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Rule-Based Fuzzy Logic Controller with Adaptable Reference

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Abstract**—**This paper attempts to model and design a simple fuzzy logic controller with Variable Reference. The Variable Reference (VR) is featured as an adaptability element which is obtained from two known variables – desired system-input and actual system-output. A simple fuzzy rule-based technique is simulated to show how the actual system-input is gradually tuned in to a value that closely matches the desired input. The designed controller is implemented and verified on a simple heater which is controlled by PIC Microcontroller harnessed by a code developed in embedded C. The output response of the PIC-controlled heater is analyzed and compared to the performances by conventional fuzzy logic controllers. The novelty of this work lies in the fact that it gives better performance by using less number of rules compared to conventional fuzzy logic controllers.

Keywords**—**Fuzzy logic controller, Variable reference, Adaptability, Rule-based.

I. Introduction

PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) controllers, based on mathematical values and equations, are making use of closed loop control algorithms, which are tuned to the required performance by trial-and-error methods. These controllers have proved to be showing a promising performance in the cases where the systems are operating under linear conditions. Although constantly improving in performance, mostly with an element of adaptability embedded in the recently developed controllers, the PID controllers have got limitations in cases when the condition-dynamics of a plant change abruptly for some reasons. To combat such changing system conditions, there is the need of a more robust type of controller which is able to provide a more responsive adjusting performance. Fuzzy logic control is an intelligent control technique that is based on the human expert knowledge in the form of a series of IF-THEN rules, which are structured so as to operate on variables belonging to sets defined by membership functions instead of binary logic.

The simplest rule-based fuzzy logic proportional controller can be formed by at least three rules as compared to PD, requiring nine rules or PID controller requiring a minimum number of twenty seven rules [1]. For a constant operating frequency of the controller, the overall processing time is proportionally increased to the number of rules used in the implementation of the system. It is, therefore, simple to prove that the overall speed of the PID controller is reduced by a factor of nine compared to the overall processing speed of a proportional controller besides a larger memory requirement and lacking from the problem of robust adaptability.

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Adaptive fuzzy logic controllers are in the focus of a number of researchers over the recent years. For instance, Miller and Davison [2] proved that the adaptive controller can be developed to provide arbitrarily good transient and steady-state response, but the controller uses a very high gain and is not practical for implementation. While in [3], the Fuzzy Basis Function Expansion (FPBE) is proposed to be used in the adaptive reference fuzzy controller, although this method has resulted in an excellent performance for controlling a plant based on the unknown parameters which are dependent on known variables. Similarly, adaptive techniques have discussed in [4-6], but the techniques suggested are mathematically extensive and very hard to be implemented with the available general purpose microcontroller architectures.

In this work, a simple and a less complex variable reference (VR) is suggested which is based on the principles of rules-based proportional (P) fuzzy logic controller requiring three rules only. In fact, the VR controller suggested in this work is making use of two proportional controllers, thus requiring a total of six rules. Consequently, a controller with better performance when compared to a PID controller is obtained, requiring less processing time and memory space requirement from the view point of controlling the parameters of a plant requiring robust performance. The adaptability feature comes with the ability of varying its reference input based on the desired system-input and system-feedback. By varying the reference input, the system error can be varied to speedily tune the system-output in order to meet the final steady state which is sensitive to any system changes.

II. Fuzzy Sets, Fuzzy Rules, and Fuzzy Logic Controller

Fuzzy sets for the input variables of a fuzzy logic controller are derived from a universe ranging from a minimum lower end (binary logic 1) to a maximum upper (binary logic 1), the values of which at a point depend on the relative degree of membership of the membership function, thus giving us ultimately more than two for a given input variables. In the case of proportional fuzzy logic controller (P), the input variable is Error (E) only and requires only three rules; a Proportional Derivative (PD) controller uses two input variables of Error (E) and Error Difference (ED) and requires nine rules; while a Proportional Integral Derivative (PID) controller uses three variables -- Error (E), Error Difference (ED) and Error Integral (EI), requiring twenty seven rules.

