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Energy Savings in Industrial Processes: A Case Study of Strategies and Tuning Procedures for PI and PID Controllers

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Abstract: Considering that the energy consumption of a given system can be directly related to its dynamics, this work presents a study accomplished at the Laboratory of Energy Efficiency (LEENER) and Industrial Process Laboratory of the Federal University of Juiz de Fora (UFJF). The work makes comparison studies among some different tunings for the flow control on pumping systems and tuning procedures for PID strategies for controlling industrial processes. The objective is to evaluate the energy efficiency of such strategies, by means of the analysis of energy consumption of the system.

Keywords: Energy Efficiency, Process Control, Tuning Methods, PID Controllers

1. INTRODUCTION

The growing demand for new energy sources, the amount of capital directed to the improvement of renewable energy sources efficiency and to the several studies for constructing new electrical generation units are today outstanding points in the global energy scenario. Against this background, sustainable questions regarding the new generation units can be highlighted, if one considers their environmental consequences. Discussions concerning the Fukushima Nuclear Installation accident, in Japan, and the Belo Monte Hydroelectric, in Brazil, are self explaining situations that need no additional comments.

So, it is almost mandatory that energy be utilized more efficiently, minimizing losses; one can think about a "virtual source" of electric power: the energy saved by any consumer will be available for satisfying the needs of any other consumer. It is, undoubtedly, the "cleaner" energy we can get, without any damage to the environment (Pinto, 2007). A possible strategy for saving energy is to focus on the design of policies for the sectors with the greatest saving potentials, for example, the most demanding energy sectors.

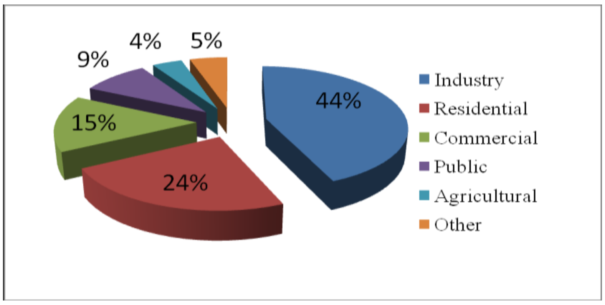

Fig. 1. Energy consumption in Brazil (EPE,2009)

In Brazil, in 2009 (EPE, 2010), the industrial sector consumed 44% of all electric energy generated (Figure 1), indicating a great potential for energy saving strategies.

Inside this sector, motor systems are responsible for 62% of all the electric energy consumption, which accounts for 28.5% of the total Brazilian energy demand (PROCEL, 2011). Basically, a motor system encompasses drivers, electric motors, coupling devices and mechanical loads. In Brazil, the most utilized industrial loads are pumps, fans, compressors and conveyors; the expression "pumps" encompasses pumps and its peripherals, the most common situation in industrial environments.

Under an industrial perspective, the efficiency concept is related to the capacity of doing a process with the minimum energy consumption, costs and required time, but keeping the product quality and process safety. Reaching these results, obviously, implies that the process controllers are adequately tuned, according to the applicable specifications.

Unfortunately, it is a well known fact that, in the industrial daily practice, not only incorrect tuning procedures are utilized, but even inadequate controller strategies. This can lead to situations where some specifications like, for example, steady-state errors are reached, but the final process dynamics is not the best one, if one takes into account performance indexes for the controlled processes. In such cases, even if one utilizes equipment and strategies that, conceptually, can be more efficient under an energetic perspective, the results can be totally adverse, if the controller's choices, and tuning procedures, are not the correct ones. It is no secret that, in practice, several industrial loops operate with incorrect strategies, disabled control modes or inadequate structures. Even for the PID controller, technical reports show that the derivative mode, D, in the operators jargon, has close connection with the terms "Disabled", "Disaster" or "Do not utilize…" (Cooper, 2011).

Considering existing conceptual analysis and the published references about the PID strategy (Aström, 1995; Aström, 2006; Normey-Rico, 2007; Visioli, 2006, just to quote a few), it becomes clear that, in several circumstances, one can talk about a mismatch between PID potentiality, the accumulated knowledge about it and its practical utilization, at least under some operators' views.

