Loss Evaluation of Distribution Transformers in Iran's Electric Power System

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***Abstract*— Transformers are efficient devices of which the need for increasing their efficiency may not attract any attention at first. However, because of their great number utilized in the distribution section, the energy losses of them is great and the need for improving efficiency in them is increased continuously. This paper is an attempt to calculate the Total Ownership Cost (TOC) of distribution transformers implementing no load loss factor 'A', load loss factor 'B', and the initial cost of each transformer on the basis of year 2004 data in Iran's power grid. Therefore, two loss evaluation methods widely used in the country's energy sector are introduced and compared based on accredited yearly data used in the calculations.**

***Index Terms*—Distribution transformer, Loss evaluation factors, Transformer losses, Total ownership cost.**

I. Introduction

TRANSFORMERS are electro-magnetic devices used to transform electric power between voltage levels. Basically, there are three main elements in a transformer: the primary winding, the secondary winding, and the core. The magnetic core which is made of laminated iron is encircled by the conducting windings and their functionality is based on coupled electric and magnetic fields.

The transformer is the most efficient of electrical machines, with efficiencies typically in the high 90's. In spite of this, the cost of losses is an important factor in specifying and purchasing transformers, especially distribution transformers which play the main role in the power grid's losses. Although their efficiency is high in comparison to other electrical apparatus, but because of the great amount used in the distribution network, their electric loss is much more than other devices and a minor increase in the efficiency of them can buy great economical advantages for the country.

The optimum utilization of distribution transformers by the electric utilities instead of constructing and developing the power grid gains a huge amount of finance and profit of which can be used in the right order. Therefore, loss evaluation of distribution transformers during their life cycle contributes to the design, purchase, and utilization of them and makes it possible to compare various transformers and choose the most economical one by considering different factors.

The cost of losses is the most important factor in selecting a transformer, because it is quite possible for the estimated value of future losses to exceed the first cost of a transformer. So the right balance between the initial expenses and the upcoming loss expenses should be considered when buying a transformer. To understand the various ways in which this balance may be estimated it is essential to be acquainted with the electrical nature and different types of distribution transformer losses.

II. Types of Transformer Losses

For a distribution transformer operating at a constant voltage and frequency, the losses can be determined by two parts known as no load loss and load loss.

A. No Load Loss

No load loss sometimes called core loss or iron loss is mainly caused by the core steel due to the time-varying nature of the magnetizing force and results from hysteresis and eddy currents in the core materials. In simple words we can say the core loss is present whenever the transformer is energized, and because the distribution transformer is constantly connected to the power grid, it represents a great amount of loss. No load loss includes dielectric loss and conductor loss due to excitation currents as well but as we mentioned the dominant no load loss is the core loss [1].

They are proportional to the frequency and maximum flux density and independent to the load, during the utilization of the distribution transformer no load loss is constant and has no changes. In order to reduce this type of loss it is essential to use laminated steel bands with high permeability, thin width, and high resistance [2].

B. Load Loss

Load loss sometimes called copper loss or winding loss is mainly caused by the winding conductor. Unlike no load losses which are constant and always present, load losses vary with the square of the load current carried by the transformer and include (1) the resistive heating losses (RI^2) in the windings due to both load and eddy currents, (2) stray losses due to leakage fluxes in the windings, core lamps, and other parts, and (3) the loss due to circulating currents in parallel windings and parallel winding strands. For

Manuscript received June 26, 2008.

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distribution transformers, the major source of load losses is the RI^2 losses in the windings [2], [3].

In order to reduce this type of distribution transformer loss it is essential to lessen winding's resistance by implementing materials such as copper or by using a conductor with larger cross-sectional area [3]. However, increasing the cross-sectional area of a conductor by reducing the number of winding turns, demands an increase in flux which increases the iron weight and iron loss. Therefore, a trade-off has to be made between the load loss and the no load loss [2]. Figure 1 illustrates transformer losses and the load's effect on them [3], [4].

