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TECHNICAL NOTE
LIFE CYCLE COST ANALYSIS OF DESIGN OPTIONS SELECTION FOR ENERGY EFFICIENCY IMPROVEMENT OF ELECTRIC MOTOR

P.A.A. Yanti[a,b] *and T.M.I. Mahlia*[a]
[a]Department of Mechanical Engineering, University of Malaya,
50603 Kuala Lumpur, Malaysia
[b]Petronas Carigali Sdn. Bhd. Level 18, Tower 1, Petronas Twin Towers
50088 Kuala Lumpur, Malaysia
Email: yanti_padli@petronas.com.my

ABSTRACT

Literature on energy efficiency standards and labels for electric motor are widely available. However, very limited articles discussed about the method to calculate life-cycle cost analysis of potential energy efficiency improvement for electric motor. This paper presents the life-cycle cost analysis of energy efficiency improvement of electric motor based on engineering/economic analysis. The least efficient model from a survey in the market was selected as a baseline model. The method includes the selection of design options that will increase efficiency and calculate its life cycle cost (LCC) analysis and payback period. LCC was calculated as a function of several design options based on potential efficiency improvement. The study found that, efficiency improvement can be achieved, if manufacturers willing to adopt more efficient design options with a little additional investment for the product. Furthermore, the method can be used for other product without major modification.

Keywords: Life cycle cost; Engineering/Economic analysis; Electric Motor; Cost benefit; Energy efficiency standard; Design options

NOMENCLATURES

BEC	Baseline energy consumption (Wh)
ES	Energy Savings (Wh)
DEC	Energy consumption of new design option (Wh)
LCC	Life cycle cost, (RM$)
N	Life time of the appliance, (year)
OC	Annual operating cost, (RM$)
OH	Operating hour
PAY	Payback period, (year)
PC	Purchase Cost, (RM$)
PF	Price of fuel or electricity (RM$)
PI	Power input (Watt)
PWF	Present worth factor
r	Discount rate, (%)
t	Time (year)

1. INTRODUCTION

Industrial sector is a major energy consumer in Malaysia, its accounts for 45% of the total electricity consumption in the country. More than 60% of electricity consumption in industrial sector is consume by electric motor. Therefore it is very important to propose energy efficiency standards and labels for electric motor to reduce energy growth in this sector.

This study is about life cycle cost analysis of design options selection for energy efficiency improvement of electric motor in support of energy efficiency standards and labels in Malaysia. Energy efficiency standards and labels for electric motor are presently formulated in many countries. The program is usually set based on input and advice from industry, R&D organization. Experiences in the US proved that the manufacturers have to be motivated to adopt advanced technologies in order to meet tough new energy efficiency standards established by the US Department of Energy.

2. SURVEY DATA

Based on survey of 955 models, electric motors efficiency in industrial sector in Malaysia is about 90.9. The electric motors data are necessary for further calculations of the average power output, average efficiency in the industrial sector, operating hours, annual efficiency improvement, increment cost, average lifespan and annual discount rate. These data was obtained from variety of sources. The average power output and the electric motors efficiency was obtained from the survey data in the industrial sector. The annual efficiency improvement is about 0.109% (Yanti, 2008). The list of potential energy efficiency improvement based on design option are shown in Table 1, and baseline input data are presented in Table 2 (Yanti, 2008; DES, 2007; Masjuki *et al.*,2001; Mahlia *et al.*, 2001).

Table 1 Potential design option improvement

No	Design Option
0	Baseline Design
1a	Use Grade 1 of electric steel (10%)
1b	Use Grade 2 of electric steel (11%)
1c	Use Grade 3 of electric steel (12%)
2a	Use plus stuck (10%)
2b	Use plus 2 stuck (20%)
2c	Use plus 3 stuck (30%)
3a	Increase flux density (10%)
3b	Increase flux density (20%)
3c	Increase flux density (30%)
4a	Increase conductor's volume (5%)
4b	Increase conductor's volume (10%)
4c	Increase conductor's volume (15%)
5a	Increase slot design 10%
5b	Increase slot design 20%
6a	Narrowing air gap 5%
6b	Narrowing air gap 10%
7	Improve rotor insulation
8	Optimize bearing selection
9	Use efficient fan design
10	Use variable speed drive
11a	Reduce lamination in rotor & stator 5%
11b	Reduce lamination in rotor & stator 10%
11c	Reduce lamination in rotor & stator 15%
12	Use helical gear
13	Use worm gear
14	Use strand depth
15a	Increase rotor bar size (10%)
15b	Increase rotor bar size (20%)
16	Increase end ring size

