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Comparative study of PID controller and sliding mode controller for the setpoint overshoot method

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Abstract:

This paper deals with the study of comparative study of PID controller for the overshoot of setpoint in tuning. The main objective of this paper is to compare time specification performance between conventional controller PID and sliding mode controller for setpoint overshoot in tuning. The goal is to determine which strategy deliver better performance with respect to time. The two controllers are presents such as Sliding Mode Control (SMC) and Proportional Integral Derivative (PID) controlling the setpoint response experiment and it mainly uses information about the first (overshoot) which is very easy to identify the setpoint experiment is similar to the classical Ziegler-Nichols experiment. Based on simulations for range of first order with delay process, simple correlations have been derived to give PI controller setting similar to those of SIMC tuning rules. And here we developed Modified Setpoint Overshoot Method i.e. MSOM by using SMC. The proposed tuning method , originally derived for first order with delay process, has been tested on wide range of other process typical for process control applications and results are comparable with SIMC tuning and MSOM tuning model. The effectiveness of proposed method is evaluated by simulations conducted on MATLAB/SIMULINK.

Keywords

PID, SMC, MSOM

1.Introduction

The Sliding Mode Control has unique place in control theories. Here by using sliding mode control a simple method is developed for tuning of undefined process using closed loop experiments. The setpoint experiment is similar to classical Ziegler-Nichols method but controller gain is typically about one half so the system is not at stability limit with sustained oscillations. Based on simulations for first order with delay process simple correlations have been derived to give PI controller setting similar to those of SIMC tuning rules. This method is then compared with newly developed method by using sliding mode control.

The proportional integral controller is widely used in process industries due to its simplicity,robustness and wide range of applicability in the regulatory of the PID controllers donot use derivative action. Even though PI controller only has two adjustable parameters it is not simple to find good setting and many controllers are poorly tunned. The objective of this paper is to derive a method which is simpler to use than the present ones. So, the Sliding Mode Control (SMC) approach, which is one of the variable structure control is robust control technique.

Most tuning approach are based on an open plant model (g); typically given in terms of plant's gain (k), time constant (τ) and time delay (θ). In this paper the objective is to derive controller tuning based on closed loop experiments using sliding mode control and compare it with the previous one in which PID controller is used with SIMC rules. Skogested proposed the modified SIMC method where integral time is regulated for process with a large value of process time constant τ. The modified setpoint overshoot method in which sliding mode control is used to reduce the more time for process with large value than SIMC method.

This is the approach of the classical Zieler-Nichols method which requires very little information about the process. There are several disadvantages of Ziegler-Nichols method. First the system needs to be brought its limit of instability and number of trials may be needed to bring the system to this point. Another disadvantage is that the Ziegler-Nichols method do not work on all process. A third disadvantage of Zieler-Nichols method is that it can only be used on process for which the phase lag exceeds -180^o at high frequencies. For example it does not work on simple second order process.

Hence, there is need of an alternative closed loop approach for plant testing and controller tuning which avoids the instability concern during the closed-loop experiment, reduces number of trials and works for wider range process. The proposed new method satisfies these concerns:

1. The method uses a single closed-loop experiment with proportional only control. This is similar to the

Ziegler-Nichols method, but the process is not forced to its stability limit and it requires less trial-and-error adjustment of the P-controller gain to get to the desired closed-loop response.

2. Of the many parameters that can be obtained from the closed loop setpoint response, the simplest to observe is the time (tp) and magnitude (overshoot) of the first peak which is the main information used in the proposed method.

3. The proposed method works well on a wider range of processes than the Ziegler–Nichols method. In particular, it works well also for delay-dominant processes. This is because it that makes use of a third piece of information, namely the relative steady state change $b = y(\infty)/y_s$.

4. The method applies to processes that give overshoot with proportional only control. This is less restrictive than the Ziegler–Nichols method, which requires sustained oscillations. Thus, unlike the Ziegler–Nichols method, the method works on a simple second-order process.

In summary the proposed method is simpler in use than existing approaches and allows the process to be kept under closed loop control. It means SMC gives better approach than PID controller.

2. PID Controller

Today there is universal use of PID concept in applications requiring accurate and optimized automatic control. The feature of PID controller is the ability to use the three control terms of proportional, integral and derivative influence on controller output to apply accurate and optimal control. The block diagram shows the principles of how these terms are generated and applied.

