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PC Software for Teaching Transformer and Induction Motor Economics*

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This paper presents an interactive software package implemented using a PC environment, which is designed to allow undergraduate students to conveniently analyze the costs of losses and initial investment for transformers and induction motors. The software reported in this paper is believed to be the first to offer an educational tool for machine analysis based on sound economics. The software package is completely menu-driven, and contains appropriate help commands and instructions which enable it to be used without additional documentation. The use of the software in the classroom and laboratory environment provides the students with a better understanding of both the physical machine losses and engineering economics.

SUMMARY OF EDUCATIONAL ASPECTS OF THE PAPER

1. The paper discusses materials for a course in:

   Power System Economics, Machine Analysis.

2. Students of the following departments are taught in this course:

   Electrical Engineering, Civil Engineering.

3. Level of the course (year):

   Junior/Senior.

4. Mode of presentation

   The software is ideally suited for presentation on small, low cost, highly interactive computer systems for use in classroom and laboratory environment.

5. Is the material presented in a regular or elective course?

   Regular course.

6. Class or hours required to cover the material:

   One semester (Senior Design Course).

7. Student homework or revision hours required for the materials:

   Homework assignments.

8. Description of the novel aspects presented in your paper:

   As an educational tool, software of this nature would go a long way toward illustrating the concepts of cost effectiveness to the power engineering student.

9. The standard text recommended in the course, in addition to author's notes:

   No standard text is required.

10. The material is/is not covered in the text.

    The material is not adequately addressed in most textbooks.

BACKGROUND

THE BASIS of most design decisions is economic. Designing a system that functions properly is only a part of the engineer's task. The system must also be economical and show an adequate return on the investment. In the design of electric machines, the engineer will search for the design that will have the minimum investment cost.

Various methods of economic analysis of engineering alternatives are being used by power engineers [1–6]. A method called 'minimum revenue requirement discipline' (MRRD) presented in [3, 4] has begun to receive broader acceptance among power engineers. An extension of this method using present worth analysis called 'present worth of revenue requirements' (PWRR) [3–6] is particularly adatable to electric machines economic studies. A recent tutorial course [7] sponsored by the PES Power Engineering Education Committee, provides an introduction and overview of engineering economics and illustrates current applications of tools and techniques for power systems studies.

The course presents thought-provoking

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approaches to new problems, as well as valuable reference material. To illustrate its versatility in practical applications, this paper presents an interactive software program for economically analyzing the cost of losses and initial investment for transformers and induction motors. The interactive nature of this program makes such studies effective and easy to use. With the support of a PC, this new software can be a useful teaching tool for machine analysis and refresher training in cost effectiveness.

Application of this software in teaching, studying and investigating an appropriate solution to cost analysis is the primary objective. To achieve this objective, the design of the package features:

- installation in any DOS personal computer (PC);
- an interactive input format, the input devices being the keyboard and the mouse;
- enhanced the effectiveness of trial-and-error type studies, this is an immediate result of the specification of the cycle of modifying data application activation and output probing;
- a more flexible execution due to the program being modulized;
- help for the user to better understand the output information;
- as the purpose of the package is for educational usage, the package is written in Microsoft, FORTRAN-77.

SOFTWARE DESCRIPTION

The software package is interactive and menu-driven, requiring no external documentation for the majority of its uses. Upon starting, the student is given the option of accessing a detailed instruction file, creating or editing a data file, or running a saved case. The initial point of entry to the software 'MACHINELOSS' is the main menu. As shown in Fig. 1, the main menu displays the prime functions of MACHINE LOSS. All options on the main menu cause immediate activation of selected modules except for machine analysis. When selected, the machine analysis option causes the activation of the analysis menu. Figure 2 illustrates the logical structure of the entire system and Fig. 3 lists the main analysis modules available from the analysis menu.

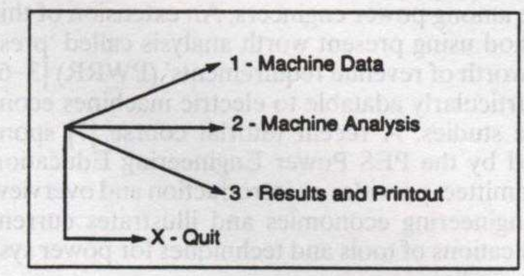

Fig. 1. The main menus.

