

Design of PLC-based Smith Predictor for Controlling Processes with Long Dead Time

Asim Vodencarevic

Abstract – This paper presents a realization of a PLC-based Smith predictor control scheme on the Siemens S7 platform. The Smith predictor consists of a process model and a pure dead time element. The process model represents a first order plus dead time – FOPDT approximation of the actual process dynamics. Many technological processes can be approximated reasonably accurately with a FOPDT dynamic model. Even if the process to be controlled is not first order in its nature a FOPDT Smith predictor still can be used to provide better loop response.

Advanced control structures are seldom used in processes controlled by a single PLC. Significant improvements can be made in the quality of the final products in manufacturing by reducing process performance variability.

Keywords - Dead time, First order plus dead time, FOPDT, S7 PLC, Second order plus dead time, SOPDT, the Smith predictor

I. INTRODUCTION

The continuing improvement of programmable logic controllers (PLCs) has provided very powerful hardware and software tools for obtaining maximum performance from control loops. The main objective of any control loop is to minimize process variability. This is the most important condition to ensure uniform product quality and thus minimize product waste. This can be applied to any industry. Keeping process parameters at their nominal values is the main requirement for any control loop.

In practice, many control loops are tuned by trial and error procedures and thus are operating far from optimal, delivering poor performance. Dead time resulting from transportation of materials and energy is often found in process industries. Processes with large dead time are found to be very hard to control. This is due to the fact that dead time reduces gain and phase margin which can lead to instability. Therefore, gain has to be limited to preserve stability which effectively reduces loop performance. In many cases, a simple PID controller can't provide the desired loop performance, which means that more advanced control structures must be applied.

Manuscript received October 29, 2009.

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Advanced control concepts (adaptive control, model based control, model predictive control, Smith predictor etc.) are typically implemented in distributed control systems – DCS and applied in controlling large and complex processes. For this reason, most DCS systems have built-in functional software structures made for more advanced control designs. This paper presents an implementation and application of the Smith predictor control structure on the Siemens S7 300/400 PLC platform and discusses why and where it can be used to improve plant performance. Software function block, a standard STEP 7 software tool for programming and configuring Siemens S7 300/400 programmable logic controllers, is used to develop the Smith predictor.

II. THE SMITH PREDICTOR STRUCTURE

The structure of the Smith predictor is given in fig. 1.

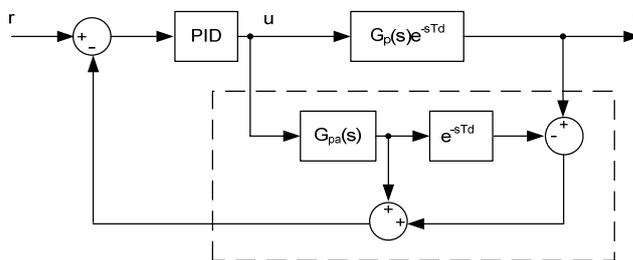


Figure 1. The structure of the Smith predictor

The Smith predictor is basically a dead time compensator. It was first introduced in 1957. Since then, an important research has been carried out in field applications. The basic idea is to separate the linear transfer function part from the dead time part. The key thing is to make a good approximation of the process dynamics $G_{pa}(s)$ and dead time. The overall transfer function can be found by using block diagram algebra:

$$W(s) = \frac{Y(s)}{R(s)} = \frac{G_{PID}G_p}{1 + G_{pa}G_{PID}} e^{-sTd}$$

If $G_{pa} = G_p$, i.e. if there is an exact process model, then the overall transfer function becomes:

$$W(s) = \frac{Y(s)}{R(s)} = \frac{G_{PID}G_p}{1 + G_pG_{PID}} e^{-sTd}$$

In this paper, a PLC realization of a discrete Smith predictor based on a first order with dead time (FOPDT) process model is presented. Its advantages in practice are also discussed.

The overall closed loop transfer function without the Smith predictor is:

$$W_w(s) = \frac{Y(s)}{R(s)} = \frac{G_{PID} G_p e^{-sT_d}}{1 + G_{PID} G_p e^{-sT_d}}$$

A clear advantage of using the Smith predictor is it doesn't introduce dead time in the closed loop transients (denominator of the closed loop transfer function doesn't contain a dead time).

