A Study into the True Life Cycle Costs of Electric Motors

Irfan Ameer

Dr. Herbert Iu
School of Electrical & Electronic Engineering, University of Western Australia

Dr. Melinda Hodkiewicz
School of Mechanical Engineering, University of Western Australia

Geoff Down
CEED Client: The Water Corporation

Abstract

This CEED project, done in conjunction with the Water Corporation, assesses the financial viability of upgrading electric motors to a higher efficiency equivalent in light of rising electricity costs and carbon emission taxes. Selected motors owned by the corporation are used to explore induction motor life-cycle cost relationships. A predictive life cycle cost model is to determine the likelihood of an electric motor benefiting from a higher efficiency upgrade based on its size, speed, efficiency, operational period, cost of rewinding and maintenance regime. Based on the availability, and accuracy of data, cost elements are determined parametrically, analogously or probabilistically. Probabilistic cost distributions are further tested by simulation modelling software to explore data uncertainty. The application of these models is used for fixed speed electric motors in both water and wastewater pump stations. The findings of this project are important to the Water Corporation to reaffirm or modify their current management strategies for electric motors.

1. Introduction

The purpose of this project is to address these questions:

- What is the true annual 'cost' of purchasing, operating and maintaining an electric motor over its entire life cycle?
- Under what conditions would an old electric motor benefit from an upgrade to a higher efficiency motor of the same size, considering its efficiency, operating period, cost of rewinding and maintenance regime?
- Do only heavily used large electric motors benefit from an upgrade?

1.1 Project Motivations and Client Interests

The Water Corporation (WC) utilises over 3000 electric motors of varying sizes to drive an assortment of pumps, bores and compressors throughout Western Australia for the transferral of clear-water, wastewater and seawater. They are one of the largest consumers of electricity on the South-West Interconnected Systems (SWIS) grid of Western Australia.

The WC has a keen interest in monitoring the energy usage and efficiency of its electric motors, due to pumping operations accounting for over 80% of the WC's energy consumption (Energy Efficiency Opportunities, 2008). In addition, on 15th December 2008 the Federal Government announced the introduction of a Carbon Pollution Reduction Scheme (CPRS) by 2011. The impact of the CPRS is not to be understated considering the WC emit over 400,000 tonnes of greenhouse gases annually with 90% of these emissions attributed to electricity requirements for removing and treating wastewater, supplying drinking water and managing drainage networks and irrigation (WC Annual Report, 2008). As a result, carbon emission costs have to be incorporated in future cost analysis models of electric motors.

According to the WC's pump station design standard, an Annual Assessed Cost (AAC) formula has been devised to account for yearly costs of electric motors. The efficiency-based AAC formula is specified as:

$$AAC_{EB} = FcC + N_1T_1W_1\eta_1^{-1}(100- \eta_1^{-1}) + N_2T_2W_2\, \eta_2^{-1}(100- \eta_2^{-1})$$

Fc: Interest & Sinking Fund Factor; ($r = 8\%$, $t = 20$ yrs – 0.1019)
C: Capital Value including National Preference Agreement escalations; \$
N_1 (N_2): Annual operating period at duty point 1(2); hrs
L_1 (L_2): Losses at duty point 1(2); kW
T_1 (T_2): Energy cost at duty point 1(2); \$/kWh
W_1 (W_2): Motor output at duty point 1(2); kW
η_1 (η_2): Motor efficiency at duty point 1(2); %

1.2 Literature Review Results

In industry, simplistic approaches of costing electric motors such as the simple payback period, annual energy savings and present worth life cycle analysis have been preferred (El-Ibiary, 2003). These methods tend to operate on a comparative basis – given the motor's technical specifications and the annual running time, a choice between two motors is made based on which motor offers the better energy cost savings. The formula for the annual energy savings calculation is:

$$\text{Annual Energy Savings} = kW_{rating} \times L \times C \times H \times \left(\frac{100}{E_A} - \frac{100}{E_B}\right),\ E_B > E_A$$

L: Load of the motor (changes according to its efficiency) (%)
C: Electricity cost (\$/kWh)
H: Running Hours (hrs)
E_B: Efficiency of Motor B (Higher Efficiency Motor)
E_A: Efficiency of Motor A (Lower Efficiency Motor)