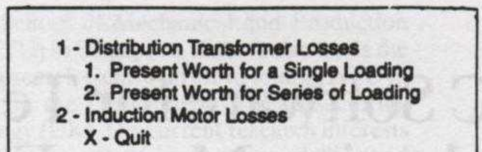

Fig. 2. Analysis menu.

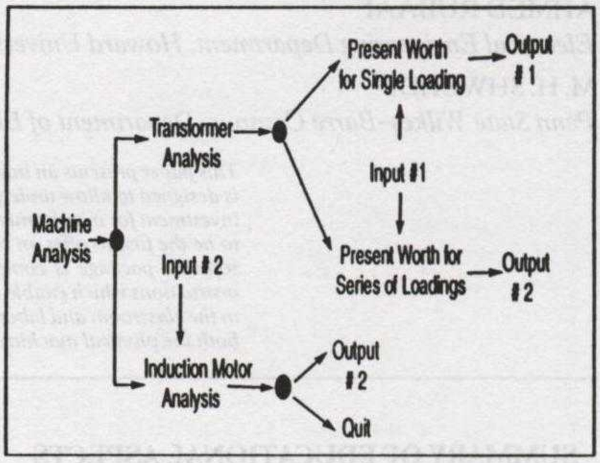

Fig. 3. The system structure.

The following are the main modules discusssed in the paper:

(1) distribution transformer losses;
(2) induction motor losses.

DISTRIBUTION TRANSFORMER LOSSES

A software program has been developed to compute the following transformer properties.

1. Given a desired average loading, calculate the costs of losses and initial investment over the life of the transformer.
2. Compute the costs of losses and initial investment over the life of the transformer for the following loadings:

- if the transformer is loaded at 100% of rated value over the life of the transformer;
- if the transformer is loaded at 90% of rated value over the life of the transformer;

- If the transformer is loaded at 10% of rated value over the life of the transformer.

The program considers three types of distribution transformer losses:

- core losses;
- high voltage winding losses;
- low voltage winding losses.

The above losses can be determined separately by two simple tests. These two tests are referred to as the open-circuit test (or determination of the core losses) and the short-circuit test (or the determination of the copper losses) in the transformer. However, the students may utilize the manufacturer's short-circuit, open-circuit and nameplate data to compute the losses. The user can obtain this data easily by requesting this information on a request for quotation (RFQ), to the manufacturer.

Furthermore, the students must also have in mind a figure for a normal transformer loading and economic figures used by the industry for financial analysis [6]. The program is written to calculate the electrical characteristics of the transformer as:

$$H_{\text{Req}} = (P_{sc})/(I_{sc})^2$$
$$L_{\text{Req}} = (H_{\text{Req}})/(ALFA)^2$$
$$ALFA = (HKV)/(LKV)$$

where:

I_{sc} = short circuit amperage;
P_{sc} = short circuit losses;
HKV = high voltage rating;
LKV = low voltage rating;
H_{Req} = the resistance of the high voltage winding,
L_{Req} = the resistance of the low voltage winding;

The losses in the low side winding are given by

$$LP = (L_{\text{Req}})(L_{sc})^2.$$

The losses in the core are calculated as

$$P_{\text{core}} = P_{oc} - LP.$$

For loading conditions, the current on the high side and the low side can be found respectively as

$$HI = (P_{\text{TEST}})/(HKV)$$
$$LI = (P_{\text{TEST}})/(LKV)$$

where:

I_{oc} = open circuit amperage;
P_{oc} = open circuit losses;
P_{TEST} = Average yearly loading on the transformer in W.