Table 2 The input value of baseline models

Variable	Class I
Average power output	58.67 kW
Average efficiency of motor	90.9 %
Average Operating hours	7200 hr/year
Annual efficiency improvement	0.109%
Discount rate	7%
Current average electricity price	RM 0.21/kWh
Incremental cost	RM1968

Note: 1US $ ≈ RM3.20

3. METHODOLOGY

The life-cycle cost and the engineering/economic analysis is carried out to analyze potential efficiency improvement of new design options that are already adopted by existing models in the market. The steps for conducting this analysis include (i) identification of the manufacturing process of the product, (ii) selection of baseline units, (iii) selection of design options, (iv) efficiency improvement of each design option, (v) efficiency improvements of combined design options, (vi) cost for each design option (vii) cost-efficiency curves, and (viii) energy savings potential (Hakim & Turiel, 1996; Turiel *et al.,* 1997). Each step will be discussed in the following sections.

3.1 Manufacturing process of the product

Before conducting energy efficiency improvement, the process assembly should be identified to understand the manufacturing process of the product. This part is necessary to identify the component of the product that can be improved by the manufacturer since some of components of the product are produced and supplied by vendors or by other manufacturers.

3.2. Selection of baseline units

The baseline unit of the product serves to provide basic design features for this analysis. For products without any existing standards, the baseline models is the product with efficiency equal to minimum or average of the existing models in the market. Selecting the least efficient model as the baseline is recommended since this permits analysis at all possible levels of efficiency improvement (Turiel *et al.,* 1997).

3.3. Selection of design options

Design options are the changes to the design of the baseline model that would increase energy efficiency. The potential design options selected is based on the substitution of more efficient components to baseline product. The data for potential design improvement is collected from manufacturers of the baseline unit or from literatures

3.4. Efficiency improvement of each design option

Efficiency improvement of each design option can be determined by improvement of components to the baseline models. The design options are usually selected based on inputs from manufacturer of the baseline models and other possible improvements available in the market or literatures.

3.5. Efficiency improvements of combination design options

The combination of design options is the cumulative changes to the design that improve energy efficiency of the baseline model. Calculations are conducted for various components substitution in accordance with the inputs from manufacturers, market or from literatures. For combination design options, energy savings, and efficiency improvement are determined through cumulative improvement of each design option.

3.6. Cost estimation for each design option

The increment cost for each design option is the cost products with improved design. The expected cost of manufacturing each additional design option is obtained from manufacturer. When manufacturer costs are unavailable, the cost is estimated based on retail price, or from the designs option that already exists in market.

3.7. Life-cycle Cost

A life cycle cost (LCC) analysis calculates the cost of a system or product over its entire life span. For this study, LCC is used to calculate the cost of energy efficiency improvement of the product based on each design option, and combination design options. The LCC is the sum of investment cost and the annual operating cost discounted over the lifetime of the product. LCC is calculated by the following equation (Turiel *et al.,* 1997):

$$LCC = PC + \sum_{1}^{N} \frac{OC_t}{(1 - r)^t} \qquad (1)$$

If operating expenses are constant over time, the LCC is simplified to the following equations:

$$LCC = PC + (PWF)(OC) \qquad (2)$$

3.8. Operating Cost

Before calculating the LCC, operating cost should be determined. The operating cost of electric motor is a function of the annual energy used and electricity price. The operating cost for electric motor can be calculated by the following equation:

$$OC = \frac{PI \times OH \times PF}{\eta_{em}} \qquad (3)$$

3.9. Present Worth Factor

Present worth factor (PWF) is the value by which future cash flow to be received to obtain current present value. The present worth factor can be calculated by the following equation:

$$PWF = \sum_{1}^{N} \frac{1}{(1+r)^t} = \frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right] \qquad (4)$$

