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Comparison of PID and FLC type controller designed for ohmic heating system

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Abstract – In this study, mathematical modeling of an ohmic heating system has been done, firstly. Then, two different control approaches, PID and fuzzy logic control, have been considered to control of mathematically modeled ohmic heating system. An optimal PID controller has designed based on Ziegler-Nicholas method. In order to make a comparison, a fuzzy logic controller (FLC) has also been designed and obtained results have been compared, finally. Based on the obtained results, FLC has showed more powerful, stable and convenient control action to control of an ohmic heating system. Applying designed FLC, it can be concluded that the ohmic heating system behavior is more stable and has less settling time with no overshoot have been observed.

Keywords – Fuzzy, PID, FLC, Fuzzy Logic Control, Ohmic Heating

I. INTRODUCTION

Ohmic heating (OH) is a technique in which a substance is heated by the direct passage of electric current through it. The experimental setup employing this technique is illustrated in Figure 1. This method has a history spanning approximately a century [1, 2]. At present, it continues to exhibit a high level of usability, and its potential suggests that it is anticipated to remain effective for an extended period in the future. The provided figure showcases the experimental arrangement used for this technique. The longevity and sustained relevance of this system can be attributed to its historical development and its ongoing applicability.

Ohmic heating offers several advantages, including sectional temperature homogeneity, high speed, ease of control, high efficiency, and product integrity [3, 4]. Studies exist that characterize this both positively and negatively from an economic standpoint. These studies suggest that despite possible increases in production costs, frozen products can still achieve their goals in post-production logistics [5]. Furthermore, the modern Insulated Gate Bipolar Transistor (IGBT) technology allows the transition from conventional sinusoidal ohmic heating to Pulsed Ohmic Heating (POH), enabling low amortization costs for production machinery [6].

Various designs of ohmic heating have been proposed in the literature. Numerous applications of ohmic heating are based on different alternative waveforms, leading to various studies on the frequency dependence of conductivity in ionic solutions. In the literature, both first-principle models [7] and empirical studies exist [8]. The results indicate that, despite being specific to each analyzed substance, significant fluctuations occur at very low frequencies (typically below 10 Hz) with a relatively smooth behavior above this threshold. This allows the effective and beneficial operation of AC techniques in the processing of foods through ohmic heating.

Earlier designs were oriented towards grid usage [6], but some studies indicated that 50-60 Hz could lead to electrode corrosion [9, 2, 6]. Therefore, Pulsed Ohmic Heating (POH) devices have been developed. The most common output stages for POH, which are more advantageous if POH is desired, involve IGBT [10] full bridges or three-phase bridges [11]. Previously, designs based on grid frequency relied on the phase angle control of thyristors and even [12]. Control is necessary to achieve the desired temperature change and meet the varying power demand. Voltage control in the system is implemented with H-bridges or inverters.

In some designs, the output stage does not control the output voltage level, and consequently, the electric field. Therefore, an input stage is added to the bridge for this purpose [11]. For safety reasons, an output transformer is mandatory, but in previous literature, this requirement has not always been consistently applied in a technical context [13].

The proposed converter consists of a diode bridge rectifier, a phase-shift controlled full-bridge converter, a multi-stage output transformer, and control algorithms. The full bridge (H-bridge) converter is one of the most widely used applications in power electronics, capable of functioning both as a rectifier and an inverter with either voltage or current input.

While an algorithm is suggested for controlling voltage fluctuations on the DC-side capacitor of an active power filter, other control techniques have been employed to manage DC current imbalance in the transformer of a dynamic voltage restorer. [14].

In this study, the main aim is to design and implement a convenient controller for an ohmic heating system. For this purpose, an ohmic heating system mathematically modeled based on system physical parameters and used materials inside of it. Then, an optimal PID controlled has been designed based Ziegler-Nicholas design criterion. In order to increase the accuracy and stability at the output of the ohmic heating system, a FL based controller has also been designed. Obtained results have been compared for 5kW ohmic heating unit. FLC has showed more powerful, stable and convenient control action to control of an ohmic heating system with less settling time and no overshoot.

