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Full Length Research Paper

Fuzzy and three-step control of refiner system to get stable freeness for recycled paper

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This paper presents the design of refiner control system for recycled paper stock preparation as a complete solution to fulfill refiner control requirements. This control system is based on Specific Energy Consumption (SEC) control (indirect freeness control) providing uniform refining during production range changes or changes in consistency and flow. In addition, SEC controller provides minimizing paper breaks, optimizing energy consumption and maximizing overall quality. The designed controller includes some interlocks that are very important for refining control systems such as low and high pressure, insufficient stock flow, low consistency and automatic unloading limit values. The system is equipped with two types of controllers which are power controller and SEC controller. Fuzzy and three-step algorithms for control process have been developed in the microcontroller unit. C++-based software was developed to communicate between the host computer and the designed microcontroller unit over the RS232 interfacing unit.

Key words: Fuzzy control, freeness, refiner system, specific energy consumption, three-step control.

INTRODUCTION

The pulp and paper industry is one of the complex and innovative manufacturing industries. The industry benefits significantly from new advances in expert control system technologies (Mercangöz and Doyle, 2006). One of them is the refining control systems to get stable freeness for recycled papers.

Refining is the most important stage in paper production as it affects greatly paper machine efficiency, quality criteria, and especially the final paper properties. Refining ensures that the paper machine runs smoothly and determines the quality of the paper. A refiner conditions mechanically the fibers in paper stock to produce the fiber qualities required in the operation of the paper machine. The final purpose of refining is to maintain the desired properties in the finished sheet, including mechanical strength, smoothness, opacity, etc (Proulx, 2000).

Freeness is a measure of the rate at which water drains from a stock suspension through the screen. In other words, freeness is the resistance of pulp fibers to the flow of water. In many cases there is a correlation between freeness values and either a target level of refining of pulp or the ease of drainage of white water from the wet web. As the degree of refining increases, the stock freeness or drainage rate decreases. Freeness is an important physical property of the pulp where it is a measure of the degree of refining for chemical pulps. Typically, the refiner level fluctuates, indicating variation in one or more of the refiner inputs. Better control of the refiner inputs is attempted to improve the freeness precision (Dienes et al., 2005; Latva-Kayra, 2001; Bard et al., 1999).

There are many interesting varieties in refiner design ranging from manually adjusted operation to fully integrated automatic processes. Efficiency implementation of refiner control depends on the consistency and flow rate. It is well known that consistency variation affects refining efficiency. For example, at the same specific refining energy, tensile strength increases at higher pulp consistency (SIEMENS AG Paper stock refiner control, 2010). In a refiner control processes can be accomplished depending on constant power control and specific energy control.

In constant power control, refiner is controlled at an established net power set point. In this control, to fix the variation of freeness, consistency and flow should be

