Quantitative Thermography for Electric Motor Efficiency Diagnosis

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Abstract

Global climate change is one of the most important challenges and threats to economic, social and environmental sustainability. Reducing electrical power demand is an important and necessary step in lessening global climate change and preserving our energy resources for future generations. The objective of this work is the development and demonstration of a quantitative thermographic system to rapidly and non-invasively determine in-use electrical motor efficiency.

The development has included testing of four motors in a controlled laboratory setting. This setting permits the complete and steady measurement of electrical power draw, mechanical load applied in addition to the thermal imaging. It provides a reliable means to validate the quantitative thermographic system. The thermographic technique proved to be reliable for all motors at 60% or more of full load.

1. Introduction.

Adequate energy supply is central to the current quality of life in industrialized countries. Much of the current energy supply is derived from non-renewable resources and therefore at some point in the future these energy sources will diminish or end.

All forms of energy supply result in some form of negative environmental impacts. Most notably, fossil fuel consumption leads to generally diminished air quality and greenhouse gas emissions that contribute to global climate change. The Kyoto Accord represents an important first step but only a first step in the reduction of greenhouse gas emissions. Nipper estimates we will need to cut the use of fossil

fuels by 60% to allow CO₂ levels to stabilize at twice the pre-industrial level [1].

To preserve our energy resources for future generations and to preserve our environment it is essential that every effort is made to use energy as efficiently as possible.

Electric motors are an integral part of a modern society. Approximately 75% of the industrial electricity consumption goes to electrical motors [2]. They power robotic assembly lines, mixers, pumps, fans, machine shops, and a host of other devices. They are located in places that usually are not considered to be motors, but they are inside air conditioners, compressors, copiers and even computers. Pumps, using 31% of industrial electricity, followed by compressors (18%) and fans (16%) are the largest users of electricity in industry [2].

An electric motor's environmental impact derives from the summation of impacts over the five stages of its life cycle: pre-manufacturing, manufacturing, transportation, use, and disposal [3]. Over 99.4% of the environmental impact from a motor is attributed to the electricity the motor uses during its operational lifetime [4]. Therefore, to reduce the environmental impact of a motor driven system one must increase the operating efficiency of the system, which directly reduces the electrical consumption of the motor driven system. Seven ways have been identified for increasing the efficiency of a motor driven system: motor sizing, motor efficiency, repair practices, adjustable speed drive, electrical system tune up, mechanical design, and maintenance. Table 1 provides an estimate of the potential savings by each of these ways. A total reduction of between 20 and 50% is possible.

Table 1. Opportunities for increased efficiency within the US [5, 6]

Savings Measure	Conservative Estimate of Potential Savings (TWh/yr)	Percent of Total Power Used by Motors#
Motor Size	8.	0.7
Motor Efficiency	34.	3.1
Improved Repair Practices	15.	1.4
Adjustable Speed Drives	75 – 300	6.8 - 27.
Electrical Tune-Up	14 - 72	1.3 - 6.5
Improved Mechanical Design	30 - 50	2.7 - 4.5
Better Maintenance	34 - 98	3.1- 8.9
Total	210. - 580.	19. - 52.

Based on an estimate of 1100 TWh/yr of total electrical consumption of motors.

The savings from motor size, motor efficiency, adjustable speed drives and improved mechanical designs are most easily achieved when the motor driven system is installed or overhauled. These make up a possible 35.4% of the potential savings and can be thought of as for new systems. Other savings, from improved repair practices, electrical tune ups and better maintenance are a continual process, and add up to a possible 16.8% of savings. These savings can be achieved by monitoring a system and acting when a diagnostic system indicates it would be beneficial. An improved diagnostic system would allow us to know when a new or old system needs work and when an old system should be replaced or at least how much it is costing in wasted energy.

In this research and development program, quantitative thermography has been chosen as a potential diagnostic system. Quantitative thermography has the advantages of directly measuring the product of waste heat that is hot surfaces, plus it is non-invasive and infrared cameras are becoming increasingly common tools at industrial operations as part of preventative maintenance programs. The development challenge is to transform the thermal images providing surface temperatures into waste heat flow rates which is then sufficient to determine efficiency. This development is being conducted in two phases. The first phase is in a controlled laboratory setting in which the electrical motors can be monitored to validate the diagnostic. The second phase is in an uncontrolled industrial facility. This paper will report on the progress of this first phase.

