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The Peculiarity of the Load Factor Variable Assumptions in Transformer Total Owning Cost Sensitivity Analyses

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Abstract— *It's a fine business move, if prior to investing in transformers, we analytically identify the most cost-effective and energy-efficient transformer. In the total owning cost (TOC) economic analysis, it is helpful to determine how sensitive the TOC is to several factors of interest, so that the proper attention may be given to them in the decision process. Also, the manufacturers become better equipped to engineer each design to the unique situation of each customer; and the utilities are then able to compare multiple designs so as to find the optimum for their peculiar load profile. Usually, in sensitivity analyses, when the load factor (LF) is being varied to observe the trend in the ∆TOC (TOC difference between the transformer offers of interest); all other input variables of the TOC model are assumed constant. However, it is herein argued that any transformer TOC what-if analysis whose approximations wholly undermine the load pattern, to vary LF independent of the load related variables; could significantly affect the capitalization of losses, which may result in errors in judgment regarding the future uncertainties and relative importance among the input variables of the TOC model. This article is therefore an attempt to investigate this error in assumption/procedure, in the light of fostering sounder judgment towards ultimately maximizing energy savings at the lowest TOC, as long as the transformer is concerned. The sensitivity level with a comprehensive LF variation was observed in this study to at least double that obtained otherwise, and the magnitude and sense of the ∆TOC were significantly influenced by the peculiarity of the load dynamics.*

Keywords— *Load factor, Load losses, Load profile, Sensitivity analysis, Total owning cost, Transformer.*

I. INTRODUCTION

The total owning cost (*TOC*) is the equivalent first cost of acquiring and operating a transformer or reactor over the predicted life of the equipment [1]. Many end users claim that the evaluation of transformers based on the purchase price does not suffice during the procurement process, and the loss evaluation procedure is now well established across end users in many nations. This is now evident by the fact that the *TOC* method is a standard practice in the industry [2][3][4]. The *TOC* method provides an effective way to evaluate various transformer initial purchase prices and cost of losses. The goal is to choose a transformer that meets the requirements for both the specification and the lowest *TOC* [5].

In [11], it was made clear that the load on a transformer varies from time to time. The maximum demand is the greatest short time average demand occurring during a long period of time under consideration. The area under the load curve divided by the corresponding number of hours represents the average load. While the ratio of the area under the load curve to the total area of the rectangle in which it is contained gives the load factor [11].

The author in [12] noted that as the number of consumers on a transformer increases, the contribution to the peak demand of each consumer decreases and the rate of fluctuation drops. Since the service requirements of many consumers coincide with respect to time, peaks and valleys result in the load curve. Average demands are measured over a fixed time period – usually 15, 30 and 60 minutes; and the maximum demands vary accordingly. Annual load factor cannot remain constant from year to year because of the difference between the annual growth rate in peak demand and the annual average load growth rate [12].

Generally, rural transformers that have only aperiodic loading are designed to minimize no-load losses rather than load losses. While, transformers designed for use in urban centres (with high loading for long periods of time) will tend to be designed with a preference for lower load losses. The no-load losses are constant regardless of the load, but the load losses increase with the square of the load. Thus, load losses can be very high relative to the no-load losses during peak periods [19].

Loss Factor (*LSF*) is the ratio of the average transformer losses to the peak transformer losses during a specific period of time. The *LSF* has a nonlinear relationship with the load factor and is an estimation based on various load studies [13][14]. If the system (or individual transformer) load factor is known, the loss factor can be calculated for the system of transformers or the individual transformer. However, the loss factor should be determined from the transformer's load profile, if it is known. Each network branch bears a different loss factor, as each branch is subjected to a different load curve. The load factor and loss factor are principally influenced by the shape of the load curve, and peripherally by the size of the transformer and its per unit loading [1].

The work in [6] emphasized that the *TOC* computations are based on a host of possible assumptions. One of the first things investors must consider about this cost is how sensitive it is to the assumptions. Sensitivity (what-if) analysis, is a method of looking at the possible outcomes, given a change in one of the factors in the analysis. It illustrates the effects of changes in assumptions and focuses only on one change at a time so that the effect of each change on the conclusion can be assessed independently of the effect of other changes [6]. However, we know that diverse factors could change throughout the life of the transformer.

Sensitivity analysis is important in building confidence for a model. It plays an important role in model validation and verification [15]. On the basis of the *TOC* of a transformer, no decision is properly made unless the sensitivity of that decision to variation in the critical variables of interest, is assessed [16]. The *TOC* model is usually analyzed for its sensitivity to inputs such as: availability factor, load factor, discount rate, cost of electricity, transformer lifetime, Peak/Off-Peak Energy Loss Cost etc. [9][10]. The relative degree of sensitivity of the *TOC* to each parameter is indicated by the slope of the curves (the steeper the slope of a curve, the more sensitive the *TOC* is to the variable) [7][8].

Perhaps, owing to the difficulty of anticipating the load pattern, the sensitivity of the ΔTOC to the *LF* assumptions, as computed by diverse researchers e.g., [9][10]; appears to downplay on the fact that the transformer load losses, average load, minimum load and/or peak load; cannot annually remain constant throughout the useful life of the machine, while the *LF* is assumed to vary during the same period. It does not seem realistic, conceding the strong correlation between *LF* and the load losses on one hand as well as *LF* and the minimum/maximum load, on the other; which are all inputs to the *TOC* model.

For the rarity of articles that expound on how the *LF* ought to be varied with respect to the transformer *TOC* in a typical sensitivity analysis, this study therefore simulates different assumptions or procedures to the *LF*/ΔTOC relation so as to recommend the one that proves true-to-life; as an attempt to set sensitivity analyses on a more robust pedestal for a most rewarding investment decision, as it relates to transformers.

