th and 9th are for direct motor supply cutout for end positions.

The code is still under debate, as it might be required for some rows to change the black to white and the white to black, because there are several signal inversions made: the action of the hex inverter, the optic switch of the relay which activates it when LOW signal is received.

As a laboratory test, we installed a temperature and humidity sensor inside the valve to measure the enclosure and we concluded that we can incorporate it into the final product. The sensor will be measured by a separate microcontroller with WiFi capability. Being an experimental product, we can test in this way if in the long term, the anti-moisture resistor is correctly calculated to prevent moisture apparition. The data would either be readily accessible or sent to a certain terminal.

In order not to keep the anti-moisture supplied with power continuously, we developed a thermostat based on an 8-pin microcontroller. It measures a PT1000 sensor placed on the radiator of the resistor. Once the measured temperature reaches 85 °C the relay turns off power supply, powering on only when the temperature falls below 50 °C.

In Figure 7, you can see the schematic of the board.

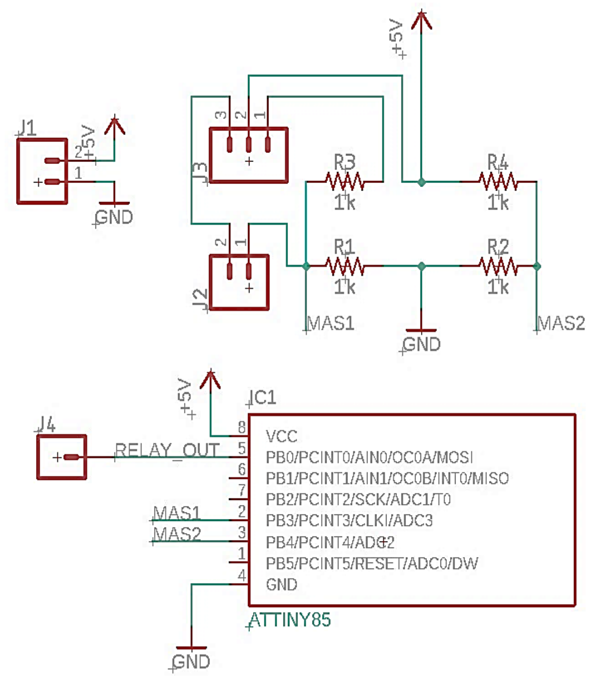

Figure 7. Microcontroller based thermostat

The board has a Wheatsone bridge with its measuring nodes connected to the microcontroller ADC's. The connectors are as follows: J1 is the power connector, J2 is the temperature sensor connector, J3 is a selector pin header (selection between PT1000 probe and bridge test resistor), J4 connection for output to relay.

After the board was made, its functionality was tested, and the values measured were verified. The accuracy of the ADC is of 10bit resolution, the value measured being a representation of the voltage present on that ADC channel with a correspondence of 0 to 1023 for 0 V to 5 V.

From the difference in voltage on the two nodes, the resistance of the thermistor is calculated. Depending on which voltage is bigger from the two (measured at the nodes), the algorithm chooses if the temperature is negative or positive; based on this, the resistance is introduced in one of the following formulas, for negative temperatures-(1) and for positive temperatures-(2):

$$R_t = R_0[1 + At + Bt^2 + C(t - 100°C)t^3] \quad (1)$$

$$R_t = R_0(1 + At + Bt^2) \quad (2)$$

where:

A = 3.9083 x 10-3 °C -1

B = -5.775 x 10-7 °C -2

C = -4.183 x 10-12 °C -4

Regarding control and communication, the basic functions will be controlled by a PLC which will be situated in a control box no more than 100 meters apart from the valve.

Functions such as intermediate positions detected via microcontroller will be sent wirelessly to the PLC in the following manner: the microcontroller will have a 433 MHz RF emitter on the valve side and another microcontroller will have a 433 MHz RF receiver and a four-output board (either relays, solid-state relays or optic isolators) connected to four PLC inputs which will represent a 4 bit value for data transfer between the microcontroller and the PLC. This will be considered as an optional feature when the intermediate positions will be needed inside the PLC software.

Other functions such as temperature and humidity of the valve chamber and position data can be viewed using 2 methods. One method is to have a WiFi router in the vicinity of the valve/control box. The microcontroller with WiFi capability (ESP32) will have a simple html page which will only show the data and will be accessed by calling the device IP only on the local network [19]. The other method is to have one ESP32 mounted in the valve's electronics box and a second one installed in the user's terminal (PC/laptop), the communication can be done without the need of a WiFi infrastructure, through a direct protocol specially designed for ESP32/ESP8266 microcontrollers called ESPNOW, which is similar to 2.4 GHz connectivity between a mouse and it's dongle.