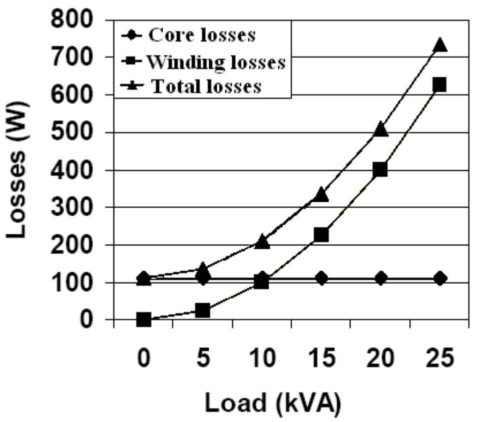

Fig. 1 Load effect on transformer losses

III. Loss Evaluation Methodology

Electric Utilities evaluate new distribution transformers through a loss formula. The loss formula indicates how the utility estimates the capitalized value of no load and load losses for new transformers over the service life which is usually a 30 year period [5]. This loss formula known as Total Owning Cost (TOC) [1]-[3], equals to:

$$TOC = IC + A \times P_o + B \times P_k \tag{1}$$

where:
TOC total owning cost
IC initial transformer purchase cost
A assigned cost of no load losses per-KW
P_o no load loss in watts
B assigned cost of load losses per-KW
P_k load loss in watts at transformers rated load

The purchase price and the energy losses are the two key factors in comparing and specifying different transformers. The purchase price is paid at the moment of purchase, while cost of losses shows itself during the transformer's lifetime. Generally the costs are converted to the moment of purchase by assigning capital values. When transformers are compared with respect to energy losses, the process is called loss evaluation and the A and B parameters are known as loss evaluation factors [6].

Several procedures have been used before in calculating A and B factors, and in this paper two of these methods will be discussed. These two loss evaluation methods are widely used in Iran's energy sector by the principal utilities in hold of electric power distribution and mainly Tavanir Company.

IV. First Method: A Probabilistic Approach

This method of calculating A and B factors relies on accredited data obtained annually to determine various parameters such as the interest rate, cost of a KWh energy, lifetime of the transformer, and average loading current which can be estimated by statistical figures recorded. Therefore, the calculations in this research are based on accredited statistical figures [3], [5] to reach approximate values for A and B loss evaluation factors used in determining the TOC of a distribution transformer.

In this method the no load loss factor A and load loss factor B values are submitted to the transformer manufacturers on a request for quotation. The manufacturer then designs a distribution transformer in response to the price offer by utilizing a combination of different materials so it could come to the optimum TOC price to obtain the order [2]. The factors A and B are formulated as follows:

$$A = \frac{(1+i)^n - 1}{i\,(1+i)^n} \times C_{kwh} \times HPY \tag{2}$$

$$B = \frac{(1+i)^n - 1}{i\,(1+i)^n} \times C_{kwh} \times HPY \times (\frac{I_l}{I_r})^2 \tag{3}$$

where:
i interest rate
n lifetime in years
C_{kwh} kWh price in Rials/kWh
HPY number of hours in a year that the transformer is connected to the power grid, which is 8760 hr. /year
I_l loading current
I_r rated current

And the values implemented in equations (2) and (3) are as follows:

$$i = 18\%,\ n = 30,\ C_{kwh} = 400\frac{Rials}{KWh}$$

Using the values given, in equation (2) results no load loss factor A=2209.24 (US$/KW). The price computed for A is constant and doesn't vary with the changes in the loading current.

There is considerably more uncertainty in calculating the load loss factor B due to various loading currents of a distribution transformer in a year. So it is important to use reliable data calculating this factor. In addition to energy cost of losses, this factor should reflect how the transformer is loaded. At first as shown in Table I, several amounts have been considered for the loading current to point out the great difference of the B values from one ratio to another. This fact means that if the data considered isn't approximate to the real figures, the results upcoming will be absolutely incorrect [2].

TABLE I
B RESULTS ON BASIS OF LOADING CURRENT CHANGE

$(I_l / I_r)\%$	B (US$/KWh)		
	i=18%	n=30	C_{KWh}=0.046
20	88.37		
30	198.83		
40	353.48		
50	552.31		
60	795.33		
70	1082.53		
80	1413.92		
90	1789.49		
100	2209.24		

According to Table I as the loading current I_l increases, the cost for each KWh of load loss rises as well and finally when the transformer is working during full load this amount of loss expense equals to the no load losses cost. In Iran's distribution system most of the transformers have an average annual loading current rate lower than 50% [3], [5], as it is so in developed countries as well [4] and this means that the expenses paid for load losses is much more less than no load losses.

V. SECOND METHOD: A MORE DETERMINISTIC APPROACH

In this method more realistic parameters are involved in calculating A and B loss factors and due to this it is much more deterministic than the first method. The loss evaluation factors are calculated as follows [3], [7]:

$$A = SI + 8760 \cdot EC \cdot RF \cdot PW \tag{3}$$

$$B = SI \cdot AVL^2 \cdot K^2 + 8760 \cdot LSF \cdot AVL^2 \cdot EC \cdot RF \cdot PW \tag{4}$$

where:
SI system investments in $/KWh
EC energy cost in $
RF additional loss recovery factor
PW present worth
AVL average peak load factor
K peak allocation factor
LSF loss factor

Each of these parameters will be introduced in this section respectively.