II. MATERIALS AND METHOD

The design specifications of an ohmic heating power converter are rooted in the application parameters briefly outlined below. These parameters play a crucial role in determining the requirements for such a converter. In Table 2, you'll find typical values and the corresponding ranges of requirements. The determination of the operational capacity (y) of food processing lines is intricately linked to economic considerations within the constraints of product yield. This primary parameter encompasses various factors, including processed particle size (if applicable), technological feasibility, machine cost, the prescribed pipe diameter, and, consequentially, the resultant section (S). These considerations collectively shape the design imperatives for an ohmic heating power converter, ensuring optimal performance and efficiency within the designated application context. If the density (ρ) of the processed food is known, it becomes feasible to determine the velocity (b) within the pipe using the equation b = y / (ρS). These parameters play a pivotal role in defining typical applicator dimensions, primarily because inline application (aligned with liquid flow) is preferred for reasons encompassing electrical safety and heat uniformity [15,16]. The length (L) of the applicator typically represents a degree of freedom for the designer. Another crucial aspect in ohmic heating is understanding the relationship between the electrical conductivity of the processed material and the temperature of the liquid medium. It's widely acknowledged that the electrical conductivity of materials commonly used in the food industry tends to increase with temperature [17-19]. Simultaneously, numerous studies in the literature [9, 6, 19, 15] have examined typical conductivity values extensively as reported. The temperature-dependent conductivity, denoted as $\sigma(T)$, is defined by the equation $\sigma(T) = \sigma_0 + \alpha T$, where T represents the absolute temperature, α stands for the assumed constant temperature coefficient of conductivity, and σ_0 is the conductivity estimated based on known data at absolute zero. The conductivity at room temperature is represented as $\sigma_\alpha = \sigma(T_\alpha)$. The conductivity range reported in Table 1 encompasses all potential foods that may undergo ohmic heating across a wide temperature range, as derived from the literature. Typical values for α can be obtained from Table 1 [19].

Table 1. Typical Values and Ranges of Parameters Used in Food Processing

Quantity	Symbol	min	max	unit
Capacity	y	2	12	ton/h
Pipe diameter	d	50	140	mm
Applicator length	*L*	200	1000	mm
Applicator area	*S*	1960	15390	mm^2
Intensity	*ρ*	800	1500	kg/mm^3
Specific heat	*c*	0.84	4.1	kJ/(kgK)
Speed	*b*	0.087	7.64	km/h
Electrical conductivity	σ	0.05	5	*S*/m
Conductivity coefficient T	α	2	13	m*S*/(mK)
Resistance (theoretical)	R_T	2.5	10180	Ω
Resistance (smart)	R_S	102	260	Ω
Resistance (practical)	*R*	2.5	260	Ω
Voltage	V_{rms}	70	3800	V
Temperature change	*ΔT*	4.1	128	K

Starting from Ohm's law, and assuming a constant conductivity hypothesis along with the applicator, it is possible to establish the theoretical range of resistance in the converter, denoted as (l) for the minimum and (h) for the maximum, as illustrated in equation (1).

$$R_{T,l} = \frac{L_l}{\sigma_h . S_h}, R_{T,h} = \frac{L_h}{\sigma_l . S_l} \tag{1}$$

This yields an extensive range (approximately 4000 times). When it's feasible to adjust the applicator size for each product, a "smart" range can be achieved.

$$R_{S,l} = \frac{L_h}{\sigma_h . S_l}, R_{S,h} = \frac{L_l}{\sigma_l . S_h} \tag{2}$$

This helps to notably mitigate the widening of the range, but it can impose significant limitations when a section alteration becomes necessary at the final stage. Hence, constraining the section from changing is suitable to maintain its integrity. From a thermal standpoint, the S/L ratio is vital for maximizing the temperature change, $\Delta T = T_o - T_i$ (where T_o represents the outlet temperature and T_i stands for the inlet temperature). This ratio is calculated by integrating the differential equation (3) derived from fundamental principles [10].

