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Process Control of Ice Plant System- Precise Full Range Bidirectional Automatic Control of Expansion Valve with Unidirectional Pulses

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Abstract
The parameters which are influencing the efficiency of Ice plant refrigeration process control system are torque (motor pulley size) of the induction motor, ammonia gas pressure, opening of expansion valve, salt solution density, atmospheric temperature etc. Presently, the ice plant system is equipped with manually controlled expansion valve. The thermo-dynamic property of ammonia gas is continuously changing during one complete cycle of water to ice block formation. Under this situation, the expansion valve delivers ammonia gas and partially ammonia liquid in to the cooling coil. The ammonia liquid does not contribute to the heat transfer between water and ammonia liquid and hence goes as a waste and reduces the efficiency of the system. The proposal is for automatic adjustment of expansion valve.
using Delta-sigma modulator (DSM) based control circuit. The proposed control circuit provides precise full range bidirectional automatic control of expansion valve with unidirectional pulses. The proposed control circuit ensures that the refrigerant ammonia circulates in the cooling coil in gas form only. The expansion valve is controlled by a stepper motor which in turn controlled by the proposed control circuit. The proposed technique reduces the ice formation time and power consumption.

Keywords: Delta Sigma Modulator, Expansion valve, Cooling coil, unidirectional pulses, Automatic control.

Introduction
Liquids absorb heat when changed from liquid to gas. Gases give off heat when changed from gas to liquid.For an air conditioning system to operate with economy, the refrigerant must be used repeatedly. For this reason, all ice plants use the same cycle of compression, condensation, expansion, and evaporation in a closed circuit. The same refrigerant is used to move the heat from onearea (to cool this area) and to expel this heat in another area. Different refrigerants are used and we will consider the ice plant system with ammonia as refrigerant.

The basic refrigeration cycle in the ice plant system is shown in Fig.1.The refrigerant comes into the compressor as a low-pressure gas, it is compressed and then moves
out of the compressor as a high-pressure gas. The gas then flows to the condenser. Here the gas condenses to a liquid, and gives off its heat to the circulating water. The liquid then moves to the receiver and then to expansion valve under high pressure. This valve restricts the flow of the fluid, lowers its pressure and converts to gas form as it leaves the expansion valve. The low-pressure ammonia gas then moves to the cooling coil (evaporator), where heat from the saline water (in which the ice canes are immersed) is absorbed. Thus the water in the ice canes are cooled and converted into ice blocks. As a hot low-pressure gas, the refrigerant moves to the compressor where the entire cycle is repeated.

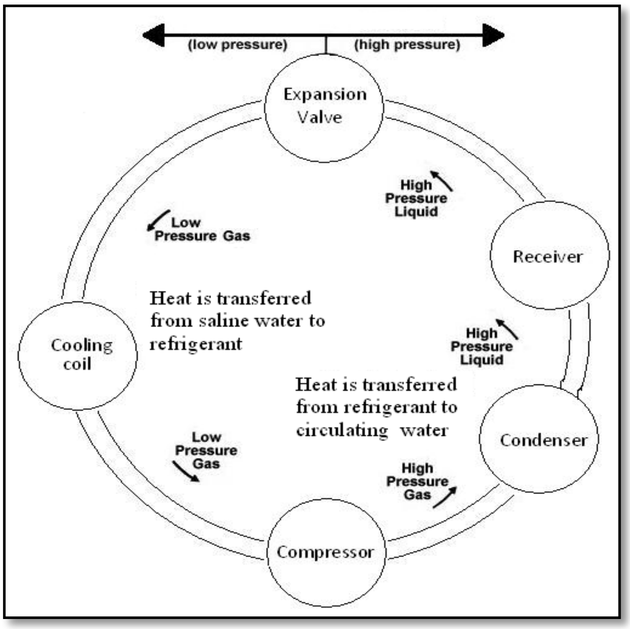

Figure 1: Refrigeration cycle in ice plant system

There are several papers in which methods are suggested to reduce ice formation time and power consumption. In [1], the results suggest that, the addition of bio-nucleant may help induce ice nucleation and increase freezing temperature thereby reduces the energy consumption of ice formation for cold storage.