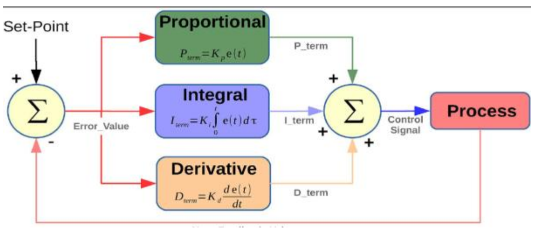

Fig.1, Block diagram of PID controller in feedback loop

It shows PID controller which continuously calculates an error value e(t) as the difference between desired setpoint SP = r(t) and measured process variable PV = y(t), and applies a correction based on proportional, integral, and derivative terms. The controller attempts to minimize the error over time by adjustment of control variable u(t), such as the opening of a control valve, to a new value determined by weighted sum of control terms.

The overall control function can be expressed mathematically as:

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The overall control function can be expressed mathematically as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt},$$

Where, , K_i, and K_d, all non-negative, denote the coefficient for the proportional, integral, and derivative terms, respectively.

Most tuning approaches are based on an open-loop model (g); typically given in terms of the plant's gain (k), time constant (τ) and time delay (θ)for an extensive list of methods. To improve the load disturbance rejection, here we derive this modified setpoint overshoot method where the integral time is reduced for process with large value of the process time constant τ_c. This method modify the proposed methods of the tuning of the PID controller. SIMC is one of the method of the overshoot the setpoint, the SIMC rule has one tuning parameter, the closed-loop time constant τ_c, and for "fast and robust" control is recommended to choose $\tau_c = \theta$, where θ is the (effective) time delay.

2.1. SIMC PI tuning rule

In fig 2 we show the block diagram of conventional feedback control system, where g denotes the process transfer function and c the feedback controller. The other variables are the manipulated variable u, the measured and controlled output variable y, the setpoint y_s and the disturbance d which is here assumed to be a "load disturbance" at the plant input and load disturbance to the output are:

$$y = \frac{cg}{1+cg} y_s + \frac{g}{1+cg} d \quad (1)$$

In process control, a first order process with time delay is common representation of process dynamics:

$$g(s) = \frac{k e^{-\theta s}}{\tau s + 1} \quad (2)$$

Here k is the process gain, τ the dominant lag time constant and θ the effective time delay. Most process in the process industries can satisfactorily controlled using PI controller:

$$c(s) = K_c\left(1 + \frac{1}{\tau_1 s}\right) \quad (3)$$

which in the time domain corresponds to

$$u(t) = K_c e(t) + \frac{K_c}{\tau_1} + \int_0^t e(t)dt \quad (4)$$

where e = y_s – y. The PI controller has two adjustable parameters, the proportional gain K_c and integral time τ_1. The ratio $K_1 = K_c/\tau_1$ is known as integral gain.

The SIMC tuning rule is analytically based and widely used in the process industry. For the process in Eq.(2), the SIMC tuning rule gives

$$Kc = \frac{\tau}{k(\tau c + \theta)} \quad (5)$$

And $\tau_1 = \min\{\tau, 4(\tau_c + \theta)\}$ (6)

Note that the original IMC tuning rule always uses $\tau_1 = \tau$, but the SIMC rule increases the integral contribution for close to integrating process (with τ large) to avoid poor performance (slow settling) to load disturbance. There is one adjustable tuning parameters, the closed loop time constant (τ_c), which is selected to give the desired trade off between performance and robustness. Initially, this study is based on the "fast and robust" setting

$$\tau c = \theta \quad (7)$$

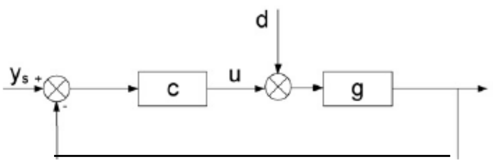

Fig.2 Block diagram of feedback control system

which gives a good trade-off between performance and robustness. In terms of robustness, this choice gives a gain margin is about 3 and a sensitivity peak(M_s-value) of about 1.6. On dimensionless form, the SIMC tuning rules with $\tau_c = \theta$ become

$$K_c' = kKc = 0.5\,\frac{\tau}{\theta} \quad (8)$$

$$K_1' = \frac{kKc}{\tau_1/\theta} = max\left(0.5, \frac{1}{16}\frac{\tau}{\theta}\right) \quad (9)$$

The dimensionless gains K_c' and K_1' are plotted as a function of τ/θ. We note that the integral terms (K_1') is relatively important for delay dominant process $(\tau/\theta < 1)$, while the proportional term K_1' is more significant for process with a smaller time delay.

For a wide range for first order plus delay process with a unit time delay (θ=1). First order delay process with a unit time delay (θ=1)

$$g(s) = \frac{e^{-s}}{\tau_s + 1} \quad (10)$$

The process time constant τ varies from 0 to 100. The time to reach first peak (t_p) increases as per as τ.

