Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 31
ISSUE 2
December
2008

System integration of a multivariable process plant utilising an intelligent control technique

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Received 22.10.2008; published in revised form 01.12.2008

Analysis and modelling

ABSTRACT

Purpose: The research objective is to maintain a desired process outlet temperature. Firstly, communication between the control system and the process field devices by means of Profibus-PA and Profibus-DP is established. Secondly the process flow rate and level in the supply vessel must be controlled in the same system. The final manipulated variable, an air-to-open control valve is regulated to achieve the research objective [2]. The paper will discuss introductory aspects of Profibus and simulated results on the knowledge based controller as the research is on-going.
Design/methodology/approach: The research project comprises the design, engineering and analysis of a multi input/output rule-based process control system on the Profibus communication platform. A programmable logic controller is configured to control the plant and a Profibus system is used to communicate input and output signals between the field instrumentation and the process control system.
Findings: The plant and control knowledge derived for the design of the decision-making control algorithm in the research was obtained from available data in the open-loop mode as the plant is still to be commissioned. The designed algorithm will be tested on the process plant in comparison with the simulated results in order to evaluate its feasibility in a networked control system for temperature, level and flow on a Profibus-DP and Profibus-PA network. A mathematically-based control strategy will contribute to increasing the settling time tremendously thereby impacting negatively on factors like production time and quality.
Practical implications: The process control system will monitor and control measured variables such as flow, temperature and level on a typical industrial plant. The plant will be used to transfer technology education and training to industry and practitioners alike.
Originality/value: The control strategy emerging from this research may be applied to similar process plants in industry.
Keywords: Profibus; Intelligent control; PLC (Programmable Logic Control)

1. Introduction

Profibus is the powerful, open and rugged bus system for process and field communication in cell networks with few stations and for data communication. Automation devices such as PLC's (Programmable Logic Controllers), HMI's (Human Machine Interface), sensors or actuators can communicate via this bus system. The IEC 61158/EN 50170 standard makes allowance at the same time for the future since existing plants can be expanded using components that conform to the standard. Profibus is part of TIA (Totally Integrated Automation), the uniform, integrated product and system range from Siemens for efficient automation of the entire production process, for all sectors of industry [1].

Control solutions based on traditional methods use mathematical models made up of one or more equations. Coming up with the equations for the system consists of examining the system, determining what the response is, and then developing a set of equations that produce the same output over the desired range. Equations resulting from this step are referred to as ODE's (Ordinary Differential Equations). The second technique is based on a rule base architecture by means of an intelligent decision-making process. It entails plotting a set of inputs to outputs, to form a two- or three-dimensional surface. This is a powerful approach because it allows the observation of system stability more easily. The major advantage in this technique is that process automation and control objectives are established more efficiently and effectively [2].

The research objective is to maintain a desired process outlet temperature. Firstly, communication between the control system and the process field devices by means of Profibus-PA and Profibus-DP is established. Secondly the process flow rate and level in the supply vessel must be controlled in the same system. The final manipulated variable, an air-to-open control valve is regulated to achieve the research objective [2]. The paper will discuss introductory aspects of Profibus and simulated results on the knowledge based controller as the research is on-going.

2. Research overview

When a Profibus device is added in the control system configuration, the device gets new memory space assigned, which does not conflict with the existing configuration. The existing configuration and program does not need to be edited. This makes Profibus the perfect for 'instrument expansion' or 'complete machine copying' [3].

The main problem in maintaining a consistent temperature is nullifying the effect of outside influences, as seen in Fig. 1, and the fact that there exists a time delay on the principle of temperature measurement. For example, when the inlet process flow rate varies or the supply vessel level varies, the desired outlet process temperature can be greatly affected, and it becomes necessary to quickly readjust it to the desired value. The other contributing factor, the time delay, also affects the optimisation of the process temperature control drastically, due to the fact that temperature measurement is based on the principle of absorption, introducing an added problem [4].