III. DISCRETE TIME EQUIVALENTS OF CONTINUOUS SYSTEMS

There are numerous ways to obtain a discrete time equivalent of a continuous time system. The simplest way is to use numerical integration. First order systems can be described with the following differential equation:

$$\dot{y} + ay = au$$

The solution of this differential equation is given in the following form:

$$y(t) = \int_0^t [-ay(\tau) + au(\tau)] d\tau$$

Choosing time in discrete steps $t = kT$ allows for more ways to perform numerical integration. The most common methods used are:

- Forward difference method,
- Backward difference method,
- Trapezoidal (Tustin) method.

All of these methods use some form of approximation of the continuous variable "s" (Laplace operator) with the discrete variable "z" according to the following table:

Method	Approximation
Forward difference	$s \rightarrow \frac{z-1}{T_s}$
Backward difference	$s \rightarrow \frac{z-1}{T_s z}$
Tustin	$s \rightarrow \frac{2}{T_s} \frac{z-1}{z+1}$

Table 1. Approximation of complex variable "s"

where T_s is a sample time.

The continuous transfer function of a FOPDT system is given in the following form:

$$G_I(s) = \frac{K_p}{(T_p s + 1)} e^{-sT_d}$$

where K_p represents process gain, T_p represents the process time constant and T_d represents dead time.

Applying Tustin's rule to the FOPDT transfer function, a discrete time equivalent transfer function can be obtained in the following form:

$$H_I(z) = \frac{Y(z)}{U(z)} = \frac{K_p}{\frac{2T_p}{T_s} \frac{z-1}{z+1} + 1} z^{\frac{T_d}{T_s}}$$

which yields the following difference equation:

$$y(i) = A \{ B y(i-1) + C [u(i-d) + u(i-1-d)] \},$$

where the coefficients A, B, C and d are calculated according to these relationships:

$$A = \frac{1}{2T_p + T_s}, B = 2T_p - T_s, C = K_p T_s \text{ and } d = T_d / T_s.$$

The last difference equation that describes a FOPDT system can be used to implement the Smith predictor function block in any PLC capable of handling these calculations. This can significantly improve loop performance.

To implement such a system in a PLC, all calculations must be executed on a consistent timed basis. This means that a function block that contains the program code must be called cyclically with an exact time period.

IV. IMPLEMENTATION OF THE SMITH PREDICTOR IN A SIEMENS S7 300/400 PLC SYSTEM

Since Siemens dominates the European PLC market, a PLC from the S7 300/400 series is chosen as a platform in which the Smith predictor is implemented. However, most of the conclusions are equally applicable to any other brand of PLC with similar characteristics, such as Allen-Bradley PLC and similar.

In the previous discussion it was concluded that the Smith predictor function block must be implemented on a platform which performs calculations of all coefficients on a regular time basis. On the Siemens S7 300/400 platform this is possible by using cyclic interrupt blocks such as OB31, 32, 33,...38. Cyclic interrupt blocks are called at exactly equal intervals. These cyclic interrupt blocks interrupt the free-running PLC program normally placed in organization block OB1 at exact time intervals and return to the interruption point afterwards. Processing of a PLC program with cyclic interrupts, on the S7 300/400 platform is given in fig. 2.

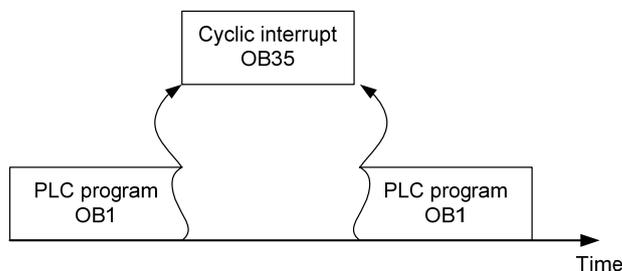


Figure 2. S7 PLC program execution

Cyclic organization blocks with default cyclic time intervals sorted according their priorities are presented in table 2.