System Investment: The amount of investment in the power grid to regain one KW of the distribution transformers power loss at systems peak load is called System Investment (SI), and it is estimated as follows [3], [5], and [7]:

$$SI = (1 + CM)(GC \cdot IGC + TC \cdot ITC + DC \cdot IDC) \tag{5}$$

where:
CM capacity margin of the power grid
GC unit cost of generation capacity
IGC incremental generation capacity
TC unit cost of transmission capacity
ITC incremental transmission capacity
DC unit cost of distribution capacity
IDC incremental distribution capacity

Present Worth: Levelizing is done in order to consider fluctuations in some variables such as energy cost which is not constant every year throughout the life of a distribution transformer. In other words, changes in these variables are transformed into a fixed equivalent value for the entire 30 to 40 years life of the distribution transformer. This is done by using the Present Worth formula below [1], [8]:

$$PW = \frac{(1+i)^n - 1}{i\,(1+i)^n} \tag{6}$$

where:
i interest rate
n lifetime in years

Recovery Factor: A part of the energy generated from the power plant is consumed by itself and a portion of it is wasted in the transmission path towards the consumer. Therefore, in order to regain one KWh of distribution transformers energy loss, there should be 1.15 times KWh energy generated at the power plant considered as Recovery Factor (RF) [3].

Average Peak Load Factor: Distribution transformers losses is dependent to the amount of load and because of the fact that all of the distribution network's load passes through transformers path, the loading current factor can be assumed as the transformer's load factor. Average peak load factor (AVL) is the ratio of transformers annual peak load to its nominal rating. According to year 2004 figures in Table II, maximum network load is 28,144MW and total distribution transformer capacity is 58,152MVA, so AVL equals to 0.5 approximately [3], [9].

Peak Allocation Factor: In order to balance energy losses at peak load, peak allocation factor (K) is used. It is the ratio of transformer load during system's peak load to transformers peak load [3].

$$K = \frac{1+e^{C_{RF}}}{1+e^{\frac{C_{RF}}{LF}}} \quad (7)$$

Loss Factor: Transformer's load loss mainly relies on loading conditions and its load curve [3]. In order to calculate the average load loss of distribution transformers, Loss factor formula is used considering LF=67.2%. It is the ratio of distribution transformer's average annual load loss to the peak value of load loss [1]. The equation below expresses it:

$$LSF = (1-X)\cdot LF^2 + X \cdot LF \quad (8)$$

The constant X is usually considered as a number between 0.08 to 0.3 [3]. In this paper X=0.16 has been considered for calculations [1].

TABLE II
POWER INDUSTRY FACTS IN YEAR 2004 [5], [9]

Power Industry Info	Figures in Year 2004
Max. Network Load (MW)	28,144
Power Plant Nominal Rating (MW)	37,300
Power Plant Practical Rating (MW)	33,801
Total Distribution Transformer MVA Capacity	58,152
Distribution Transformer Overall No.	311,700
Total Generation Sector Installation Value ($)	6,780,248,000
Total Transmission Sector Installation Value ($)	4,990,533,000
Total Distribution Sector Installation Value ($)	4,794,322,000
Capacity Margin	13%
Energy Price in 2004 (US$/KWh)	0.046
Network Load Factor	67.20%

Using figures given in Table II and [9] concluded GC=241, TC=177.32, DC=170.35 all in ($/KW) and IGC=1.18, ITC=1.33, IDC=1.33, CM=13% [5], which are used to calculate parameters in table below to reach A and B loss evaluation factors.

TABLE III
COMPUTED LOSS EVALUATION FACTOR PARAMETERS

SI	PW	RF	AVL	K	LSF
843.56	5.52	1.15	0.5	0.82	0.49

The loss evaluation factors can be calculated now, by referring to equations (3) and (4) and implementing the figures in Table III, resulting A=3385.66 (US$/KW) and B=453.21 (US$/KW).

VI. SENSITIVITY ANALYSIS CHART

The influence of each parameter on loss factors A and B which had been calculated based on the probabilistic method could be compared using the Sensitivity Analysis chart. This chart illustrates the differences between the minimum and maximum output values and the effect of each parameter on A and B factors. There are curves with different slopes in this chart; steep slopes, positive or negative indicate that those input parameters forming it have considerable effect on the loss factors, while almost horizontal curves have little or no effect on the output. The slopes of the line also indicate whether a positive change in the variable has a positive or negative effect on the output [2].