$$\frac{dT}{dl} = \frac{\sigma(T) E_{rms}^2 S}{cy} \tag{3}$$

The outcome of this integration is depicted in equation (4), where 'c' signifies the specific heat of the food. 'E_{rms}' represents the RMS (root mean square) value of the electric field within the applicator, determined by the RMS electrode voltage 'V_{rms}' and the length of the applicator 'L'. 'E_{rms}' is calculated as $E_{rms} = V_{rms} / L$.

$$\Delta T = \frac{\sigma(T_i)}{\alpha} \left[exp\left(\frac{\alpha V_{rms}^2}{cy} \frac{S}{L} \right) - 1 \right] \tag{4}$$

The equation above covers all parameters relevant to the design and results from the exponential temperature distribution along with the applicator due to varying conductivity. During the process, if there is a negligible change in electrical conductivity, i.e., when $\sigma(T_i) \sim= \sigma(T_o)$, we can revert to a more common linear temperature distribution along the pipe (equation 5) by using the limit process with α approaching zero.

$$\Delta T = \frac{\sigma(T_i) V_{rms}^2}{cy} \frac{S}{L} = \frac{V_{rms}^2}{R_{eq0}} \frac{1}{cy} = \frac{P}{cy} \tag{5}$$

Both equation (4) and equation (5) aim to maximize the temperature change by optimizing the ratio of *S/L* ($S / L = S_h/L_l$) when other parameters are kept constant. This naturally leads to the practical range of resistance described in equation (6), which is utilized in the subsequent stages of the design process.

$$R_l = R_{T,l}\ , R_h = R_{S,h} \tag{6}$$

Equations (4) and (5) depict the temperature change under the assumption of (α = 0) zero conductivity temperature dependence (α → 0, simplified case). Comparing the two equations allows us to assess the accuracy of using the simplified model and provides a more precise calculation of the equivalent applicator resistance compared to equations (1), (2), and (6). This comparison aids in defining ohmic heating.

Conductivity Correction Factor (OHC^3) *r*

$$r = \frac{\Delta T_{(4)}}{\Delta T_{(5)}} = \left[exp\left(\frac{\alpha V_{rms}^2}{cy}\frac{S}{L}\right) - 1\right]\left(\frac{\alpha V_{rms}^2}{cy}\frac{S}{L}\right)^{-1} \tag{7}$$

At a given value of the applicator (*l*), the minute power distributed within the food substance is as follows:

$$\mathrm{d}P = \sigma E_{rms}^2 S\mathrm{d}l = \sigma\big(T(l)\big)\frac{V_{rms}^2 S}{L^2}\,\mathrm{d}l \tag{8}$$

It is possible to calculate the electrical power generated within the applicator, denoted as *P*.

$$P = \frac{cy\sigma(T_i)}{\alpha}\left[exp\left(\frac{\alpha V_{rms}^2}{cy}\frac{S}{L}\right) - 1\right] \tag{9}$$

P can also be expressed electrically as $P = V_{rms}^2/R_{eq}$, where R_{eq} is the equivalent resistance seen in ohmic heating. As a result,

$$R_{eq} = \frac{1}{r}\frac{L}{\sigma(T_i)S} = \frac{R_{eq0}}{r} \tag{10}$$

in this context, the geometrically computed equivalent resistance R_{eq0}, taking into account constant conductivity, is adjusted with a factor dependent on the α coefficient. It's essential to restrict the electrode voltage as well. The upper limit within the range is primarily constrained due to insulation considerations. This results in a minimum ΔT_l achievable with the highest load resistance (R_eq=R_h), accompanied by a limit where $V_{rms} < V_h$, ensuring that $P < P_h$.

$$\Delta T_l = \frac{\min\,(V_h^2/R_h\!:P_h)}{c_h y_h} \tag{11}$$

This parameter holds significant importance in assessing the variety of food types that can be effectively processed by an ohmic heater at a reasonable cost, without necessitating an excessive number of heaters to achieve the desired temperature change. Estimating the lowest practical voltage value offers valuable insights into establishing limits for both the hardware design and determining the minimum controllable output voltage of the converter. Given the target ΔT_l, the minimum voltage value, $V_{rms,l}$, is derived by inversely applying equation (5) for the lowest food resistance.