In the engineering fields of heating, refrigerating, and air-conditioning, the global warming caused by the refrigerants is a big problem that must be solved. At the present stage, however, there are no perfect solutions for next generation refrigerants and heat pump/refrigeration systems by which the global warming is successfully prevented. In [2], important four ways which are (1) natural refrigerants, (2) low GWP synthetic refrigerants, (3) refrigerant management, and (4) refrigerant mixtures are introduced. From a drop-in test, feasibility of the refrigerant mixture has been proved.

In [3], thermo physical properties of hydrofluoro-olefin refrigerants using databases are evaluated with experimental data. Then, the fundamental cycle performance of air conditioning by using major refrigerants is studied based on their thermo physical properties. The results show that there is no adequate refrigerant for air conditioning applications. Heat pumps with new refrigerants including refrigerant mixtures must be developed as fast as possible. It leads to that HFC refrigerants must be used taking care until the new refrigerants will be available.

The research paper [4] presents an experimental study of using a vapor compression refrigeration system (VCRS) for cooling a steam power plant condenser. The results reveal that using a VCRS is capable of providing a steam condenser with a more constant and lower coolant temperature than traditional wet and dry cooling technologies. In [5], the efficiency of proposed method is compared with that of Internal Model Control (IMC) and proves to be better in the performance index.

Several refrigerants have emerged as substitutes to replace R22, the most widely used fluorocarbon refrigerants in the world. These include the environmentally friendly hydrocarbon (HFC) refrigerants R134a, R410A and R407C.Considering the recent trends of replacement of ozone depleting refrigerants and improvement in system efficiency, in paper [6], R407C can be a potential HFC refrigerant replacement for new and existing systems presently using R22 with minimum investment and efforts.

In this proposal a method of reducing the ice formation time and hence reducing the power consumption is proposed. Presently, in the ice plant system manually controlled or float controlled expansion valve is used. The cooling coil is kept in vertical position in the saline water tank. The refrigerant ammonia if it is gas form can circulate in the cooling coil. The liquid portion of ammonia will be retained at the bottom of cooling coil and will not contribute to the heat transfer and will go to the drain as waste. This will reduce the efficiency of the system and wastage of refrigerant.

To reduce the ice block formation time and to reduce the electrical power consumption, Delta- Sigma modulator (DSM) based control circuit is used. The circuit works for the full range of input signal. It preciously controls the expansion valve for the full scale. The control is achieved by unidirectional pulses. It ensures that the ammonia enters only in gaseous form in to the cooling coil, thereby it reduces ice formation time, electrical power consumption and charging of ammonia gas.

Proposed Technique

The flow rate of ammonia gas and the pressure at the outlet of expansion valve is measured by flow meter and pressure meter respectively. The pressure signal is fed to the Arduino interface board. The Mat lab software can read the analog signal when Arduino library is installed. Simulink model file is generated to process the data by the proposed Unidirectional Delta-Sigma modulator. The DSM and stepper motor are matched pair because the output pulses from the DSM can directly drive the stepper motor. But in the case of existing conventional DSM the normalized input range is limited to 0.5. Additionally, the conventional DSM will give a stream of positive and negative pulses such that the average value of the digital pulses over a period is equal to the average value of the discrete input for the same period [7], [8]. If the positive pulses open the valve then the negative pulses will close the valve but over the sampling period the valve will be opened are closed proportional to the discrete input. To avoid this opening and closing of valve for a given discrete signal, full range unidirectional DSM is proposed. If the input to the DSM is positive, pulses of amplitude 1V and 0V is generated. If the input to the DSM is negative, pulses of amplitude -1V and 0 V is generated. Hence, the output will drive the stepper in clockwise or in anti-clockwise direction for a given sample.

The pulse train generated by Simulink is fed to Arduino board from the laptop. The digital output of Arduino board is fed to the stepper motor which opens or closes the expansion valve such that the ammonia medium is delivered at the outlet only in gas form.