Consider designing a PD controller where the input variables **E** and **ED** belong to their fuzzy values via the membership functions (Fig. 3) with a universe of discourse ranging from -4 to +4 for input **E** and from -10 to +10 for input **ED**.

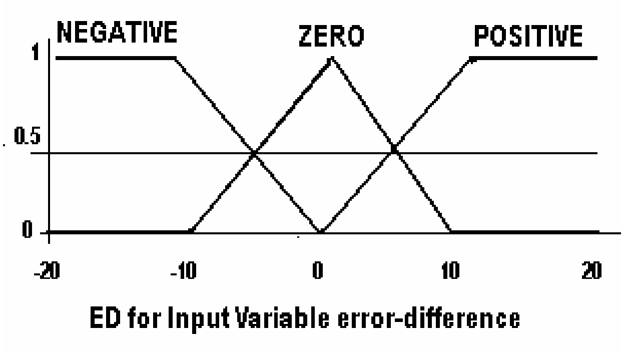

Fig. 1 Membership Function

For a given set of input conditions of **E**, the error membership function gives one set of Negative, Zero and Positive, while a value of **ED** gives another set of values for Negative, Zero, and Positive. The minimum of the two values of Negative, Zero and Positive are chosen which ultimately try to fire the set of IF-THEN rules, in this case nine only which are shown plotted in Fig. 2.

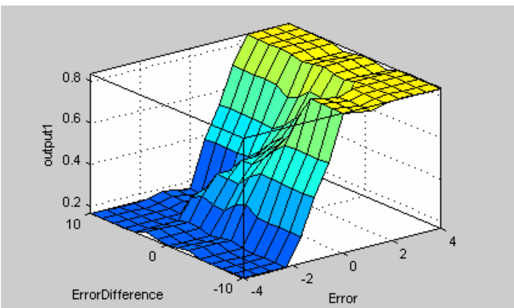

Fig. 2 Plotting of Basic Rules

For the given values of E and ED only those rules will fire whose condition parts are satisfied. Assuming four rules (rules 5, 6, 8 and 9) are fired with their respective weights (e.g., weights 0.5, 0.5, 0.4 and 0.4 respectively), which give us the following values of "positive", "zero" and "negative" Positive = $\sqrt{0^2 + 0^2 + 0^2+0.4^2} = 0.4$, Zero = $\sqrt{0.5^2} = 0.5$, and Negative = $\sqrt{0^2 + 0^2 + 0.5^2+0.4^2} = 0.64$. The final output (%) for the given pair of E and ED values under the fired set of rules, is obtained using ROOT-SUM-SQUARE (RSS) defuzzification method as $\{(0.4x100)+ (0.5x0) + (0.64x-100)\}/(0.4+0.5+0.65) = -15.58$ % which is required output within the available range of -100 to +100.

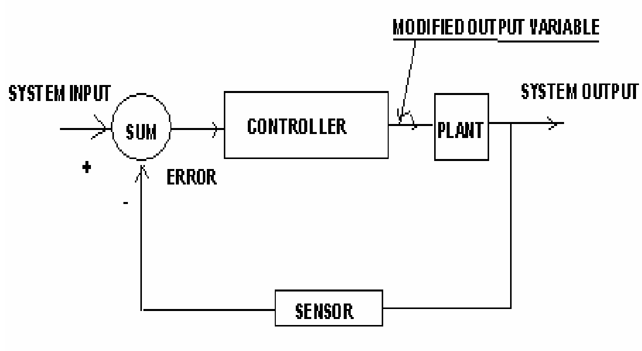

Fig. 3 Fuzzy Logic Controller

III. Fuzzy Controller Design

A fuzzy logic controller (Fig. 3) shows that system-input is directly compared with the feedback which is in fact the system-output sensed by the sensor. The difference between the system input and the feedback (ERROR) is fed back to the fuzzy logic controller which is implemented in a software algorithm for making the hardware to run the parameters that are to be controlled. The step response of a proportional controller (P) driving a load such as dc motor is shown in Fig. 4 and Fig. 5, showing clearly how the actual system-input starting from a minimum is gradually brought up to the desired level.

