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A FUZZY CONTROLLER BASED DEMAND-SIDE MANAGEMENT SYSTEM DESIGN FOR OPTIMIZATION OF INDUCTION FURNACES.

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ABSTRACT
The paper is a design of an automated Demand-side management system that will optimize electricity usage in a manufacturing plant using induction furnaces, through a multi-furnace controller. The multi-furnace controller controls two furnaces which alternate in between being a melting and a holding furnace. The control system selectively delivers preselected percentages of available power to furnaces. The power supply delivers power to both furnaces. A capacitor station in parallel connection to the power supply and the furnaces is tuned to form a tank circuit therewith and acts as the power factor correction device. Switches control the selected power delivered to the furnaces respectively and control the delivery of a first portion of the power for holding molten product in the hold furnace as the master control. Simulation model was design using fuzzy logic controller. The results show that using the multi-furnace controller results in a 30% decrease in the operating costs of the furnaces as demonstrated by the model plots.

KEY WORDS
Demand-Side-Management, Fuzzy Controller, Induction Furnaces

1.0 Introduction
One of the methods that can be used to reduce electricity bills in industry is to implement Demand-side management (DSM) systems to monitor electricity usage. The opportunities of DSM were highlighted in integrated energy resource planning and development in Zimbabwe [1]. These opportunities became more of motivators to the work developed in 2010 in a country recovering from a financial crisis. The paper highlights a design of an automated Demand-side management system that will optimise electricity usage in a manufacturing plant using induction furnaces. The multi-furnace controller controls two furnaces which alternate in being a melting and a holding furnace. A Matlab based SCADA system program was developed as an electricity demand manager and simulated to analyze the reduction in operational costs by implementing the Demand Side Management system. The model was developed based on the multi-controller models developed in the following literature [2] and [3].

1.1 Effects of high electricity costs in Zimbabwean industry.
Most of the manufacturing companies in Zimbabwe are operating at less than 30% of their production capacity. The average capacity percentage utilisation for manufacturing sector for 2007/2008 was 18.9 %, [4]. At this capacity the high electricity bills which are normally viable when there is high production seem to be too costly for the struggling companies. This has left many companies cutting down their operations. Eskom South Africa has managed to implement a successful DSM program the application and usage of more efficient appliances and also to change the demand profile [5]. In conserving electricity, focus should be made on where the potential savings are. In foundries, the potential for cost savings from demand control and load shifting is excellent and these areas of focus are melting, motors, compressed air and lighting [6].

2.0 Demand Side Management.
Demand Side Management (DSM) is the planning and implementation of electric utility activities designed to influence customer uses of electricity in a way that will produce desired changes in the utility’s load shape [7]. DSM aims to improve final electricity-using systems, reduce consumption, while preserving the same level of service and comfort especially in winter [8]. It entails actions that influence the quantity or patterns of use of energy consumed by end users, such as actions targeting reduction of peak demand during periods when energy-supply systems are constrained. Peak demand management does not necessarily decrease total energy consumption but could be expected to reduce the need for investments in networks and/or power plants. Peak load management in Electrolytic Process industries focusing on time-of-use tariff and peak tariffs with the aim to reduce peak demand by strategically shifting load using mix-integer nonlinear programming was analyzed in [9]. This work led to a reduction of peak demand of 5.7%. Similar work by [10] applied Artificial Neural Networks (ANN) to manage peak load in DSM was reviewed from which the fuzzy logic controller was developed using Matlab software for this paper.

2.1 Benefits of Demand Side Management.
DSM is aimed at addressing cost reduction, environmental and social improvement, network reliability and improved markets. Within foundries much of the electricity is consumed by the melting processes followed by motors. The detail of the distribution in the different foundries is shown in Table 1. Some of the benefits of the DSM are summarized in Table 2.

### 3.0 Furnace Model.

To build a model for the holding furnace the energy balance equation based on work by [3] as shown in Equation 1 was used:

\[
[P_{\text{con}}(\tau) - P_1(\tau) - P_{\text{tl}}(\tau)]d\tau = cm(\tau)dt
\]

**Equation 1**

where
- \(P_{\text{con}}(\tau)\) the power consumed by the mixer,
- \(P_1(\tau)\) the active power losses in the inductor,
- \(P_{\text{tl}}\) the total thermal losses,
- \(c\) the specific heat of the melt,
- \(m(\tau)\) the melt weight in the crucible,
- \(dt\) the elementary time interval, and
- \(d\tau\) the change in the melt temperature in the time \(d\tau\).