Some of the reasons for this mismatch can be found in aspects like insufficient knowledge of the PID modes functionality, the complexities associated with the industrial dynamics and inadequate, or even conservative, attitudes toward the tuning procedures. In the current industry reality, highly competitive and innovation-based, small details can account for all the differences. In such a situation, adequate control strategies for the industrial processes can be an efficient way for improving plant productivity, process throughput and quality; additionally, even marginal improvements in process control and operation can deeply impact economical and environmental aspects.

As a case study, two situations will be considered: initially, flow control strategies in an industrial pumping system and, in the sequence, an analisys utilizing distincts PID tuning procedures for level, pressure and flow loops, in an industrial pilot plant; the conclusions will be based on the practical results obtained, considering the energy consumption.

The work is structured as follows: first, the pilot plants are presented, then the identification, the tuning procedures and then the results obtained. The conclusions end the paper.

2. FLOW CONTROL STRATEGIES

Flow control are based on two procedures: strangulation valve and/or frequency inverter. The first one, acting on the tubing geometry, changes the liquid flow by means of pressure drop alteration and, although more utilized, is not so efficient, for the motor runs continuously at full voltage and practically without mechanical load variation (Souza, 2008). The inverter, on the other side, changing the supplied voltage frequency, actuates on the pump angular velocity with no pressure drop on the tubing; the pump flow, pressure and power change following the similarity laws (Centrais, 2005):

- Flow versus angular velocity:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad (1)$$

where Q_i is the nominal flow and N_i the angular velocity of the pump – for equations (1), (2) e (3);

- Pressure versus angular velocity:

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \qquad (2)$$

where H_i is the nominal pressure;

- Mechanical power versus angular velocity:

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \qquad (3)$$

where P_i is the nominal mechanical pump power.

Equation (3) shows that large power variations can be achieved even with small changes in the angular velocity, indicating that the inverter, when controlling the flow, can induce large alterations on the demanded power. The pump nominal pressure also changes with the angular velocity variation allowing, for some cases, the inverter utilization only for small ranges of the working flow; the minimum working pressure demanded by the hidraulic head of the system dictates such condition (Junior, 2007).

3. PILOT PLANT

The Pilot Plant utilized for the first analysis, located at the LEENER Laboratory, in the UFJF, encompasses a pumping system, a 1.015 HP centrifugal pump, two tanks (suction and repression), tubing with sensors and an electropneumatic strangulation valve (Fig. 2, left). This plant will be utilized for the analysis of the two flow control strategies.

Fig. 2. Pumping Systems (left); Industrial Process (right)

3.1 *System Identification*

First, the loops were identified and then the tuning procedures utilized on both strategies. The identification procedures were based on the Ziegler & Nichols (ZN) reaction curve method, for both loops (Campos, 2006); Figure 3 ilustrates the procedure for the inverter strategy and, for limited space reasons, only this dynamics will be displayed here, as an example case.

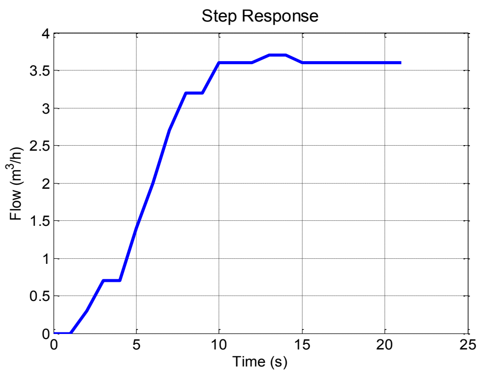

Fig. 3. Open Loop Response with Inverter

3.2 Tuning Procedures

The ZN, a Heuristic procedure and the IMC methods (Campos, 2006) were utilized for tuning both loop controllers. ZN and Heuristic methods were selected for their widespread utilization in the industrial environment; on the other hand, the IMC method for allowing changes in the process dynamics through the "λ" parameter (Table 01):

Table 01 – IMC Tuning – PI Controller

Controller	Model	K_P	T_I	Sugestion
PI	$G(s)=\dfrac{Ke^{-\theta s}}{\tau s+1}$	$\dfrac{2\tau+\theta}{K\cdot 2\lambda}$	$\tau+\left(\dfrac{\theta}{2}\right)$	$\dfrac{\lambda}{\theta}>1,7$

3.3 Pumping System Results

Three tests were then applied for both strategies utilizing differents tunings for the controller, for the following setpoints alterations: from 0.0 to 2.0 m^3/h, from 1.2 to 2.8 m^3/h and from 2.8 to 1.2 m^3/h. The results for the inverter strategy are displayed on Table 02; Figure 4, as an example, ilustrates the process dynamics for the first setpoint change.