2. Methodology.

Humber College's electromechanical lab was used as the controlled setting. The lab consists of a series of small electric motors all with electrical

monitoring equipment and with a mechanical dynamometer. The motors used are components of a LabVolt Computer-assisted 0.2 kW Electromechanical Training System (#8006). Table 2 provides the specifications of the 4 induction motors used. The lab permits the motors to be run at constant and known torque and under constant and known electrical conditions.

A FLIR ThermoCAM E4 thermographic camera was used to capture still pictures in the infrared (IR) region. This camera has a focal plane array in an uncooled microbolometer capable of 160x120 resolution. Its temperature range is -20 to 250° C with a thermal sensitivity of 0.12° C [7]. Overall, it is a competitively priced camera that is commonly used for preventive maintenance.

Four motors were run at constant load until they reached thermal steady state with the surroundings. Steady state was judged based on the stability of the thermal images. Generally 30 minutes were required to reach steady state from a cold start

Table 2: Motor Specifications

AC Induction Motor	¼ hp
	4 Pole
Synchronous Speed	1800 rpm
Power Supply	3 Phase
	208 V
	60 Hz
Face Area	0.0137 m ²
Housing Area	0.0817 m ²
Coil Area	0.0318 m ²
Pulley Area	0.0138 m ²
Support Cross Sectional Area	0.006 m ²
Conduction Length	0.020 m
Thermal Conductivity	79.4 W/mK

and about 20 minutes from a change in load.

A series of thermal images were captured for each condition. These images included front and top thermograms. The lab's housing prevented images from all other angles.

Each motor was run for a series of different torques to allow the creation of torque vs. efficiency curves for the four motors.

Data analysis consisted of two parts. The first is the determination of the efficiency based on the electrical and mechanical measurements. This is considered the true efficiency of the motor at the specified conditions. Equation 1 provides the definition of this electrical efficiency.

Equation 1

$$\eta_e = \frac{P_{mechanical}}{P_{electrical}}(100) = \frac{N\tau \frac{\pi}{30}}{\sqrt{3}VI \cos(\theta)}(100)$$

The second part of the data analysis is the determination of the efficiency based on the IR images. The key component of this analysis is the determination of the total thermal loss from the motor. This thermal loss is the result of three dominant modes for waste heat to escape a motor: conduction, convection and radiation [8] as depicted in Figure 1. The total thermal loss is the summation of each of the three modes (Equation 2). This total thermal loss is then used to determine the motors efficiency using Equation 3. In the laboratory setting this IR based efficiency has relied on the measured mechanical load.

Equation 2

$$P_{thermal\ loss} = P_{conductive} + P_{convective} + P_{radiative}$$

Equation 3

$$\eta_{IR} = \frac{P_{mechanical}}{P_{mechanical} + P_{thermal_loss}}(100)$$

Determining each of the loss terms relied on surface temperatures from the images and classical heat transfer equations. Figures 2 and 3 identify the key temperatures that were obtained from each image. The temperatures are the motor housing, the motor

face, the motor coils, the pulley and the support hot and cold ends. The FLIR camera's software permits acquisition of an average temperature over an area as well as point values.

The conduction loss was determined from the temperatures at either end of the support legs and from the physical properties of the motor according to Equation 4.

Equation 4

$$P_{conduction} = \frac{\lambda A_c (T_h - T_c)}{d}$$

The convective loss was determined based on the temperatures of the motor housing, motor face and coils, the physical areas of all of the surfaces according to Equation 5. Equation 5 is a simple convective model which is well suited for the temperature ranges found with running motors and is typically used with motors [8].

Equation 5

$$P_{convection} = 3A(T_m - T_s)^{1.25}$$

The radiative loss was determined based on the same surface temperatures and the emissivity of the surfaces according to Equation 6. The emissivities were obtained from FLIR's reference table for black plastic paint and checked against a reference standard.

Equation 6

$$P_{radiation} = \epsilon \sigma A (T_m^4 - T_s^4)$$

The end result is a calculated thermal loss term that relies on the thermal images alone and a calculated efficiency that relies on the mechanical load on the motor as measured by the dynamometer.

From the calculated efficiencies, the operating cost of the motors can be calculated. Additionally, the cost differential of operating the given motor and a replacement motor can be determined using Equation 7 [2].

Equation 7

$$S = HP * ML * Hr * 0.746 * \$kWh * \left(\frac{100}{Eff_A} - \frac{100}{Eff_B} \right)$$

Figure 1. Energy transfer modes

The annual savings can then be used in a net present value calculation along with the motor replacement cost to find the net present value. This will allow it to be determined whether it makes economic sense to replace the motor. The efficiency of the replacement motor, the cost of the replacement motor and the required rate of return interest rate are all critical parameters in the replace or not decision. If the net present value is greater than 0 then it makes purely economic sense to replace the motor. These calculations were performed using Equation 8 [9].

