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Framework of Simulation Approach to Increase Energy Efficiency

Mostafa G. Varzaneh, Rupy Sawhney
Department of Industrial Engineering
University of Tennessee-Knoxville
Knoxville, Tennessee 37996, USA
mghafoor@utk.edu, sawhney@utk.edu

Abstract

This paper introduces a framework of simulation based energy management, which can make economic analysis possible for each of the devices in a production line. The data collection and modeling is based on regression methods and does not require academic knowledge about electrical engineering which made the data collection simple and straight forward. Based on the recommended framework energy efficiency improvement can be tested and economically analyzed in every scenario. Energy and Sustainability Group in ISE department at UTK developed a toolbox based on the framework to simulate energy consumption in production line. This toolbox can be considered as an expansion block to SimEvents toolbox in MATLAB. The toolbox works as a development of production line simulation software and can be utilized for optimization of production planning and energy concurrently.

Keywords
Energy, Energy Management, Simulation, Green Manufacturing

1. Introduction

Although energy management in production lines was a concern for many years but in recent years, this topic received higher attention in literature and industry. The main reasons can be categorized as following:

- Awareness about environment, greenhouse gases, … (Cantana 2009)
- Deregulation of power market (Kirschen 2003)
- Rising electricity and energy prices (Solding 2006)
- Competitive market which makes the energy part considerable (Liu 2011)
- Natural disasters like Japan earthquake, which made some source of energy unavailable (Endo 2012)

Energy conservation methods have been developed and most of them are not complicated. Besides, powerful simulation software have been developed and widely used in measurement, strategic planning, optimization …. But lack of an accurate tool to calculate estimated energy consumption, energy save, breakeven point... might be a deterrent factor in energy planning and conservation. In the current paper a simulation tool and framework is recommended in order to consider energy consumption in machining and production facilities.

Energy conservation strategies can be categorized into two main areas:

- Improvement of facilities and devices
  In this case, total energy consumption will be reduced by changing tools and using more efficient devices
- Improvement of processes
  This strategy will change energy consumption via production scheduling/planning.

Energy analysis can be performed via variety of approaches like visualization/monitoring, simulation, OR modeling …. In addition to diverse approaches -because all the energy parts are not contributing directly to production- various studies reported different ideas and assumptions about categorizing total energy consumption. In general, significant part of energy consumption is associated with indirect production like start-up and maintenance processes (coolant, oil pressure …). Although the percentage is not the same for different technologies, but as enlightenment in automotive manufacturing actual machining consumes only 14.8% of total energy consumption. (Dahmus and Gutowski 2004, Gutowski et al. 2006)

Solding and Thollander (2006) considered activates like ventilation, lighting, space heating as supporting processes. Skoogh *et al.* (2012) considered more states: busy state (product is loaded), idle state (machine is starving or blocked), down state (failure), standby state (low energy consumption mode).

Cannata et al. (2009) recommended a cross-layer infrastructure for production control. Four states of energy consumption considered: activation mode, idle mode, set-up mode, and operation mode. The objective of Hobino et al. (2012) was to reduce the energy consumption per unit of product. Starting state, idle state, producing state, stopping state, and aborting state (representing failure) have been considered in this study. Seow et al. (2011) considered two general energy states: direct and indirect energy, they referred to environmental energy as indirect energy . Direct energy is divided into theoretical energy and auxiliary energy. Theoretical energy can be calculated based on volume or weight of processed material and total energy consumed. Indirect energy is total energy of each zone divided by number of processed items. Arena™ simulation software has been utilized in this study.

Some researches focused on one specific device or one part of production, Liu et al. (2011) focused on painting process in automotive manufacturing. Total energy has been devided into two parts: energy consumption by production process and building energy consumption (HVAC, lighting…). For building energy consumption EnergyPlus have been used. Meike et al. (2012) concentrated on industrial robots in automotive industry, explained structure and permanent magnet machines and drive system.

Visualizing, monitoring can provide a better sense about conservation opportunities. Behrendt et al. (2012) introduced energy monitoring procedures and surveyed 232 machine tools with three size categories. Power demand has been analyzed in idle mode and working mode with different rates. Machining power in different states analyzed measured and reported. Sensor network has been recommended to measure amount of electricity and steam and visualizing the basic unit for energy.(Ikeyama et al. 2011) Different operational conditions can be visualized and monitored, like: normal energy and stopped condition, performance decrement condition, idling or tact delay, and defective condition.(Endo et al. 2012)

The recommended tool by ISE group provides a visual sense about different states of energy consumption through simulation. Moreover, the data collection for this tool is very simple while effective which can be easily utilized by industrial engineers.