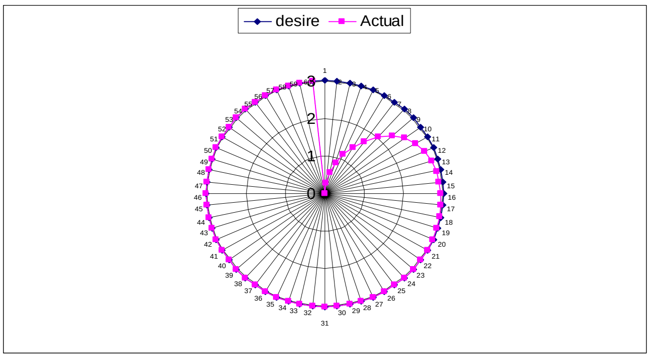

Fig. 4 Step Response of Proportional Controller

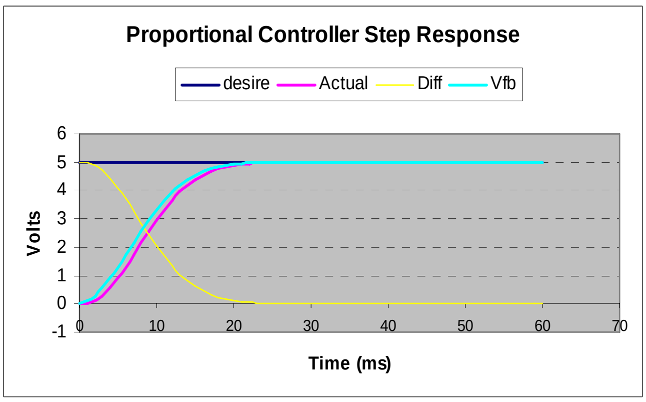

Fig. 5 Step Response of Proportional Controller

IV. Fuzzy Rules and System Response

In fuzzy controllers the kind of controlling modes used has resulted into increasing the number of rules required in each case, with a minimum number of rules required in each case is increased exponentially with the number of input variables according to Rules = L_{val}^{Lvar}, where L_{val} is the number of fuzzy linguistic values (negative, zero, positive) used, while L_{var} is the number of input variables employed. Increasing the number of variables leads to increasing the number of rules used, thus leading to increasing the burden on the processor, besides affecting rise times, settling times, overshoot and stead-state errors. Some rules–based reduction methods have been developed such as Single Value Decomposition (SVD) to reduce the number of rules, and hence the system's complexity. The methods require advance knowledge on fuzzy theory and some prior advance mathematical operations which are incapable to be solved by the general purpose microcontroller. The responses of P, PD and PID (shown in Fig. 6) show how increase in the number of rules has influenced the rise time with P being the best, however PID being the best in the overshoot and steady-state stability.

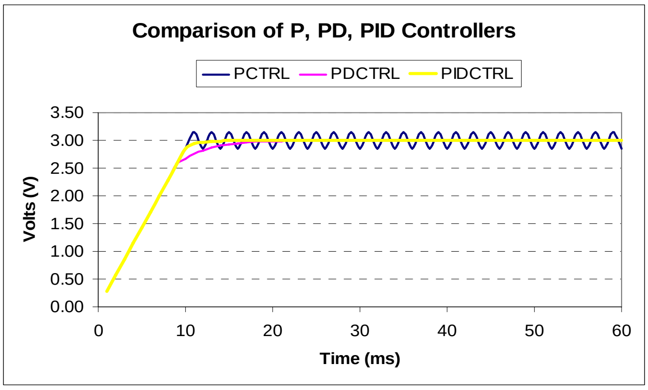

Fig. 6 Step Response of P, PD and PID

The step responses of PD and PID controllers (Fig. 7, Fig. 8) show that PID gets to its desired value earlier (step 13) than that of a PD controller (step 18).