A. Effective Parameters on the A Factor

Each of the input parameters of the A loss factor have their own impact on it. Energy cost (EC) and lifetime cycle (n) has a positive correlation to A factor, but the interest rate has a negative effect. These effects have been indicated in figure 2, according to the base point figures i=18%, n=30, and EC=400 (Rials/KWh) equivalent to 0.046 (US$/KWh).

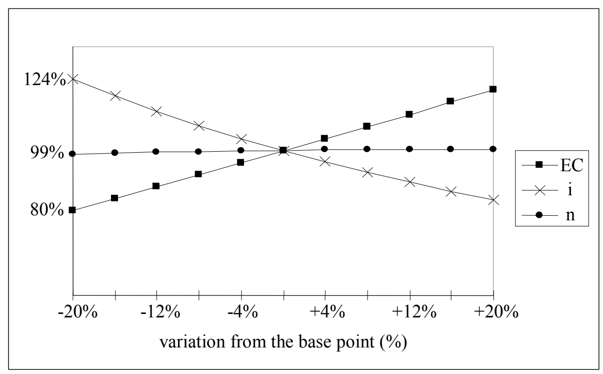

Fig. 2 Sensitivity Analysis chart of A factor

It can be observed that the parameters with the highest effect in order are interest rate, energy cost, and lifetime cycle of the distribution transformer. It can be seen that a 20% decrease in interest rate from i=18% to 14.4%, induces the A loss factor to arrive to 124% of its base value. This indicates that a lower interest rate leads to a higher A factor, showing the negative correlation between them.

B. Effective Parameters on the B Factor

The parameters influencing loss factor B are energy cost, lifetime cycle, and load ratio with positive correlations and the interest rate with a negative relation. The figure below clarifies this correlation.

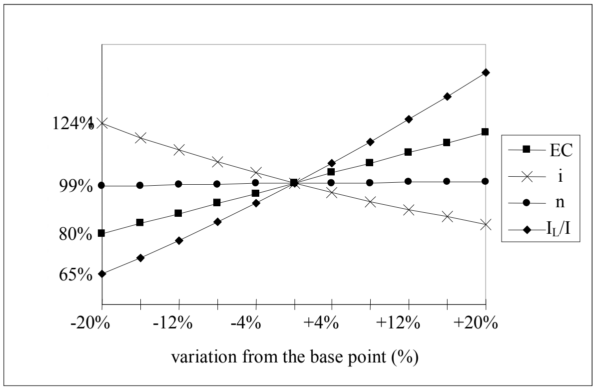

Fig. 3 Sensitivity Analysis chart of B factor

It can be seen that the changes in the load ratio, interest rate, energy cost, and lifetime cycle have the highest effect respectively. For example, a 20% decline in loading current induces the loss factor B to decrease 35% from its base value.

VII. TOC Results

The two methods which had been implemented calculating loss evaluation factors A and B, can be compared clearly by the results we have gained using them separately in Equation (1). In Table IV, TOC results have been presented based on our A and B loss factor outputs and Iran-Transfo Co. data on no load and load losses and the initial cost of distribution transformers in year 2004 on the basis of DIN 42503 standard. Thus, as it was explained in section IV, the average annual loading current rate has been considered 40% and due to this fact, B=353.48 US$/KW(Table I) used to evaluate TOC based on method 1 calculations.

VIII. Conclusion

Iran's electric power distribution network with more than 20,000,000 individual industry and public consumers [10], [11] is facing a power loss of 18.02% [11]. This great amount of loss is partially because of the fact that distribution transformers are currently purchased on a first cost basis without regarding their losses. Total Ownership Cost (TOC) has not been usually taken into account. Therefore, one of the main goals of the country's energy sector is optimizing electric energy consumption by considering transformer losses cost during its lifetime and utilizing more efficient distribution transformers.

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TABLE IV
TOC Results Based on Method 1 and 2 Computations

KVA Rating	No. of transformers sold by Iran-Transfo in 2004	DIN 42503 Standard			Total Ownership Cost (US$)	
		P_{NL} (w)	P_L (w)	IC (US$)	Method 1	Method 2
50	1836	210	1250	1698	2604	2975
100	1938	340	2150	2179	3690	4304
200	2376	570	3600	3211	5743	6772
250	1140	610	4450	3603	6524	7685
315	2155	720	5460	4124	7645	9036
400	919	850	6450	5385	9543	11186
500	426	1000	7800	6380	11346	13300
630	269	1200	9300	7379	13317	15657
800	252	1420	11000	9077	16102	18870
1000	124	1750	13500	10810	19448	22853
1250	114	2100	16400	12525	22961	27067
1600	11	2550	19800	15956	28588	33563