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D6114 Diesel Engine Speed Control: A case Between PID Controller and Fuzzy Logic Controller

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***Abstract* - The engine speed controller of a conventional diesel engine is called a Governor. In order to control engine speed, the governor controls the amount of fuel using fuel rack. This study presents a development of speed control of D6114 diesel engine by using PID controller and a self-tuning fuzzy PID controller to overcome the appearance of nonlinearities and uncertainties in the systems. The self-tuning fuzzy PID controller is the combination of a classical PID and fuzzy controller. The mathematical model of the diesel engine is also done by using System Identification technique. First, PID controller was applied; then, a fuzzy logic control algorithm is used to estimate the PID coefficient in order to handle such uncertainties to produce a better control performance. Simulation tests were established using Simulink of Matlab. The obtained results have demonstrated the feasibility and effectiveness of the proposed fuzzy approach comparing to the PID controller. Simulation results are represented in this study.**

Index Terms* - *Diesel Engine, PID Controller, Self Tuning Fuzzy PID Controller, Mathematical Modeling.

I. INTRODUCTION

Diesel engines have been widely used as power sources in practice. Diesel engine driven systems include automobiles, ships and backup power generating units [1].

As is well known, diesel engines are highly nonlinear devices and their characteristics vary as a function of power output, speed, ambient temperature, etc. Such nonlinear behaviour makes the design of engine control systems a very difficult task. Traditionally various forms of the PID controller have been used for speed control in diesel engines due to their simplicity. A great deal of research has also gone into providing more robust and optimal PID controllers through various tuning techniques

including Zeigler Nichols, Cohen-Coon and the Chien, Hrones and Reswick (CHR) methods [2], although in practice these techniques usually only provide a starting point for further r manual tuning by experienced engineers [3].

II. CONTROL SYSTEM DESCRIPTION

A. PID control

The PID controller has been widely used since its invention in 1910 [4]. There are many PID control configurations, but the most common implementation of this controller is the feedback - loop with a single input and a single output, as explained in [5].

Different sources estimate the share taken by PID controllers at between 90 and 99%. Some of the reasons for this situation may be given as follows.

a) PID controllers are robust and simple to design.

b) There exists a clear relationship between PID and system response parameters.

c) Many PID tuning techniques have been elaborated during recent decades, which facilitates the operator’s task.

d) Because of its flexibility, PID control could benefit from the advances in technology. Most of the classical industrial controllers have been provided with special procedures to automate the adjustment of their parameters (tuning and self-tuning).

However, PID controllers cannot provide a general solution to all control problems. In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller [6] , [7]. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point, and the degree of system oscillation.

A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error in outputs by adjusting the process control inputs.

$$e(t) = r(t) - y(t)$$

The transfer function of PID controller is

$$G(s) = k_p + k_d(s) + \frac{k_i}{s} \quad (1)$$

Where kp, kd, and ki are the proportion coefficient, differential coefficient, and integral coefficient, respectively.

B. FUZZY CONTROLLER

Fuzzy Logic was initiated in 1965 by Lotfi A. Zadeh [8], and applied by Mamdani, [9], in an attempt to control system that is structurally difficult to model. Since then, FLC (fuzzy logic control) has been an extremely active and fruitful research area with many industrial applications reported. Otherwise, all researchers have shown that Fuzzy Logic and Fuzzy PID controllers can provide improved control and robustness over traditional PID (9). As a result FLCs have found use in the speed control of various marine/traction engines [10], [11].

FLC have been reported to be successfully used for a number of complex and nonlinear processes. Sometimes FLC are proved to be more robust and their performances are less sensitive to parametric variations than conventional controllers [12].

The fuzzy control systems are rule based systems which are based on expert knowledge. The fuzzy theory based on fuzzy sets and fuzzy algorithms provides a general method of expressing linguistic rules so that they may be processed quickly by a computer.

The variables in fuzzy logic system may have any value in between 0 and 1 and hence this type of logic system is able to address the values of the variables those lay between completely truths and completely false. The variables are called linguistic variables and each linguistic variable is described by a membership function which has a certain degree of membership at a particular instance.