Equation 8

$$NPV = S \left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) - C$$

Object Parameter	Value
Emissivity	0.95
Atmospheric Temperature	20.0 °C
Atmospheric Transmission	0.99
Label	Value
Support: Max	40.9 °C
Support: Min	39.6 °C
Pulley: Average	33.8 °C
Face: Average	46.0 °C
Coil: Average	60.1 °C

Figure 2. Front view of motor thermograph

Object Parameter	Value
Emissivity	0.95
Atmospheric Temperature	20.0 °C
Atmospheric Transmission	0.99
Label	Value
Housing: Average	48.9 °C

Figure 3. Top view of motor thermograph

3. Results and Discussion.

The four motors were tested under a total of 28 conditions (Table 3). Full load is 1.3 Nm for these motors. Each thermal calculation is an average from 2 to 4 steady state images.

For a standard motor the operating efficiency increases as loads increase until a critical threshold is passed, usually close to or greater than full load. This trend was observed for both the actual efficiency as well as the efficiency determined by the thermographic method. The efficiencies are all relatively low which is not uncommon for small, laboratory scale electric motors.

There is a good agreement between the actual efficiency and that calculated based on the IR images. Six of 28 times the efficiency calculated from the electrical means was higher. Additionally when the electrical results were higher they were only slightly higher, an average of 2.3 percentage points with a maximum difference of 4.7 percentage points. When the efficiency was higher for the thermographic method the average difference was 7.7 percentage points with a maximum overestimate of efficiency of 25.6 percentage points.

Figure 4 shows the thermal based efficiency versus the electrical based efficiency for the averaged steady state thermographs. It is evident that the cluster of results all show good agreement between the two measures of efficiency. The agreement deteriorates at lower efficiencies and at these lower efficiencies the IR image efficiency is biased high.

Table 3. Summary of Motor Efficiency Results

Motor	Applied Load (% of full)	Efficiency (%)	
		Actual	IR Calculated
1	6	14.1	23.8
	61	58.5	65.0
	70	60.8	67.5
	74	63.5	65.2
	78	64.4	65.2
	106	66.4	65.0
	134	63.8	59.6
2	19	30.8	42.0
	78	60.2	62.6
	79	59.6	61.7
	83	60.2	63.6
	88	60.9	60.1
	109	61.8	60.0
	117	58.8	60.5
3	40	46.0	60.5
	47	49.8	60.4
	55	50.5	64.2
	62	53.5	59.7
	65	55.3	60.7
	69	57.0	67.4
	87	58.0	62.1
4	9	15.0	40.6
	28	36.9	55.0
	87	64.1	71.0
	92	67.8	69.0
	97	69.0	68.3
	101	63.4	71.3
	127	65.2	60.5

Figure 5 presents the data as a function of the percentage of full load. The ordinate is the percentage error associated with the thermographic efficiency measurement. The IR technique is clearly successful for all cases with a motor operating at more than 60% full load. At these loads, the maximum overestimation was 7.2 percent and the average difference was only 5.1 percent. Overall, the error range is from -171% underestimated to 7.2% overestimated. Also, all the cases with an error of worse than -30% were for motors with loads of 40% or less.

The increased error for the low load case should be expected, in the thermal calculations the mechanical power is relatively small, 15%, compared to the thermally lost power. When taking ratios of numbers as such, it tends to magnify any slight error.

Figure 4. Efficiency Calculation Comparison

Figure 5. Error in IR based technique vs. Load

For the higher loaded cases the mechanical power is around 60% of the power, and comparing numbers that are more similar any slight inaccuracy is not magnified.

Figure 6 illustrates the distribution of energy flow for one of the four motors. These results are representative of all four motors. For higher load conditions, electricity conversion to mechanical energy is 60 to 70% efficient. The remaining energy is converted into heat. Around 7% of the energy is expelled from the motor by radiation, 7% by convection and 18% by conduction.

For higher load conditions, approximately 15% of the heat loss is through each of radiation and natural convection, and the remaining 70% is lost through

Figure 6. Electrical Energy Distribution (Motor #1)

conduction. In an industrial setting this distribution of heat loss is not expected to prevail. The metal support for the laboratory motors enhanced conduction considerably. Industrial motors will run hotter and thus the radiative term will be more significant and industrial motors are often cooled through forced convection which increases the convective term.

