

AC 2007-446: A MATHCAD APPLICATION FOR TEACHING ENERGY ECONOMICS AND EFFICIENCY IN UNDERGRADUATE ELECTRIC MACHINES COURSES

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A Mathcad Application for Teaching Energy Economics and Efficiency in Undergraduate Electric Machines Courses

Abstract

A novel use of Mathcad designed for undergraduate electric machines courses bridges existing knowledge and skill gaps in the study of engineering economics and energy efficiency. Combining economics, efficiency and machine theory with detailed computer-based examples prepares students for employment where these principles must be applied to make design decisions. Mathcad supports custom designed documents called electronic handbooks that explain complex topics and provide reusable computational templates. This work uses Mathcad electronic handbook tutorial format to present economic and machine theory for finding the life-cycle costs of induction motors driving general industrial loads. The developed material provides the basis for a design project that includes technical and economic aspects.

I. Introduction

Generally, engineering economics topics have been de-emphasized in engineering programs and replaced with other material. Some electrical engineering programs have eliminated the requirement for engineering economics in favor of other discipline-specific courses. While the trend is to eliminate this material, a need continues to exist for economic decision making in electric power conversion courses as well as other areas of engineering.¹

Deregulation of electric utilities introduced significant energy price volatility especially for industrial users. Electric machine efficiency and energy costs are a significant component of an industrial consumer's operating expenses. The lifetime of electric machines is long. Incorrectly specified machines are inefficient, costly to own, and unprofitable.

Combining motor theory and engineering economics provides students with the necessary tools and relevant context for learning these topics. Emphasizing the efficiency-load relationship promotes the proper motor sizing and industrial energy conservation. Introducing typical electric rate structures and computing power costs connects machine theory with current energy policies. Including machine reliability, energy costs, and system power losses gives students a systems view of economic decision-making, a valuable asset in industrial practice.

This paper proposes to supplement currently available material with an electronic book, written using Mathcad software, that introduces three-phase induction motor theory, demonstrates how efficiency relates to machine load, and reviews engineering economic principles. Electric rate structures are discussed, and finally, a life cycle cost analysis is conducted comparing two alternative machines.

II. Construction of the Mathcad Electronic Book

An electronic book format, developed with Mathcad, is an ideal platform for technical tutorial work. Mathcad is a general mathematical program that merges live calculations, word processing, and graphing into a single, easily mastered environment. The program displays mathematical symbols in standard form on the screen, so developed documents are similar to a printed book except that any change in a numerical value will reflect throughout the document. This makes the format ideal for exploring cause and effect relationships between problem variables and solutions^{2,3}. The electronic book was developed using Version 2001 and is upwardly compatible with newer releases and is intended for student use.

A Mathcad electronic book is a collection of hyperlinked Mathcad documents which open in a separate window from the main program. A table of contents links the user to topics and calculations. Electronic book users can cut and paste solution templates and examples into their own work. The book itself may be annotated and modified by the user without affecting the original documents. Electronic book construction consists of creating individual files, inserting relevant hyperlinks, and developing the table of contents. Constructing a handbook file, which acts as the electronic binding for the individual files, completes the process.⁴

All tutorial files follow the same format. Introductory theory with supporting equations begins each section. A numerical example, called a “Quick Test” follows, demonstrating theory and equations with an annotated example. Fig.1 shows a typical tutorial page for a Quick Test that includes unit definitions and a hyperlink indicated by bold, underlined text in the tutorial.

Quick Test 2: Motor Model Circuit Calculations

These variables are defined so that the Mathcad units system will work with the motor equations. They are used throughout the book.

$$\text{rpm} := 1 \quad \text{pole} := 1 \quad \Omega := \text{ohm}$$

A three phase, 10 hp, 60 Hz, six pole, wye connected 240V induction motor is modeled in **Figure 2**. It has the following circuit parameters:

$$\begin{array}{lll} R_1 := 0.294 \cdot \Omega & X_1 := 0.453 \cdot \Omega & f := 60 \cdot \text{Hz} \\ R_2 := 0.139 \cdot \Omega & X_2 := 0.189 \cdot \Omega & X_m := 12.79 \cdot \Omega \end{array}$$

Using the method described above find: a.) the motor stator current magnitude and phase shift b.) the rotor current when the machine has a shaft speed of 1176 rpm c.) the rotor developed power.

Fig. 1. Typical Electronic Book Page Showing a Quick Test.