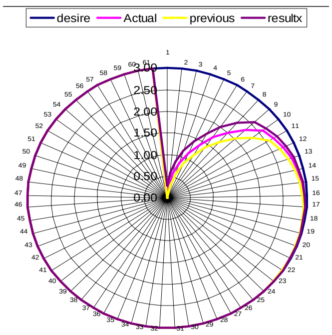

Fig. 7 Step Response of PD Controller

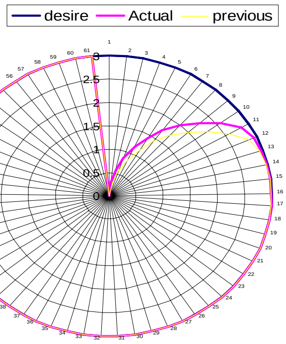

Fig. 8 Step Response of PID Controller

V. Variable Reference Fuzzy Logic Controller

The variable reference fuzzy logic controller is designed based on the simple proportional controller with a bit modification to the reference input. As shown in Fig. 9, the first fuzzy logic controller, **CONTROLLER 1** using three rules, is integrated for obtaining a better reference input for the second fuzzy controller **CONTROLLER2**, also using three rules.

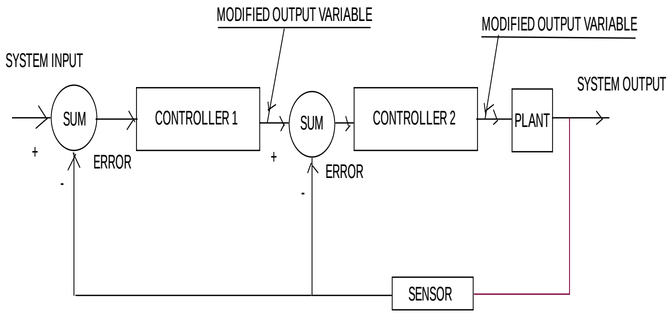

Fig. 9 Proposed Fuzzy Logic Controller with Variable Reference

The two controllers are cascaded in series with an overall effect of modifying (or prior processing) the system input and system feedback before it is being fed to the plant. The adaptability of the reference input, result in the acceleration of the final processing and improved performance of the overall controller in term of rise time, zero steady-state error, no overshoot and clearly enhanced stability.

VI. System Design and Simulation

The rules of the first controller are made to be similar to those of the second controller; both are implemented and weighted to produce their respective outputs. The output of the first microcontroller is applied as input to second controller, thus going through the same decision logic and inference engine once again. The combined output of the two series controllers is fed back to be compared with the system input and output of the first controller for producing another set of output values, thus ensuring the system-input to speed up achieving the values needed as desired input to the plant (Fig. 10).

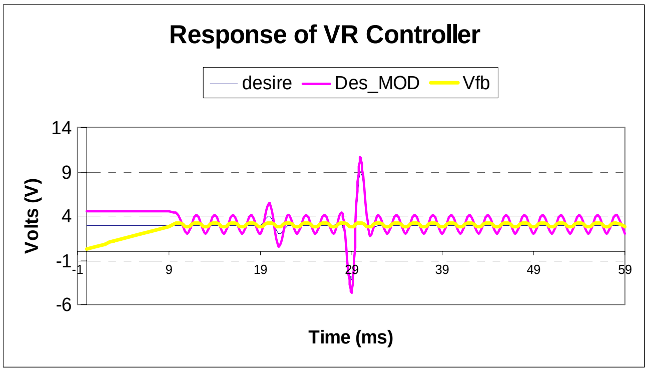

Fig. 10 Response of the VR Controller

It is also noted that the system output produced during a given cycle is smaller than the values of the corresponding inputs and the modified output of the first controller. If the system input is changed momentarily at certain points, the modified desired (Des_MOD) and the final output (Vfb) are certain to reflect the change instantaneously. The suggested variable reference (VR) controller stands out with a clearly marked difference in terms of rise time, when compared with its contemporary P, PD and PID controllers as in Fig. 11 and Fig. 12. However stability of the VR controller gets affected if it is made to operate over a narrower range.