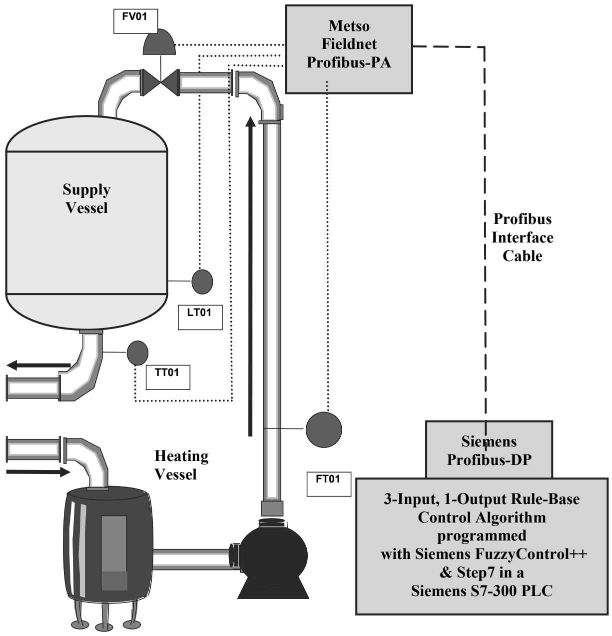


Fig. 1. Process plant layout

3. Profibus protocol

The three variants that have been specified for different applications are as follows:

- Profibus-FMS (Fieldbus Message Specification):- required for automation in general, at universal speed, on a wide range of applications.
- Profibus-DP (Decentralised Periphery):- required for manufacturing automation, for faster data processing. Required for efficient and cost effective applications.
- Profibus-PA (Process Automation): required for process automation. Processing is application-oriented. Required for intrinsic safety and bus powered applications. It is one of three Profibus variants that are compatible with each other.

In the research project, Profibus connects the process control stations and automated systems with the field devices, thus replacing the analogue 4 to 20 mA transmission technique. In addition to the simple start-up and self-diagnostic functions, the fast fieldbus communication provides the user with the option of realising real-time capable state control systems as well as monitoring status and error messages parallel to the process [1].

Profibus-PA was mainly designed for applications in explosion hazardous areas. This technology makes possible for the power supply over the bus, however, it can also be used for other production facilities. Bus technology combined with the two-wire technology simplifies the construction of plants in many areas without having to give up known device standards and connection techniques.

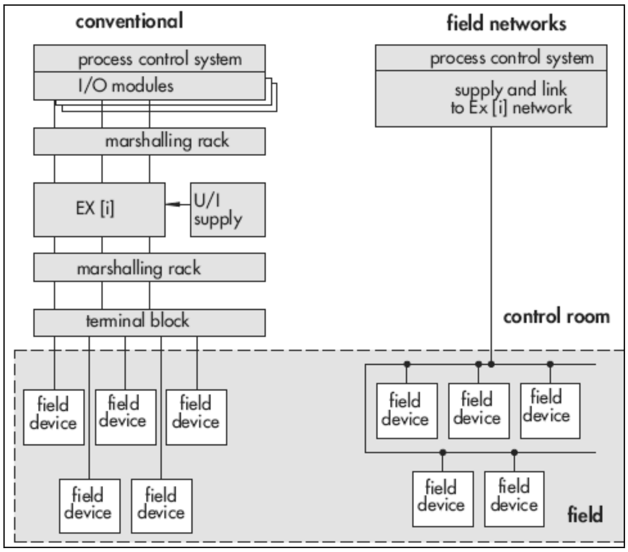


Fig. 2. Transmission networks [5]

The comparison in Fig. 2 shows the differences in the wiring of a bus system schematically. Connected with this are extended device functions as well as new terminology. A segment coupler is installed between the Profibus-DP and the PA segment. It adapts the different transmission techniques and powers the devices of the PA segment.With Profibus-PA, as with DP, three device types can be differentiated as follows:

- Class-1 master (DPM1) is the central control unit of a system, e.g. a PLC, which exchanges data with the field devices within a specified message cycle. All measured values and set point values required to control the system as well as the device status data are transmitted. When compared with conventional techniques, the cyclic communication of the class-1 master assumes tasks of the analogue 4 to 20 mA standardised signals and additionally enables the bidirectional exchange of data.
- Class-2 masters (DPM2) are used for operation and monitoring purposes as well as during start-up. The associated exchange of data takes place if required. Therefore, class-2 masters require acyclic communication services exclusively.
- A slave is a peripheral or field device which communicates only when requested by a master. Actuators receive input information from the master and actively influence the process. Sensors collect state and process data and provide the master with this information (Samson AG, 2008).

