THE USE OF ON/OFF FEED CONTROL FOR PAN BOILING

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Abstract

Feed control of pans can be achieved using actuated on/off valves in place of conventional control valves. This is achieved without a noticeable degradation in control performance by the use of time proportional on/off actuation (pulse width modulation). This type of control offers cost savings, particularly for continuous pans with multiple loops. The requirements and techniques for implementing this type of control are discussed. The selection of an appropriate length of on/off cycle is discussed, supported by calculations based on measured plant dynamics to quantify the extent to which oscillations are damped by the process. The specific advantages of on/off feed control are discussed.

Keywords: automation, tuning, continuous pans

Introduction

The suppliers of the first continuous pan installed in South Africa proposed that it be supplied with only three feed control loops despite having 15 compartments. Because this level of automation was considered insufficient, feed control loops were fitted to each compartment. The cost-effective solution of achieving this was the use of modified commercial temperature controllers which actuated the feed valves on a time proportional on/off basis. The controllers proved to be entirely satisfactory (Graham and Radford, 1977).

When the Felixton factory was built with continuous pans on all three grades of massecuite (Rein,1983), no compromise was made on the control equipment, and all the compartments of all these continuous pans were fitted with conventional PID controllers and proportionally actuated feed valves. During subsequent experiments, one of the continuous A-pans was converted to use time proportional on/off feed control on all 12 compartments, demonstrating that any degradation in control performance was minimal and that there were a number of benefits to this type of control.

A number of subsequent continuous pan installations have been installed with time proportional on/off feed control as the preferred choice. This type of control has been shown to approximate full proportional control very closely, rather than the poor control associated with conventional on/off controllers sometimes referred to as 'bang-bang' control. Although on/off feed control can also be applied to batch pans, the major advantages appear to be achieved with continuous pan installations.

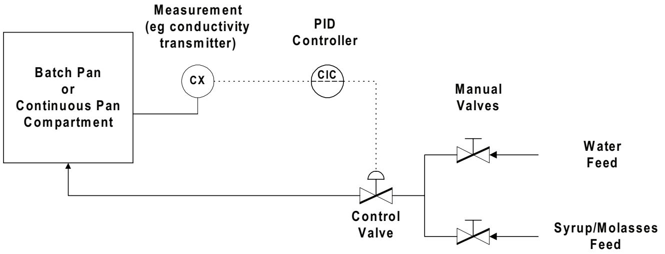

Figure 1. Conventional arrangement for Pan feed control.

Hardware for on/off control

Conventional feed control of a batch pan or the individual compartment of a continuous pan is normally configured as shown in Figure 1.

A sensor (often a conductivity transmitter) measures the condition of the massecuite in the pan. The signal from this transmitter is fed into a controller (ideally a full proportional integral derivative, or PID, controller) which varies the feed into the compartment by adjusting the feed valve position, so as to maintain the massecuite condition at a specified setpoint. The decision on whether to feed with either water or syrup (or molasses) is normally made separately, either manually or as part of a higher level supervisory control.

The use of on/off feed control still requires an appropriate process measurement and a proportional integral derivative (PID) controller. The change is that the proportional output of the controller (0 to 100%) is not used to position the opening of the feed valve, but is interpreted as the percentage of time that the feed valve should be held fully open, the valve being fully closed for the balance of the time. This 'time proportional on/off control' must work to a basic cycle. As discussed later, a cycle of 30 seconds is a reasonable compromise for industrial continuous pans. With this cycle, a 20% controller output will be interpreted as requiring the feed valve to stay fully open for 6 seconds and fully closed for 24 seconds as shown in Figure 2. This is equivalent to what is called 'pulse width modulation' in electrical engineering.

Whilst it is possible to design external circuitry to convert the output of a conventional analog controller into a time proportional on/off signal, this is an undesirable complication. The major advantage occurs when control is implemented in programmable controllers (eg programmable logic controllers or PLCs) where the conversion into a time proportional signal can be done in software as described later.