If the differential acquisition cost of Motors A & B is known, the simple payback period can be calculated by dividing this differential acquisition cost by annual energy savings. The present value of savings determines the amount you can currently save by purchasing the higher efficiency motor (El-Ibiary, 2003). It can be calculated by the following formula:

$$\text{Present Value of Energy Savings} = \text{Annual Saving} \times \frac{(1+i)^n - 1}{i(1+i)^n},$$

the interest rate, $i = \frac{100 + i_1}{100 + i_2.}$. ($i_1$ = internal rate of return, i_2 = inflation rate)

Both the efficiency-based AAC and the present value formulas have serious limitations in their current implementations as neither account for installation, operating or carbon emission costs. There is no clear distinction between on-peak and off-peak operational usage despite energy costs being significantly greater for on-peak usage. Motors don't always run at fixed, discrete duty points (i.e. 50, 75 or 100% load), but rather at some intermediate, varying load. This makes it difficult to estimate running hours at different duty points for the efficiency based AAC case.

For this project, a differential life cycle cost model is constructed on Microsoft Excel to calculate both the AAC incurred by the existing motor against the potential AAC incurred by a new, high efficiency motor. This model will address the shortcomings faced by using simple formulas to estimate these costs. The outcomes of this model will assist the WC to assess their strategies on replacing or repairing electric motors.

2. Electric Motor LCC Model Development

2.1 Modelling Pump Parameters

A parametric life cycle cost model was developed with analogous and predictive elements. All of the technical specifications of both the motors (efficiency at duty points, full-load and three phase voltage and current) and the attached pumps (flow, head and efficiency) are provided in the pump test reports. Using these figures, parametric equations are used to calculate both the output water and electric power. If more than one pump test report is done at a particular pump station and there are records indicating that the same pump has been overhauled, then annual deviations in pump parameters (flow, head and efficiency) are calculated with the assumption that on the year of the next overhaul the pump is restored to manufacturer's specifications. If any of this information is unavailable then the pump parameters from the last available pump test report are used and assumed to be constant throughout the motor's lifecycle as the extent of pump deterioration is unknown.

2.2 Operational Factors

Running hours for motors belonging to wastewater pump stations are obtained using the WC's Asset Management Data Register. Future running hours are modelled using the simulation software's (Crystal Ball) CB Predictor tool. CB Predictor is a time-based forecasting tool that analyses historical data and extrapolates future run time estimates based on underlying trends using regression techniques. Tariff codes and on/off-peak power consumption data are obtained from the WC's Power Allocation database which is recorded on a pump station usage basis. As most wastewater pump stations have two identical motors, the ratio of Motor A's runtime to the total runtime of both motors determines the portion of power consumed from Motor A. A similar method is used to obtain the on-off peak ratio. Emission factors (kg CO_2-e/kWh) are predicted from the latest WA estimates published by the Department of Climate Change. All inflation factors and indices are taken from the WC's latest FIS (Financial Impact Statement) spreadsheet.

2.3 Maintenance Considerations

Scheduled maintenance costs are subdivided according to minor and major motor service tasks. Determining annual minor/major service costs requires taking the average of all the minor/major service orders at a specific pump station. The cost per motor is assumed to be equally distributed amongst all motors at the pump station, if identical. Frequency of future major service orders and pump tests are determined by how frequent these orders have occurred historically. Historical cost data is scarce and unreliable for determining unscheduled maintenance costs like motor overhauls and rewinds. For this case, cost estimates are provided by WA Rewind according to motor size.

2.4 Acquisition Costs

CMG provided acquisition costs, motor testing costs and technical specifications of their latest motors within both the Standard & Premium Efficiency range. After having conversations with electricians and electric engineers at the WC, labour hours spent disconnecting the old motor and connecting a new motor is estimated to be proportional to motor size. Costs of spare parts including ball bearings are provided by SKF Bearings. Crystal Ball is the simulation software used to model any variable which exhibits an underlying distribution.