The basic Fuzzy inference system may take fuzzy inputs or crisp inputs depending upon the process and its outputs, in most of the cases, are fuzzy sets.

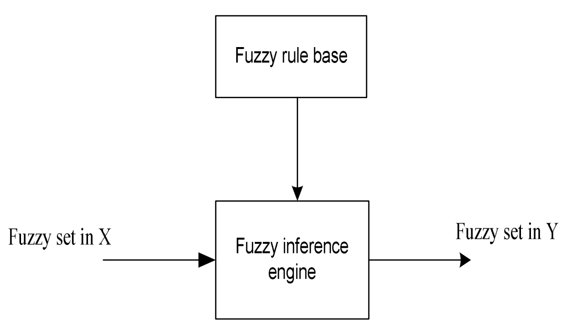

Fig.1 A pure fuzzy system

The fuzzy inference system in Figure 1 can be called as a pure fuzzy system due to the fact that it takes fuzzy sets as input and produces output that are fuzzy sets. The fuzzy rule base is the part responsible for storing all the rules of the system and hence it can also be called as the knowledge base of the fuzzy system. Fuzzy inference system is responsible for necessary decision making for producing a required output.

In most of the practical applications where the system is used as a controller, it is desired to have crisp values of the output rather than fuzzy set values. Therefore a method of defuzzification is required in such cases which convert the fuzzy values into corresponding crisp values.

In general there are three main types of fuzzy inference systems such as; Mamdani model, Sugeno model and Tsukamoto model. Out of these three, Mamdani model is the most popular one. There are also various defuzzification techniques such as, Mean of maximum method, Centroid of area method, Bisector of area methd etc [13].

(1) Self-Tuning Fuzzy PID Controller Design

Figure 2 shows the basic configuration of a Fuzzy Logic Controller, which comprises four principal components: a fuzzification interface, a Knowledge base, decision making logic, and a defuzzification interface [14].

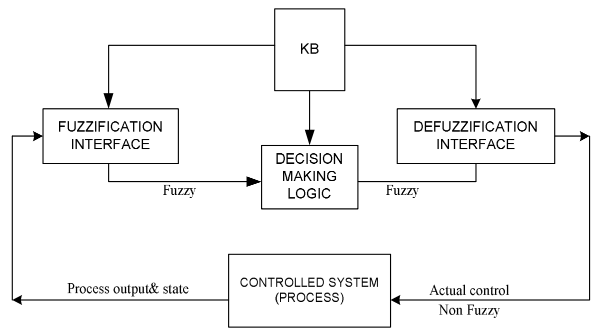

Fig. 2 Basic configuration of fuzzy logic controller (FLC)

The self-tuning of the PID controller refers to finding the fuzzy relationship between the three parameters of PID, KP, KI and KD and "e" and "de", and according to the principle of fuzzy control modifying the three parameters in order to meet different requirements for control parameters when "e" and "de" are different and making the control object produce a good dynamic and static performance. The structure of the self-tuning fuzzy PID controller is shown in Figure 3.

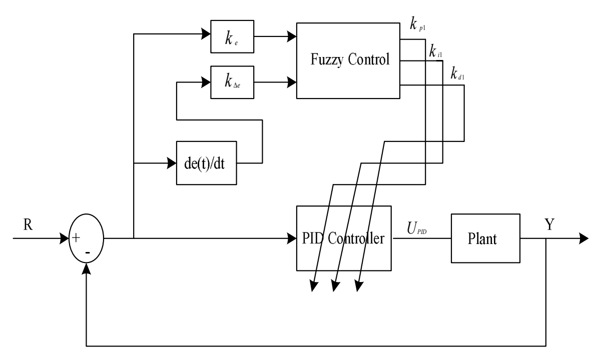

Fig. 3 Self-tuning fuzzy PID controller

(2) Fuzzifier and Rule-Base Formation

The fuzzifier transforms the measured crisp input X to the fuzzy sets defines in Vx, where Vx is characterized by a membership function $\mu_f : V_x \rightarrow [0,1]$, and is labeled by a linguistic term such as "negative big (NB)," "negative medium

(NM),” “negative small (NS),” “zero (ZR),” “positive small (PS),” “positive medium (PM),” and “positive big (PB).”