The losses in the high side and low side windings for loading conditions are

$$HP_{\text{Loss}} = (H_{\text{Req}})(HI)^2$$
$$LP_{\text{Loss}} = (L_{\text{Req}})(LI)^2$$

The hourly kW losses on transformer loading are

$$\text{Total losses (kWh)} = (HP_{\text{Loss}}) + (LP_{\text{Loss}}) + (P_{\text{core}})$$
$$\text{Cost of losses per year} = (Y_{\text{cost}}(HP_{\text{Loss}})\,(8\,760) + (Y_{\text{cost}}(LP_{\text{Loss}})\,(8\,760) + (P_{\text{core}})(Z_{\text{cost}})$$

where:

Y_{cost} = cost of energy (\$/kWh);
Z_{cost} = cost of capacity ((\$/kWh)(year)).

ECONOMIC ANALYSIS

Decision making in the selection of design alternatives has been given the utmost importance in engineering practice. This is particularly true for power system design, where the equipment cost has been rapidly increased in recent years. Implementation of a poor choice from the design alternatives may result in serious financial consequences affecting the entire company operation. Although various methods for economic evaluation of design alternatives have been developed, the present worth method is commonly used in practice [5].

The economic life of electrical machines is generally 30–45 years. The value of annual operation expenses is related to the time these expenses occur. Because of this, the concept of present worth is utilized. The software program considers the following.

(1) Present worth (PW) of the annual cost of all losses spread over the life of transformer:

Total present worth over the life of the transformer = (present worth of transformer losses) + (present worth of carrying charges of transformer)

Present worth of transformer losses = (cost of losses per year) × (present worth factor)

Present worth factor = $[(1 + i)^n]^{-1}/[(1 + i)^n(i)]$

where i is the interest rate per period and n is the life of the transformer.

(2) Present worth of carrying charges, which includes initial investment interest and dividends paid to banks and investors to buy the transformer:

Present worth of carrying charges of transformer = (carrying charges (\$)) × (present worth factor given future worth)

Present worth factor given future worth = $[(1 + i)^n]^{-1}$.

Carrying charges (\$)

Carrying charges consist of the following

- debt return;
- equity return;
- federal income tax;
- property tax;
- depreciation;

where

(1) debt return is interest paid on bonds and borrowed money;
(2) equity return is dividends paid to shareholders.

Debt return and equity return can be defined then as cost of capital. Also combine federal income taxes and property taxes and define as 'taxes'.

We can then redefine carrying charges as the sum of the following:

- cost of capital;
- taxes;
- depreciation.

Typical values of total fixed charges and its component are given in Table 1.

Table 1. Typical values of carrying charges

Cost of capital	10–14%
Taxes	5–9%
Depreciation	3–3.2%

Depreciation rate

There must be periodic depreciation charges to the income in order to recover the cost of equipment before its usefulness is exhausted. The annual depreciation charge in terms of percentage of capital investment is calculated as follows:

Depreciation = $(1/n)$[(cost investment) − (salvage value)].

INDUCTION MOTOR LOSSES

The motor analysis can be chosen at the machine menu and could be very similar to the transformer analysis. When the induction motor analysis option is selected from the menu of Fig. 2, the student is prompted for values of percentage slip, no-load test results, blocked-rotor test results and dc test results of the motor, which are then used by the program to calculate the losses. Details of how the students could perform a present worth analysis over the life of the actual motors are given in the section entitled 'Computer Usage'.

Examples

Selected examples of how the package could be used in the classroom are presented in this section. These examples can be used as homework assignments.

Example 1—induction motor. In the Machines Laboratory, the students are asked to do the following in connection with a 5-hp, 220 V, 3-phase wound-rotor induction motor:

(1) Set up and perform laboratory tests under both blocked-rotor and no-load running test conditions. Take measurements required by these tests and measure stator resistance using a dc test. Table 2 shows the results of the laboratory tests.
(2) Perform a present worth analysis over the life of the actual motor.

Table 2. Induction motor test data

No load test	120 V	1.3A	60 W
Blocked-rotor test	35 V	2.5 A	120 W
DC Stator resistor test	4 V	1 A	

Example 2—single-phase transformer. Open and short circuit tests of a single-phase transformer with ratings of 500 kVA and 2300/208 V are provided to the students to perform present worth analysis. Table 3 shows the test data.