2. Sliding Mode Control

The Sliding Mode Control inherently gives robustness to the controlled system, the existence of the outer compensator drastically changes the overall dynamics of converter variables, and therefore the robustness has to be guaranteed by an appropriate selection of compensator parameters. The sliding mode control (SMC) approach, which is one of the variable structure control, is a robust control technique. SMC is non linear control method that alters the dynamics of a non linear system by application of a discontinuous control signal (or more rigorously, a set-valued control signal) that forces the system to "slide" along a cross section of the system's normal behavior. The state-feedback control law is not a continuous function of time. Instead, it can switch from one continuous structure to another based on the current position in the state space. Hence, sliding mode control is a variable structure control method. The multiple control structures are designed to overshoot the setpoint by tuning of this controller. We are selecting as an integral-differential equation acting on some tracking error,that is linear and stable. A process used to design a controller should guarantee system stability, settlement time of interest as well as minimum overshoot.

The sliding-mode control is used in this approach to design a hysteresis-based quadratic boost converter that provides a regulated output voltage of 400-V DC from an input voltage in the range of 15-25-V DC. In this paper, the definition of a simple sliding surface for the regulation of the input inductor current yields the indirect control of the output voltage by forcing the mentioned current to reach a desired reference value in the equilibrium state. Therefore, if the current reference in the sliding surface is modified by the action of a PI compensator processing the output voltage error, it will be possible to regulate the output voltage to a desired level. Thus, the proposed controller consists of two loops, namely, an inner loop for input inductor current control and an outer loop establishing the reference for the inner loop to ensure the output voltage regulation. Hence, to cope with the parameter uncertainty, a robust loop shaping method is chosen to synthesize the PI compensator with robustness constraints. The values of PI gains *Kp* and *Ki* are obtained for the stable range given by the Routh–Hurwitz stability test using a geometrical analysis in the Nyquist diagram involving the maximization of the integral gain.

2.1 MSOM SMC tuning rule

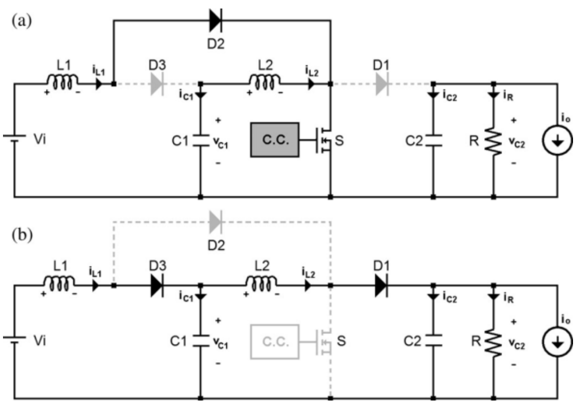

Fig.3 Quadratic boost circuit configurations: (a) ON-state; and (b) OFF-state.

The quadratic boost converter is a fourth-order structure with two commutation cells in synchronous operation. The first cell is composed of controlled switch *S* and diode *D1*, which constitute a boost converter stage together with inductor *L2* and capacitor *C2*. The second cell is composed of diodes *D3* and *D1*. As shown in Fig. 3, this converter has two circuit configurations for continuous conduction mode operation (CCM). In ON-state, switch *S* is on, diode *D2* is on, and diodes *D1* and *D3* are off. In OFF-state, switch *S* is OFF, diode *D2* is OFF and diodes *D1* and *D3* are ON. The bilinear model is obtained from the differential equations derived for each converter state

$$\frac{di_{L_1}}{dt} = \frac{v_i}{L_1} - \frac{v_{C_1}}{L_1}(1-u)$$

$$\frac{di_{L_1}}{dt} = \frac{v_i}{L_1} - \frac{v_{C_1}}{L_1}(1-u)$$

$$\frac{dvC_1}{dt} = -\frac{i_{C_1}}{C_1} + \frac{i_{L_1}}{C_1}(1-u)$$

$$\frac{dvC_1}{dt} = -\frac{i_{C_1}}{C_1} + \frac{i_{L_1}}{C_1}(1-u) \qquad (11)$$

The control variable *u* is the gate signal of the controlled switch *S*, so that *u* = 1 during ON-state and *u* = 0 during OFF state. Current source i_0 models the possible output load disturbances. Operation in CCM is guaranteed through the selection criteria for *L1*, *L2*, *C1*, and *C2* values

In steady state, i.e., derivatives equal to zero, the control variable *u* can be replaced in (11) by its average value represented by the duty cycle *D* yielding the relation.