Table 02 – Energy Consumption – Inverter Strategy

PI Controller with Inverter			
Test	CE1 (Wh)	CE2 (Wh)	CE3 (Wh)
ZN	3	2	1
IMC - 1	31	24	13
IMC - 2	3	2	1
Heuristic	14	12	6

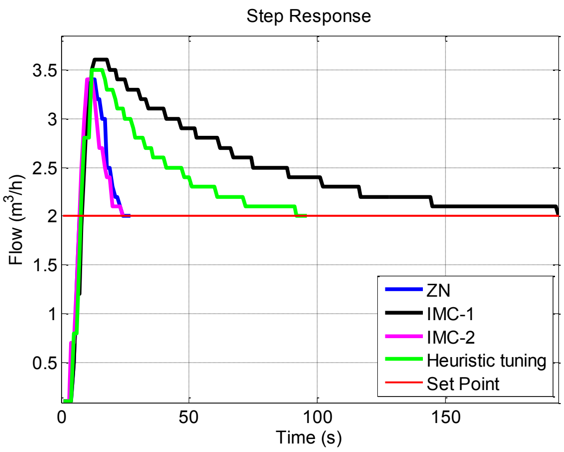

Fig. 4. Set point variation from 0.0 to 2.0 m^3/h.

Figure 5 displays a comparison among the results. Tests 2 and 3 show the same set point variation, although reverse - and very close settling times – but the energy consumption was quite different. A qualitative comparison of these results shows that test 3 has demanded less energy when the setpoint was lowered, which can be explained by the fact that, in test number 2, the system remains running for a longer time with greater flow values, just the opposite situation that ocurred on test 3. As the energy consumption is related with the system flow, the test 3 should present a lower consumption, just in the way it happened.

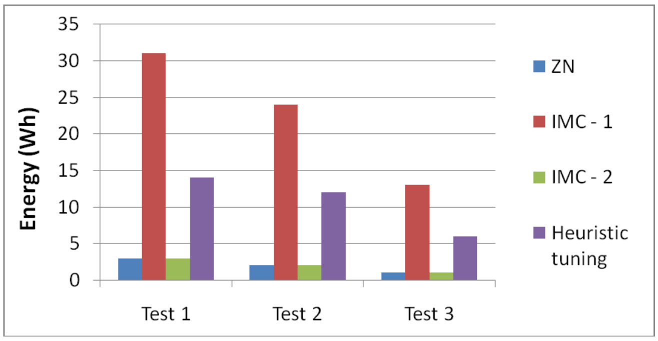

Fig.5. Energy consumption comparison - Inverter

For the strangulation valve strategy, it was not possible to reach null flow because of the pump shut-off point; so, the first set point change was not implemented (from 0.0 to 2.0 m^3/h). Table 3 displays the results of the set point variations from 1.2 to 2.8 m^3/h and from 2.8 to 1.2 m^3/h.

Table 03 – Energy Consumption – Valve Strategy

PI Control		
Test	CE (Wh)	CE (Wh)
ZN	13	9
IMC - 1	54	30
IMC - 2	8	4
Heuristic	66	40

The final results for this case are sumarized on Figure 6 which shows the energy consumption for these situations.