When implemented using a PLC, the different hardware requirements of conventional proportional control versus on/off time proportional control can be summarised as follows:

Conventional proportional control:

- analog output from PLC.
- current to pressure (I/P) converter.

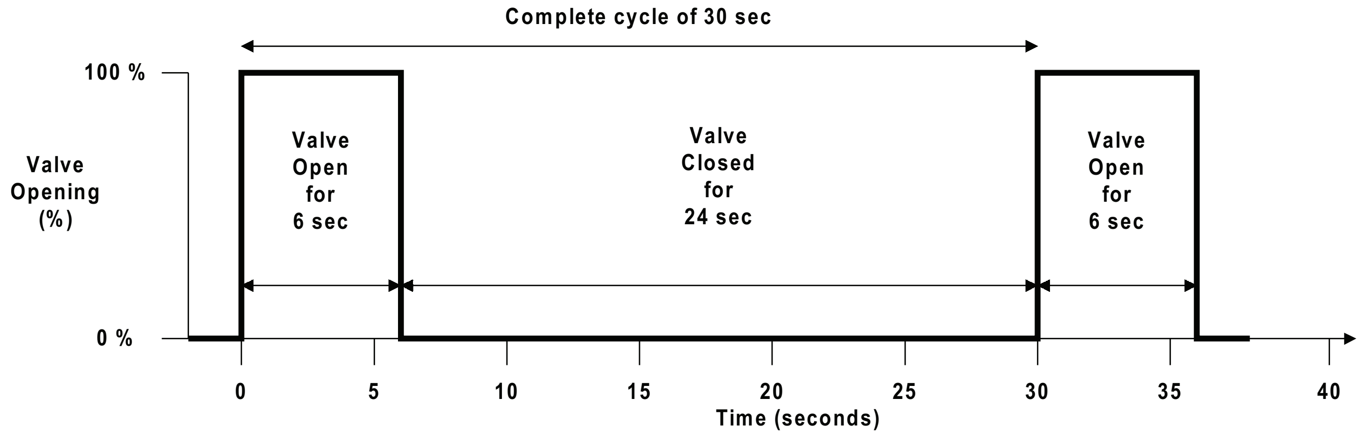

Figure 2. Example of time proportional on/off feed control with a 30 second basic cycle.

- control valve on feed line (with capability of being positioned between 0 and 100%).

Time proportional on/off control:

- digital output from PLC.
- solenoid valve (driven by PLC and supplying air to the actuated feed valve)
- actuated valve on feed line (either fully open or fully closed).

There is a cost saving on all three requirements when on/off control is used. For continuous pans with multiple compartments the savings are multiplied by the number of compartments and can be considerable.

Conventional control with a proportionally set control valve requires that the valve is appropriately sized for the particular duty. To achieve good control performance, standard practice is to ensure that at least 30% of the dynamic pressure loss occurs across the control valve (Coulson *et al*., 1983). In consequence it is not possible to compensate for an oversized control valve by adding a restriction or throttling a manual valve on the same line.

With on/off control, the sizing of the actuated valve is no longer critical. The total dynamic pressure loss of the valve and piping combined must be sized to limit the maximum flow to an acceptable level. The average flow is then a simple linear function of the average valve opening. Thus a 50% valve opening will result in a flow of 50% of the maximum flow (providing that the speed at which the valve opens and closes is fast relative to the overall on/off cycle time). The consequence of this linear action is that it is possible to size the feed valve to have a minimal pressure drop and then size a restriction in the feed line to achieve the required maximum flow. It is also possible to have different restrictions installed on the supply lines for water and syrup/molasses, so that either feed option requires approximately the same average valve opening. With this effective equalising of the gain of the process for either water or syrup/ molasses feed, the controller tuning requirements become the same and it is no longer necessary to determine tuning parameters that are a compromise between two different requirements.

Algorithms for on/off control

A number of different algorithms are possible for implementing on/off control, with differing levels of complexity and performance. The intention is not to replace the PID control algorithm but to convert its output from the conventional 0 to 100% into a time proportional on/off signal. Whilst the PID control calculation will normally be available as a built-in function in a PLC, it is possible to code a specific algorithm to achieve this if the control is implemented in a generic computer (for example see Auslander *et al*., 1996 or Astrom and Hagglund, 1996). For convenience the descriptions of the algorithms which follow assume a 30 second cycle.