$$\frac{v_{C_1}}{v_i} = \frac{v_{C_2}}{v_{C_1}} = \frac{1}{1-D} \qquad (12)$$

from which it can be deduced the ideal static transfer function of the converter *M*(*D*)

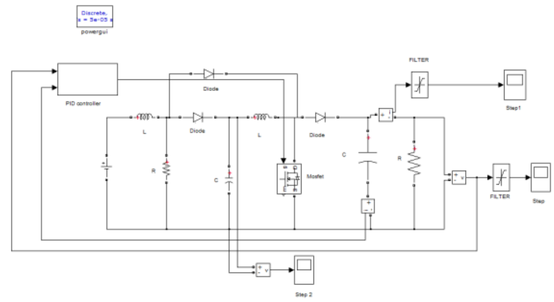

Fig.4 General representation of proposed control scheme

$$M(D) = \left(\frac{v_{C_2}}{v_{C_1}}\right)\left(\frac{v_{C_1}}{v_i}\right) = \frac{1}{(1-D)^2} \qquad (13)$$

Besides, input voltage perturbations, load variations, and the uncertain value of the parasitic resistances in all components contribute to introduce voltage drops, deviating the actual output voltage of its expected value. Therefore, to obtain a regulated output voltage it is required a closed-loop feed-back control system. The presence of the right half-plane zeros in the dynamics of the high-order boost derived converters precludes the use of a single-loop compensator processing the output voltage error. Therefore, the voltage regulation will be performed by a two-loop control scheme whose inner loop will process a fast variable like the input inductor current, whereas the outer loop will establish the reference of the inner loop by treating a slow variable as the output voltage error. Fig. 4 illustrates the hysteresis-based two-loop control, where the inner current loop is defined by means of a sliding surface and drives the converter to a stable equilibrium point. The outer loop generates the required reference $I_E(t)$ at the output of a PI compensator in order to keep constant the coordinate of the output voltage in the equilibrium point in spite of input voltage perturbations or load changes. The dynamic behavior of $I_E(t)$ is considerably slower than that of the input inductor current and, therefore, it is possible to separate the analysis of inner and outer loops.

3. Analysis and Simulation

The simulation have been conducted for different process and the proposed tuning procedure provides in all cases acceptable controller setting with respect to both performance and robustness.

For each and every process PI setting were obtained based on step response experiments with three different overshoot and SIMC method and proposed MSOM settings are compared.

The performance of closed loop is evaluated by introducing a unit step change in both setpoint and load disturbances. (y_s=1 and d=1).

Output performance (y) is qualified by integreting absolute error, $IAE = \int_0^{\infty} |y - y_s|$. The total variable (TV) of input (u), is the sum of all its moves up and down, is calculated by manipulated variable. If we discretize the input signal then $TV = \sum_{i=1}^{\infty} |u_{i+1} -$ where signal sequence is [u_1,u_2,u_3,…,u_i…]. The integral of absolute value of derivative of the input, $TV = \int_{i=1}^{\infty} |du/dt|$, so TV is a good measure of smoothness. So, to evaluate the robustness, we compute the maximum closed loop sensitivity, defined as $M_s = max_w |1/[1 + gc(jw$

The result for process, all results are without detuning (F=1). The complete results for all cases are available in a technical report.

As expected, when the method is tested on first order plus delay process, similar to MSOM responses, independent of value of overshoot. In typical cases see fig.5-6. For models that are not first order plus delay, the agreement with the MSOM method is the best for intermediate overshoot.(fig7-8). A overshoot typically give "slower" and more robust PI settings, whereas a large overshoot gives more aggressive PI-settings. In some since this is good, because it means that a more "careful" step response results are more "careful" tunings.

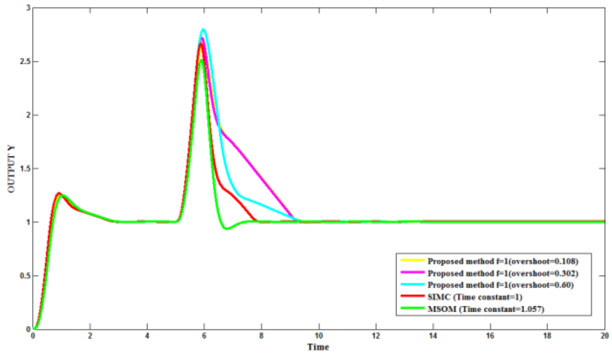

Fig.6 Responses for SMC of integrating process.