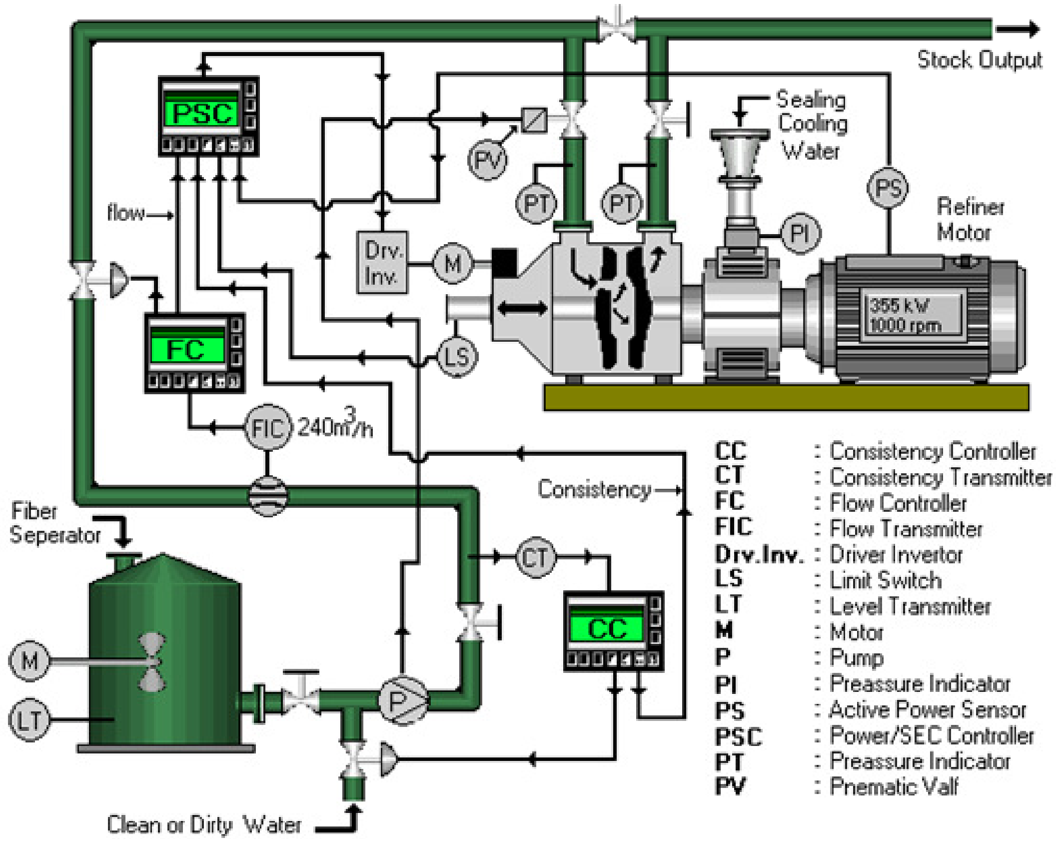

Figure 1. General block diagram of refining system.

always constant. If the flow and consistency variables change over the time, a more complex controller will be required.

Specific energy control is more useful control system in the industry. Specific energy control depends on three input signals which are power, consistency and flow signals. These signals are considered to calculate the amount of energy consumption on each unit weight of solids in the stock. The calculated specific energy is compared to a set point, and refining power is controlled accordingly. Since the specific energy control takes into consideration power, consistency and flow, the quality of refining depends on these changes in process conditions. If the flow and consistency change over the time, then power set point reference changes, so energy saving will be obtained.

In this text, we are presenting to a designed the microcontroller based fuzzy and three-step Power/SEC controller of the refiner system for recycled paper in KMK paper Incorporation in Kahramanmaras city, Turkey. The designed control system provides to uniform refining, to minimize paper breaking, to maximize paper quality and to save 15% energy consumption. Also the controller protects the refiner from low and high pressure, less stock flow, low consistency and automatic unloading limit values.

MATERIALS AND METHODS

System structure

The general block diagram of the controlled refining system is shown in Figure 1. The system includes three controller units; consistency controller, flow controller and Power/SEC controller. Consistency controller controls the consistency of the pulp adjusting the amount of water inlet into the suction side of the stock pump. Flow controller controls the total fiber flow into the refiner. The Power/SEC controller is the main controller unit and controls the complete refiner system.

In a refiner, the stock suspension flows between rotating sets of knives or bars. There are some types of refiner system designs, including counter-rotating disks, double-sided disks, conical plug and shell arrangements. However, the method of adjustment is the same in all the refiner systems. The degree of refining increases with reducing the clearance between the bars. Clearance is adjusted by the reversible loading motor. In this study, the designed controller has been applied on the double-sided disks and conical plug system type refiner. The loading motor was controlled by the inverter driver. The power of the loading motor is 0.25 kW, and the rotation speed is fixed at 15 Hz. As shown in Figure 1, Consistency Controller (CC) reads the consistency from the consistency transmitter and controls the water drainage by using the proportional valve. In the same way, Flow Controller (FC) reads the