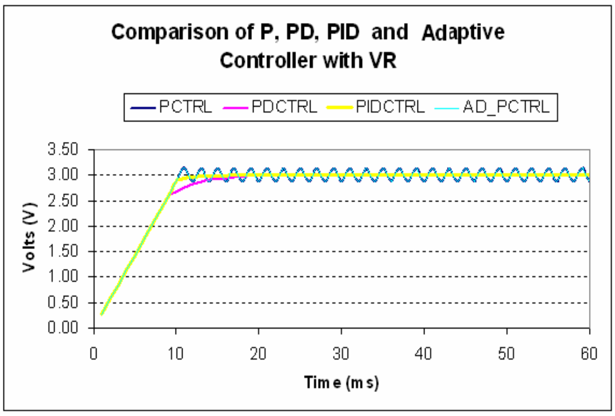

Fig. 11 Comparison of P, PID and Adaptive (VR) controllers

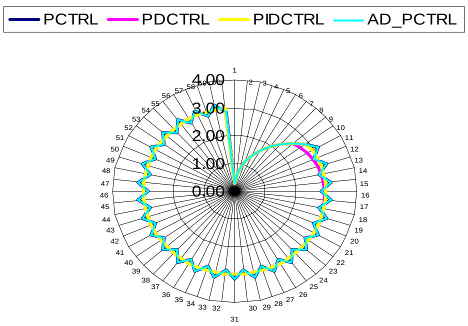

Fig. 12 Comparison of P, PID and Adaptive (VR) controllers

The performance of the VR controller designed is the best when compared to the performances of P, PD and PID controllers through a comparative simulation analysis. The simulation is done by implementing the IF-THEN rules in Microsoft Excel Worksheet, which use a given set of input data for calculating error, error difference which fire the relevant rules. Using the weights of the fired rules with their appropriate weights of zeros, positives and negatives, the new output is calculated by the RSS method which is continued to calculate new sets of error, error-difference, and hence new set of positive, zeros, negatives, and newly generated outputs till the time the desired input is achieved.

VII. System Implementation and Testing

The proportional (P), proportional derivative (PD) and adaptive reference proportional derivative (ARPD) fuzzy controllers are implemented in embedded C by Custom Computer Services (CCS), using ICD-U40 In-Circuit Debugger/Programmer for programming a PIC16F877 microcontroller which is used for controlling the temperature of a heater. A temperature sensor is used to sense the temperature for feeding it back to the microcontroller. From the tests conducted, it has been concluded that the developed controller is able to stabilize the heater with an error of ±0.37 V ≈ ± 0.185°C as against a PD controller controlling the same heater with an error of ± 0.5 V ≈ ± 0.252°C. Fig. 13 through Fig. 16 below show the response of the P, and PD fuzzy controller with the range of fuzziness set to 0.488 volt, 0.098 volt and 0.049 volt respectively for showing the effect of reduction in range. It has been shown that the system amplification is increased by decreasing the range, which leads to making the output unstable for a range set to 0.049 volt. The PD controller puts the designer to task by meeting the challenge of achieving the desired final state if the range is kept higher; making the PD fuzzy controller a challenging task as it requires a number of trials and errors for tuning in order to ultimately satisfy the required loading conditions.