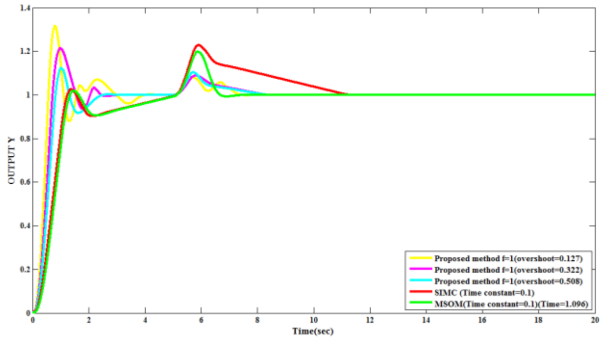

Fig.7 Responses for SMC of second order process .

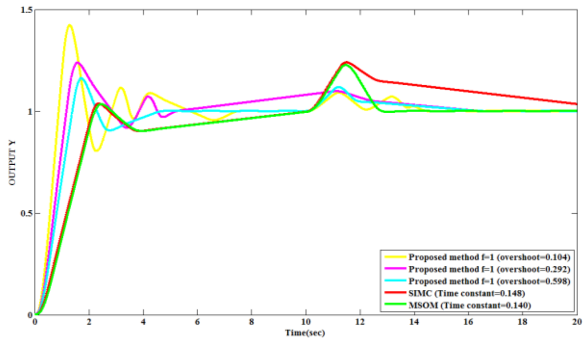

Fig.8 Responses for SMC of high-order process .

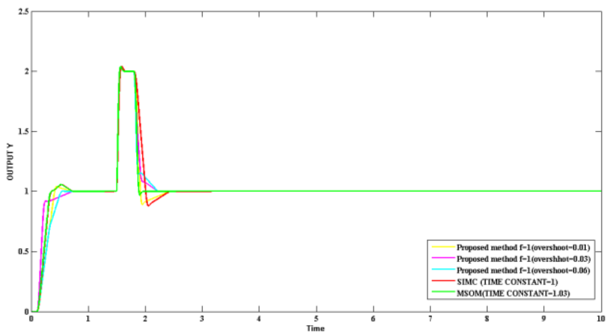

Fig.5 Responses for SMC of pure time delay process g = e^{-s} setpoint changes at t=0; load disturbance of magnitude 1 at t = 15.

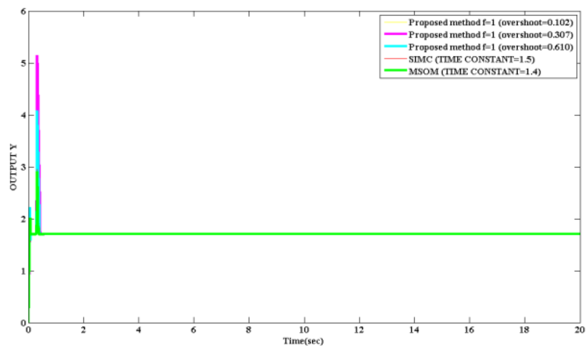

Fig.9 Responses for SMC of third-order integrating process.

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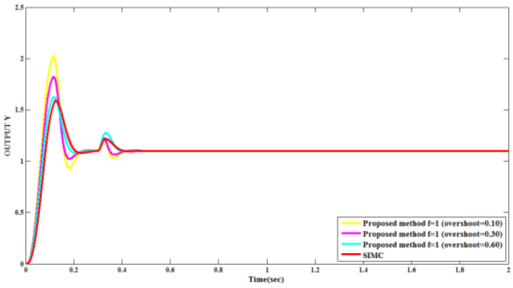

Fig.10 Responses for SMC of first –order unstable process.

From these graph we can see that the time response of the SMC is better than the PID controller in setpoint overshoot. We can easily compare both responses of SIMC and MSOM clearly.

4. Conclusion

A simple and new approach for SMC tuning has been developed. And this approach is compared with previous one PI controller and we conclude that SMC gives better response than the previous one. It is based on a single closed-loop setpoint step experiment.

A good trade-off between robustness and sped of response is achieved with F = 1, but one may use F > 1 to get a smoother response with more robustness and less input usage.

The Setpoint Overshoot Method works well for a wide variety of the processes typical for process control, including the standard first-order plus delay processes as well as integrating, high-order, inverse response, unstable and oscillating process. The method gives a SMC controller, but for dominant second-order processes where derivative action may give large benefits, one can use a SMC in the setpoint experiment, to end up with aSMC.

Compared to the classical Ziegler–Nichols closed-loop method, including its relay tuning variants, the proposed overshoot method is faster and simpler to use and also gives better settings in most cases. The new overshoot method is therefore well suited for use in the process industries as has already been verified.

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