1.1. Features and Specifications

Based on reviewed papers, the following energy states can be considered in every energy modeling project:

- Direct Energy
- Supporting Activities Energy Consumption
- Reducible States
  - Startup
- Wasted Energy
  - Idle mode
  - Standby
  - Failed condition
- Environment Energy Consumption
  - Light
  - HVAC

Depending on the objectives and applications of the study, some of the states can be excluded. For instance in some cases failed condition is not a point of interest or there is no energy consumption in that state. Environmental energy consumption has its complications and commercial software can handle that, so in this study HVAC is not considered. The framework introduced in this paper is applicable to all type of consumption but as the first step to this research the main focus will be on motor consumption and ohmic (constant) loads based on the reasons discussed later in the paper. The reader is encouraged to apply the introduced regression based method to other loads and applications.

2. Importance of motor modeling

Major fraction of energy consumption in industry is consists of electrical motors. In most of the industries -with different names and application- a motor is playing the main rule and in some devices more than one motor are utilized. Application of motors in wind blowers, pumps, and machining tolls … shows the variety of roles that motors play in industrial facilities. In EU motors consume 65% of electrical energy and in US this number rises to 75% and up to 80% in Canada. (Saidur 2010) Based on the facts, motors are the most important parts in energy consumption modelling and there should be a tool to give a visual sense and help in modeling.

Modeling motors in software like MATLAB, PSCAD… needs so many parameters which are not familiar to industrial engineers and production managers. Without accurate parameters modelling startup, working mode and idle mode will not be authentic. Data collection requires considerable amount of time even in normal cases and requiring detailed motor parameters will increase the data collection time considerably. In this paper a compromised method for modelling industrial motors have been introduced. Recommended toolbox doesn't need detail data for motors and other devices and it doesn't require knowledge about electrical engineering.

3. Motor startup modelling

During startup, motors consume more energy and this amount can rise to 8 times of full load. Consequently, startup energy has to be considered in motor modeling. For some type, different motors has been modeled and analyzed with mathematical and statistical techniques.

3.1. Startup energy for 3 phase induction motors

14 types of induction motors has been considered and startup data has been collected for all motors in per-unit format. Figure 1 shows the startup current versus time for these motors. Regression methods has been used to obtain the best model which fits all the simulated motors. This lead to an order 2 exponential estimator. As it shown in figure 2, the R-square criteria shows the regression model explains 90% of variations in data. There are some dynamic variations that remain unexplained which is not a point of interest in energy management applications.

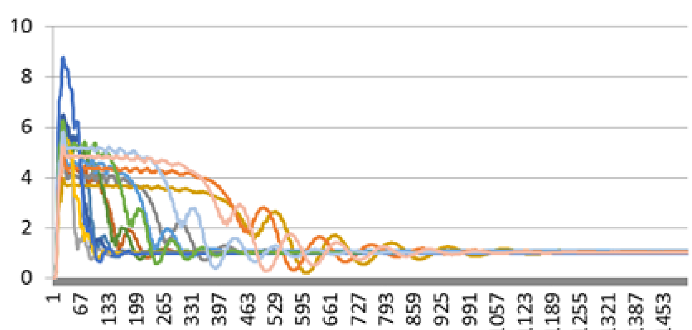


Figure 1. Startup current of motors (per-unit)

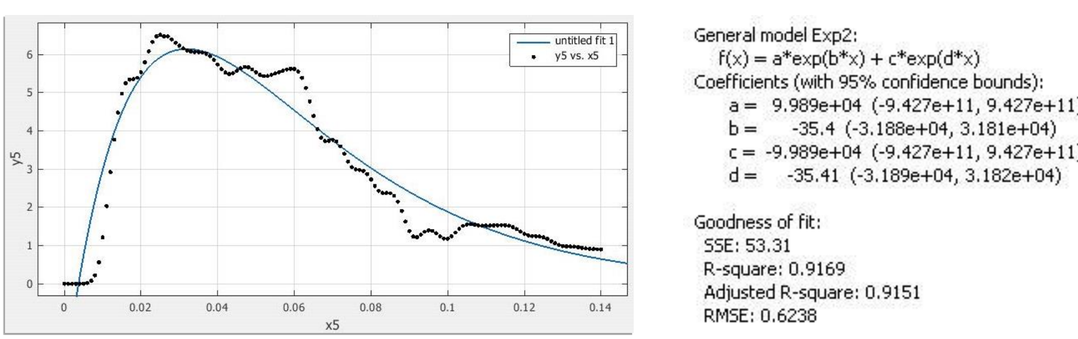


Figure 2. Regression model for 3 phase induction motor

Generally, order 2 exponential equation can be described as:

$$a * e^{b*t} + c * e^{d*t} \tag{1}$$

Since most of the applications care more about total energy consumption during startup, the integral of the area under startup current and order 2 exponential estimator has been compared which show 92% of accuracy.

3.2. Single phase motors:

Single-phase induction motors are largely used in low power applications and where 3 phase power is not available. Following starting methods are commonly used:

- Split-phase windings
- Capacitor-type windings
- Shaded stator poles

As it is illustrated in Figure 3 it is possible to consider the starting current as a constant current for all starting methods. The constant start current and time will be obtained from energy audit.

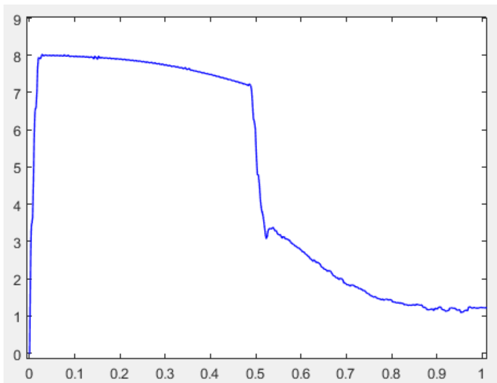
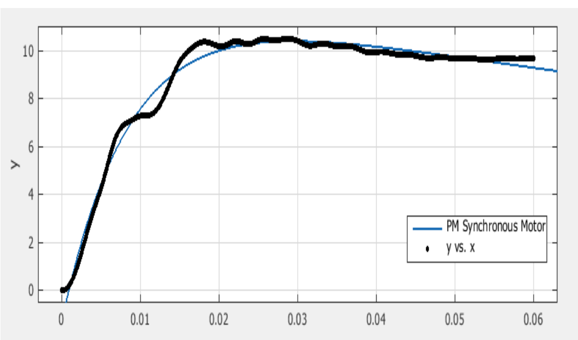


Figure 3. Startup current for single phase motor

3.3. Permanent Magnet Synchronous Motor:

14 different PM synchronous motor have been simulated and analyzed. Regression analysis of this type of motors shows that startup current can be described by an order 2 exponential model with the least R-square of 95% for all motors.



General model Exp2:
f(x) = a*exp(b*x) + c*exp(d*x)
Coefficients (with 95% confidence bounds):
a = 12.66 (12.6, 12.72)
b = -5.14 (-5.238, -5.042)
c = -14.01 (-14.06, -13.96)
d = -114.4 (-115.3, -113.5)

Goodness of fit:
SSE: 1122
R-square: 0.9849
Adjusted R-square: 0.9849
RMSE: 0.3059

Figure 4. Regression model for permanent magnet synchronous motor

3.4. Finding model parameters

For single phase motors the job is not complicated but for 3 phase induction and permanent magnet synchronous motors complications arises. The introduced method in this section is rooted in least square estimation of nonlinear regression models. The main difference is all the point has not been considered in the model because of physics of the problem and prior knowledge which discussed above. This simplification makes the data collection easier and less expensive.

As it is illustrated in Figure 5 there are 2 points on the diagram that can help finding the regression parameters. In addition to those numbers, at the start point, current and time are zero, which has been considered in the model. The followings are the points needed for the toolbox:

- Maximum point: for the maximum point of current the following data should be collected
  - I_{max}: The amount of maximum current
  - t_{max}: The time that maximum current occur
- Settle point: after variations and transients, finally the current will go to steady state. This point is called settle point and the following data are needed for the model
  - I_{settle}: Steady state current
  - t_{settle} : The point of time that the current stops major fluctuations

After some math operation, the objective function of the least square estimation is as follows:

$$f = (a+c)^2 + (I_{max} - a * e^{b*t_{max}} - c * e^{d*t_{max}})^2 + (I_{settle} - a * e^{b*t_{settle}} - c * e^{d*t_{settle}})^2 + \left(t_{max} - \frac{log(a*b) - log(-c*d)}{d-b}\right)^2 \quad (2)$$

The first term derived from start time condition which tries to make the current at time zero as small as possible. The second term and third term are obtained from maximum point and settle point. The last term is calculated from first order derivative that makes sure the time of maximum current in the model is not far from real maximum time.