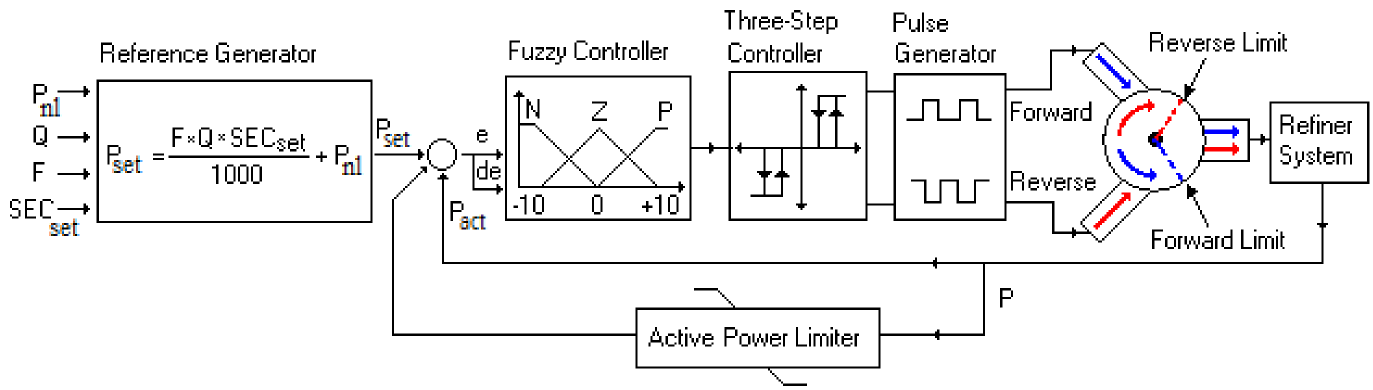

Figure 2. Block diagram of the Power/SEC controller.

Figure 3. The constructed controlled system in KMK paper incorporation.

stock flow from the flow transmitter and controls the stock flow to refiner system by using proportional valve. Power/SEC Controller (PSC) is more complex controller than CC and FC controllers. This controller acts depending on four control inputs, active power, flow, and consistency and SEC set point values. SEC set point value depends on active power, flow and consistency as indicated in Equation (1).

$$SEC(\frac{kWh}{Tone}) = \frac{P_{act} - P_{noload}}{0{,}0010 * Flow(m^3/h) * Consistency(g/ml)} \quad (1)$$

The general block diagram of the controlled system is shown in Figure 2.

Active no load power (P_{nl}), consistency (Q), flow (F) and SEC_{set} set point parameters are applied to reference generator to produce *Pset* reference value. These parameters except for SEC_{set} set point are taken from the transmitters. SEC_{set} set point is entered from the keypad by the operator. P_{nl} is 45 kW constant value of refiner motor at no load. P_{act} is the actual power of refiner motor changes between 0 to 355 kW and measured by (0-50 A, 100 V to 4-20 mA) power transducer. Consistency is measured by (2-7 g/100 ml to 4-20 mA) consistency transducer produced by METSO® Inc. Flow is measured by (0-240 m^3/h to 4-20 mA) flow transducer produced by ABB® Inc (Figure 3).

As previously stated, the system could be controlled in two controller modes, which are power and SEC controllers. In the power controller mode, consistency and flow are assumed to be a constant, therefore, there is no need to reference generator. In the SEC control mode, the set point (P_{set}) is produced by the reference generator for every 200 ms time intervals according to calculated in Equation (1).

If the active power limiter exceeds the determined alarm level, loading motor waits for the 10 s and then operates reverse direction and finally the load is reduced by the controller. When the active power limiter exceeds the trip value, the loading motor is operated reversely and than the motor is stopped.

Fuzzy and three-step control of the system

Fuzzy controller utilizes from the human perceptions and experiences. Fuzzy controller can be easily modeled by linguistically. In recent years, it has been used on many control applications where the system is complex.

Fuzzy controller is the essential part of the refining control system and was built up in the PIC18F452 microcontroller. The controller has two inputs and single output. The input variables error (e) and error deviation (de) of the fuzzy controller are defined as:

$$e(k) = P_{set}(k) - P_{act}(k) \quad (2)$$

$$de(k) = e(k) - e(k-1) \quad (3)$$

The input signals are measured by the 4-20 mA current sensors. These signals are read by the 10-bit ADC module embedded in microcontroller unit.

The concept of fuzzy set theory is the membership function (μ) as probability theory can have a value of between 0 and 1. In Figure 4, the μ function has a linear relationship with the x-axis called universe of discourse. This produces triangular shape fuzzy sets. Fuzzy sets are represented by symmetrical triangles and commonly used because they give good results, and computation is simple (Burns, 2001). When the universe of discourse is discrete and finite the fuzzy sets of input variables (NB, NS, Z, PS, PB) are expressed in Equation (4):

$$A = \sum_{i=1}^{n} \mu_A(x_i)/x_i \quad (4)$$

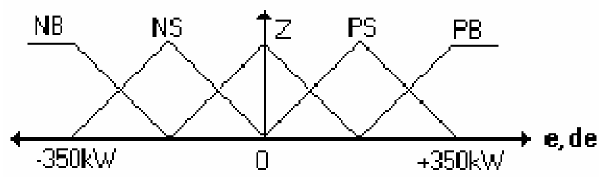

Figure 4. Membership function of input variable.