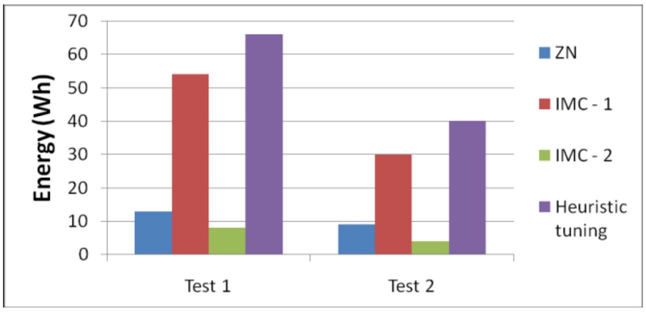

Fig.6. Energy consumption comparison - Strangulation Valve

4. INDUSTRIAL LOOPS IDENTIFICATION

The industrial Pilot Plant, utilized for the subsequent tests, is a double tank system, allowing control of the main process variables: flow, level, pressure and temperature (Figure 2, right). It runs under 4 to 20 mA signals, with a Supervisory and a Programmable Logic Controller (PLC); the individual loops can also be controlled by analogical PIDs, with embedded autotuning procedures. For this stage some common tuning procedures utilized in the daily industry operation were selected: the ZN, the Integral of the Error and the IMC tuning procedures (Campos, 2006).

4.1 Flow loop: identification

First, the flow loop was identified; for getting the better transfer function parameters, the identification procedures from ZN, Hägglund, Smith and Sundaresan (Coelho, 2004) were utilized, and the final selected model, for a FOPDT process, was obtained by the ZN procedure:

$$G(S) = \frac{2.3e^{-5s}}{11s+1} \quad (5)$$

4.2 Pressure loop: identification

The same procedure was utilized for the pressure loop and the best fitting was again for the ZN procedure, giving the FOPDT transfer function:

$$G(S) = \frac{2.4e^{-4s}}{15s+1} \quad (6)$$

6.3 Level loop: identification

Considering the level loop specificities, especially the nonlinearities of the cylindrical tank, some adjustments were made: it was decided to utilize a load perturbation and the Friedman tuning procedure (Campos, 2006) instead of the Integral Error tuning procedure. The transfer function was

$$G(S) = \frac{0.275e^{-3S}}{166s+1} \quad (7)$$

5. INDUSTRIAL LOOPS RESULTS

5.1 Flow loop

The results for the PI, PID and autotuning procedures, for the flow loop, are summarized on Tables 6 and 7. One can see, at a first glance, that different tuning strategies can lead to varied active (Wh) and reactive (Var) energy consumption, under the same process setpoint perturbation. It is also outstanding the performance of the autotuning procedure, embedded on the analogical PID, when compared with the other ones (Figures 7 and 8). Although the PID data sheet gives no information about the autotuning procedure, its behavior suggests the relay method (Astrom, 2006).

Table 06 – Energy Consumption – Flow Loop

PI Control		
Set point variation from 0.0 to 1.8 m^3/h.		
Tuning Procedure	Active (Wh)	Reactive (Var)
ZN	80	460
Integral Error	40	270
IMC	50	360

Table 07 – Energy Consumption – Flow Loop

PID Control		
Set point variation from 0.0 to 1.8 m^3/h.		
Tuning Procedure	Active (Wh)	Reactive (Var)
ZN	70	410
Integral Error	30	230
IMC	60	420
Autotuning	10	10