In order to solve the model Newton direction with Goldestein step length has been utilized. Equations 3-6 represent the gradient of the least square estimator function. Figure 6 illustrates how the optimization model finds the regression parameters very fast and in a few iterations.

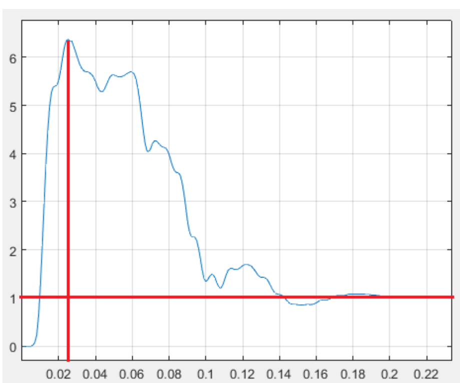


Figure 5. Important points

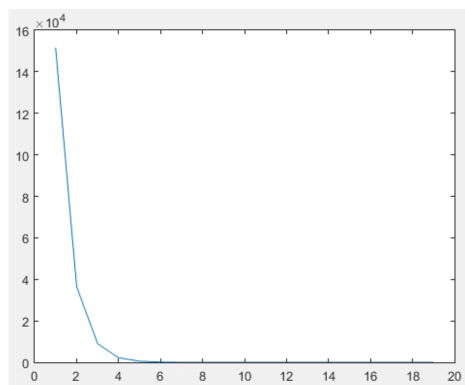


Figure 6. Objective function value vs iteration

$$\frac{\partial f}{\partial a} = 2a + 2c + 2e^{b*tm} * (a * e^{b*tm} - \mathfrak{I} + c * e^{d*tm}) + 2e^{b*ts} * (a * e^{b*ts} - Is + c * e^{d*ts}) + \frac{2 * tm + \frac{log(a*b) - log(-c*d)}{(b-d)}}{a * (b-d)} \quad (3)$$

$$\frac{\partial f}{\partial b} = 2 * \left(\frac{1}{b * (b-d)} - \frac{log(a*b) - log(-c*d)}{(b-d)^2}\right) * \left(tm + \frac{log(a*b) - log(-c*d)}{b-d}\right) + 2 * a * tm * e^{b*tm} * (a * e^{b*tm} - \mathfrak{I} + c * e^{d*tm}) + 2 * a * ts * e^{b*ts} * (a * e^{b*ts} - Is + c * e^{d*ts}) \quad (4)$$

$$\frac{\partial f}{\partial c} = 2 * a + 2 * c + 2 * e^{d*tm} * (a * e^{b*tm} - \mathfrak{I} + c * e^{d*tm}) + 2 * e^{d*ts} * (a * e^{b*ts} - Is + c * e^{d*ts}) - \frac{2 * tm + \frac{log(a*b) - log(-c*d)}{b-d}}{c * (b-d)} \quad (5)$$

$$\frac{\partial f}{\partial d} = 2 * c * tm * e^{d*tm} * (a * e^{b*tm} - \Im + c * e^{d*tm}) + 2 * c * ts * e^{d*ts} * (a * e^{b*ts} - Is + c * e^{d*ts}) - 2 * \left(\frac{1}{d * (b - d)} - \frac{log(a * b) - log(-c * d)}{(b - d)^2}\right) * \left(tm + \frac{log(a * b) - log(-c * d)}{b - d}\right) \tag{6}$$

4. Other energy states

Other energy states (Idle, working …) are not complicated too find and most of industries are collecting those data. In idle mode most of support activities are not working, the operator needs to leave the machine running idle and consider the minimum energy consumed. It's important to run the machine long enough to make sure all the transients and supporting activities are gone. For working mode, the machine has to start processing a part and the minimum amount of energy consumption should be considered in order to exclude supporting activities energy. The rest of the energy consumption is related to supporting activities which mostly occur periodically.