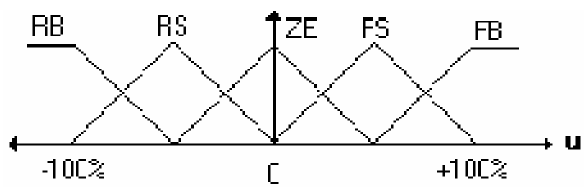

Figure 5. Membership function of output variable.

Table 1. Fuzzy rules of the controlled system.

de/e	NB	NS	Z	PS	PB
NB	RB	RB	RB	RS	RS
NS	RB	RS	RS	ZE	ZE
Z	RS	RS	ZE	FS	FS
PS	ZE	ZE	FS	FS	FB
PB	FS	FS	FB	FB	FB

The membership function of each input variable is shown in Figure 4. The ranges of error and error deviation change between the powers of loading motor from -350 kW to +350 kW. So, these signals are scaled to appropriate values and then applied to the microcontroller based fuzzy controller unit.

Five fuzzy sets are defined for each input variables. For the variable of fuzzy sets have the following linguistic terms:

NB =Negative Big
NS =Negative Small
Z =Zero
PS =Positive Small
PB =Positive Big

The output of fuzzy controller has to be in two directions of control which are the forward and reverse directions as seen in Figure 5. If the error is positive, the loading motor will run forward direction. Contrarily, if the error is negative, the loading motor will run reversely. Since the fuzzy manipulated output is applied to three step controller; the fuzzy output is scaled from -100% to +100%.

The linguistic terms of the output fuzzy sets are:

RB =Reverse Big
RS =Reverse Small
ZE =Zero
FS =Forward Small
FB =Forward Big

The fuzzy control rules can be represented as a mapping from input linguistic variables *e* and *de* to output linguistic variables *u* as follows:

$$u(k+1) = FLC(e(k), de(k)) \tag{5}$$

From the input and output variables, the following fuzzy rules can be defined as shown in Table 1.

Assume that any rule from the rule base table is defined in the following statement:

IF e is A AND de is B THEN u is =C

Hence, the statement can be written as follows:

$$\mu_C(u) = \max[\min(\mu_A(e), \mu_B(de))] \tag{6}$$

Equation (6) is referred to as the max-min fuzzy inference process or max-min fuzzy reasoning. According to defined fuzzy rules, the output defuzzification is performed by the centroid method as shown in Equation (7).

$$Q(kT) = \frac{\sum_{i=1}^{n} u_i \mu_{out}(u_i)}{\sum_{i=1}^{n} \mu_{out}(u_i)} \tag{7}$$

Controller output generates the fuzzy-manipulated output from -100 to 100 according to forward or reverses directions. The digital manipulated output is applied to a three-step element and a pulse generator that creates the pulses for the loading motor. The switching frequency of the controller can be reduced by determining the threshold of three-step element.

In the three-step control mode, the actuating signal has three binary output states. These are FORWARD, REVERSE and PAUSE, respectively. Depending on the input variable, a characteristic curve is used to calculate pulse duration. The form of the characteristic curve is defined by the minimum pulse or minimum break time and the ratio factor as shown in Figure 6 (SIEMENS AG Standard Software for S7-300 and S7-400 PID Control. Users Manuel, 2010).

A correctly adjusted minimum pulse or minimum break time can prevent working life of switching elements and actuators. The positive and negative pulse durations are calculated by multiplying the input variable in (%) with the period time:

$$PulseDuration = \frac{InputVariable}{100} * PeriodTime \tag{8}$$

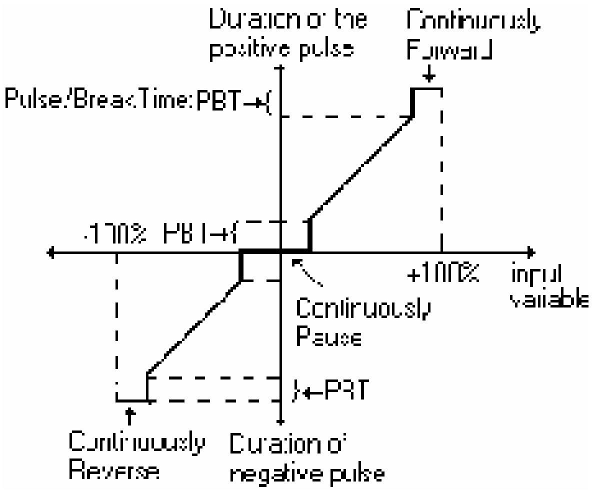

Figure 6. Symmetrical characteristic curve of the three-step controller.