The ultimate assessment of this diagnostic technique is not the accuracy of the efficiency but more importantly on whether the decisions made based on the diagnostic are correct. The key decision is whether to replace a given operating motor. Table 4 presents the results of the Net Present Value (NPV) calculations as one basis for making such a decision. It is recognized that there are many other economic models that could be used. NPV is used here simply for illustration purposes. It was assumed that the replacement motor would operate at an efficiency of 72%, the replacement cost was \$130, the required rate of return interest was 15%, and the project term was 10 years. These calculations neglect installation costs and possible tax complexities.

The decision of whether to replace the motor or not is based on whether the NPV is positive or negative. For 14 out of 21 conditions the IR image technique makes the same recommendation as the true efficiency data. All of the disagreements correspond to the IR image technique recommending not replacing the motor, that is missing an opportunity. All of these missed opportunities were with motors running underloaded.

A non-invasive and quick technique to identify two-thirds of the inefficient electric motors in industry would be a considerable benefit to industry and society.

Table 4. Summary of Net Present Values for Motor Replacement

Motor	Applied Load (% of full)	NPV(\$)	
		Actual	IR Calculated
1	61	138	-37
	70	112	-63
	74	56	-21
	78	43	-15
	106	33	25
	134	173	234
2	78	158	34
	79	177	52
	83	175	22
	88	164	109
	109	195	166
	117	339	167
3	62	276	50
	65	243	41
	69	213	-63
	87	260	61
4	87	70	-113
	92	-22	-75
	97	-52	-58
	101	118	-116
	127	102	185

Assumptions: $\text{Eff}_A = 72\%$, $C = \$130$, $n = 10$ yr, $i = 15\%$

4. Conclusions.

- The quantitative thermographic method has proven accurate for laboratory motors that are loaded in excess of 60% of full load
- The thermographic method offers a noninvasive motor efficiency test
- This method should easily recognize motor that are running substantially below the expected efficiency
- Financial modeling illustrates the potential to identify two-thirds of the inefficient motors in operation

5. Nomenclature.

P = Power (W)

A = Surface area of the motor (m²)

T_m = Temperature of the motor (K)

T_s = Temperature of the surroundings (K)

T_h = Hot Temperature of the support (C)

T_c = Cold Temperature of the support (C)

ε = Emissivity

σ = Boltzman constant

λ = Thermal Conductivity (W/mK)

A_c = Contact Area (m²)

d = Conduction distance (m)

N = Rotations per minute (RPM)

τ = Torque (Nm)

η_e = Electrical Efficiency (%)

η_t = Efficiency (%) based on IR images

θ = Phase angle

S = Savings / year

HP = Motor Horse Power

ML = Motor Load

Hr = Operating hours per year

\$kWh = Cost per kWh

Eff_A = Motor Efficiency of Motor A

Eff_B = Motor Efficiency of Motor B

NPV = Net Present Value

i = required interest rate

n = term of project

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7. References.

- [1] Nipper, Simon, "Energy Is Now Part of the Big Picture," *Facilities Management*, November, 2000 pp. 14-15.
- [2] Bonnette, Austin H., "Understanding the Changing Requirements and Opportunities for Improvement of Operating Efficiency of AC Motors," *IEEE Transactions on Industry Applications*, 1993, pp. 600-610.
- [3] Graedel, Thomas, E., "Streamlined Life-Cycle Assessment," Prentice Hall, New Jersey, 1998.
- [4] Rennie, Ian, "Improving Motor Efficiency for a Better Environment," *ABB Review*, 2000, pp. 20-27.
- [5] Bonnette, Austin H., "An Overview of How AC Induction Motor Performance Has Been Affected

by the October 24, 1997 Implementation of the Energy Policy Act of 1992,” *IEEE Transactions on Industry Applications*, 2000, pp. 242-256.

- [6] Moreira, Julio C., “Simple Efficiency Maximizer for an Adjustable Frequency Induction Motor Drive,” *IEEE Transactions on Industry Applications*, 1991, pp. 940-946.
- [7] FLIR, *ThermaCAM E4 Operator’s Manual*, FLIR Systems, Danderyd, Sweden, 2004.
- [8] Wildi, Theodore, “*Electrical Machines, Drives, and Power Systems*,” Prentice Hall, NJ, 2002.
- [9] Riggs, James L., Rentz, William F., Kahl, Alfred L., and West, Thomas M., *Engineering Economics*, McGraw-Hill Ryerson Limited, Toronto, 1986.