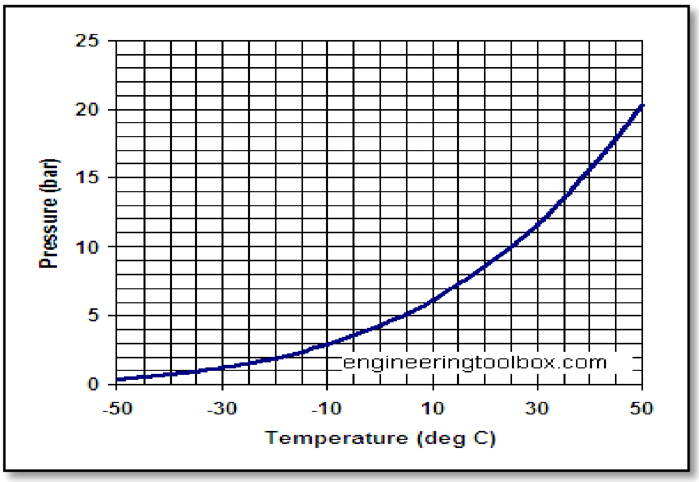

Figure 2: Pressure Vs. Temperature of Ammonia

The variation of pressure of the ammonia refrigerant when the temperature is increased is shown in Fig.2. Ammonia boils at -34 deg. centigrade. From liquid state ammonia changes to gaseous state for temperature above -34deg. centigrade. Let us maintain the outlet temperature of ammonia gas at -30deg. centigrade. At this temperature the ammonia medium will be in gaseous form. The pressure of ammonia gas at -30 deg. centigrade is 1.2 bar. During one complete cycle, the thermo dynamic properties of ammonia changes. If the pressure increases above 1.2 bar, the opening of expansion valve is increased so that the pressure drops down to 1.2 bar. If the pressure drops below 1.2 bar, the opening of expansion valve is decreased so that the pressure pulls up to 1.2 bar. The control circuit which is designed using Simulink reads the outlet pressure value and opens or closes the expansion valve through stepper motor such that the pressure is maintained at 1.2 bar. That is at the outlet of expansion valve, the ammonia medium is maintained in gaseous form only. The outlet area of expansion valve is directly proportional to the flow meter reading

A. Block Diagram of Proposed unidirectional DSM

The block diagram of the proposed DSM is shown in the circuit of Fig.3. The input to the DSM, x is dc signal of value unity. The gain element in the feedback path (n) is equal to 1.5 which is the supply voltage of the circuit. The DSM circuit is operated by clock with period T_C. In Fig. 3,P_i refers to the pressure signal in volts at the outlet of expansion valve. P_{ref} refers to the voltage which is equivalent to the reference pressure (1.2 bar). The Sample and Hold (S/H) circuit samples the input signal, y_{analog} which is the error voltage from the pressure meter, at a sampling period T_U (update period)and the error signal is used to control the operating period of the DSM.

The range of y_{analog} is -1.5 to +1.5 which is the supply voltage of the CMOS circuit. T_U and T_C are selected such that $T_U >> T_C$. The average values of outputs of the first integrator, second integrator, and quantizer during i^{th} update period are denoted as x_1, $x_2$and z respectively. The output of sign block is +1 when the input is above zero, -1 when the input is below zero and zero when the input is zero. The sign block functions as single bit quantizer and in addition provide zero output for zero input. During a positive transition of update signal, the SR flip-flop is set. When the SR flip-flop is set (phase Φ_{on}), the switches s_1 to s_7 are closed (shown by thin dotted lines) and DSM starts functioning. The DSM output consists of a sequence of pulses of amplitude +1 and 0 when the input amplitude is positive. When the input amplitude is negative, the DSM output consists of sequence of pulses of amplitude-1 and 0. The resolution of DSM output, Δy is given by,

$$\Delta y = \frac{T_C}{T_U} \, | \, y_{\max} \, | \qquad (1)$$

The resolution, Δy is integrated when the R-S flip-flop is set. The integral value of Δy, $(\Delta y)_{cum}$ is compared with $|y|$. When $(\Delta y)_{cum} > |y|$, the SR flip-flop is reset (phase Φ_{off}). The switches s_1 to s_7 are opened, the DSM stops functioning and output is zero for the remaining sampling period since the quantizer output is clamped to analog ground through a switch. All the integrators, denoted as I_1, I_2, and I_3 are reset to zero and cumulative addition of Δy also stops. Δy is selected such that $(\Delta y)_{cum}$ is less than $|y_{max}|$ (supply voltage 1.5 V) in the update period. When y is negative, the quantizer output is inverted (not shown in figure) to get correct sign for the output. During next positive transition of update cycle the DSM operating cycle is repeated.