A study conducted by NAMUR (standardisation committee of the instrumentation and control industry, AK 3.5) showed that compared to conventional systems, Profibus-PA achieves cost savings of more than 40 % in planning, wiring, start-up and maintenance. At the same time, users gain a variety of functions as well as a considerable amount of safety [5].

Figs. 3 and 4 represent a comparative analysis of field interfacing based on conventional and Profibus technology. Fig. 5 represents a comparative analysis of panel wiring based on conventional and Profibus technology. The benefits of Profibus technology can clearly be seen from these Figures [5].

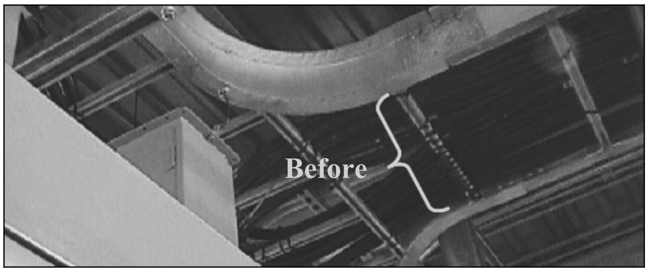


Fig. 3. Field wiring before Profibus technology (Courtesy Emerson Process Management)

Fig. 4. Field wiring after Profibus technology (Courtesy Emerso Process Management)

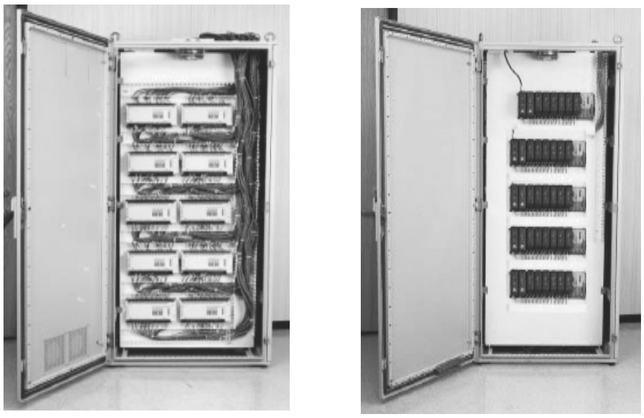


Fig. 5. Panel wiring before (on left) and after (on right) Profibus (Courtesy Emerson Process Management)

The final correcting element in the research project is a Metso control valve based on Profibus-PA, IEC61158-2, EN50170-2 with an intelligent fieldbus positioner. To ensure the optimum solution for a wide range of specific applications, the positioner has been developed for both Foundation Fieldbus H1 and Profibus PA. On-line valve diagnostics are continuously stored throughout the life of the device. Essential on-line valve diagnostics maximise run-time performance and can reduce valve maintenance expenditure by up to 50%. The performance trends of the valve and its impending need for servicing are closely monitored and maintenance can be planned [6].

4. Intelligent control technology

The aim of the control strategy in this research project is to maintain a constant process outlet temperature by means of intelligent technology, in order to improve on control stability. A three-input one-output knowledge-based controller is configured as shown in Fig. 6.

The control algorithm is not confined to standard mathematical limits, but is configured for specific process conditions, i.e. steam flow, process temperature, steam valve, temperature valves. Research and development on the project is conducted in collaboration with tertiary education and industry, focussing on optimising control.

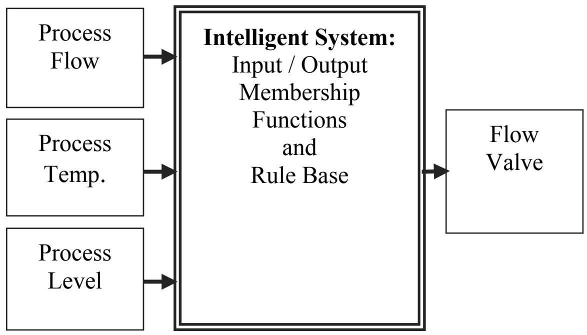


Fig. 6. Intelligent control strategy

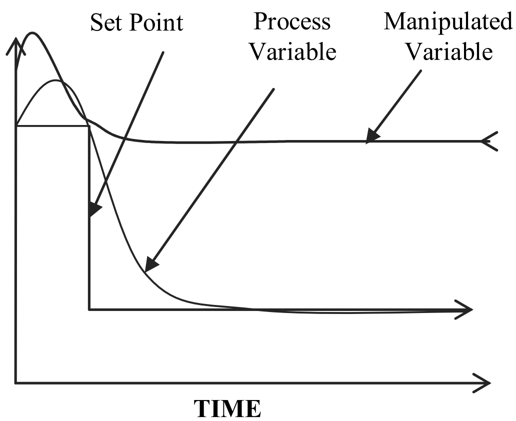


Fig. 7. Anticipated response of the intelligent control algorithm

Fig. 7 represents the proposed response of intelligent technology, one that is responsible for intelligent decision-making. The response of the control algorithm minimises instability, optimising control, thereby improving on plant efficiency and product quality [7].