Cyclic OBs	Time interval in ms	Priority class
OB30	5000	7
OB31	2000	8
OB32	1000	9
OB33	500	10
OB34	200	11
OB35	100	12
OB36	50	13
OB37	20	14
OB38	10	15

Table 2. Cyclic interrupt organization blocks

The Structured Control Language – SCL is chosen as a programming language to implement the Smith predictor function block. SCL is an optional software package to the STEP7 software. SCL is a high level programming language with syntax similar to Pascal. An S7 SCL program is normally written in a source code editor and then compiled. After code compilation, appropriate functions, function blocks and data blocks are created. The Smith predictor is implemented in the form of a function block with its associated data block so results of all calculations are preserved between program calls. The function block is placed in cyclic interrupt block OB35 with a 100ms time interval.

An example of the Smith predictor function block call is given in fig. 3.

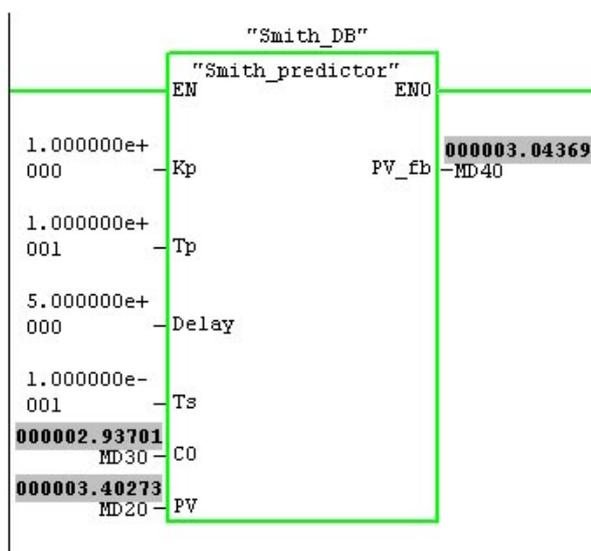


Figure 3. The Smith predictor function block call

The Smith predictor function block has six inputs and one output. The implemented predictor structure contains a FOPDT model which means that actual process dynamics are approximated with first order plus dead time dynamics. In addition to the estimated process gain, time constant and dead time and cycle (sample) time, the controller output and the process variable are needed in order to calculate the output that is going to be used as the feedback signal in the closed loop system. They cycle (sample) time must match the time interval at which the function block is executed i.e. time interval of OB processing the Smith predictor.

The required inputs and output routing of the Smith predictor block can be determined from the structure presented in fig.1.

At first, the FOPDT model built in the structure of the Smith predictor may seem to be a limitation, since most processes have more complicated dynamics. While it is true that FOPDT model may not represent the optimal approximation of such processes, it is still a much better solution than not using the FOPDT Smith predictor at all. This will be shown by analyzing applications of the FOPDT Smith predictor to different types of technological processes. This is very important keeping in mind that most PLC controlled processes involve application of simple PID control algorithms which causes loop responses far from the optimal.

V. SIMULATION RESULTS

Performance of the Smith predictor is tested using different process models. Complete tests are carried out on the S7 PLC platform using PLCSIM software to simulate an actual PLC. Process dynamics are simulated using first order plus dead time and second order plus dead time software blocks created for this purpose.

First, the FOPDT Smith predictor performance is going to be tested with the process described by the following transfer function:

$$G(s) = \frac{2}{(10s+1)} e^{-5s}$$

According to Internal Model Control – IMC tuning method, the following PI controller can be calculated as:

$$K_C = \frac{1}{K_P} \frac{T_p}{T_d + T_C}, T_i = T_p,$$

where the PI controller is given in the ISA dependant form:

$$G_{PI}(s) = K_C \left(1 + \frac{1}{T_i s} \right).$$

K_C is the controller gain, T_i is the integral time constant (reset time) and T_C is the so called closed loop constant which can be computed in different ways. In this paper, T_C is calculated according to the following formula:

$$T_C = \max \{ 0.1 \cdot T_p, 0.8 \cdot T_d \}$$

The following PI controller is obtained from the given process parameters:

$$G_{PI}(s) = 0.56 \left(1 + \frac{1}{10s} \right)$$

This PI controller will produce the loop response shown in fig. 4. As can be seen, the loop response has an overshoot of about 9 % and a settling time of 30s (calculated according 2 % criterion). Since the dead time is 5s and is one half of the process time constant gain stability is reduced and it is clear that further increase of gain will increase the amplitude of oscillation and even make the loop unstable. Indeed, by doubling the controller gain to 1.2 loop response becomes very nearly unstable as shown in fig.5.