The energy balance equation given above assumes that losses in the lead wires, the bank of capacitors, and the magnetic core are negligible. This does not affect the balance accuracy and allows for simplification of the structural model of the mixer. The fractions of energy losses in the system are 1.1% in the lead wires, 0.8% in the bank of capacitors, and 0.1% in the magnetic core [3]. Using energy balance equation a first-order linear differential equation can be written as summarized in Equation 2.

\[
\frac{dt}{d\tau} = \frac{P_{\text{con}}(\tau) - P_1(\tau) - P_{\text{tl}}(\tau)}{cm(\tau)}
\]

**Equation 2**

The first-order linear differential equation formulates a Cauchy problem with the initial condition \(t(0) = t_0\). The solution to the Cauchy problem is written as shown in Equation 3:

\[
t(\tau) = t_0 + \frac{1}{c} \int_0^\tau \frac{P_{\text{con}}(\tau) - P_1(\tau) - P_{\text{tl}}(\tau)}{m(\tau)} d\tau
\]

**Equation 3**

Equation 4 shows the results of taking the Laplace transform \(t(p)\):

\[
t(p) = t_0 + \frac{1}{c} \int_0^\tau \frac{P_{\text{con}}(\tau) - P_1(\tau) - P_{\text{tl}}(\tau)}{m(\tau)} d\tau
\]

**Equation 4**

From experiments carried out using an induction crucible mixer carrying 4 tons of cast iron the following observations were made:

1) The total thermal losses through the mixer lining (kW) are shown in Equation 5:

\[
P_{\text{tl}}(l, t) = -26 + 0.08l + 0.05t - 1.3 \times 10^5lt
\]

**Equation 5**

2) The inductor current (A) is shown by Equation 6:

\[
I_l(U_l, t) = -0.7 + 3.3U_l + 4 \times 10^{-3}l + 0.02U_l
\]

**Equation 6**

### Table 1: Area where foundries use electricity [11]

<table>
<thead>
<tr>
<th>Foundry type</th>
<th>Melting</th>
<th>Motors</th>
<th>Compressed air</th>
<th>Lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Demand % kW</td>
<td>Consumption % kW</td>
<td>Demand % kW</td>
<td>Consumption % kW</td>
</tr>
<tr>
<td>Iron</td>
<td>78</td>
<td>66</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>(68-89)</td>
<td>(54-84)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>68</td>
<td>49</td>
<td>35</td>
<td>47</td>
</tr>
<tr>
<td>(59-88)</td>
<td>(43-65)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bronze</td>
<td>59</td>
<td>38</td>
<td>–</td>
<td>57</td>
</tr>
</tbody>
</table>

### Table 2: Benefits of the DSM [12]

<table>
<thead>
<tr>
<th>Customer Benefits</th>
<th>Societal Benefits</th>
<th>Utility Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfy electricity demands</td>
<td>Reduce environmental degradation</td>
<td>Lower cost service</td>
</tr>
<tr>
<td>Reduce / stabilize costs</td>
<td>Conserve resources</td>
<td>Improve operating efficiency, flexibility</td>
</tr>
<tr>
<td>Improve value of service</td>
<td>Protect global environment</td>
<td>Reduce capital needs</td>
</tr>
<tr>
<td>Maintain/ improve lifestyle and productivity</td>
<td>Maximize customer welfare</td>
<td>Improved customer service</td>
</tr>
</tbody>
</table>
3) The inductor electrical losses in kW are given by Equation 7:

\[ P_l(U_l, l) = 5.4 - 0.06U_l - 0.081 + 1.9 \times 10^{-4}U_l^2 - 7.6 \times 10^{-5}l^2 + 8.8 \times 10^{-3}U_l l \]  

Equation 7

4) \( \cos \phi \) of the inductor–charge system is shown in Equation 8:

\[ \cos \phi(l) = -7 \times 10^{-6}l^2 + 0.002l + 0.036 \]  

Equation 8

Where

- \( l \) is metal level in furnace (with respect to the level corresponding to the completely filled furnace),
- \( t \) is the melt temperature
- \( U_l \) is the inductor voltage

The value of \( l \) ranges from 30% to 100%, \( t \) ranges from 1200°C to 1400°C, while \( U_l \) ranges from 90V to 500V.