$$V_{rms,l} = \sqrt{\Delta T_l c_l y_l R_l} \tag{12}$$

The choice of switching frequency f_{SW} and the suitable waveform selection of the converter are crucial factors to consider. This is because they impact not only the system's performance, such as electrode corrosion and fouling, but also the design's compactness, which includes the volume of passive components like transformers, for the recipient. Unlike the early stages of ohmic heating, which typically utilize low-frequency (50-60 Hz) sinusoidal voltages (as noted by Skudder and Stirling in 1992), it's now recognized that even with the adoption of square waves, high frequencies can effectively minimize electrode corrosion, particularly when employing bipolar pulses (as highlighted by Samaranayake et al. in 2006 and Varghese et al. in 2014). This explains why many modern ohmic heating devices operate within the 10-60 kHz frequency range, known as Pulse Ohmic Heating (POH) devices.

In studies, it has been deemed suitable to employ an intermediate value of f_{SW} = 30 kHz to align with dual-layer discharge and ensure minimal corrosion, despite the relatively high voltages and electric field values resulting from power switching [9]. This decision aims to maintain satisfactory passive density and mitigate efficiency loss.

III. CONTROLING OF OHMIC HEATER

A. PID

The PID controller has been taken into account for the ohmic heater. The correct selection of the control parameters of the PID controller is critical. Otherwise, the process intended to be controlled can become even more unstable. In this thesis, the parameters of the PID controller designed for the ohmic heater under consideration have been optimized and designed using the Ziegler-Nichols Method, denoted as K_p, K_d, K_i.

The Ziegler-Nichols method is an empirical method used to determine the parameters of a PID controller. It was developed by John G. Ziegler and Nathaniel B. Nichols. The gains for the I (integral) and D (derivative) of the PID controller are set to zero. The "*P*" gain, K_p, is increased until the output of the control loop oscillates steadily with an ultimate gain, K_u. Mark this critical value of K_c as the ultimate gain, K_u. K_u and the oscillation period T_u are then used to adjust the gains *P*, *I*, and *D* depending on the type of controller used and the desired behaviour.

It cannot be used for first-order systems because when the multiplier from K_d and the multiplier *1/s* from K_i combine, the system enters directly into a second-order system. That is, if the control form is *P*, *PI*, or *PD*, this method cannot be used. Instead, trial and error can be used to select the most suitable parameters. As a result, the Ziegler-Nichols method is used for systems of two or higher orders.

B. Fuzzy Controller Design

In this section, a fuzzy logic controller is used to control ohmic heating system. Fuzzy controllers are developed to imitate the performance of human expert operators by encoding their knowledge in the form of linguistic rules. After the invention of fuzzy logic by Zadeh, the fuzzy modeling and fuzzy identification of systems have found numerous practical applications in control, prediction and inference. In this paper, due to the need for the speed of the system to be regulated, fuzzy logic based controllers are used to control of the ohmic heating system.

B1. Fuzzification Process Of The Fuzzy Logic Controller

Error and change of error values have been selected as input parameters for the fuzzy logic controllers. Equally divided triangular type 3 pieces membership functions have been used for fuzzification of error, e, and derivation of error, de. Definition of the error is the difference between reference temperature, T_{ref}, and measured temperature of the system, T_{meas}. For the k^{th} sampling instant the error is:

$$e(k) = T_{ref}(k) - T_{meas}(k)$$

The change of error can be expressed as

$$de(k) = e(k) - e(k-1)$$

where $e(k-1)$ is the error value in the previous sampling time.

B2. Rule Base Design

Relationship between input and output of the system is the most important part of the fuzzy logic based control. This relationship must be obtained correctly to improve the performance of the fuzzy logic based control system. This relationship is called rule base or If–Then rules. Basis of the determination of the rules is that the reference output set point is tracked with a minimum steady-state error.

	de		
e	NB	ZZ	PB
NB	NB^{1}_{du}	NB^{2}_{du}	ZZ^{3}_{du}
ZZ	NB^{4}_{du}	ZZ^{5}_{du}	PB^{6}_{du}
PB	ZZ^{7}_{du}	PB^{8}_{du}	PB^{9}_{du}

B3. Defuzzification process

As the third and final step, results obtained from overall rules are entered to the defuzzification process. To convert fuzzy values into crisp values a center of area (COA) method, proposed by Mamdani, has been used.