The time at which the states of different blocks are updated, is labeled on each block or on set of blocks (shown by thick dotted lines) in Fig.3. During each sampling period, the bit stream at the output of quantizer gives the digital representation of input signal. The average value of bit stream at the output during each sampling period gives the sampled analog value of the error signal.

The input signal to DSM is dc signal. For dc input if the DSM is operated with sufficiently low clock period, the average value of the digital output will be a good approximation of the input. This leads to better SNR in the higher range of input signal. As far as the DSM is concerned, the input is 1V and the feedback gain, n=1.5. The operating period of the DSM is only varied proportional to the absolute amplitude of the error signal. In DSM with signal dependent operating period, when n=1.5,

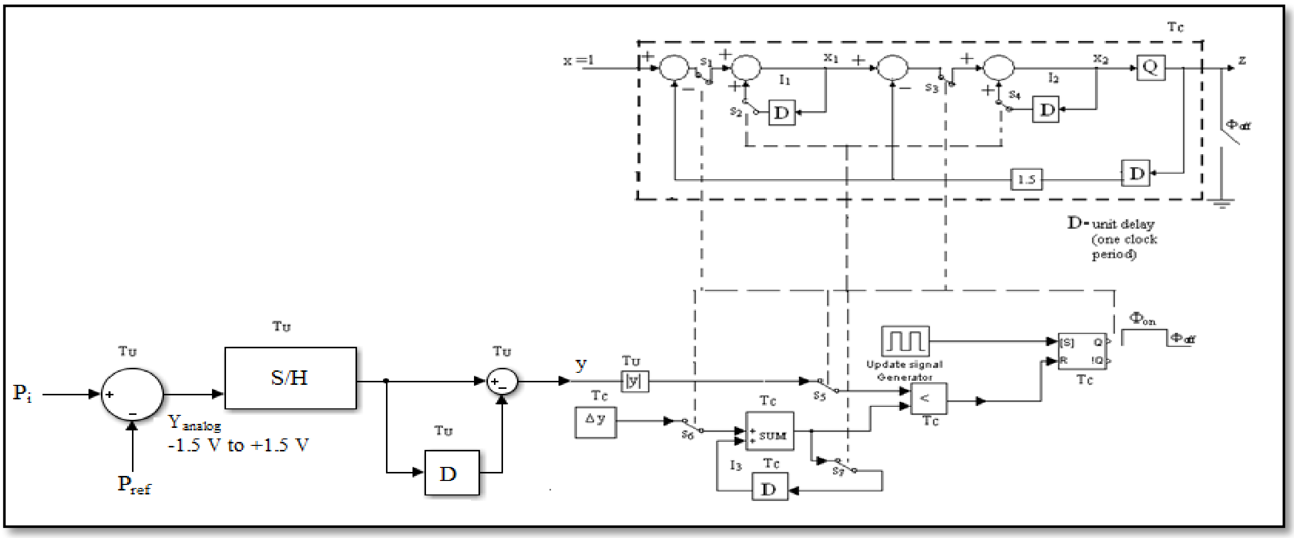

Figure 3: Schematic diagram of proposed DSM.

$$x_1(k)_{\max} = 1.5x \qquad (2)$$

$$x_2(k)_{\max} = 1.5x \qquad (3)$$

Where $x_1(k)$ and $x_2(k)$ represent the first integrator output and second integrator output respectively during k^{th} clock period in a sampling period. When x=1,

$$x_1(k)_{\max} = x_2(k)_{\max} = 1.5 \qquad (4)$$

The upper bounds of the state variables are constant and never overload the quantizer and hence the proposed DSM is stable for the full scale range of the input signal.The amplitude of the analog input signal (error signal) controls only the operating period of the DSM and hence the state variables and stability does not depend upon the amplitude of the input signal.