3. Rewind/Replace Scenario Analysis Results and Discussion

In the rewind/replace scenario analysis, the maintenance manager is faced with two options - either rewinding the old motor causing a drop in efficiency, or purchasing a brand new motor. The AAC of both options are calculated in parallel and the payback period (output) determines how long it takes to break even after purchasing a more energy efficient motor. To ensure the comparison between the two motors are valid, maintenance costs are omitted and all of the pump and motor parameters (except motor efficiency) were kept identical. Several pump stations housing different size motors were chosen on the basis of proven data availability and reliability. Duty motors from a selection of these pump stations are presented in table 1.

Pump Station Name	Motor Size (kW)	Δ AR Efficiency (%)	Δ Average Electric Output Power (kW)	Required Annual Operating Hours (hrs)
Grindleford Dr	37	4.4	1	6700
Karalundie Wy	45	5.4	1.1	5125
Whipple St	55	5	1.2	4600
Leach Hwy	75	2.4	1.2	5850
Kalamunda Rd	90	6.1	3.6	1815
Rivermoor Loop	96	4.9	3.6	3100
Sheldrake St	110	2.7	1.6	4975
Slade St	139	1.7	1.7	8172
Perth Central	150	2.2	2.7	5200
Mirrabooka WPS	185	3.8	6	2225

* Carbon Tax is fixed at $50/tonne
** Payback Period is fixed at 3 years
***For this scenario all motors are assumed to be replaced in 2011

Table 1 Motor runtime required to upgrade electric motor as a function of changes in motor efficiency and electric power.

The after rewind efficiency represents the efficiency difference at an identical load between the new and old motor after the old motor has been rewound. According to Motor Masters International, rewinding motors larger than 37 kW will lead to an efficiency drop of 0.5% (Quality Motor Rewinding an Energy Efficiency Measure, 2008). The decrease in average electric output power represents the power saved by utilising a more efficient motor.

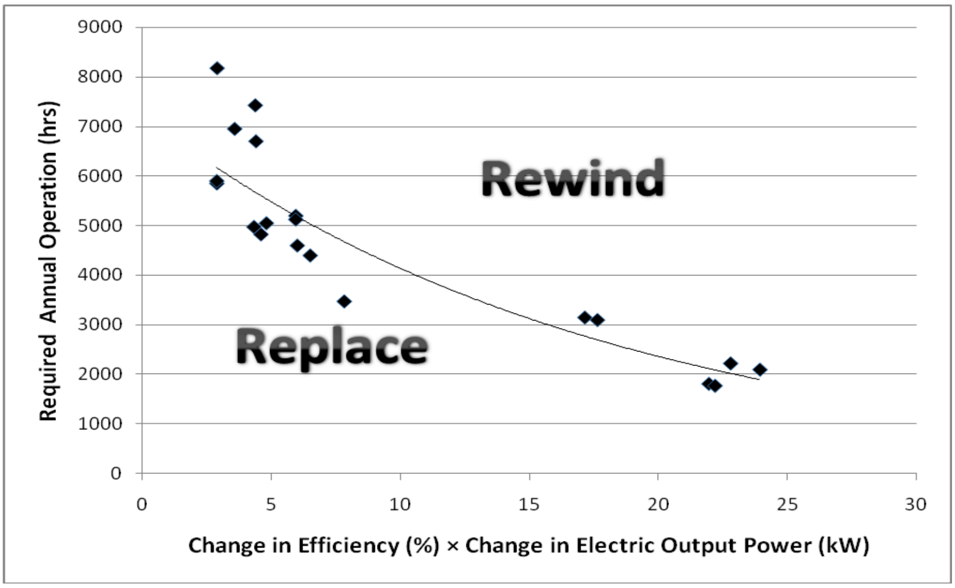

Figure 1 Relationship between the product of motor efficiency change and electric power change with operating period

As both the efficiency and electric power variables in Figure 1 assume equal importance, they are multiplied together and plotted against the required annual operating period. The exponential curve represents the three-year payback period line. If an electric motor burns out - requiring a rewind, WC staff can utilise this model to determine whether or not to rewind the old motor or purchase a new motor. For example, if a new motor has a 4% higher efficiency and saves 4kW of power over its predecessor, then we identify when x=16 (4×4) intersects the curve (≈ 3000 hrs) and if the new motor needs to run for more than 3000 hours annually to recover its acquisition costs within three years, then it's better to rewind the motor than to replace it.