Assume that all the control rules have the same form, each of which is given by

$$\text{IF situation THEN action} \tag{2}$$

Stating a local relationship between the current control situation and the corresponding control action suggested by the expert. e (t) and de(t) are selected as input variables of the fuzzy inference and defined as two variables representing the situation. K’P, K’I and K’D are selected as output of the fuzzy system and defined as a variable representing the action. Notice that variables for e(t), de(t), K/p, K/i, and K/d assume linguistic terms as their values such as positive-big, negative-small, and zero, etc. Thus, rules may be formally expressed for our fuzzy system by:

$$Rule\,i: If\,e(t)\,is\,A_{1i}, de(t)\,is\,A_{2i}\,then\,k_p^{'} = B_i\,and\,k_i^{'} = C_i\,and\,k_d^{'} = D_i \tag{3}$$

Where A, B and C are linguistic terms which in this study can be NL, NM, NS, ZR, PS, PL and PB.

The rules designed are based on the characteristic of the marine diesel engine and properties of the PID controller. Therefore, based on these principles, a set of rules have been derived and are summarized in Table 1.

Table I. Rule base of the fuzzy logic controller (kp, ki, kd)

e\ec	NB	NM	NS	Z	PS	PM	PB
NB	PB NB PS	PB NB NS	PM NM NB	PM NM NB	PS NS NB	Z Z NM	Z Z PS
NM	PB NB PS	PB PB NS	PM NM NB	PS NS NM	PS NS NM	Z Z NS	NS Z NZ
NS	PM NB Z	PM NM NS	PM NS NM	PS NS NM	Z Z NS	NS PS NS	NS PS Z
Z	PM NM Z	PM NM NS	PS NS NS	Z Z NS	NS PS NS	NM PM NS	NM PM Z
PS	PS NM Z	PS NS Z	Z Z Z	NS PS Z	NS PS Z	NM PM Z	NM PB Z
PM	PS Z PB	Z Z PS	NS PS PS	NM PS PS	NM PM PS	NM PB PS	NB PB PB
PB	Z Z P B	Z Z PM	NM PS PM	NM PM PM	NM PM PS	NB PB PS	NB PB PB

$$k_p = k_p^{/} + \Delta k_p$$

$$k_i = k_i^{/} + \Delta k_i$$

$$k_d = k_d^{/} + \Delta k_d$$

Here K/p, K/i, and K/d refer to the previous value of the PID parameters whereas KP, Ki, and Kd refer to the new corrected values of the parameters after a particular tuning step was completed.

For simplicity, the same universe of discourse and the same fuzzy set are adopted for fuzzy input/output variables. The membership functions of isosceles triangles are used as the fuzzification function which is used to convert a crisp value into a fuzzy singleton within the universe of discourse.

III. Mathematical Modeling of Diesel Engine

We start our analysis with the development of a simplified nonlinear engine model for speed regulation.

The mean-value model of diesel engine is based on the conservation of mass and energy and the ideal gas law. According to the mass conservation law, the change of mass in the volume is equal to the difference of the flows into and out of the volume.

A. Volumetric efficiency model

The volumetric efficiency is typically in the range 1/2 to 1 for diesel engines. It is independent of the cylinder size, and it is a measurement of engine performance as an air pumping device. It is defined in Taylor as: “The mass of fresh mixture which passes into the cylinder in one suction stroke, divided by the mass of the mixture which would fill the piston displacement at inlet density” [15]. The volumetric efficiency can be represented by equation:

$$\eta_v = \eta_0 \left[1 - K \left(\frac{n}{n_0} - 1 \right)^2 \right] \tag{4}$$

Where: η_0 is the maximum volumetric efficiency; n_0 is the rotational speed (r / min) and K is the Coefficient