The final component of each section is a student assignment to be completed using Mathcad. These assignments encourage students to use the presented material in ways that promote

knowledge of the problem variable interactions. Live math and the problem templates allow students to focus on the cause and effect relationships and conduct “what if” experiments without performing tedious hand calculations or using difficult to follow spreadsheets.

III. Contents of the Electronic Book

The electronic book has five major topics. The first topic is steady-state three-phase induction motor theory. The presented motor theory is based on the equivalent circuit model.⁵ This model requires rotor and stator resistances, rotor and stator leakage reactance, and the motor magnetization reactance parameters. Locked-rotor and no-load tests find these parameters. Solving the equivalent circuit model gives the rotor and stator currents as a function of motor slip, s . After rotor current is obtained, the rotor developed power and motor losses can be found for any operating point. The tutorial introduces the motor developed torque equation and demonstrates how to plot the motor torque-speed curve from the developed power found from the equivalent circuit.

Machine load factor and efficiency are critical factors in the ownership cost of industrial motors.⁶ The second topic defines efficiency and discusses the losses incurred in motor operation. Example efficiency calculations use the results of the first topic to plot machine efficiency as a function of slip. An example compares the efficiency of a 15 hp motor at two operating points emphasizing how different motor loads affect efficiency and input power.

The engineering economics section introduces fundamental formulas and procedures for conducting an economic comparison between alternatives. The third section includes all time value of money functions with illustrative examples.⁷ It includes an explanation of present worth analysis with a detailed example that compares three alternatives. The example includes annual maintenance and operating costs of equipment.

Since energy costs comprise a significant part of an industrial motor’s operating cost, the tutorial includes an introduction to electric rate calculations. This section explains the concepts of power demand, time-of-use and seasonal pricing. Numerical examples show how to calculate demand, time-of-use charges, and demand charges. Typical components of an industrial electric bill are discussed and illustrated with a numerical example.

The final tutorial section utilizes the previously presented material to determine the life cycle costs (LCC) of two alternative 100 hp induction motors: a standard and a high-efficiency model. An introduction covers the required steps in conducting a LCC analysis.⁸ The introduction defines acquisition and sustaining costs generally, and then applies these concepts to the motor analysis problem. Motor acquisition costs are purchase price and disposal costs. The sustaining costs include repairs, preventative maintenance, motor feeder losses, lost production, and energy costs. The tutorial computes the annual sustaining costs using the data given in an example.

A present worth analysis of the motor alternatives identifies the least cost motor choice over the machinery life. Break-even cost plots of the alternatives show the time required for the higher purchase cost of the high-efficiency motor to be recovered by its lower energy costs. A vital cost plot compares the expenses of alternatives and identifies the most significant cost components.

The process can be repeated using only the most significant costs. A sensitivity analysis conducted on these costs can improve the analysis.⁸ A final LCC project, similar to the presented example, ends the electronic book. This project uses all important concepts presented and requires students to combine motor theory with engineering economic analysis to support their selection. The final project results, which include all calculations and a written justification, require development of a Mathcad document encompassing all tutorial subject materials.

IV. Life-Cycle Cost Example Results

The LLC example compares the operation of a standard and high-efficiency 100 hp three-phase induction motor operating a conveyor system over a 15 year life. The problem definition contains all cost data and electric rate information. Repair costs are estimated using mean time between failure (MTBF) values. The example uses a simple time-of-use rate with no demand charge. A normally distributed histogram of load factors, shown in Fig. 2, models the mechanical load.

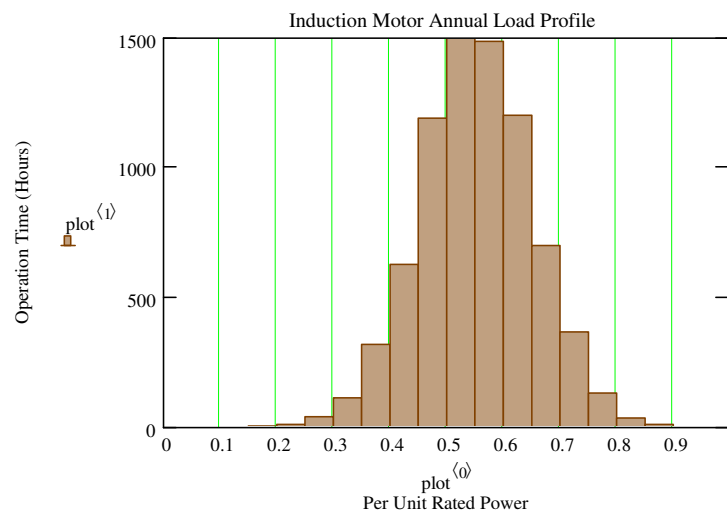


Fig 2. LCC Example Load Factor Distribution.