The technology comprises a framework that is specified by two types of human knowledge:

- Plant Knowledge, referred to as indirect adaptive: IF-THEN rules that describe the behaviour of the plant e.g. "IF the flow control valve opens, THEN the process flow will increase", where "open" and "increase" are characterised by sets. The plant knowledge comprised the physical, visual status of the plant. The positions of the manipulated variables and the process variables were monitored, in order to maintain a desired process temperature.
- Control Knowledge, referred to as direct adaptive: control rules that state in which situations what control actions should be taken, e.g. "IF the process flow increases, THEN the output of the controller should decrease", where, "increase" and "decrease" are characterised by sets. The control knowledge comprised the actual transmission signals of measurement and control data of the three process loops [8].

5. The intelligent controller architecture

Siemens FuzzyControl++ software configuration tool is used to develop a three input-one output controller based on the following plant and control variables:

- Process temperature
- Process flow rate
- Process level
- Position of flow control valve
- Input data signal for temperature
- Input data signal for level
- Input data signal for flow
- Output data signal for flow

The generic structure of the intelligent controller is represented in Fig. 8:

- Editing inputs – the data from the plant is converted to membership functions.
- Fuzzification – the grouped, real values are converted to fuzzy values.
- Inference – IF-THEN rules are assigned to process the fuzzy values, that specify the control strategy.
- Defuzzification – the data generated from the control algorithm is converted back to real values.
- Editing outputs – the real values are converted to membership functions, to be generated as corrective signals to the plant.

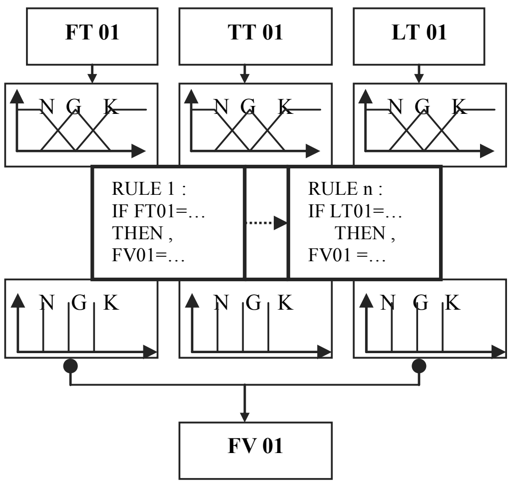


Fig. 8. Generic structure of the 3-Input, 1-Output Controller

Fig. 9 and Table 1 represent the edited input membership function in trapezoid form, for only fluid temperature. This facilitates fuzzification of a crisp value by scaling and mapping the input's domain, a linguistic variable, into an internal computer code. Table 2 represent the edited output membership function in singleton form, for the process control valve. This facilitates de-fuzzification of the internal computer code to a crisp value by scaling and mapping the output's domain [9].

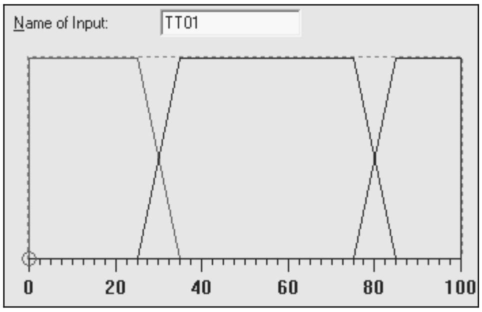


Fig. 9. Edited process temperature (graphical)

Table 1.
Edited process temperature (actual)

MEMB. FUNCT.	PT 1	PT 2	PT 3	PT 4
L_tem	0.0	0.0	25.0	35.0
M_tem	25.0	35.0	75.0	85.0
H_tem	75.0	85.0	100.0	100.0