3.10. Payback Period

The payback period (PAY) measures the amount of time required to recover the additional investment (increment cost) on efficiency improvement that reduces operating costs. PAY is found by solving the following equation (Turiel *et al.,* 1997):

$$\Delta PC + \sum_{1}^{PAY} \Delta OC_t = 0 \qquad (5)$$

In general, PAY can be found by interpolating between the two years when the above expression changes sign. If the OC is constant, the equation can be written as the following form:

$$PAY = -\frac{\Delta PC}{\Delta OC} \qquad (6)$$

The PAY is the ratio of incremental cost (from the baseline to become more efficient) to the decrease in annual operating cost. If PAY is greater than the lifetime of the product, it means that the increased purchase price is not recovered by reducing operating cost.

3.11. Energy Savings

The unit energy savings associated with each design option is the baseline energy consumption minus the energy consumption of the product with each or cumulative design options that related to efficiency improvement of the product. It can be expressed using the following equation:

$$ES = BEC - DEC \qquad (7)$$

4. RESULTS AND DISCUSSIONS

Before calculating energy efficiency improvement, the process of manufactured and assembly of electric motor should be identified. Many of electric motors assembled in Malaysia. The enclosure, slot, rotor and shaft are usually produced by electric motors manufacturer. Other components such as fan and controller are supply by the vendors. The electric motor manufacturing flow diagram is presented in Figure 1.

The design options are changes to the design of the baseline model that will improve energy efficiency of the product. Selection of design options are based on substitution of the present components to more efficient one in to the product. Some of the options are already adopted by existing model and others are being developed. The potential improvement of design options are determined based on input and suggestion from manufacturers, market and literatures.

Normally, improved steel properties can make more efficient electric motors. Standard motors use low-carbon laminated steel for the rotor and stator. Such steel typically has electrical losses of 6.6 watts per kg. Higher efficiency motors are built with high-grade silicon steel, which typically reduces hysteresis and eddy current losses by half, to only about 3.3 watts per kg. In other hand, reducing lamination thickness in rotor and stator steel also lowers eddy current losses. Improved insulation between laminations, when applied with enhanced quality control, will further reduce these losses.

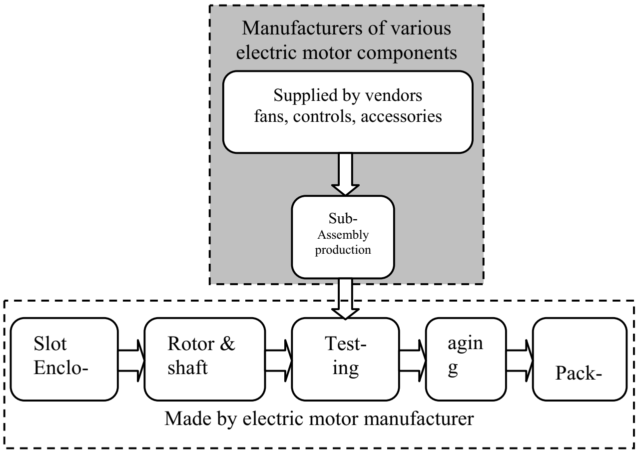

Figure 1 Manufacturing flow diagram of electric motor

By increasing conductor's volume, higher efficiency motors utilize bigger copper conductors to lower the winding resistance, with the conductors sized 35% to 40% larger than needed to simply satisfy the motor output horsepower requirement. To accommodate the larger volume of copper in the windings and required additional slot insulation, the winding slot cross-sectional area is increased and the stator core is lengthened. A longer core yields an important additional benefit in the form of improved motor power factor.