Table 3. Transformer test data

Open-circuit test		Short-circuit test	
Voc =	208 V	Vsc =	95 V
Ioc =	85 A	Isc =	217.5 A
Poc =	1 800 W	Psc =	8 200 W

In this example, the students are asked, to do the following:

(1) Perform a single present worth analysis for an average yearly loading of 20 kW.
(2) Perform a series present worth analysis by first analyzing the transformer at full load and decrease the loading by 10% for 10 or more loadings.

Typical machine specifications for the economic factors are also provided to the student:

Initial investment	
(1) transformer	$6 000
(2) induction motor	$3 000
salvage value	$0.00
cost of released generation	63.86 ($/kWh) (year)
cost of released generation	0.0165 $/kWh
interest rate	9.21%
yearly cost of money	11.24%
property tax	7.96%
cost of capital	11.24%
life of machine	30 years

Computer usage

A model of the computer program is provided to the students with a default data file. All information is under interactive control of the students during program execution.

When the students execute the machine analysis, a menu is displayed as shown in Table 4. Table 4 shows steps that the student has to take in order to perform a present worth analysis over the life of the induction motor. In Table 4, the software requires the student's response in order to proceed with the analysis. Once the student has completed his responses through the self-explanatory interactive commands, the screen shown in Table 5 is displayed. The program will start analyzing motor losses and will output to the screen an output file to show the student's present worth analysis of the investment and losses associated with it. Output data can be displayed in tabular form and can be printed out. Completed printed output for the induction motor example is shown in Table 6.

When the students execute the transformer analysis a menu is displayed on the screen. The menu is similar to the motor prompts—the dif-

Table 4. Machine analysis menu

1...FIND DISTRIBUTION TRANSFORMER LOSSES--SINGLE PHASE
2...FIND INDUCTION MOTOR LOSSES --THREE PHASE
3...QUIT

ENTER CHOICES: <enter 1 for transf, 2 for motor, or 3 to exit >

6) the next prompt depends on which machine you are analyzing. Lets see what happens in the case of a motor. The following will appear.

COST OF ENERGY ($/KWH)=0.0165:
<hit return to use .0165 or enter desire value and return to change cost of energy>

COST OF CAPACITY ($/(KWH)(YR)=63.86:
<hit return to use 63.86 or enter desired value>

NO-LOAD TEST RESULTS

ENTER P_{oc}(no-load core losses)watts :<enter no load circuit power>
ENTER volts :<enter no load voltage>
ENTER Ioc amps:<enter no load urrent>

BLOCKED ROTOR TEST RESULTS
ENTER P_{sc}(full-load copper loss) watts:<enter blocked rotor watts>
ENTER V_{sc} volts:<enter blocked rotor voltage>
ENTER I_{sc} amps:<enter blocked rotor current>

DC TEST RESULTS
ENTER Vdc volts:<enter dc voltage>
ENTER Idc amps:<enter dc current>
ENTER Slip:<enter slip at synchrous speed>

Table 5. Input data for the induction motor

ENTER	EXPLANATION OF ENTRIES
Output	..enter output file name
2.	..choose motor loss analysis
	..accept default value or ENTER DIFFERENT COST OF RELEASED GENERATION
	..accept default value or ENTER DIFFERENT COST OF CAPACITY
60	..no load power measurement three phase
120	..no load voltage
1.3	..no load current measurement
2.5	..blocked rotor current measurement
120	..blocked rotor power three phase measurement
35	..blocked rotor voltage measurement
4	..DC test for dc voltage
1	..DC test for dc current
.03	..motor slip for syncronous speed
	..<return> accept default value for cost of money(%)
	..<return> accept default for cost of capital (%)
	..<return> accept default value for life of transformer (years)
	..<return> acept default value for salvage value of transformer (%)
	..<return> accept default value for yearly property tax (%)
3000	..initial investment of motor.