The motor developed power as a function slip can be solved for an unknown slip when rated power, a load factor, and friction, windage, and stray losses are known. Fig. 3 shows the electronic book excerpt which defines developed power function in terms of s and computes motor losses for the standard motor. Solving the equivalent circuit model finds the rotor current, $I_2(s)$, and stator current, $I_1(s)$. Rotor and stator losses are computed from motor parameters and these currents. The calculation assumes constant friction windage and stray losses that are 3% of total rotational losses. Core losses are assumed constant and computed at operating voltage and rated slip.

The Mathcad program in Fig. 4 computes the slip for each load level in the histogram using the rotor developed power balance equation. The example uses 20 load factor levels. The input power function, $P_{in}(s)$ takes the computed slip values as an argument and returns the motor input power for each load level.

Total rotor power developed $P_r(s) := 3 \cdot \left[\frac{R_{2s} \cdot (1-s)}{s} \right] \cdot (|I_{2s}(s)|)^2$ $P_r(s_{s_rated}) = 84980.8W$

The rated shaft power of the motors is: $P_{rated} := 100 \cdot \text{hp} \cdot \frac{746 \text{ W}}{1 \cdot \text{hp}}$ $P_{rated} = 74600W$

Recompute the rotational and core losses since the rated values are for rated voltage (460V) operation. The rotational losses are the sum of the core, stray, friction and windage losses. The core losses depend on the operating voltage and increase when operating at 480V.

Total rotational power loss: $P_{rots} := P_r(s_{s_rated}) - P_{rated}$ $P_{rots} = 10381W$

Find the core losses from the total rotational losses:

Assume stray, friction and windage losses are 3% of rated output power

$P_{fws} := 0.03 \cdot P_{rated}$ $P_{fws} = 2238W$

$P_{cores} := P_{rots} - P_{fws}$ $P_{cores} = 8142.8W$

Total stator power loss: $P_{stator}(s) := 3 \cdot (|I_{1s}(s)|)^2 \cdot R_{1s}$

Total rotor power loss: $P_{rotor}(s) := 3 \cdot (|I_{2s}(s)|)^2 \cdot R_{2s}$

Fig. 3. Standard Motor Power and Losses Computation Procedure.

Define slip array index $j := 0..19$ Compute the slips for the load factors using P6.1

$$s_{s_j} := \text{for } j \in 0..19 \begin{cases} ss \leftarrow 0.05 \\ LF \leftarrow 0.05 + j \cdot 0.05 \\ s_{s_j} \leftarrow \text{root} [P_r(ss) - (LF P_{rated} + P_{fws}), ss] \end{cases} \quad (P6.1)$$

The total input power as a function of motor slip is given by: $P_{in}(s) := P_{rotor}(s) + P_{stator}(s) + P_{cores} + P_r(s)$

Check values at rated shaft load $s_{s_{19}} = 0.05$ $P_{in}(s_{s_{19}}) = 90.818kW$

Fig. 4. Program for Computing Motor Slips at Different Load Factors.

The annual energy is found by multiplying the operating hours at a given load factor by the input power found from each output load factor. Cable losses are found from the computed stator current at each load factor and the cable resistance. Multiplying these values by the electric rate

gives the annual power cost. Table 1 summarizes the acquisition, sustaining, and energy costs of the standard and high-efficiency motors.

Table 1. Motor Cost Summary

	Standard	High-Efficiency
Total Acquisition Cost (TAC)	\$17,850	\$20,400
Annual Sustaining Cost	\$11,866	\$11,769
Annual Energy Cost	\$19,491	\$18,843
Total Annual Operating Cost (TAOC)	\$31,357	\$30,612

Fig. 5 is the present worth calculation for both motors using a rate of return of 12% ($i=0.12$) and a 15 year life ($n=15$). The functions $PV(n,i,FS)$ and $PVS(n,i,A)$ find the present value of a future sum, FS, and series of amounts, A, respectively. The disposal cost, D, is \$800 for both motors. This calculation shows that the present worth of the high-efficiency machine is lower than the standard machine; it is the desired alternative since it represents the lowest cost.