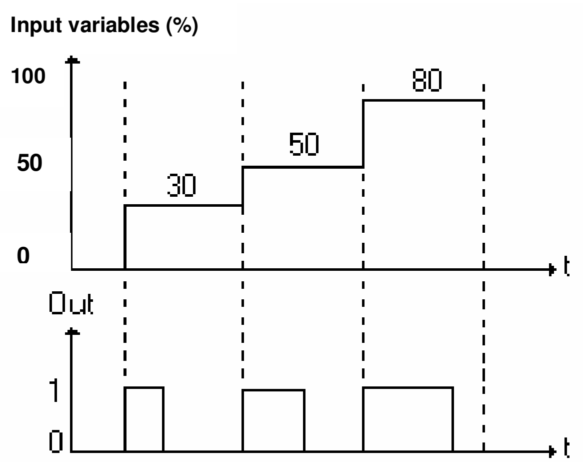

Figure 7. Pulse duration modulation.

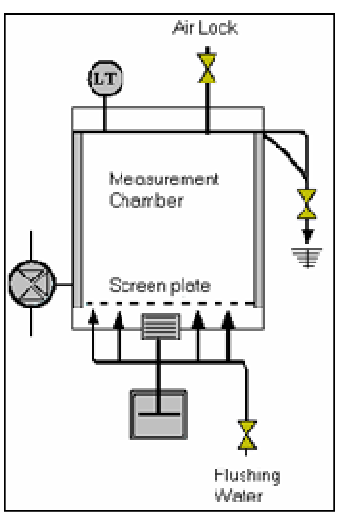

Figure 8. Freeness measurement system.

The function of pulse generator is to transform the manipulated value of fuzzy controller by modulating the pulse duration into a pulse train with a constant period. The duration of a pulse per period is proportional to the input variable as shown in Figure 7.

Freeness measurement

The measurement principle of freeness is available today according to TAPPI T227 standard which is one of the classical methods of determining the freeness and called Canadian Standard Freeness (CSF). In this method, the sample must be taken by manually and not suitable for on-line measurement. In this standard, consistency must be fixed to 3% and the water temperature approximately at 20°C. However, several manufacturers produce on-line freeness measurement devices used this standard (Bard et al., 1999). These manufacturers use this standard. Kajaani®KSF-measurement is an improved version of this standard. This measurement could be determined from the following parameters and depicted in Figure 8 (Metso Automation Company, 2010).

(i) Dimension of measurement chamber
(ii) Sequence of measurement
(iii) Bottom of screen plate
(iv) Identical dewatering curve

In the first step, the level sensor is read and stored to the memory. The level data is translated into dewatering volume info calculation (level multiplied by cross sectional area) from dewatering curve (Metso Automation Company, 2010).

A mathematical dewatering volume curve V(t) is fitted into the measured values Figure 9a. The volume curve V(t) is mathematically converted into a water flow curve V'(t) Figure 9b. The moment of time, t_{KSF}, is determined mathematically:

$V'(t_{KSF}) = 8.83$ ml/s

where 8.83 ml/s is the flow constant through the bottom discharge orifice of the laboratory instrument. This value can be replaced by any customized value if desired.

Freeness is then calculated giving the Equation (9) from the dewatering curve in Figure 9d:

$$Freness = V_{(t_{KSF})} - 8.83 * t_{KSF} - 24ml \tag{9}$$

where, 24 ml is the volume of the bottom section of the funnel in the laboratory instrument.