Table 2.
Edited flow valve (actual)

MEMB. FUNCT.	VALUE
FF_clo	0.0
F_clo	10.0
SS_clo	25.0
S_clo	35.0
half	50.0
S_ope	65.0
SS_ope	75.0
F_ope	90.0
FF_ope	100.0

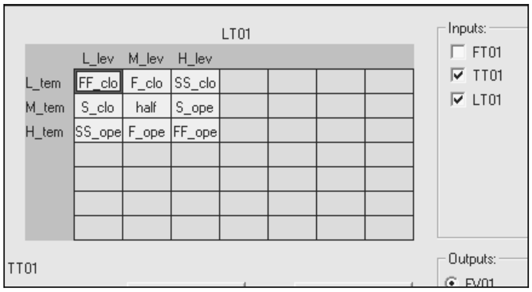
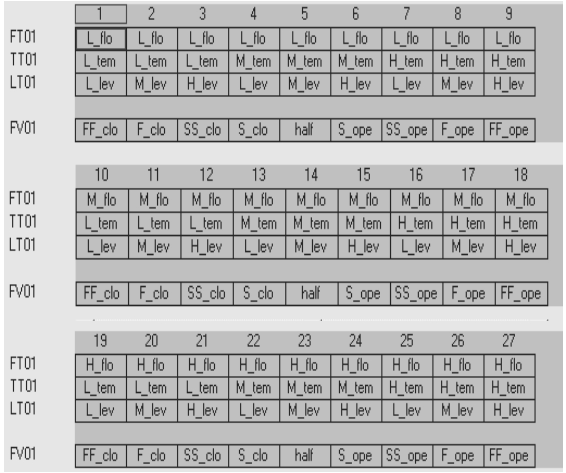


Figure 10: Rules for Level and Temperature

Fig. 10 represents only the rules assigned to the process temperature and level, for the valve position to regulate the process medium as indicated in Table 2, out of the twenty seven rules for the system as indicated in Fig. 11. The system can be configured with up to two hundred rules in total. The facts and rules (declarative knowledge) are represented separately from decision-making algorithms (procedural knowledge) [10].



	1	2	3	4	5	6	7	8	9
FT01	L_flo	L_flo	L_flo	L_flo	L_flo	L_flo	L_flo	L_flo	L_flo
TT01	L_tem	L_tem	L_tem	M_tem	M_tem	M_tem	H_tem	H_tem	H_tem
LT01	L_lev	M_lev	H_lev	L_lev	M_lev	H_lev	L_lev	M_lev	H_lev
FV01	FF_clo	F_clo	SS_clo	S_clo	half	S_ope	SS_ope	F_ope	FF_ope

	10	11	12	13	14	15	16	17	18
FT01	M_flo	M_flo	M_flo	M_flo	M_flo	M_flo	M_flo	M_flo	M_flo
TT01	L_tem	L_tem	L_tem	M_tem	M_tem	M_tem	H_tem	H_tem	H_tem
LT01	L_lev	M_lev	H_lev	L_lev	M_lev	H_lev	L_lev	M_lev	H_lev
FV01	FF_clo	F_clo	SS_clo	S_clo	half	S_ope	SS_ope	F_ope	FF_ope

	19	20	21	22	23	24	25	26	27
FT01	H_flo	H_flo	H_flo	H_flo	H_flo	H_flo	H_flo	H_flo	H_flo
TT01	L_tem	L_tem	L_tem	M_tem	M_tem	M_tem	H_tem	H_tem	H_tem
LT01	L_lev	M_lev	H_lev	L_lev	M_lev	H_lev	L_lev	M_lev	H_lev
FV01	FF_clo	F_clo	SS_clo	S_clo	half	S_ope	SS_ope	F_ope	FF_ope

Fig. 11. Rules for level and temperature

6. Analysis of rule base

In order to clearly analyse all input signals the process flow rate input signal was set for 2 cycles per screen, 10% aspect ratio, 0% phase angle, the process temperature input signal was set for 3 cycles per screen, 50% aspect ratio, 0% phase angle and the process level input signal was set for 4 cycles per screen, 30% aspect ratio, 0% phase angle as indicated on Fig. 12. These adjustments made it possible to clearly allow all three inputs to be visible at all times on the screen when analysing the simulated signals. It was not necessary to adjust the output signal as the membership functions were configured as singletons and there was a single output signal. Fig. 12 represents the debugging stage that clearly indicates the point of analysis at the vertical solid line, where the active rules 22, 23, 25 and 26 are present, as seen graphically in Fig. 13.