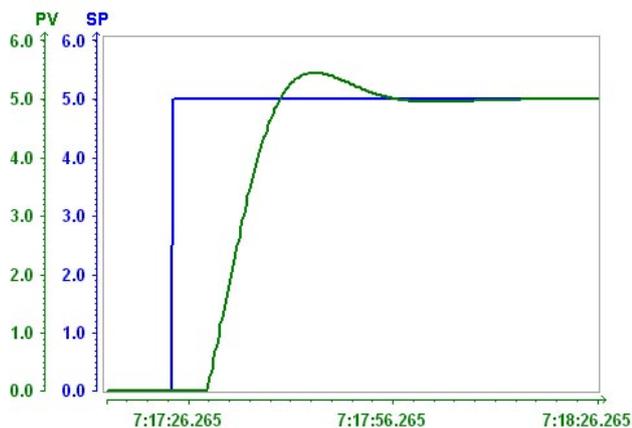


Figure 4. Loop response with $K_C = 0.56$ and $T_i = 10s$

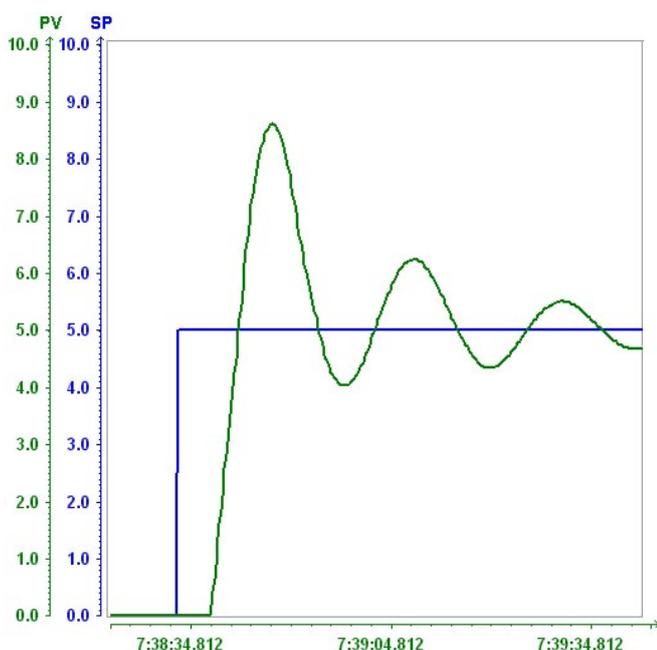


Figure 5. Loop response with $K_C = 1.2$ and $T_i = 10s$

From the previous analysis, it is clear that if overshoot is not desirable, further decrease of the controller gain is necessary. On the other hand, decreasing the controller gain will increase the settling time making the loop response slower.

Applying the FOPDT Smith predictor with $K_C = 0.56$ and $T_i = 10s$ the PI controller parameters will produce the loop response shown in fig. 6.

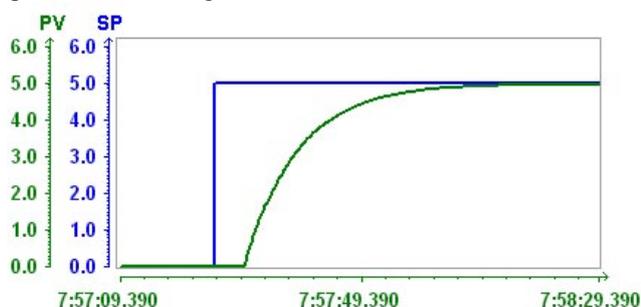


Figure 6. Loop response with the Smith predictor and PI controller with $K_C = 0.56$ and $T_i = 10s$

From the loop response in fig. 6, it is clear that the PI controller with $K_C = 0.56$ and $T_i = 10s$ when the Smith

predictor is applied will not produce overshoot and settling time is about 38s.