RESULTS AND DISCUSSION

Experimental results

Consistency and flow controllers were designed by PI controllers using Siemens Spart DR21® controller unit. SEC controller was implemented in PIC18F452 based microcontroller unit using the fuzzy and three step controllers' algorithms (Figure 10). The visualization software (Figure 11) was developed by using C++ programming language to observe the controller capability of the controller's outputs. The developed software communicates to microcontroller unit by using RS232 interface at 19200 baud rate and draw graphics on the PC screen for visualization. The software reads the COM1 port of the computer every 200 ms period of

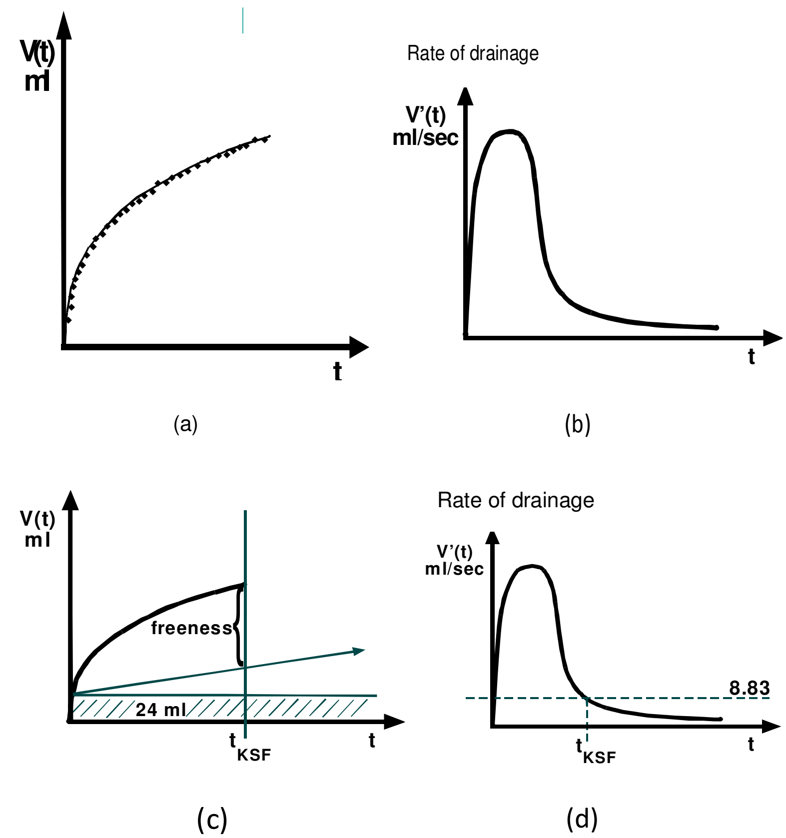

Figure 9. Freeness measurement. (a) Mathematical dewatering volume curve (b) Water flow curve, (c) Determining of the moment time, (d) Freeness.

Figure 10. The constructed controller unit.

time and then saves converted digital samples to the database file. The designed controller system is shown in Figure 10. The designed controller can be selected two controller modes which are power and SEC controller. In power controller mode, active power set point (P_{set}) of refiner motor is held on a fixed specified power value which selectable between 100 to 355 kW. Since the consistency and flow changes over the time, the desired freeness value fluctuates and refiner motor always runs in specified power value. However, in the SEC controller mode, SEC_{set} is determined by the operator and (P_{set}) is calculated by the reference generator depending on flow and consistency. Therefore, SEC controller tunes the freeness fluctuations arising from the variations of the flow and consistency by changing the P_{set} value. However, P_{set} does not change in power mode and energy consumption is fixed. Energy consumption was analyzed by using energy analyzer in both power and SEC controller mode, showing that SEC controller has been performed approximately with 15% energy saving. The first experiment was carried out according to the SEC_{set} values of the 10, 15 and 17.5 kWh/ton, respectively. When the set values are entered to the SEC controller unit, the controller calculates the P_{set} value by using Equation (1). These relations are shown in Table 2.

If the SEC value is increased, similarly, freeness linearly increases depending on SEC_{set} values as shown in

Figure 11. The developed software in C++ for visualization and adjustment some parameters.

Table 2. Changing in the freeness and power variables depending on the controlled input SEC parameters.

SEC (kWh/ton)	P_{set} (kW)	Q (g/100 ml) (%)	F(3 m/h)	Freeness (ml)
10.00	105	4.10	151	520
15.00	140	4.16	154	560
17.50	155	4.15	155	580

Table 2. This process was carried out by the fuzzy controller successfully and the system response is shown in Figure 12 as graphically. The performance of the designed controller system was tested by randomly changing SEC values between 4 to 11 kWh/ton as shown in Figure 13. The test result shows that the control system has perfect responses. The controller rise time was measured of approximately 20 m as shown in Figure 14.

Conclusions

The pulp and paper industry comprises a wide range of researches on the control systems technology. Well designed controllers improve the quality of freeness. The designed control system successfully improves of fiber quality, uniformity, productivity and energy savings.