IV. RESULTS AND DISCUSSION

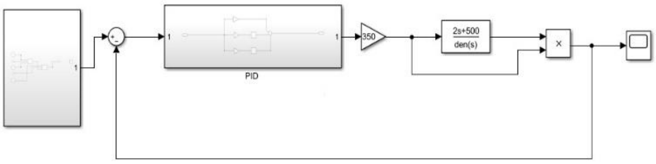

Figure1. Simplified power control loop MATLAB/Simulink model

The parameters of the PID controller have been optimized using the Ziegler-Nichols Method, and K_p = 300, K_i= 350, K_d = 10 have been determined. The response graph of the output with optimal PID controller for the 5kW step function at the input is provided in Figure 2.

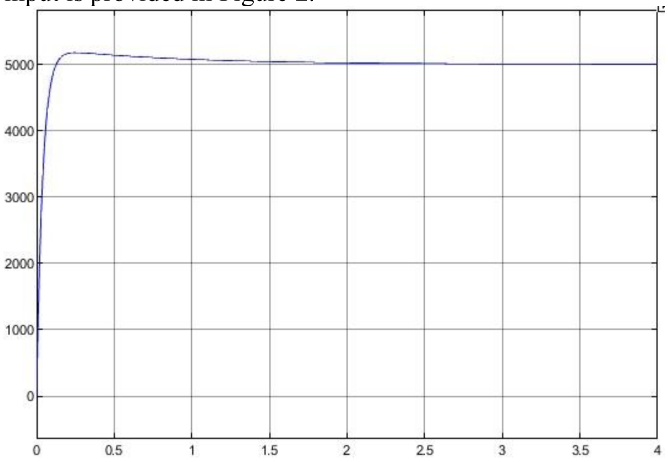

Figure 2. The output response graph for the 5kW step function at the input.

Applying designed FLC to ohmic heating system, the following output has been observed. The system response has been figured out in Figure 3 for the 5kW step function at the input with designed FLC. Based on obtained result, it can be concluded that the ohmic heating system behavior is more stable and has less settling time have been observed with the FLC.

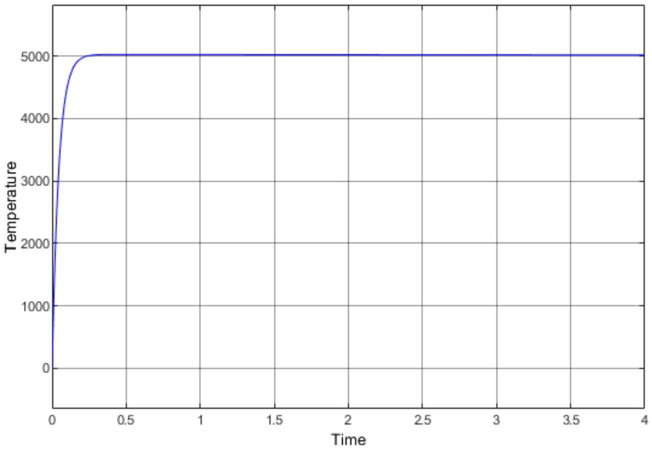

Figure 3. The response graph of the output with designed FLC for the 5kW step function at the input.

Additionally, no overshoot has been observed with the employing FLC. Both less settling time and no overshoot have been showed that the FLC is more convenient way to control of ohmic heating system.

V. CONCLUSION

An ohmic heating system has been mathematically modeled and designed two different control approaches such as PID and fuzzy logic control have been applied to control the modelled ohmic heating system. Ziegler-Nicholas approach has been applied to get an optimal PID type control based system dynamic behavior. Equally divided triangular type 3-MFs have been used in FLC.

Based on the obtained results, FLC has showed more powerful, stable and convenient control action to control of an ohmic heating system. Applying designed FLC, it can be concluded that the ohmic heating system behavior is more stable. Additionally, if PID compared to FLC less settling time and no overshoot have been observed.

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