Present value of a future sum $PV(n,i,FS) := FS \cdot \frac{1}{(1+i)^n}$

Present value of a series of end of period amounts $PVS(n,i,A) := A \cdot \left[\frac{(1+i)^n - 1}{i \cdot (1+i)^n} \right]$

$n = 15$ $i = 0.12$

Compute the present worth of the two projects to compare them economically.

$PW_s := TAC_s + PV(n,i,D) + PVS(n,i,TAOC_s)$

$PW_{he} := TAC_{he} + PV(n,i,D) + PVS(n,i,TAOC_{he})$

$PW_s = 231561.56 \text{dollars}$

$PW_{he} = 229038.97 \text{dollars}$

Fig. 5. Present Worth Calculations for Motor Alternatives.

Equations 1 and 2 are the present worth formulas from Fig.5 defined as functions of the investment period, n.

$$PW_s(n) := -(TAC_s + PV(n,i,D) + PVS(n,i,TAOC_s)) \quad (1)$$

$$PW_{he}(n) := -(TAC_{he} + PV(n,i,D) + PVS(n,i,TAOC_{he})) \quad (2)$$

Equation 1 and 2 variables and function definitions are:

$PW_s(n)$ = the present worth of the standard motor as a function of n,
 $PW_{he}(n)$ = the present worth of the high efficiency motor as a function of n,

TAC_s = total acquisition cost of the standard motor,
 TAC_{he} = total acquisition cost of the high efficiency motor,
 D = disposal costs of motors
 $TAOC_s$ = total annual operating costs of the standard motor,
 $TAOC_{he}$ = total annual operating costs of the high efficiency motor,
 $PVS()$ = present value of series function,
 $PV()$ = present value of future sum function.

Plotting these functions finds the break-even point of the alternatives graphically. The break-even point is the value of n where the costs of owning the alternatives are equal. The Mathcad Find function can compute this value numerically. Fig. 6 shows the example break-even graph. For this example, the high-efficiency motor recovers its additional acquisition cost after 4.67 years of service. The remaining example results and entire tutorial are available on the web from www.engr.siu.edu/staff1/tech/Faculty%20and%20Staff/Faculty%20and%20Staff.html.

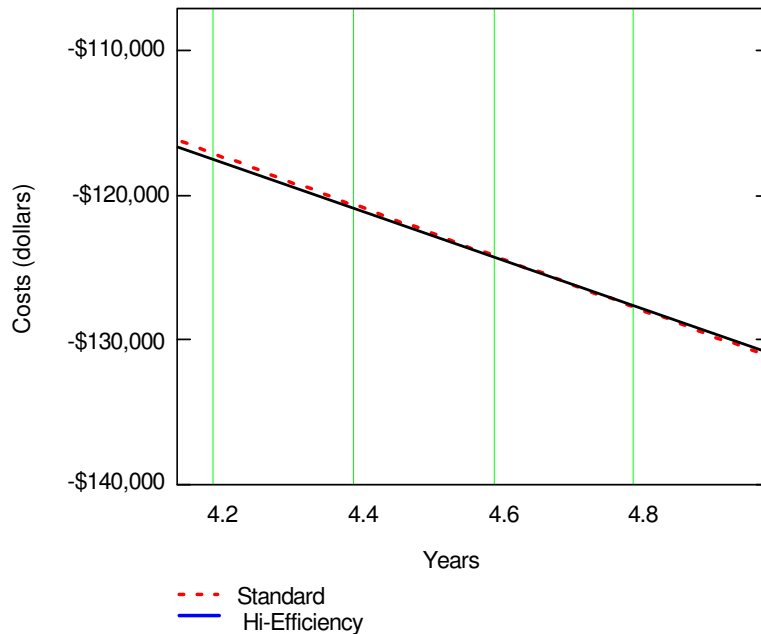


Fig. 6. Break-Even Plot of Motor Alternatives.

V. Conclusion

This paper presents an electronic book tutorial that studies the technical and economic factors of owning and operating three-phase induction motors. The tutorial introduces engineering economic principles in a relevant context. The tutorial combines motor theory, engineering economics, electric billing calculations, and life cycle cost analysis into a single, easily utilized learning tool. Live math examples promote the exploration of the underlying relationships between problem variables and the solutions. The engineering economic functions and alternative selection procedures give users necessary background for conducting life cycle cost analysis. The embedded tutorial exercises and projects re-enforce presented material and show applications of economic principles. The tutorial can be applied in electric machines courses to supplement a standard text or be used as an independent study tool.

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