When the air gap between stator and rotor decrease, it will increase the intensity of the magnetic flux, thereby improving the motor's ability to deliver the same torque at reduced power. Some losses are incurred because of unintentional, false conduction paths established in the motor manufacturing process. In higher efficiency motor manufacture, the edges of the rotor slots are treated with high-temperature insulation to reduce these losses. Lastly, electric motors need more efficient fan design, because motors designed for higher efficiency inherently run cooler than standard types. The design can incorporate a smaller cooling fan, reducing wind age losses, and resulting in quieter operation. The lists of potential design options selected by for the least efficient model are tabulated in Table 3.

Efficiency improvement and incremental cost are calculated based on selection of design options. This calculations and analysis takes into account of possible efficiency improvement for each design options independently. Usually, the incremental costs were obtained from manufacturers, market and literatures. The incremental costs are the investment cost to produce product with the new design options. The efficiency and incremental cost of combine design options is calculating from the baseline and the designs changes are accumulate together with efficiency improvement. The technology improvements are calculated based on priority of the highest efficiency improvement and lowest incremental cost and presented in Figure 2, Table 4 and Table 5.

Table 3 Potential design option improvement for electric motor

No	Design Option	Selected Design option
0	Baseline Design	-
1a	Use Grade 1 of electric steel (10%)	√
1b	Use Grade 2 of electric steel (11%)	-
1c	Use Grade 3 of electric steel (12%)	-
2a	Use plus stuck (10%)	-
2b	Use plus 2 stuck (20%)	-
2c	Use plus 3 stuck (30%)	-
3a	Increase flux density (10%)	-
3b	Increase flux density (20%)	√
3c	Increase flux density (30%)	-
4a	Increase conductor's volume (5%)	-
4b	Increase conductor's volume (10%)	√
4c	Increase conductor's volume (15%)	-
5a	Increase slot design 10%	√
5b	Increase slot design 20%	-
6a	Narrowing air gap 5%	-
6b	Narrowing air gap 10%	√
7	Improve rotor insulation	√
8	Optimize bearing selection	-
9	Use efficient fan design	√
10	Use variable speed drive (CSD)	-
11a	Reduce lamination in rotor & stator 5%	-
11b	Reduce lamination in rotor & stator 10%	√
11c	Reduce lamination in rotor & stator 15%	-
12	Use helical gear	-
13	Use worm gear	-
14	Use strand depth	-
15a	Increase rotor bar size (10%)	-
15b	Increase rotor bar size (20%)	-
16	Increase end ring size	-

The results of cumulative payback period, life cycle cost and potential energy savings for typical electric motor is tabulated in Table 6 and presented in Figure 3.

From the analysis it observed that significant efficiency improvement can be achieved if manufacturers are willing to adopt more efficient design options. Based on least efficient models, efficiency can be increased with a little investment cost. From this improvement, Malaysian product especially electric motor can pass the tough energy efficiency standards set by importing countries.