The timing–chart of the proposed DSM is shown in Fig.4. For each update period, T_U (which is a constant), the DSM circuit operating time, T_O (which is a variable proportional to $|y|$) will be in the range $0 \leq T_O \leq T_U$. T_U and T_C are selected such that $T_U >> T_C$.

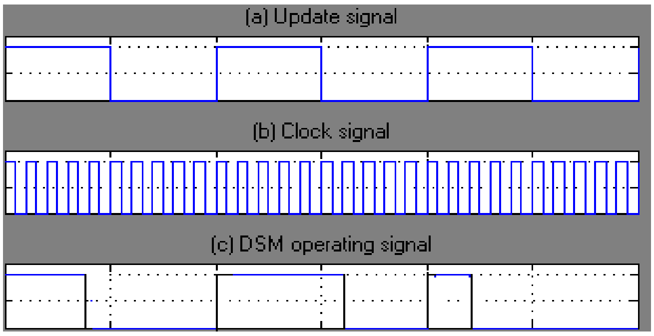

Figure 4: Timing Chart of Update Signal (Period T_U), Clock Signal (Period T_C) and DSM Operating Signal (Duty T_O).

B. Relation Between Inputs And Output

For each update period, T_U(which is a constant), the DSM circuit operating time, T_O is in the range $0 \leq T_O < T_U$, where T_O is a variable and is proportional to $|y|$. The average value of output signal during T_O (z') in each sampling period is given by,

$$z' = \frac{N_p T_C}{T_O} \qquad (5)$$

Where is the net number of pulses (number of positive pulses – number of negative pulses) at the output. In the conventional DSM, the average value of output during T_O, in each sampling period is equal to normalized input. Therefore,

$$\frac{1}{n} = \frac{N_p T_C}{T_O} \qquad (6)$$

The operating period of the DSM circuit is proportional to $|y|$. Therefore,

$$T_O = k_1 |y| \qquad (7)$$

Where k_1 is a constant. Substituting in equation (7), $T_O = T_U$ when $|y|$ = 1, results in $k_1 = T_U$. Substituting the value of k_1 in (7) results in $T_O = T_U |y|$ and substituting this value of T_O in equation (6), N_P can be given as,

$$N_p = \frac{|y| T_U}{n T_C} \qquad (8)$$

The average value of DSM output during T_U (z) is given by,

$$z = \frac{N_p T_C}{T_U} \qquad (9)$$

Substituting the value of N_P from equation (8), z can be written as,

$$z = \frac{|y|}{n} \qquad (10)$$

When y is negative, the quantizer output is inverted. Therefore z can be written as,

$$z = \frac{y}{n} \qquad (11)$$

C. Accuracy

The resolution of the proposed DSM is given by equation (1). For T_C=0.1µsec, T_U=0.24 msec and $|y_{max}|$=1.5V the resolution, Δy=0.6mV.The variation of *Pi* in terms of pressure is from 0.2 bar to 2 bar. The corresponding variation of P_i in terms of voltage is from -1.5V to +1.5V. When *Pi* is equal to 1.2 bar (reference pressure) the corresponding voltage is 0V. The stepper motor rotates by one step when 0.26 mV is applied. Therefore accuracy$\left(\frac{0.26\times10^{-3}}{1.5}\times 100\right)$ is equal to 0.017%

Simulation Results and Discussion

The software, MATLAB, is used to simulate the proposed DSM with n=1.5, $f_U(1/T_U)$ = 4.096 kHz and $f_C(1/T_C)$ =10MHz. In equations (2) and (3) are given the maximum bounds of first integrator output and second integrator output with dc input signal and are same as obtained from the simulation. If the supply voltage of cmos circuit is 1.5 V, it is necessary to limit the input of conventional DSM less than 0.1. Otherwise the upper bounds of the second integrator output become greater than 1.5V and make the DSM unstable [7], [8]. But, the proposed DSM can operate for the full range of input signal in stable condition.