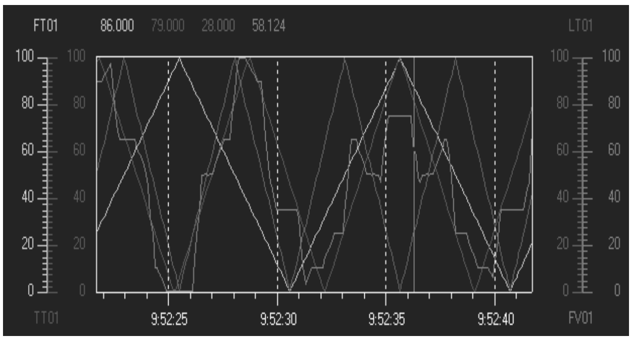


Fig. 12. 2-Dimensional analysis of rule base control

The actual membership functions and values can be verified in Table 3. From analysis in Fig. 12 it can be seen that the signal to the process control valve is maintained at 58.1% although the input variables varied. All values are assigned as a percentage of the operating range. In comparison to the actual assigned rule it can clearly be seen that the process will not be subjected to unwanted fluctuations and that rules 22, 23, 25 and 26 are active for this condition from the configured algorithm [11].

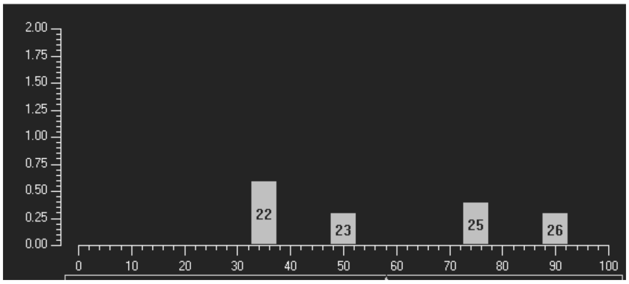


Fig. 13. Graphical rule firing analysis

Table 3.
Tabular rule firing analysis

Rule No	Flow MF	Temp MF	Level MF	Valve MF
22	H_flo (60-75-100-100)	M_tem (25-35-75-85)	L_lev (65-75-100-100)	S_clo (35)
23	H_flo (60-75-100-100)	M_tem (25-35-75-85)	M_lev (25-35-65-80)	half (50)
25	H_flo (60-75-100-100)	H_tem (75-85-100-100)	L_lev (65-75-100-100)	SS_ope (75)
26	H_flo (60-75-100-100)	H_tem (75-85-100-100)	M_lev (25-35-65-80)	F_ope (90)

The number 22 represented on Fig. 14 indicates that rule 22 is active in this region of the X-Y-Z axis. The process temperature is M_tem, the process level is L_lev and the control valve is S_clo. All the configured rules can be verified from Figure 14 in the same way.

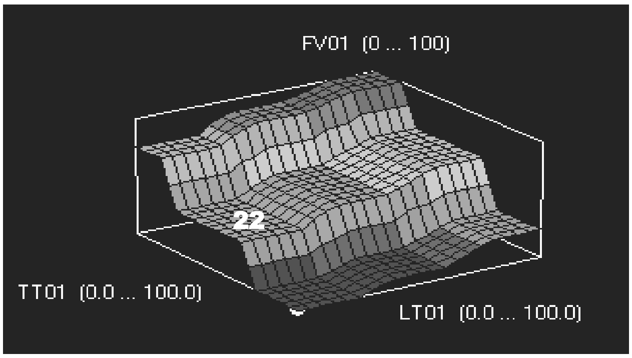


Fig. 14. 3-Dimensional analysis of rule base

Along the X-axis is an input, the process level. The three areas on the 3-dimensional representation that are parallel to the X-axis, is representative of the three input membership functions. The adjoining areas that are slanted are the areas of the membership functions that overlap each other.

Along the Y-axis is an input, the process temperature. The three areas on the 3-dimensional representation that are parallel to the Y-axis, is representative of the three input membership. The adjoining areas that are slanted are the areas of the membership functions that overlap each other.