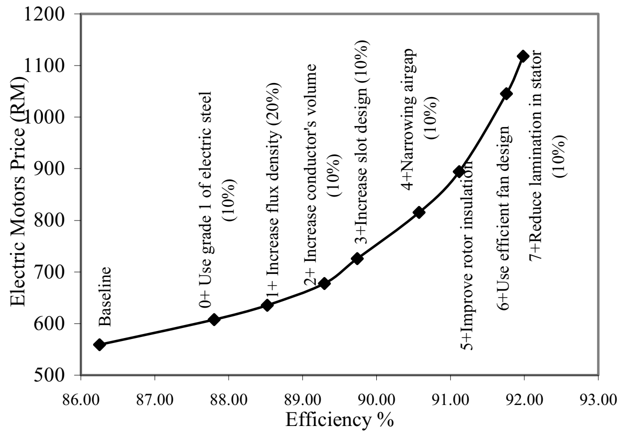

Figure 2. Impact of design options changes on price and efficiency

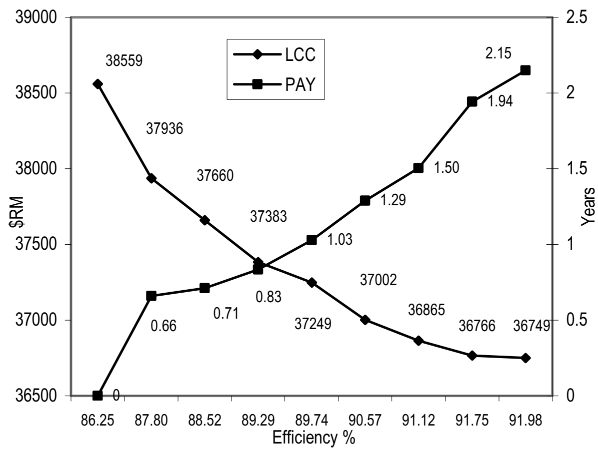

Figure 3. Payback period and life cycle cost

5. CONCLUSIONS

The life-cycle cost analysis of design option selection for electric motor energy efficiency improvement is presented in this study. This is very useful as a reference to calculate potential energy efficiency improvement of the product which is correlated with its investment cost. It can be concluded that a significant improvement could be achieved if manufacturers are willing to adopt more efficient design options. The calculation found that even the least efficient model can still reach significant improvement by using better grade of electric steel, increasing flux density, conductor's volume and increase slot design, narrowing air gap, improving rotor insulation, using efficient fan and reducing lamination in rotor and stator. The study also found that the investments are quite low compare to energy efficiency improvement. Through this design option improvement, hopefully the product can pass the tough energy efficiency standard set by developed countries. The manufacturer should be encouraged to adopt cost-effective of more efficient design options.

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Table 4 efficiency and incremental cost design options

Design Option	Technology Improvements	Efficiency %	Efficiency Imp %	Price Imp %
0	Baseline Design	86.25	0	0
1a	Use Grade 1 of electric steel (10%)	87.80	1.80	8.7
3b	Increase flux density (20%)	88.52	0.82	4.9
4b	Increase conductor's volume (10%)	89.29	0.87	7.5
5a	Increase slot design 10%	89.74	0.50	8.6
6b	Narrowing air gap 10%	90.57	0.93	1.6
7	Improve rotor insulation	91.12	0.60	1.4
9	Use efficient fan design	91.75	0.07	2.7
11b	Reduce lamination in rotor & stator 10%	91.98	0.25	1.3

Table 5 Efficiency and incremental cost of combined design options

No.	Design Options	Eff. %	Cum Eff %	Price RM	Cum Price %	ES kWh
0	Baseline Design	86.25	0	559	0	0
1	0+Use Grade 1 of electric steel (10%)	87.80	1.8	608	8.7	351
2	1+Increase flux density (20%)	88.52	2.6	635	13.6	510
3	2+Increase conductor's volume (10%)	89.29	3.4	677	21.2	677
4	3+Increase slot design 10%	89.74	3.9	726	29.8	772
5	4+Narrowing air gap 10%	90.57	4.9	816	45.9	948
6	5+Improve rotor insulation	91.12	5.5	894	60.0	1061
7	6+Use efficient fan design	91.75	6.2	1045	86.9	1192
8	7+Reduce lamination in rotor & stator (10%)	91.98	6.4	1118	100.0	1239

Table 6 Life-cycle cost and payback periods

No	Design Option	Eff %	Price RM	OC RM	LCC RM	PAY Year
0	Baseline Design	86.25	559	4172	38559	0
1	Use Grade 1 of electric steel (10%)	87.80	608	4098	37936	0.66
2	Increase flux density (20%)	88.52	635	4065	37660	0.71
3	Increase conductor's volume (10%)	89.29	677	4030	37383	0.83
4	Increase slot design 10%	89.74	726	4010	37249	1.03
5	Narrowing air gap 10%	90.57	816	3973	37002	1.29
6	Improve rotor insulation	91.12	894	3949	36865	1.50
7	Use efficient fan design	91.75	1045	3922	36766	1.94
8	Reduce lamination in rotor & stator 10%	91.98	1118	3912	36749	2.15