For the wastewater and water pump stations in the metropolitan area, The WC's current policy with regards to motor replacement can be loosely described as 'replace when motor electrically fails and can no longer be serviced to a required standard.' This policy implies that motors which do not fail may continue to run well past its asset lifetime (25 years). Particularly in wastewater pump stations, maintenance planners tend to ensure that both the duty and standby motors are run for an equivalent time period annually. However, if one motor is left to run for a significantly longer period than the other, then that motor may be worth upgrading. Energy and emission cost savings will be realised with the new motor and scheduled maintenance costs will be minimised with the second motor due to limited use.

From Fig. 2 below, we detect a distinct upward trend between motor size and average annual costs. On/off-peak energy (≈80%) and carbon emission costs (≈15%) account for above 90% of the total annual costs incurred for nearly all motor sizes. This exemplifies the need to investigate premium efficiency motors as energy costs are the dominant cost contributor in operating electric motors after acquiring and installing the motor. Minimising the power consumption of the motors will exert the greatest influence in reducing the payback period involved in purchasing the motor. With the MEPS (Motor Efficiency Performance Standards) becoming more stringent with each revision, there is more financial incentive to upgrade electric motors which are not compliant to MEPS regulations.

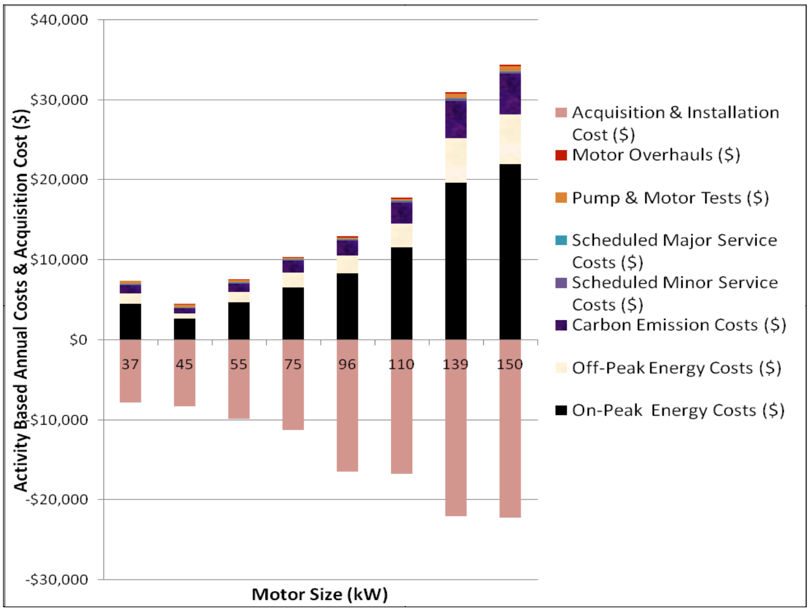

Figure 2 Activity-based average annual assessed costs incurred by an electric motor (over 25 years) as a function of motor size. Initial Acquisition & Installation Costs depicted below the x-axis.

4. Conclusions and Future Work

The outcomes of this project indicate that there is a relationship between the efficiency of a new motor, the power it saves and its annual operation in determining whether or not to replace/repair an electric motor. Upgrade requirements aren't totally dependent on how large the motor is or how heavily it's used. The annual costs of running a motor increase in proportion to size with the key cost contributor underpinning this increase being both energy and emission costs. Future work arising from this project within the WC includes implementation of this model to larger electric motors and variable size motors housed in clear-water pump stations, groundwater and wastewater treatment plants. This model is durable as all dynamic factors can be modified to reflect changing circumstances. Conducting repair/replace scenarios of motors in high voltage pump stations should also be considered as installation costs start to have a more significant bearing in the decision process.

5. References

Y. El-Ibiary, "An Accurate Low-Cost Method for Determining Electric Motors' Efficiency for the Purpose of Plant Energy Management," *IEEE Transactions on Industry Applications,* vol. 39, pp. 1205-1210, 2003.

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