The simplest algorithm takes the required valve output calculated at the beginning of a cycle and converts it to the required number of seconds that the valve must be held open. Thus

RequiredOpenTime = ValveOpen% / 100 * 30

The valve is immediately opened and held open for the required period, and the shut for the remainder of the cycle. At the end of the 30 second cycle period, the calculation is repeated and the new results implemented in the same manner for the next 30 second cycle.

This approach has a number of disadvantages. The output from the PID control algorithm is only updated every 30 seconds, even if the PID controller updates itself more frequently. If multiple control loops are implemented, as on a continuous pan, the cycles of the individual loops must be staggered to smooth out the flow, to prevent undesirable interactions between compartments and to facilitate reliable measurements of the total feed flow. A simple method of staggering the loops is to operate the 30 second cycle of each loop slightly offset relative to the previous loop.

An alternative control algorithm, which still works on average with a 30 second cycle but evaluates the PID algorithm every second is possible. Each second, the PID algorithm is calculated to determine the required valve opening. The required number of seconds that the valve must be held in the open and closed positions are then calculated:

Required Open Time = Valve Open% / 100 * 30

Required Closed Time = 30 - Required Open Time

If the valve is open, the length of time it has been open is checked against the required open time. If the valve has been open long enough it is closed, if not, it is left open. If the valve is closed, the length of time it has been closed is checked against the required closed time. If the valve has been closed long enough it is opened, if not, it is left closed.

This algorithm has the advantage that it will respond rapidly to controller output and because it does not work to a strict 30 second cycle the individual loops will operate randomly with respect to each other, removing the need to stagger the cycles of the different loops.

Effect of valve cycling on pan behaviour

Intuitively, shorter cycles of on/off actuation will result in smaller fluctuations in the process measurement in response to the changes in feed valve position. Shorter cycles will however result in more frequent actuation of the feed valve and a reduced valve life. A cycle of 30 seconds has been found to be a practical compromise for industrial continuous pans, showing no obvious deterioration in control compared with conventional, proportional, valve actuation. Butterfly valves are particularly successful in accommodating the large number of cycles required (2880 per day).

A more fundamental understanding of an appropriate cycle period for on/off control can be achieved from measurements of the dynamic behaviour of feed control loops. It is common to describe the behaviour of a process in terms of the degree to which a sinusoidal signal is either reduced or amplified as it passes from the input to the output of a process. This is shown diagrammatically for the process of feeding a pan in Figure 3.

The factor by which the sinusoidal signal is amplified or attenuated is referred to as the amplitude ratio, A, which is given by :

$$A = \frac{A_{out}}{A_{in}} \qquad (1)$$

where: A_{in} is the amplitude of the input signal

and A_{out} is the amplitude of the output signal

Love and Chilvers (1986) demonstrated that the process response of a feed control loop behaved as a pure integrator with dead-time. They showed that the amplitude ratio for the process is given by :

$$A = \frac{1}{2 \cdot \pi \cdot F \cdot C} \qquad (2)$$

where F is the frequency of oscillation in cycles per second and C is the effective capacitance of the process in seconds.

With time proportional on/off control, the input to the process is a square wave rather than a sinusoidal wave. By Fourier analysis, it is possible to represent the square wave as a combination of sinusoidal waves as shown in the Appendix. Using this technique, the signal to the feed control valve, $f(x)$, (the input to the process) is given by :

$$f(x) = \frac{1}{2} \cdot a_0 + \sum_{n=1}^{\infty} a_n \cdot \cos\left(\frac{n \cdot \pi \cdot x}{p}\right) \qquad (3)$$

where

$$a_0 = 200 \cdot k \qquad (4)$$

$$a_n = \frac{200}{n \cdot \pi} \cdot \left(\sin\left(\frac{n \cdot \pi \cdot k}{2}\right) - \sin\left(n \cdot \pi \cdot \left(1 - \frac{k}{2}\right)\right)\right) \qquad (5)$$