3.1 Multi-furnace controller.

The multi-furnace controller switch circuit is based on US patent number 5666377 which was invented by [2], which comprises a solid State Control Switch (SCR) for limiting power to the hold furnace and a plurality of selector switches for controlling which of the furnaces will receive hold power and which one will receive melt power as shown in Figure 1. The power supply comprises of a conventional inverter switch, except that it also includes a special feedback loop control responsive the selected power levels. When the first furnace is switched from a hold furnace to a melt furnace it is switched out of series with the SCR and into a direct connection to the capacitor station. When the second furnace is switched from a melt furnace to a hold furnace, it is switched into series with the SCR so the power level can be adjusted as desired. The system can be configured to always put the SCR in series to the furnace with lower demand level.

Figure 1: Schematic block diagram of a multi-furnace system [2]

The multi-furnace system comprises of a control system wherein a power supply and a capacitor station are disposed in parallel connection to the furnaces and a switch circuit control the power delivered to the furnaces respectively. This is done the following steps.

1) First furnace is set as the hold furnace and the portion of power necessary to maintain product contained in the hold furnace in molten state is identified.

2) The second step is delivering the identified portion of the power from the power supply to the hold furnace with a power control switch disposed in series with the hold furnace. The remaining portion of the power can then be delivered directly to melt furnace for melting product contained therein. The invention comprises selectively switching the furnaces alternately from either a hold furnace. The sequence of connections is shown in Figure 2.

Figure 2: Furnace connections

3.2 Fuzzy controller

Several researchers has been written pertaining to fuzzy controllers including [13], [14] and [15]. The fuzzy rule-based system is characterized by a set of rules that are defined by antecedents and consequents. Fuzzy reasoning gives us the ability to reply to a yes-no question with a not-quite, yes-or -no answer. This is the kind of thing that humans do all the time [16]. Inference rules were made by a simple logic to implement basic concept of the Fuzzy Logic using the possible actions on the switches.

The fuzzy controller system developed has three inputs to the system

i) meltTemp which represents the temperature of the melting furnace,
ii) holdTemp which represents the temperature of the holding temperature.

iii) powerRate which represents the electricity power which is being delivered to the system.

There are two outputs to the system:

1) meltThermo which represents the switch for switching on and off the melting furnace.
2) holdThermo which represents the switch for switching on and off the holding furnace.

3.2.1 Classification

The first step in fuzzy logic is to convert the measured signal \( x \) into a set of fuzzy variables [17]. This is called fuzzy classification or fuzzyfication. It is done by giving values to each of a set of membership functions. The values of each membership function are labelled \( \mu(x) \), and can be determined by the original measured signal \( x \) and the shapes of the membership functions [18]. A common classifier can be made to split the signal \( x \) into five levels as follows:

a) LP: \( x \) is large positive - Temperature is hot
b) MP: \( x \) is medium positive - Temperature is warm
c) S: \( x \) is small - Temperature is normal
d) MN: \( x \) is medium negative - Temperature is cool
e) LN: \( x \) is large negative - Temperature is cold

The operating temperatures of the melting furnace are between 1300°C and 1500°C. The operating temperatures of the holding furnace are between 1500°C and 1700°C. The melting temperature was categorized into five categories as shown in the Table 3.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Melting Temperature (°C)</th>
<th>Holding Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>1300</td>
<td>1500</td>
</tr>
<tr>
<td>Cool</td>
<td>1350</td>
<td>1550</td>
</tr>
<tr>
<td>Normal</td>
<td>1400</td>
<td>1600</td>
</tr>
<tr>
<td>Warm</td>
<td>1450</td>
<td>1650</td>
</tr>
<tr>
<td>Hot</td>
<td>1500</td>
<td>1700</td>
</tr>
</tbody>
</table>

The power supplied to the furnaces has two levels positive and negative. The power supplied to the furnaces varies from 20% to 80% of the supplied power depending on which furnace is the holding furnace at that particular time.

The fuzzy model was created by using “Sugeno Inference System” [19]. According to this system, the \( I_o \) rule can be calculated by using in the following equations:

\[
L^{(1)} = \text{If } x_1 \text{ is } F^1_l \text{ and } ... x_n \text{ then } \quad \text{Equation 9}
\]

\[
y^1 = c^1_0 + c^1_1x_1 + c^1_2x_2 \quad \text{Equation 10}
\]

Where

- \( F^1_l \) denotes fuzzy set,
- \( c^1_l \) is the real coefficients,
- \( y^1 \) is the output set and \( x_1, ... x_2 \) is the inputs.

The basic if-then rule is defined as “If (error is very small and error rate is very small) then output”. The signals error and error rate are described as linguistic variables in the fuzzy logic controller such as large negative (Cold), medium negative (Cool), Normal (Normal), medium positive (Warm) and large positive (Hot). In the same way, the input values of the fuzzy controller are connected to the output values by the if-then rules. The relationship between the input and the output values can be achieved easily by using Takagi-Sugeno type inference method.