At current stage in the project, we only tested the functionality of the microcontrollers with WiFi capability, sending data from one to another as proof-of-concept. We are yet to implement this into the current application, and we are also considering changing the microcontroller board situated in the control box to a raspberry pi, because of the greater functionality that it offers.

It could be used as a server for visualizing data and valve control by the means of EtherCAT [20] which can be implemented in this platform.

5. Conclusions

The main objective of the project is that of knowledge transfer from the project managing partner to the other two partners, Icpe and Aerofina.

Icpe has the main objective of developing an AC reversible motor to be used in valve with ATEX protection and improve on features of data visualization and control as a secondary objective. We did not focus on classic features as EtherCAT® communication or ProfiBUS®, as it mainly dependent on what type of PLC it is used inside the control box. In that matter, we searched a solution to implement both classical standard communication protocols and Internet-of-Things by the use of off-the-shelf inexpensive development boards and breakout sensor boards. The final outcome of the project will consist of three sizes of valves, the medium one having the new features described and they will be presented as working prototypes. Being a working prototype implies the use of off-the-shelf components in order to verify the concept developed.

In a future study the shift from general purpose components to purpose-built components (application based) will be developed and a separate and dedicated article will present its findings.

6. Bibliographic References

[1] S.L. Herman, Industrial Motor Control, 7th Edition, 2014, Delmar, Clifton Park, NY, USA, pp. 118-119;

[2] G. Guajardo, J. Pankiewicz, Sizing and applying limit switches, 2007, www.machinedesign.com, accessed: 2019;

[3] B. Nesbitt, Handbook of Valve and Actuators, 1st Edition, 2007, Elsevier, Oxford, UK, p. 334;

[4] D. Lobsiger, P. Giuliani, K. Rexford, Electrical Control for Machines, 7th Edition, Cengage Learning, Boston, USA, 2016, pp. 319-321;

[5] V. Mosser, Y. Haddab, Real-time broadband subnoise level signal extraction in Hall sensors, 22nd International Conference on Noise and Fluctuations (ICNF), Montpellier, France, June 2013;

[6] W. Chen, F. Du, Y. Zhuo, M. Anheuser, IEEE International Instrumentation and Measurement Technology Conference, Binjiang, China, 2011;

[7] G. Liu, B. Chen, X. Song, High-Precision Speed and Position Estimation Based on Hall Vector Frequency Tracking for PMSM With Bipolar Hall-Effect Sensors, IEEE Sensors Journal, Vol. 19, Issue 6, 2019;

[8] B.G. Liptak, Process Measurement and Analysis, Instrument Engineers' Handbook, Fourth Edition, pp. 966-937;

[9] Walt Kester, Optical encoders, Analog Devices MT-029 Tutorial, www.analog.com, accessed: 2020;

[10] Ying Huai, Roderick V.N. Melnik, Paul B. Thogersen, Computational analysis of temperature rise phenomena in electric induction motors, Applied thermal engineering, ELSEVIER 2002

[11] A. Bousbaine, Thermal modelling of induction motors based on accurate loss density distribution, Electr. Machines Power Syst. 27 (1999) 311–324.

[12] Bogdan Dumitru Vărăticeanu, Paul Minciunescu, Daniel Fodorean, Mechanical Design and Analysis of a Permanent Magnet Rotors used in High-Speed Synchronous Motor, EEA 2014 | vol. 62 | nr. 1 | art.1

[13] R. Beguenane, M.E.H. Benbouzid, Induction motors thermal monitoring by means of rotor resistance identification, IEEE Trans. Energy Convers. 14 (3) (1999) 566–570.

[14] Saurabh Vaidyaa, Prashant Ambadb, Santosh Bhoslec, Industry 4.0 – A Glimpse, Procedia MANUFACTURING, ELSEVIER, Volume 20, 2018

[15] IEC 60034-1

[16] IEC751 / ITS-90

[17] Shima Nouhi, Fateme Sadat Hoseini, Seyed Amidedin Mousavi, Gray Code and its Application in Rotary Encoder Sensors, researchgate.net October 2019.

[18] Robert W. Doran, The Gray Code, Journal of Universal Computer Science, vol. 13, no. 11 (2007), 1573-1597

[19] Alexander Maier, Andrew Sharp, Yuriy Vagapov, Comparative Analysis and Practical Implementation of the ESP32 Microcontroller Module for the Internet of Things. 10.1109/ITECHA.2017.8101926.

[20] Jacek Stój, Ireneusz Smołka, Temporal Characteristics of CodeSys Programmed Raspberry Pi and Beaglebone Black Embedded Devices. researchgate.net June 2019, 10.1007/978-3-030-21952-9_12.

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