x is the time in seconds

p is the length of the on/off cycle

k is the fraction of time that the valve is held in the open position

Using equation (1) it is possible to calculate the amplitude ratio by which each of the sinusoidal components of equation (3) will be attenuated as they pass through the process to appear as fluctuations in the process measurement. Using the same subscript, n, to reference each component from 1 upwards, it is possible to write :

$$A_n = \frac{1}{2 \cdot \pi \cdot \frac{n}{2 \cdot p} \cdot C} = \frac{p}{\pi \cdot n \cdot C} \qquad (6)$$

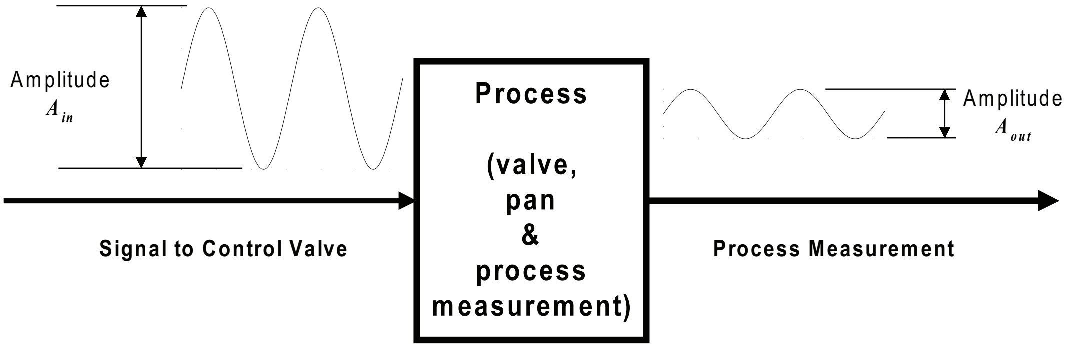

Figure 3. Attenuation of sinusoidal fluctuations as they pass through the process.

Two step tuning tests similar to those described by Love and Chilvers (1986), but using feed valve positions set at 0 and 100%, were conducted on a compartment of a continuous A-pan at Felixton fed with syrup. Cycling the measured value about the set point required an average feed valve opening of 25% (ie $k = 0.25$) and an analysis of the results showed an effective capacitance of the process of 600 seconds (ie $C = 600$). Assuming that the control is operating with a standard 30 second cycle (ie $p = 30$), it is possible to calculate numerical values for the equations presented above. The absolute values of a_n (calculated from Equation 5) give the amplitude of each of the components of the input signal to the process. These are shown plotted in Figure 4.

The magnitude of each of these components after having passed through the process can be calculated by multiplying the absolute value of a_n by the value of A_n calculated from Equation 6. These resulting magnitudes of the components of the output from the process are shown plotted in Figure 5.

It can be seen from the from these graphs that although the amplitude of largest component entering the process is about 45% this is reduced to about 0.35% when it appears on the process measurement. The combined effect of all the components appearing on the process measurement can be calculated by adding the components together, whilst taking into account that each component undergoes a phase shift of $-\pi/2$ radians as it passes through the process. The equation which describes the fluctuation in the process measurement, $f_0(x)$, is thus :

$$f_o(x) = \frac{1}{2}\cdot a_0 + \sum_{n=1}^{\infty} A_n \cdot a_n \cdot \cos\left(\frac{n\cdot\pi\cdot x}{p} - \frac{\pi}{2}\right) \quad (7)$$

Using this equation and summing the first 100 terms of the Fourier series, gives the process output shown in Figure 6 below.

The oscillation in the process measurement has a maximum variation of approximately 0.9%. At this magnitude, when combined with normal process and measurement noise it is not surprising that it is not usually possible to discern the cyclic effects of the on/off control strategy on the measurement signal. Any filtering applied to the measurement will also further reduce the amplitude of the oscillation in the process measurement.