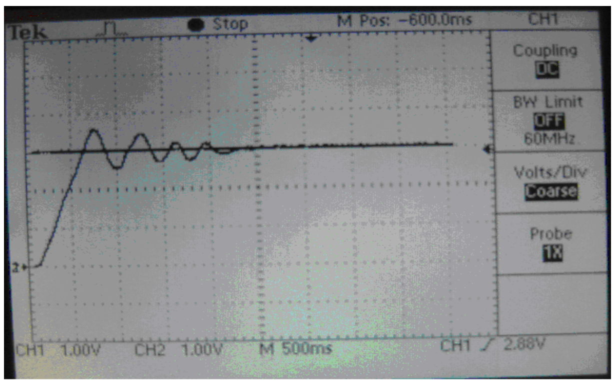

Fig. 13 Response of proportional fuzzy controller with range of 0.488 volt

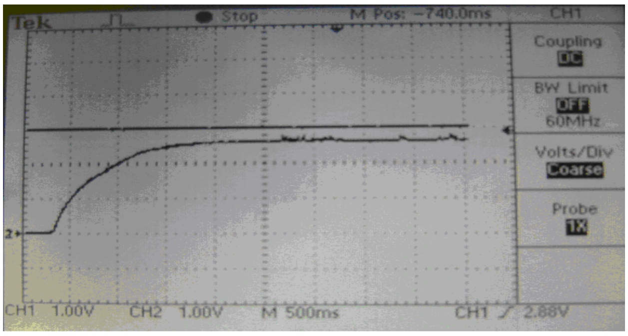

Fig. 14 Response of PD fuzzy controller with range of 0.488 volt

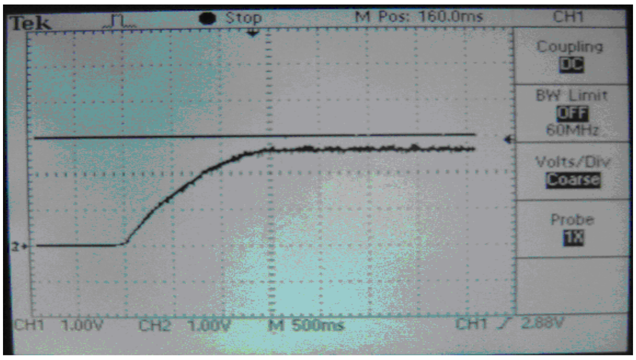

Fig. 15 Response of PD fuzzy controller with range of 0.098 volt

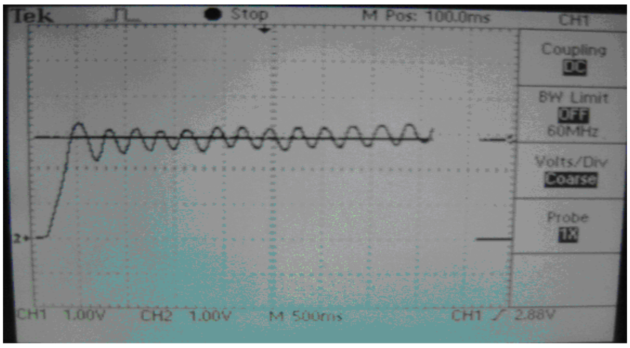

Fig. 16 Response of PD fuzzy controller with range of 0.049 volt

The suggested VRP controller (Fig. 17) has got a better rise time (0.009s), good in term of stability, no steady state error and requires no fine-tuning of errors and trials. It is proven that the simple method applied in designing the Fuzzy Controller has improved the response of the traditional fuzzy logic controller, making it handy and adaptable to the system changes.

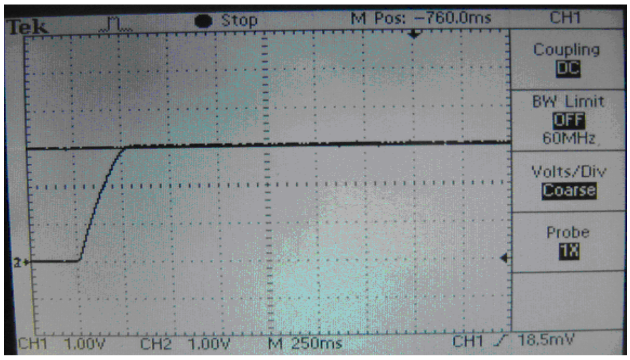

Fig. 17 Response of VRP fuzzy controller with range of 0.049 volt

VIII. Conclusion

The adaptive Variable Reference fuzzy controller is suggested based on the using proportional fuzzy controllers for better performance, avoiding the error and trials method of PID controllers and with fewer mathematical equations and fewer rules. The developed algorithm is tested on a heater as a system in order to compare it with the other contemporary fuzzy logic controller algorithms. The results show quite remarkable improvement as compared to contemporary fuzzy logic implementation techniques. The simulation results are consistent and in tandem with the practical implementation of the fuzzy controller which is tested with controlling the temperature of a heater using PIC16F877 microcontroller.

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