This study, briefly demonstrates that the automatically control of the refiner systems to get stable freeness for recycled paper. The results indicate that the designed fuzzy and three step controller has been successfully used in the refiner system. Since the consistency and flow parameters fluctuates as randomly by the time in the refiner system, SEC reference generator produces a new adjusted P_{set} value to hold the freeness at desired value. Therewith, the designed SEC controller is able to obtain approximately 15% energy saving with respect to power mode control.

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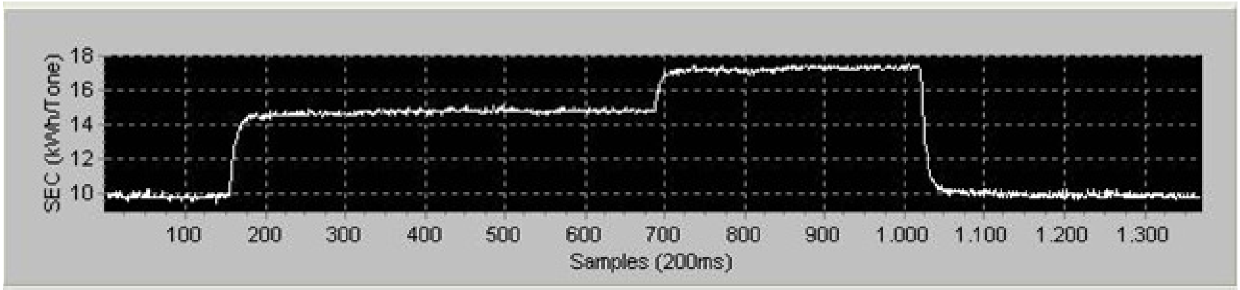

Figure 12. Controller responses according to 10, 15 and 17.5 kWh/ton of SEC values.

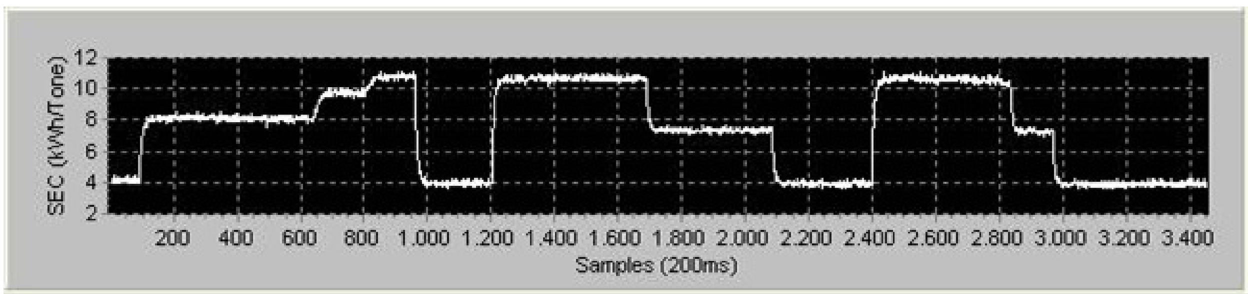

Figure 13. Controller responses based on different variable of SEC values.

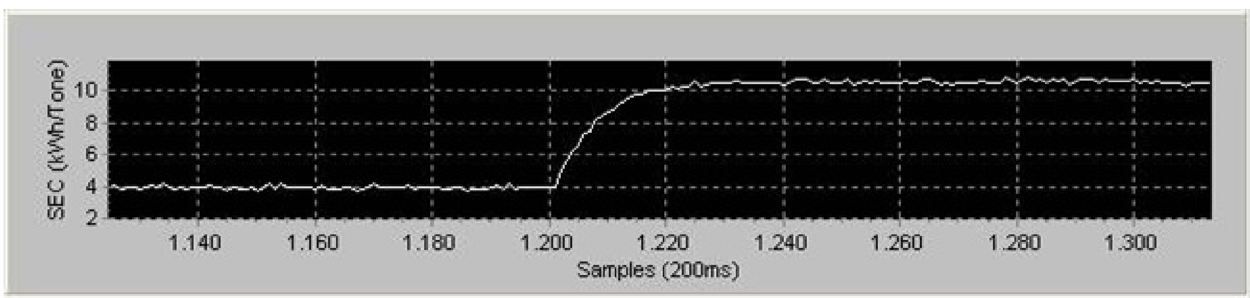

Figure 14. Controller buildup curve.

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