Table 6. A sample of the output data for the induction motor

```
COST OF RELEASED GENERATION .0165 $/KWH
COST OF CAPACITY 63.8600 $ / (KWH) (YR)

NO-LOAD TEST RESULTS
POC = 60.00 WATTS
VOC = 120.00 VOLTS
IOC = 1.30 MPS

BLOCKED ROTOR TEST RESULTS
Psc=120.00 WATTS
Vsc=35.00 VOLTS
Isc= 2.50 AMPS
DC TEST RESULTS
Vdc = 4 VOLTS
Idc = 1 AMP
S = 0.03
YEARLY COST OF LOSSES = $ 14.73
YEARLY COST OF MONEY 9.21%
YEARLY COST OF CAPITAL 11.24%
LIFE OF TRANSFORMER/INDUCTION MOTOR 30.YEARS
SALVAGE VALUE OF TRANSFORMER .00 DOLLARS
YEARLY PROPERTY TAX 7.96%
P.W. OF LOSSES($ 148.52)

INVESTMENT COST = $1000.
YEARLY COST OF LOSSES = $15.
PRESENT COST OF LOSSES = $149.
PRESENT WORTH CARRYING CHARGE ON MOTOR = $1720.
TOTAL PRESENT WORTH COST OF MOTOR = $1869.
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Table 7. Transformer menu