5. Result and Discussion

A simple simulation model has been developed as an example. The main energy block is highlighted in Figure 7. In There is a State signal which indicates that the device should turn off or remain idle when no part is in the machine. The machine remains idle if the State signal is 1 and turns off if the signal is 0. The user has the flexibility of trying more complicated signal and controls on the device. During startup and off period, machine cannot process any item so Gate signal disables the device during startup and down time. The model can handle energy consumption related to two supporting activities. In the example these parts of consumption are considered to be constant. Electrical current is shown in figure 8, user can take advantage of the visualization to understand the effect of startup, off period, supporting activates use the visual information to make more decision.

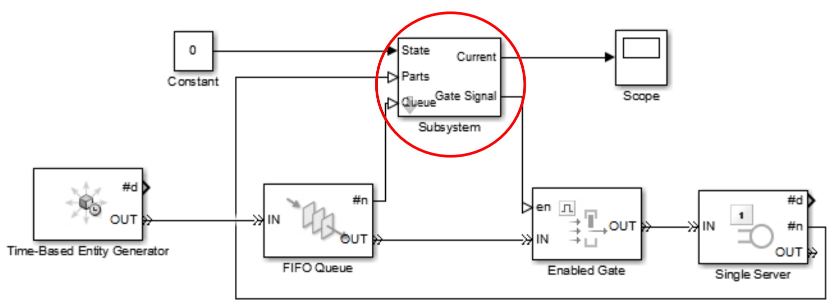


Figure 7. Simulink model

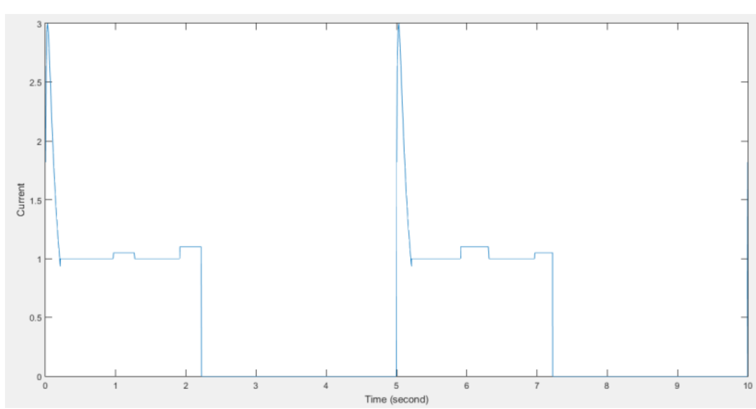


Figure 8. Current

6. Conclusion

As it concluded so far, the introduced framework is easy to utilize, data collection is not a hard process and doesn't require knowledge about electrical machinery or high tech monitoring or measurement devices. Industries can easily utilize the regression based frame work in order to:

- Compare energy consumption of different machine options for a job
- Conserve energy by taking into account the energy consumption
- Participating in demand response programs

And eventually save cost of production and take the first step toward green manufacturing at the same time.

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Biography

Mostafa GhafooriVarzaneh is a PhD student in Department of Industrial and System Engineering at University of Tennessee-Knoxville. He holds a B.S. in Electrical Engineering-Power Systems from Amirkabir University of Technology (Tehran Polytechnic) where he earned his Master in Energy Management. During his PhD carrier, he earned a certificate in reliability and Minor in Statistics. He has completed research projects related to Renewable Energies, Lean Healthcare and Manufacturing, VRP and Carrier Selection, Optimal Warehousing, Optimal Maintenance. Mostafa's main research interests include Optimization, Power Market and Lean.

Rapinder Sawhney is a Professor & Heath Fellow in Industrial and Systems Engineering at the University of Tennessee, Knoxville. He earned B.S. and M.S. in Industrial Engineering and Ph.D. degrees in Engineering Science and Mechanics from the University of Tennessee, Knoxville in 1981, 1984 and 1991 respectively. He was a Weston Fulton Professor and Department Head during 2010-2013. He is also a faculty for the newly created Center for Interdisciplinary Research and Graduate Education (CIRE) in Energy and the director of Centre for Advanced Systems Research and education (CASRE). His current research focuses on trying to use technology and innovation to enhance organizational productivity. His research group at this moment consists of 40 Postdocs, Ph.D. and Master students. He has published significant journal papers, conference papers and has submitted for 5 patents. His funded research projects are in the millions of dollars. He has worked with over 200 companies and is a recipient of various awards (Boeing Welliver Fellow, Alcoa Faculty Award, IIE Lean Teaching Award, Reuben Harris Award, and Accenture Teaching Excellence Award).