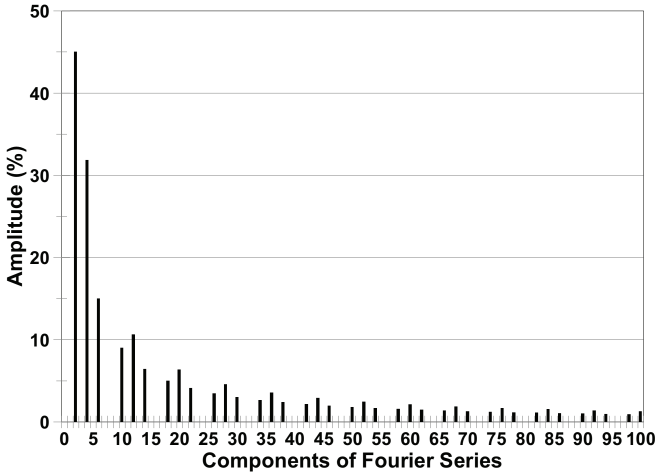

Figure 4. Amplitude of components of process input estimated using Fourier analysis.

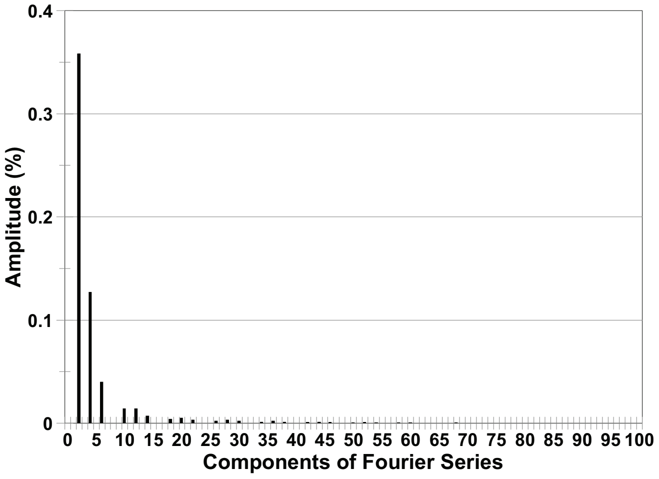

Figure 5. Amplitude of components of process measurement estimated using Fourier analysis.

Automatic tuning

Tuning of pan feed control loops can be accomplished by following the procedure described by Love and Chilvers (1986). Although this procedure is described as a manual test method, it is possible to automate the procedure in an elegant manner using the relay feedback concept of Astrom and Wittenmark (1989). This automatic tuning procedure can be applied to proportional feed valve control but it is particularly simple to implement with on/off control.

The principle behind automatic tuning (as opposed to adaptive control) is to place the controller into a special 'tuning mode' for a limited period during which special procedures are applied to determine the most appropriate tuning parameters for the controller. The controller is then switched back to the normal control mode with these new tuning parameters.

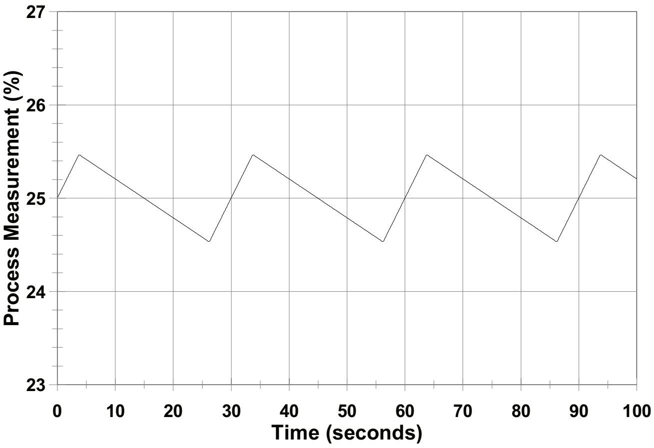

Figure 6. Fluctuations in process measurement estimated using Fourier analysis.