```
1... FIND PW OF TRANSFORMER FOR A SINGLE LOADING
2... FIND PW FOR SERIES OF LOADINGS
3... QUIT

ENTER CHOICE:<enter number of type of analysis desired>
the difference in one and two menu items are stated below
item 1. perform a single present worth analysis for a single average loading entered
        by the user.
item 2. perform a series of present worth analyses by first
        analysing the transformer at full loading and
        decrease the loading by 10% for 10 or
        more loadings. In other words you will get an
        economic analysis of the transformer for 10%,
        20%...,100% of rated loading.
```

ference is shown in Table 7. In Table 7, the student has two menu items to choose from, as listed below:

(1) perform present worth analysis for a single loading;
(2) perform present worth analysis for series of loadings.

The present worth analysis for a single loading is similar to that for series of loadings. The only difference is that the series loadings give an economic analysis of the transformer for 10, 20, . . ., 90% of rated load over the life of the transformer. When a case is chosen from the menu of Table 7, the software requires the student's response in order to proceed with the analysis. Once the student's responses have been completed, the screen shown in Table 8 is displayed. Then, the program starts analyzing transformer losses and will output to the screen an output file.

The output of the program is fashioned to show the student lifetime costs of the transformer for any desired loadings as illustrated in Table 9. This can be a useful tool since the student is often faced with a decision between a transformer with high winding

Table 8. Input data for transformer analysis

ENTER	EXPLANATION OF ENTRIES
output	..name of output file .
1	..choose distribution transformer loss analysis
500	..KVA rating of transformer
2300	..high voltage rating
208	..low voltage rating
	..<return>accept default value for hourly cost of released generation
	..<return> accept default value for yearly cost of capacity
1800	..Open Circuit losses watts
208	..Open Circuit terminal voltage
85	..Open Circuit amperage
8200	..Short Circuit losses watts
95	..Short Circuit voltage
217.5	..Short Circuit amperage
	..Choose to investigate single average loading
250000	..enter average loading in watts
	..<return> accept default value for cost of money (%)
	..<return> accept default value for cost of capital (%)
	..<return> accept default value for life of transformer (years) .
	..<return> accept default value for salvage value of transformer (%)
	..<return> accept default value for yearly property tax (%)
6000	..enter initial investment to purchase transformer
2	..get menu back and try series of loadings 90, 80,......,10%
	..<return> accept default value for cost of money (%)
	..<return> accept default value for cost of capital (%)
	..<return> accept default value for life of transformer (years)
	..<return> accept default value for salvage value of transformer (%)
	..<return> accept default value for yearly property tax (%)

Table 9. A sample of the output data for the transformer analysis.

FIND PRESENT WORTH OF TRANSFORMER FOR LOADING 500.00 KVA

HOURLY KW LOSSES ON TRANSFORMER FOR LOADING = 18.17
EARLY COST OF LOSSES =$2482.38
YEARLY COST OF LOSSES = 9.21%
YEARLY COST CAPITAL 11.24%
LIFE OF TRANSFORMER 30. YEARS
SALVAGE VALUE OF TRANSFORMER : .00
YEARLY PROPERTY TAX 7.96 %
P. W. OF LOSSES ($ 25035.60)
AVERAGE YEARLY LOADING 500.00KVA
INVESTMENT COST = $ 6000.
YEARLY COST OF LOSSES = $2482.
PRESENT WORTH OF TRANSFORMER LOSSES = $25036
PRESENT WORTH OF CARRYING CHARGES ON TRANSFORMER = $10320.
TOTAL PRESENT WORTH COST OF TRANSFORMER =$35356.

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FIND PRESENT WORTH OF TRANSFORMER FOR LOADING 50.00KVA

HOURLY KW LOSSES ON TRANSFORMER FOR LOADING = 1.95
YEARLY COST OF LOSSES = $137.97
P.W. OF LOSSES ($ 1391.52)
AVERAGE YEARLY LOADING 50.00KVA
INVESTMENT COST = $6000.
YEARLY COST OF LOSSES = $138.
PRESENT WORTH OF TRANSFORMER LOSSES = $1392
PRESENT WORTH OF CARRYING CHARGES ON TRANSFORMER = $ 10 320.
TOTAL PRESENT WORTH COST OF TRANSFORMER = $ 1171.

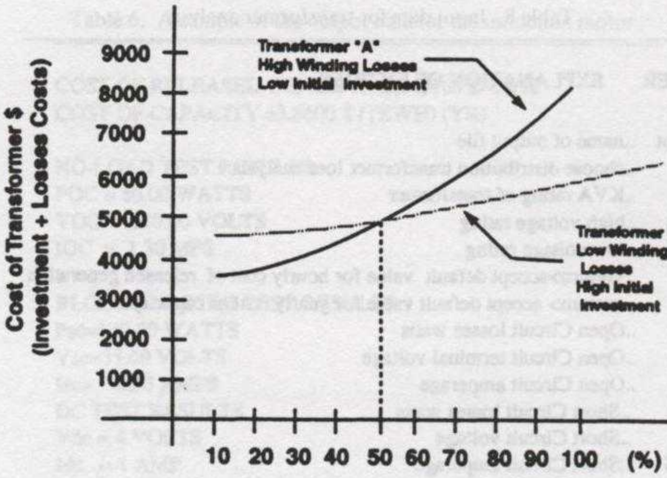

Fig. 4. Cost of transformer versus average transformer loading.

losses and a low first cost, and a transformer with high core losses and high first cost. If this match occurs the students can find a break-even loading between the transformers using the program. A graph can be developed, as shown in Fig. 4, which shows the effect of the cost of the transformer versus the average transformer loading.

As can be seen from Fig. 4, one might use transformer "A" for a low-loading transformer such as might be used on a farm. It has the high rating a farm needs during the brief seasons when there is a need to heat barns, but has the low core losses for its average low winding. However, transformer "B" would be better suited for a shopping mall since the loading is usually high and steady, and the low winding losses would not result in expensive released generation. If average loading is greater than 50% of rated value, then purchase of tranformer "B" is appropriate. If average loading is less than 50% of rated value, then purchase of transformer "A" is more suitable.

This program is useful to the user as long as he realizes that the choices made from this program are only as good as the transformer loading predictions. However, if load growth is certain in healthy growing cities or never-changing farms then this program can be used with a great deal of confidence.

CONCLUSION

This paper has described a software package that can efficiently and accurately analyze the costs of losses and initial investment over the life of transformers and induction motors. The package is ideally suited for implementation on small, low-cost, highly interactive computer systems for use in an educational environment. The software reported in this paper is believed to be the first to offer machine analysis with respect to cost effectiveness. Using this new program the student can conduct electric machine studies in a highly user-friendly manner. Here, the information received is much easier to understand.

The software is beneficial for students who are taking courses in electric machinery and energy conversion laboratories. The use of software in the classroom and the laboratory environment provides the students with a better understanding of the physical machine and the cost of losses. Not only does this enable the confirmation of theory in the students' minds, but it also provides a more complete sense of machine operation.

Currently, this software is being used for instructional purposes in undergraduate classes at Howard University.

PROGRAM AVAILABILITY

The present version of the software described in this paper is available to electrical engineering educators. Copies can be obtained from the first author, who may be reached at (+1)(202)806-5767.

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