B. Air mass flow model

Air mass flow into cylinder can be calculated as below:

$$q_{m3} = \eta_v \rho_3 V n_{sh} / 120 \tag{5}$$

$$\rho_3 = p_3 / RT_3 \tag{6}$$

η_v is the cylinder volume coefficient; V is empty volume in each cycle; n_e is engine revolution and ρ_3 is air density (kg/m^3)

C. Exhaust temperature model

According to the first law of thermodynamics, the heat balance equation for the diesel engine working process is calculated by

$$q_{mf} H_{LHV} - Q_w - P_c = \left(q_{m3} + q_{mf} \right) c_{pe} T_4 - q_{m3} c_{pa} T_3 \tag{7}$$

q_{mf} is the mass fuel quantity that is pumped into a cylinder (kg/s); H_{LHV} is fuel low calorific value (J/kg); Q_w is heat removal; Pc is work output (W); C_{pa}, c_{pe} is Inlet and exhaust gas specific heat respectively; T_4 is exhaust gas temperature (K)

Exhaust gas temperature (T_4) is calculated by

$$T_4 = T_3 + K_r \Big/ \left(1 + q_{ma} \big/ qmf \right) \tag{8}$$

Where

$$K_r = \xi_E H_{LHV} / c_{pv}$$

Kr is exhaust temperature factor

Ingredients of exhaust gas are varying with AFR, so is the molecule. Parameters of exhaust gas, such as gas constant, specific heat, etc, can be calculated from AFR [16].

D. Crankshaft rotation model

An engine rotational dynamic model is derived directly from Newton's second law as following:

$$M_i - M_f - M_L = (J_c + J_L)\frac{\pi}{30}\frac{dn_{sh}}{dt} \tag{9}$$

Where; M_L is the load torque (N m); Mf is friction torque (N m); M_i is indicated torque (N m); Jc is inertia of engine (kg·m^2) and J_L is inertia of load (kg·m_2).

Among the equilibrium equation, load torque, the indicated torque and the friction torque is calculated as:

$$M_L = K(N_e/n) \tag{10}$$

$$M_i = q_{mf} H_{LHV} \eta_i \frac{30}{\pi n_{sh}} \tag{11}$$

$$M_f = (1000\rho_f)/4\pi \tag{12}$$

K is Scaling factor and the value usually is 9545.5; N_e is engine rated power (kW); n is engine rated speed (r / min); qmf is rate of fuel supply (kg / s); H_{LHV} is the low calorific value of the fuel (J / kg); Sp is piston speed (m / s); P_f is Average friction pressure (P_a)

The average frictional pressure is calculated as follows:

$$\rho_f = 75 + \frac{48 n_{sh}}{1000} + 0.4 s_p^2 \tag{13}$$

E. Actuator model

There are many methods modeling of electromagnetic actuator; first used the experimental methods to measuring the step response or by actuator dynamic model.

The actuator of diesel engine is a direct current servomotor which is used for the control of diesel engine governor, and it is a typical second order system .The transfer function is described as equation 14 [17]. The transmission characteristics of the actuator which controls the position of the fuel rack based on the command values emitted by the control unit is expressed by the following equation:

$$\frac{H(S)}{H_g} = \frac{\omega_{nd}^2}{s^2 + 2\xi_{nd}\omega_{nd}s + \omega_{nd}^2} \tag{14}$$

Hg(S) is the link of given opening extent of fuel oil throttle. H(S) is link of actual opening extent of fuel oil throttle. ω_{nd} is the natural oscillation frequency of actuator, ξ_{nd} is the damping coefficient of actuator.

IV. Simulation Result

D 6114 type diesel engine is taken as an example, which parameters are shown in Table 2 and Table 3.

Table 2. Diesel engine parameters

Number of cylinder	6
Cylinder diameter	114 mm
Number of stroke	4
Rated speed	1500 r/min
rated power	116 KW
mean effective pressure	0.6 MPa
Speed mode	Electronic governor
Cooling method	closed water cooling fan
Starting mode	24V DC motor starters

Table 3. D6114 diesel generator set main technical specifications

Rated voltage	400V
Rated frequency	50HZ
Rated power factor	0.8
Insulation class	H
Protection grade	IP21

While, the complete Simulink block diagram for whole system including the control design and the plant is shown in Figure 4 and 5.