The sampled analog input signal of peak amplitude 1.5V and frequency 40 Hz. is shown in Fig.5 (a) which is the error signal. Fig.5 (b) shows the first integrator output of the proposed DSM, the maximum value of which is 1.5. Fig.5(c) shows the second integrator output of the proposed DSM, the maximum value of which is also 1.5. $|(x_1)_{\max}|$ and $|(x_2)_{\max}|$ remain constant at 1.5 and never overload the quantizer. Hence, the proposed DSM can be realized using cmos circuitry of supply voltage 1.5 V which results in low power consumption. Fig.5 (d) shows the output of the quantizer of the proposed DSM. When the input signal amplitude is positive, positive pulses of varying widths are present and when the input signal amplitude is negative, negative pulses of varying widths are present and thus the proposed DSM is unidirectional. It can be noted that when the input signal amplitude is zero, the DSM is not oscillating by producing positive and negative pulses. These properties of the proposed DSM are essential to smoothly operate the stepper motor which is used as actuator of expansion valve in the ice plant system.Fig.5 (e) shows the demodulated signal of the quantizer output of the proposed DSM. The demodulated signal is the average value of the quantizer output during each update period. It can be seen that the demodulated signal is equal to the sampled analog input signal.

When the error signal is positive i.e. when the outlet pressure is greater than 1.2 bar, the positive pulses at the output of proposed DSM rotates the stepper motor in the anti-clock wise direction. The expansion valve which is directly coupled with the stepper motor rotates in the anti-clock wise direction and it further opens the valve thereby reducing the outlet pressure. Similarly, when the pressure falls below 1.2 bar the stepper rotates in clock-wise direction and closes the expansion valve and thereby increases the outlet pressure. The proposed technique thus maintains the pressure at the outlet of the expansion valve as 1.2 bar and hence the refrigerant will be always in gaseous form thereby reducing the ice formation time and power consumption

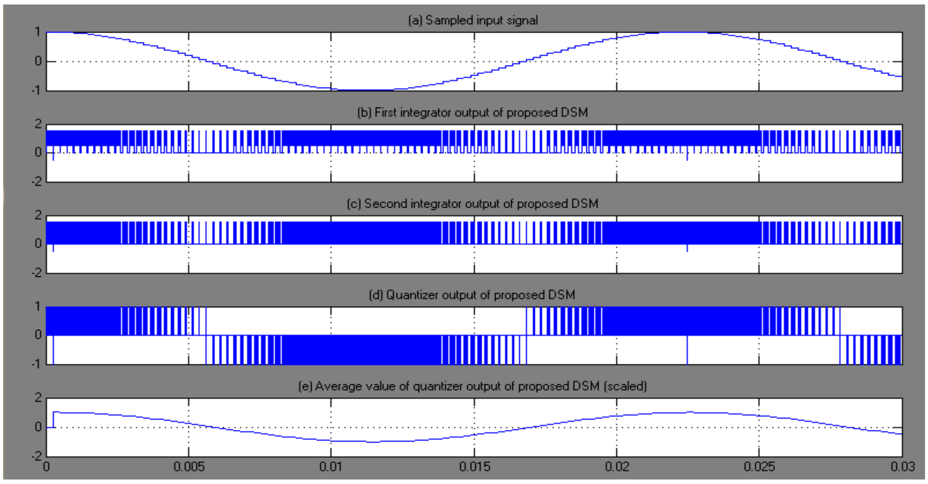

Figure 5: Outputs of proposed DSM for errorsignal. (Horizontal axis-Time in sec.Vertical axis-Voltage in volt)

Conclusion

The proposed DSM based control circuit provides precise full range bidirectional automatic control of expansion valve with unidirectional pulses. The accuracy proposed DSM is 0.017%. The proposed control circuit maintains the refrigerant in gaseous form only, when injected in to the cooling coil .Hence, the proposed system reduces the ice formation time, refrigerant consumption and power consumption.

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