The automatic tuning is achieved by replacing the conventional PID control algorithm for a short period with a relay feed back which includes added hysteresis. The magnitude of the hysteresis may need to be adjusted for particular situations, but a value of 1% of span above and below set point has proved successful in tests on a 120 m^3 continuous A-pan. For a process measurement which increases as the pan contents concentrate, and using the 1% hysteresis, the algorithm to implement the relay feedback is :

- close the feed valve
- wait for the process measurement to rise to 1% of span above set point
- open the feed valve
- wait for the process measurement to drop to 1% of span below set point
- close the feed valve

This procedure can be repeated as many times as necessary to ensure a representative measurement of pan behaviour before returning to normal PID control. The analysis of the recorded data can be automated by using a non-linear regression routine to find the points that describe the saw-tooth wave form that is expected in the process measurement. Once the fitting has been achieved, simple calculations according to the procedure of Love and Chilvers (1986) will yield the effective capacitance and dead time of the process and enable the calculation of appropriate tuning parameters for the PID controller.

Estimation of compartment feed flows on a continuous pan

A knowledge of the feed flow to each compartment of a continuous pan is a useful aide for production management, indicative of the appropriateness of the boiling profile and the relative amounts of crystallisation taking place in each compartment.

When a measurement of total feed flow is available, it is easy to determine the maximum flow to each individual compartment by momentarily shutting all other feed valves while the particular feed valve is held open. With maximum flows determined in this way, the average flow to each compartment can be estimated from the average valve output multiplied by the maximum flow (as a result of the linear characteristics of time proportional on/off valve actuation). As a check, the sum of average flows to all the individual compartments should be equal to the measured average total flow.

Conclusions

The use of time proportional on/off valve operation has proven successful for the feed control of pans. When implemented using a PLC, there is a cost benefit over the more conventional use of full proportional control of valve position. This saving can become considerable when there is a requirement to implement multiple feed control loops on a continuous pan.

With a suitably chosen cycle for the implementation of on/off control (usually 30 seconds), the effects of the cycling of the feed valve cause no readily observable fluctuations in the process measurement. This observation has been confirmed by an analysis of the dynamic behaviour of pans.

The use of on/off feed control provides a number of other benefits in addition to that of the reduced cost of the instrumentation and control equipment, viz.

- easily implemented automatic tuning.
- the estimation of feed flow to individual compartments of a continuous pan from valve position.
- insensitivity of control performance to control valve sizing.
- the ability to achieve equally good control performance with either water or syrup feed using the same feed valve.

APPENDIX

Fourier analysis can be used to represent any periodic function as the sum of a series of sinusoidal waves. Following the description of Fourier analysis presented by Boas (1966), a function *f*(*x*) with a period 2*p*, can be expressed as the Fourier series:

$$\begin{aligned} f(x) = \frac{1}{2}\cdot a_0 + a_1\cdot\cos\frac{\pi x}{p} + a_2\cdot\cos\frac{2\pi x}{p} + a_3\cdot\cos\frac{3\pi x}{p} + \ldots \\ + b_1\cdot\sin\frac{\pi x}{p} + b_2\cdot\sin\frac{2\pi x}{p} + b_3\cdot\sin\frac{3\pi x}{p} + \ldots \end{aligned} \qquad (8)$$

The evaluation of the Fourier coefficients is simplified if the periodic function can be shown to be either odd :

$$f(x) \quad \text{is odd if} \quad f(-x) = -f(x) \qquad (9)$$

or even :

$$f(x) \quad \text{is even if} \quad f(-x) = f(x) \qquad (10)$$

It is possible to describe a time proportional on/off signal in such a way that it is an even function, as shown in Figure 7.