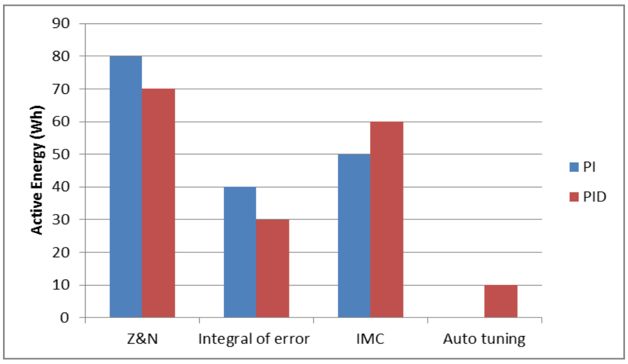

Fig. 7. Active Energy Consumption: Flow Loop

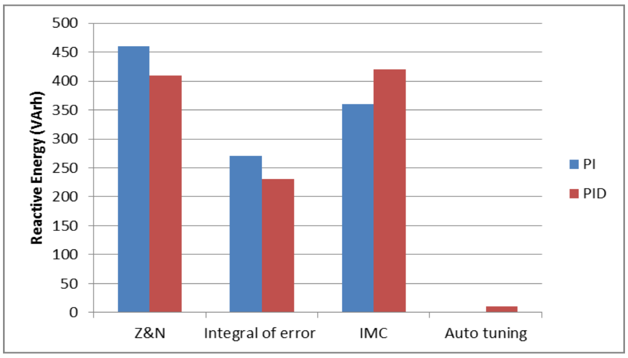

Fig. 8. Reactive Energy Consumption: Flow loop

5.2. Pressure loop

The same procedures were utilized for the pressure loop and the results are displayed on Tables 8 and 9, where the symbol ~ stands for "no significant values" :

Table0 8 – Energy Consumption – Pressure Loop

PI Control		
Tuning Procedure	Active (Wh)	Reactive (Var)
ZN	70	~
Integral Error	30	40
IMC	40	90

Table 09 – Energy Consumption – Pressure Loop

PID Control		
Tuning Procedure	Active (Wh)	Reactive (Var)
ZN	40	20
Integral Error	80	10
IMC	90	~
Autotuning	20	~

The situation (Figures 9 and 10) is analog to that obtained for the flow loop control, with the autotuning procedures showing superior performance; the IMC strategy, for the selected dynamics, exhibits a higher energy consumption.

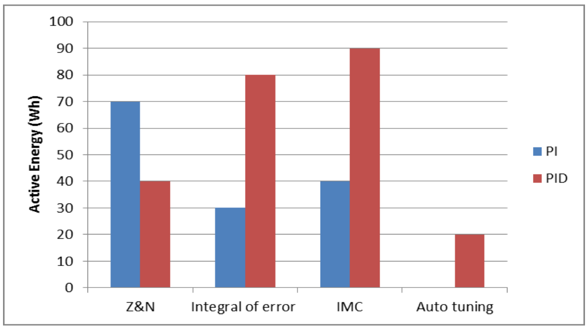

Fig. 9. Active Energy Consumption: Pressure Loop

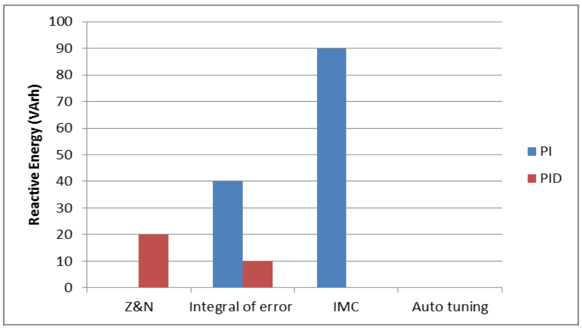

Fig. 10. Reactive Energy Consumption: Pressure Loop

5.3 Level Loop

For the level loop, the results are shown on Table 10:

Table 10 – Energy Consumption –Level Loop

PI and PID Control		
Consumption	Active (Wh)	Reactive (Var)
Z & N	80	180
Friedman	30	~
IMC	70	140
Autotuning	30	20

Figures 11 and 12, on the sequence, allow a comparison amgon such final data; the results of the Friedman tuning procedure, specific for level control, was so good as the autotuning one.

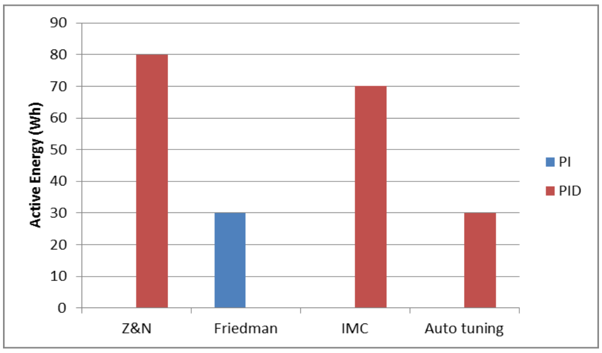

Fig. 11. Active Energy Consumption: Level Loop

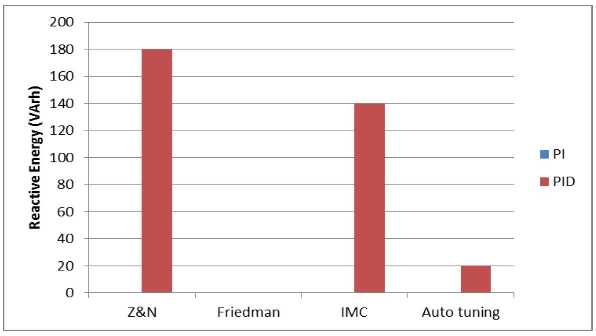

Fig. 12. Reactive Energy Consumption: Level Loop

The several results obtained will be now compared and analysed, for getting the final conclusions of the work, considering the energy consumption of the tuning procedures.