Doubling controller gain to $K_C = 1.2$ and using the FOPDT Smith predictor with a first order model that exactly matches the linear process transfer function leads to the loop response shown in fig. 7.

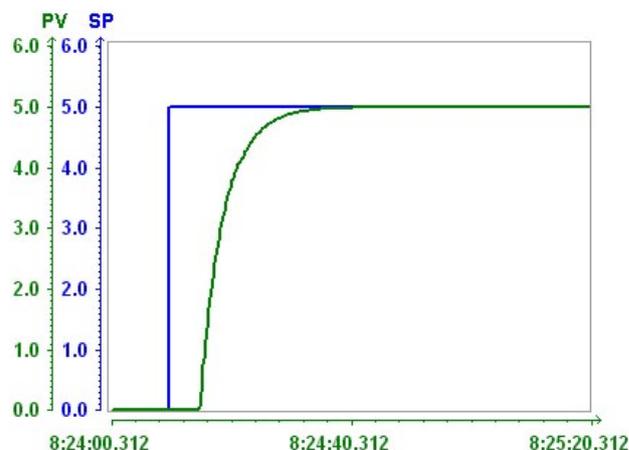


Figure 7. Loop response with the Smith predictor and PI controller with $K_C = 1.2$ and $T_i = 10s$

The loop response in fig. 7 doesn't have an overshoot and the settling time is 21s, which is much better response than without using the Smith predictor. This means that much higher gain is possible. That is the biggest advantage of the Smith predictor. As already stated, the Smith predictor block cancels the negative dead time effect in the closed loop dynamics effectively increasing gain stability margin.

The Smith predictor block applied in the previous analysis used a FOPDT model that exactly matched the process transfer function. This same structure can provide very good results even if the actual process dynamics are higher order. The key step is to estimate the FOPDT model to match the process response as closely as possible. The most important parameter to estimate is the dead time.

To illustrate this, the FOPDT Smith predictor is going to be tested with an underdamped second order process given by the following transfer function:

$$G_H(s) = \frac{1}{100s^2 + 10s + 1} e^{-5s}$$

Second order system from previous transfer function has the following parameters:

process gain $K_p = 1$, time constant $T_p = 10s$, dead time $T_d = 5s$ and damping coefficient $\xi = 0.5$.

Chien [1] suggested a robust PID controller design for SOPDT systems with the following parameters:

$$K_C = \frac{2\xi T_p}{K_p(\lambda + T_d)}, T_i = 2\xi T_p, T_D = \frac{T_p}{2\xi},$$

where $\lambda = \max\{0.25 \cdot T_d, 0.2 \cdot T_p\}$.

The following PID controller can be obtained from these process parameters,:

$$G_{PID}(s) = 1.43 \left(1 + \frac{1}{10s} + 10s \right)$$

This PID controller applied without the FOPDT Smith predictor will produce the response shown in fig. 8.

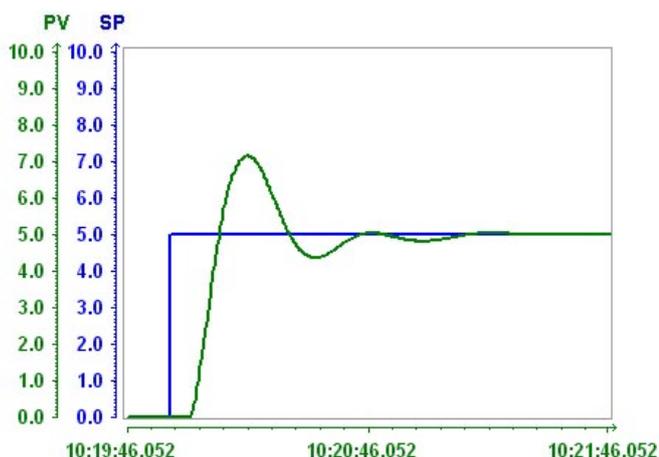


Figure 8. Response without the Smith predictor with PID controller with $K_C = 1.43$, $T_i = 10s$ and $T_D = 10s$

The filtering time constant on the derivative part of the PID controller is chosen to be 1s, so the derivative part is $10s/(s+1)$ which is realizable in practice. From fig.8 it is obvious that the overshoot is very large at about 40%.