Along the Z-axis is the output signal to the control valve. The different colours are representative of the nine output membership functions assigned for the output. Dark blue represents the minimum, Red represents the maximum and the colours in between are proportionally representative of the singletons that will be fired according to the respective rules.

7. Conclusions

With Profibus-PA at a transmission rate of 31.25 kbit/s it results in transmission times of 0.4 to 8.2ms per telegram so that per user data byte an average of 0.4 ms and 34 ms is required. This data transmission rate is sufficient, for example, to serve 10 control loops including 10 sensors and 10 actuators respectively within a control cycle time of approximately 210 milliseconds. During the evaluation, it was assumed that only one cyclic value (5 bytes user data) must be transmitted per device. With each additional value, the minimum cycle time increases by (5 x 8 bits) / (31.25 kbit/s) = 1.3 ms. Profibus-PA and -DP are equipped with a variety of safety mechanisms to ensure trouble-free communication. During the initialisation process of the system, several possible sources of error are checked. After the system is powered up, slaves are ready for data exchange only if the master has first sent a parameterisation and a configuration telegram.

After these telegrams match their own functional properties the slave accepts the commands from the master. The number of output lines configured by the master must match those actually existing in the device. The safety of the system is even higher because each class-1 master cyclically reports its own system status to all its assigned slaves within a configurable time interval using a multi-cast command. The master can be parameterised in such a manner that it can switch all slaves to a safe status and end the data transfer operation in case of a system error, i.e. when a slave fails [5].

The plant and control knowledge derived for the design of the decision-making control algorithm in the research was obtained from available data in the open-loop mode as the plant is still to be commissioned. The designed algorithm will be tested on the process plant in comparison with the simulated results in order to evaluate its feasibility in a networked control system for temperature, level and flow on a Profibus-DP and Profibus-PA network. Fig. 7 represented the anticipated response of the designed control strategy indicating the absence of process oscillations when desired conditions vary. Fig. 12 represented the response of the control strategy in a simulated environment that was designed using the Siemens FuzzyControl++ configuration tool. On analysis of the simulation it is clearly indicated that the controller's output response minimises the time to vary the control valve position in order to quickly adjust the controlled process variables to desired conditions within a time period from 09:52:25 to 09:52:40. A mathematically-based control strategy will contribute to increasing the settling time tremendously thereby impacting negatively on factors like production time and quality.

References

[1] J. Weigmann, G. Kilian, Decentralisation With Profibus DP/DPv1, Publicis Corporate, 2003, 53-75.

[2] D. Reynders, E. Wright, TCP/IP and Ethernet Networking, IDC Technologies, 2003, 21-25.

[3] IDC Technologies, TCP/IP Networking, IDC Technologies, 2000, 6.25-6.32.

[4] S. Mackay, E. Wright, J. Park, D. Reynders, Industrial Data Networks, Elsevier, 2004, 200-210.

[5] A.G. Samson, ProfibusPA Manual, Samsan AG, 2008, 21-40.

[6] I. Niemelä, O. Jenkins, E. Suojalehto, J. Vehmas, M. Ankerman, Intelligent Fieldbus Positioner Evolved to Maintain Optimum Performance, African Pulp & Paper week, Proceedings of the International Convention Centre, Durban, 2002.

[7] P. Naidoo, T.I. Van Niekerk, Knowledge Base Temperature Control on a Solar Parabolic Trough, Proceedings of the 22nd International Conference "CAD/CAM, Robotics and FOF", 2006, 753-761.

[8] H. Zhuang, X. Wu, Membership Function Modification of Fuzzy Logic Controllers with Histogram Equalization, IEEE Transactions 31 (2001) 125-132.

[9] Y. Bai, H. Zhuang, Modeless Robots Calibration in 3D Workspace with an on-line Fuzzy Interpolation Technique, Proceedings of the IEEE Conference "Fuzzy Systems", vol. 6, 2004, 5233-5239.

[10] J.P. Ylen, Improved Performance of Self-Organising Fuzzy Controller (SOC) in pH Control, Proceedings of the IEEE World Congress "Computational Intelligence", Fuzzy Systems 1, 1998, 258-263.

[11] H. Vermaak, J. Kinyua, Multi-Agent Systems based Intelligent Maintenance Management for a Component-Handling Platform, Proceedings of the IEEE International Conference "Automation Science and Engineering", 2007, 1057-1062.