For an even function, the coefficients of the Fourier series are given by :

$$\begin{aligned} a_n &= \frac{2}{p}\cdot\int_0^p f(x)\cdot\cos\left(\frac{n\cdot\pi\cdot x}{p}\right)dx \\ b_n &= 0 \end{aligned} \qquad (11)$$

It is thus only necessary to evaluate coefficients for the cosine terms, ie the a_n terms. The first term, with the zero subscript is evaluated separately as follows :

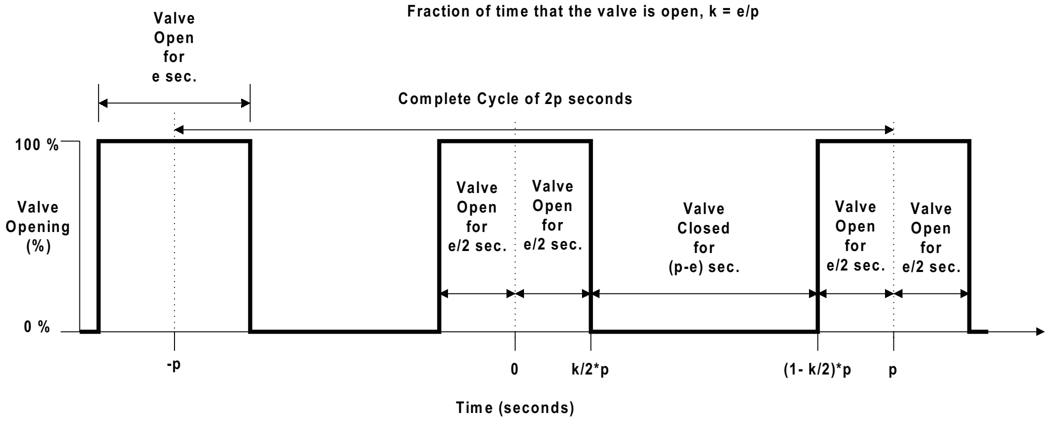

Figure 7. Feed cycle configured as an even function to facilitate Fourier analysis.

$$\begin{aligned} a_0 &= \frac{2}{p}\cdot\int_0^p f(x)dx \\ &= \frac{2}{p}\cdot\left(\int_0^{\frac{k}{2}\cdot p} f(x)dx + \int_{\left(1-\frac{k}{2}\right)\cdot p}^{p} f(x)dx\right) \\ &= \frac{200}{p}\cdot\left(\left(\frac{k}{2}\cdot p\right)+\left(p-\left(1-\frac{k}{2}\right)\cdot p\right)\right) \qquad (12) \\ &= 200\cdot k \end{aligned}$$

The subsequent terms, with subscript one and above can be evaluated generically as follows :

$$\begin{aligned} a_n &= \frac{2}{p}\cdot\int_0^p f(x)\cdot\cos\left(\frac{n\cdot\pi\cdot x}{p}\right)dx \\ &= \frac{2}{p}\cdot\left(\int_0^{\frac{k}{2}\cdot p} 100\cdot\cos\left(\frac{n\cdot\pi\cdot x}{p}\right)dx + \int_{\left(1-\frac{k}{2}\right)\cdot p}^{p} 100\cdot\cos\left(\frac{n\cdot\pi\cdot x}{p}\right)dx\right) \\ &= \frac{2}{p}\cdot\left(\left[100\cdot\frac{p}{n\cdot\pi}\cdot\sin\left(\frac{n\cdot\pi\cdot x}{p}\right)\right]_0^{\frac{k}{2}\cdot p} + \left[100\cdot\frac{p}{n\cdot\pi}\cdot\sin\left(\frac{n\cdot\pi\cdot x}{p}\right)\right]_{\left(1-\frac{k}{2}\right)\cdot p}^{p}\right) \\ &= \frac{2}{p}\cdot\left(100\cdot\frac{p}{n\cdot\pi}\cdot\sin\left(\frac{n\cdot\pi\cdot\frac{k}{2}\cdot p}{p}\right) - 100\cdot\frac{p}{n\cdot\pi}\cdot\sin\left(\frac{n\cdot\pi\cdot\left(1-\frac{k}{2}\right)\cdot p}{p}\right)\right) \\ &= \frac{200}{n\cdot\pi}\cdot\left(\sin\left(\frac{n\cdot\pi\cdot k}{2}\right) - \sin\left(n\cdot\pi\cdot\left(1-\frac{k}{2}\right)\right)\right) \qquad (13) \end{aligned}$$

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