3.2.2 Defuzzyfication

In the defuzzification process, the controller outputs represented as linguistic labels by a fuzzy set are converted to the real control (analogue) signals. In the created fuzzy model, “Sugeno’s Weighted Average” method which is the special case of “Mamdani Model” is selected for the defuzzification process. According to this model, the defuzzification is achieved by using the center of gravity method.

3.2.3 Center of gravity

The centroid of area was used. Given that \( w^1 \) is the overall truth value of the rule \( L^{(1)} \) and \( M_{F_l}(x_i) \) is the membership function described the meaning of the linguistic variable \( F_l \).

\[
w^1 = \prod_{i=1}^{n} M_{F_l}(x_i) \quad \text{Equation 11}
\]

According to “Mandami Model”, the defuzzification is achieved by using following equation

\[
y = \frac{\sum_{i=1}^{n} w^1 y^i}{\sum_{i=1}^{n} w^1} \quad \text{Equation 12}
\]

Figure 3 shows the Simulink model of the furnace controller designed that had the rules developed in the sections above.
4.0 Results

Using Matlab Version 13, furnace use was modeled and simulated. The analysis assumed an 8 hour working day and 20 day working month and the rate of US$0.10 per kilowatt-hour was used. The first case is when the furnaces are run continuously for the period. The total tonnage that can be produced for the day is 48 tonnes at a cost of $3,120 if the multi-furnace controller is used and if the furnace controller is not used, 40 tonnes of metal is produced at $3,700. For second case 3 melts per furnace are made during the period. The total tonnage that can be produced for the day is 24 tonnes at a cost of $1,560 if the multi-furnace controller is used and $2,220 if the furnace controller is not used. For third case 2 melts per furnace are made during the period. The total tonnage that can be produced for the day is 16 tonnes at a cost of $1,040 if the multi-furnace controller is used and $1,480 if the furnace controller is not used. For third case 1 melt per furnace is made during the period. The total tonnage that can be produced for the day is 8 tonnes at a cost of $520 if the multi-furnace controller is used and $740 if the furnace controller is not used.

The amounts saved per day for the different number of melts by using the multi-furnace is shown in Figure 5. The monthly amounts saved for the different number of melts by using the multi-furnace is shown in Figure 5.

Table 5: Amount saved by using multi furnace controller.

<table>
<thead>
<tr>
<th>Melts</th>
<th>Power Saved (MW)</th>
<th>Amount Saved per day ($/day)</th>
<th>Amount Saved per month ($/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6.6</td>
<td>660</td>
<td>13,200</td>
</tr>
<tr>
<td>2</td>
<td>4.4</td>
<td>440</td>
<td>8,800</td>
</tr>
<tr>
<td>1</td>
<td>2.2</td>
<td>220</td>
<td>4,400</td>
</tr>
</tbody>
</table>

The differences in furnace operations costs with and without the multi-furnace controller are shown in Figure 4.
The monthly cost for producing a ton is $1,300 using the multi-furnace controller and $1,850 when the multi-furnace controller is not used. The monthly cost per ton is shown in Figure 6.

The furnace utilization increases as the number of melts a day are increased. Considering the furnace utilization and operating costs incurred the use of the multi-furnace controller becomes more economic as the number of melts done a day increases. The furnace utilization percentages for melting the charge metal are shown in Table 6.

Table 6: Furnace melting utilization

<table>
<thead>
<tr>
<th>Total Tonnage</th>
<th>No of melts</th>
<th>Available time (Hrs)</th>
<th>Melting Time (Min)</th>
<th>Utilisation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>6</td>
<td>8</td>
<td>210</td>
<td>44</td>
</tr>
<tr>
<td>24</td>
<td>3</td>
<td>8</td>
<td>105</td>
<td>22</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>8</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>8</td>
<td>35</td>
<td>7</td>
</tr>
</tbody>
</table>

5.0 Conclusion
The paper looked at opportunities of Demand Sided Management in Zimbabwe foundries by reviewing benefits of savings in electricity in this industry. The literature of application of fuzzy logic and neural networks was given which became the foundation for the design if the fuzzy logic controller of a twin ladles induction furnace system. The design was simulated using Matlab 13 for different sizes of melts. The results show a saving of USD$13200 per month for a 3 melt size ladle and an increase in utilization of 44%.

The paper gives recommendation for installation of the fuzzy logic controller at the foundry plant for energy saving and improved profitability in Zimbabwe.

References