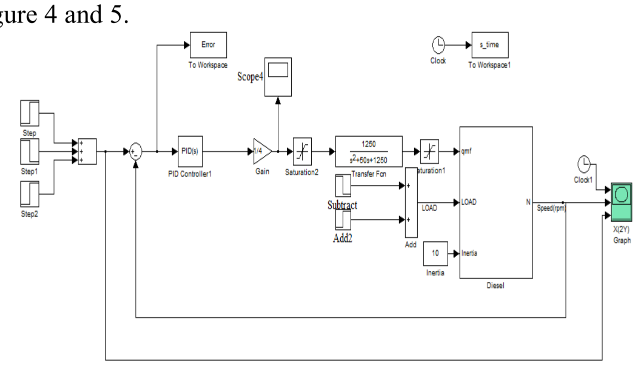

Fig. 4 SIMULINK block diagram of diesel system using PID controller

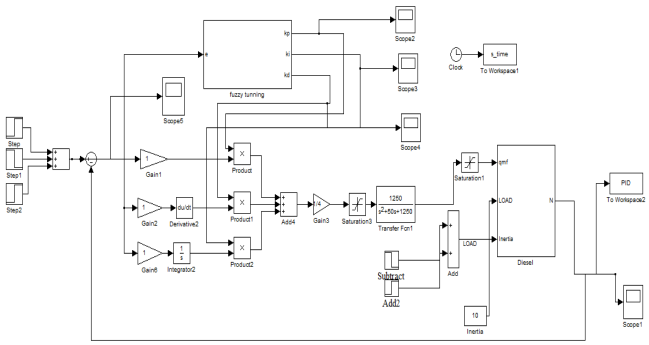

Fig.5 SIMULINK block diagram of diesel system using fuzzy self-tuning PID controller

The response of the fuzzy self-tuning PID controller is obtained using Matlab Program. A two-input and three output fuzzy controller is created and the membership functions and fuzzy rules are determined.

The results of the simulation investigating speed performance of the diesel engine system are shown in Figure 6 for the self-Tuning Fuzzy PID Controller and the conventional PID controller. These step responses performances show that the response is still slow when the conventional PID controller is applied on the system. In the other hand, when the self-tuning fuzzy PID controller is applied into the system, the response become significantly faster than PID controller.

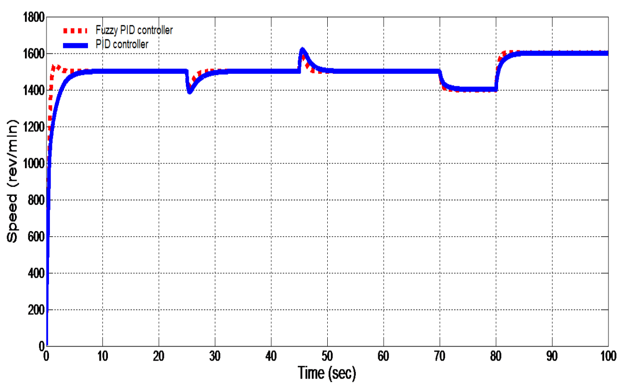

Fig.6 PID and fuzzy logic controller responses

We can show that the application of fuzzy self-tuning PID controller to the rotation speed regulation of diesel engine is able to improve the transient process of system performance and the response of the system was also faster by using fuzzy self-tuning PID controller.

V.CONCLUSIONS

Simulation was carried out using Simulink of Matlab to get the output response of the system to a step input.

The diesel engine runs very stable in both loading and unloading conditions and the Overshooting and undershooting was minimized because of fuzzy-PID tuning. And the results of the simulation show that the fuzzy-PID controller to get an output which is robust and has faster response than PID controller.

According to the simulation results, the application of fuzzy logic to the PID controller imparted it is the ability to tune itself while operating on-line. Similarly, a fuzzy self tuning PID controller to get an output which is robust and has faster response than PID controller.

VI. ACKNOWLEDGMENT

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