In order to apply the FOPDT Smith predictor, a SOPDT model must be approximated as a FOPDT model in some way. For an overdamped system, that is not really a problem. However, an underdamped system will have an overshoot which is not a feature of a FOPDT system.

An underdamped SOPDT system can be approximated as a FOPDT system according to the following relations [2]:

$$K_a = K_p, T_a = 2\xi T_p, T_{da} = \frac{T_p}{2\xi} + T_d,$$

where $G_a(s) = \frac{K_a}{(T_a s + 1)} e^{-s T_{da}}$ is a FOPDT approximation of

an underdamped SOPDT system suitable for application of a FOPDT Smith predictor. For the underdamped SOPDT system given as an example, the following FOPDT approximation can be made:

$$G_a(s) = \frac{1}{(10s + 1)} e^{-15s}$$

The structure of the FOPDT Smith predictor with a SOPDT process is presented in fig. 9.

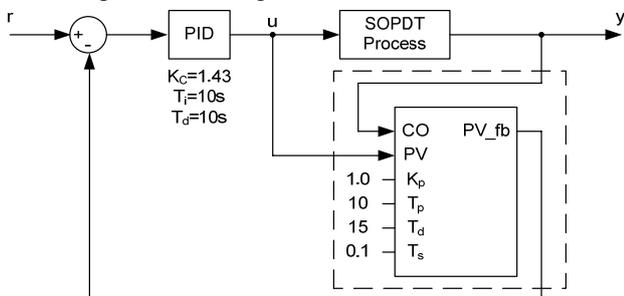


Figure 9. The FOPDT Smith predictor with the SOPDT

The response of the underdamped second order system with dead time is given in the fig. 10. From fig. 10 it can be seen that response doesn't overshoot the set point value. Also, there is not much difference in the settling time.

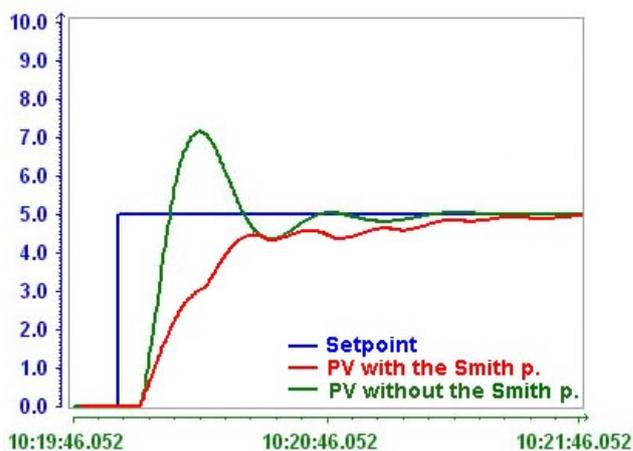


Figure 10. Response with the FOPDT Smith predictor with PID controller with $K_C = 1.43$, $T_i = 10s$ and $T_D = 10s$

From the previous discussion and examples, it is clear that the FOPDT Smith predictor can significantly improve loop performance. The FOPDT Smith predictor is a good choice whenever the ratio of the dead time to the process time constant is greater than 0.5.

VI. CONCLUSION

In this study, a PLC based realization of the Smith predictor structure is presented. The Siemens S7 300/400 series is chosen as the implementation platform. The Smith predictor is based on a first order plus dead time model of a process. This fact doesn't exclude it from use with more complex processes.

As dead time increases, the process is harder to control. Dead time generally decreases gain and phase stability margin. For this reason, a smaller controller gain must be applied which decreases loop performance. The Smith predictor function block is used first with a FOPDT process, where it improved loop response and allowed use of higher controller gain. Tests were also made on an S7 simulation model of a system with second order plus dead time – SOPDT dynamics with an underdamped response. In this case, the FOPDT Smith predictor provided much better response compared to the loop response without the dead time compensator. A requirement for application of the FOPDT Smith predictor with a SOPDT system is that a good FOPDT approximation can be made. A practical example of the application of a FOPDT Smith predictor with an underdamped SOPDT system showed that significant improvements in the loop response can be made. This can be very beneficial in manufacturing by improving product quality through reducing process variability.

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