6. FINAL CONCLUSIONS

Undoubtedly, some interesting results emerged from these essays. Initially, when analyzing strategies for flow control – strangulation valve and inverter – it is possible to see energy saving greater than 60%, when comparing the ZN and IMC tuning procedures for both strategies (Figure 13). It must be said that, for the IMC tuning procedure, it was utilized, on purpose, an overdamped dynamics, just to show what can happen when a good strategy, like IMC, is tuned in a wrong way. Considering that these results were obtained on a Pilot Plant containing only a 1.015 HP centrifugal pump, one can visualize the total energy savings potential for a whole industrial plant.

Another point is related with the correct tuning procedure: for its versatility, the IMC has been increasing its utilization in the industrial processes area. But, if inadequately tuned, the results, considering the energy savings, can be deleterious. In the two strategies utilized, it was chosen, deliberately, overdamped and underdamped dynamics, with conflicting results for these energy saving strategies, as can be seen on Figure 14.

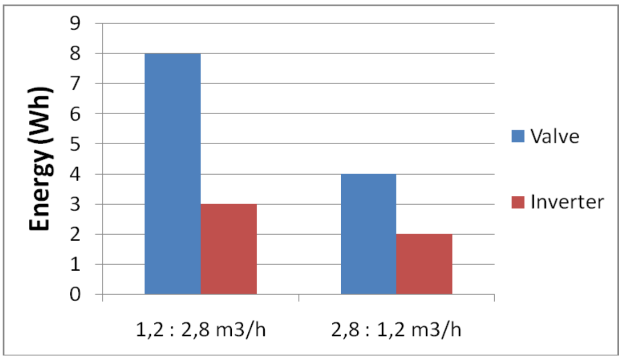

Fig. 13. Energy consumption for inverter and valve strangulating technique for ZN tuning.

The work also shows the importance of a correct heuristic and experience of the operators for selecting and adequately tuning the controllers. For the first case, the number 3 tuning procedure, a heuristic one, showed acceptable results for the inverter, but failed completely when strangulating the valve. So, depending on the results wanted, the heuristics procedures can conduct to undesirable situations.

Technically speaking, the inverter strategy for flow control can lead to greater energy saving, in a general way, when compared with the valve strangulating one. But, comparing the results, it is possible to see that the ZN technique, utilized for strangulating the valve, resulted in greater energy saving than the IMC strategy, which was improperly tuned.

Fig. 14. Energy consumption for inverter and valve strangulating technique: ZN, heuristic and IMC tuning

When analyzing the results obtained in the Industrial Process Pilot Plant the conclusions go into the same direction: the energy savings of an industrial process can be completely changed, for the same loop and the same control strategy, depending on the way the controllers are tuned.

It was possible to see, regarding the flow loop, that the best tuning procedure was the Integral of the Error; concerning the pressure loop, the Integral of the Error and the IMC showed similar performances, for the PID mode, although the PI mode was a little better, with less energy consumption.

For the loop level, with some specificity, the Friedman technique, based on heuristic knowledge of the process, showed the best results, with the greatest energy savings, comparable to the autotuning procedures of the controller.

The results for the autotuning procedures are outstanding. These strategies, that are becoming popular, can guarantee proper, robust and safety dynamics, specially concerning the energy saving policies, according to the values obtained.

As a final conclusion, it can be said that the correct tuning procedures, for the PI and PID controllers, for each particular loop, can conduct to distinct results, considering the energy saving for the process. The situation can result in unnecessary energy consumption and economic inefficiency, considering that the tuning procedures do not receive the proper attention from the process operator.

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