II. METHOD

The *TOC* model from [1] was used in this study as outlined hereunder with the variables and parameters duly defined and reasonably specified to suit the present study. The *TOC* difference for two 15KVA transformers was investigated, with their respective efficiencies being the major specification difference. Transformers *A* and *B* (T_A and T_B respectively) are the high and low efficiency transformers respectively. A 0.8 lagging power factor was assumed throughout the study for all load instances. The *TOC* difference between T_A and T_B (ΔTOC) is given in (1) i.e.,

$$\Delta TOC = (TOC\ of\ T_B) - (TOC\ of\ T_A) \quad (1)$$

As gathered from [1], the *TOC* of a transformer may be computed as: $TOC \approx P + A(NL) + B(LL)$ (2)

$$A = \frac{LM[SC+EC(HPY)].10^{-3}}{FCR} \quad (3)$$

$$B = \frac{LM(PL_L^2)[SC(RF)+EC(LSF)(HPY)].10^{-3}}{FCR} \quad (4)$$

Where;

NL and *LL* are the no-load and load losses of the transformer (Watts) respectively. As would be shown in the result section, the losses were obtained from the appropriate simulation of both transformers T_A and T_B under the corresponding *LF* assumptions.

P is the cost of acquiring the transformer ($600 and $500 for transformer *A* and *B* respectively).
A and *B* are the equivalent first cost (in USD) of no-load and load losses, per watt respectively.
SC is the levelized avoided cost of system capacity ($/kW per year).
EC is the levelized avoided cost of energy ($/kWh)
HPY is the hours of operation per year (typically 8760 hours).
FCR is the fixed charge rate (16%).
LM is the loss-on-loss multiplier (1.1per-unit).
RF is the peak responsibility factor (0.85per-unit).
LSF is the transformer loss factor (per-unit).
PL_L is the levelized annual peak load (per-unit).

Assuming that the initial transformer load and annual load growth are such that the transformer does not need to be changed out during its economic life, then the PL_L^2 value for the life of the transformer is given in (5):

$$PL_L^2 = \{\sum_{j=1}^{N}[b(1+g)^{j-1}]^2\ x\ PVF_i^j\}\ x\ CRF_i^N \quad (5)$$

Where;
N is the transformer life (30years)
g is the peak annual load growth rate (2.2%)
b is the initial transformer loading per unit of rating (85%)
i is the minimum acceptable return or the discount rate (5% per year)
j is a given year
CRF is the capital recovery factor

Equation (6) is the closed form for calculating the PL_L^2 value for the life of the transformer:

$$PL_L^2 = \frac{b^2[(1+i)^N - (1+g)^{2N}]}{(1+i)^N[(1+i) - (1+g)^2]} . CRF_n \quad (6)$$

And $CRF_n = \frac{i(1+i)^n}{(1+i)^n - 1}$ (7)

Where, *n* = the number of years in the inflation period, usually the life of the transformer.

From [13], to calculate the avoided cost of distribution capacity, per kW-year (*DC*):

$$DC = (DC')(X)(CRF_n)\frac{1-X^N}{1-X} \quad (8)$$

For this study it was assumed that: $SC \approx DC$. (9)

$$EC = (EC')(X)(CRF_n)\frac{1-X^N}{1-X} \quad (10)$$

Where, *DC'* and *EC'* are the initial demand cost ($100/KW-Year) calculated by the borrower and the initial energy cost ($0.055/kWh) respectively.

$$X = \frac{1+r}{1+i} \quad (11)$$

$$r = \frac{1+E}{1+i_g} \quad (12)$$

where, *E* (3%) and i_g (2.5%) are respectively the annual energy escalation rate and the general inflation rate.

Also, from [17] we have the annual average load (*AL*):

$$AL = \frac{Number\ of\ units(kwh)\ supplied\ in\ a\ year}{8760\ hours} \quad (13)$$

Load factor (*LF*) = $\frac{AL}{Peak\ load}$ (14)

With reference to [18], the *LSF* was computed using (15):

$$LSF = LF^2 + 0.273(LF - K)^2 \quad (15)$$

Where *K* is the minimum demand per unit of peak demand.

The method employed in this study was framed to advance the argument that in a typical *TOC* sensitivity analysis, and in the interest of a sound judgment of the *TOC* sensitivity; a power system index like the load factor, ought not be varied just the same way as economic indices like interest and inflation rates for instance.

Remember that the interest rate is not a direct function of any of the transformer *TOC* model input variables, rather, [6] buttresses that it is a function of the supply and demand for money. The supply of money depends largely on the actions of the Federal government, while the demand for money arises from the need to use money as a medium of exchange in transactions as well as the need to use money as a store of value [6]. However, various sub models of the *TOC* model are strong functions of the interest (or discount) rate.

Therefore, in a typical *TOC* sensitivity analysis, the interest rate variations will directly drive the relevant *TOC* sub models (e.g., the *EC*, *DC* sub models of (6) to (10)) and ultimately, the *TOC* model; in a seamless automatic computation. So that the effect of the input variable uncertainty on a transformer *TOC* decision could be validly assessed.

On the other hand, could the *LF* be similarly varied as the interest rate (or cost of capital) on the same sensitivity graph, without incurring substantial errors capable of derailing investors' judgment?

This question is premised on the fact that first, the vital link between the *LF* and the transformer load losses is not sub modeled within the *TOC* model. Others are, the maximum load captured in the PL^2 parameter of the *TOC* model as in (5), correlates with the *LF* via the average load as in (13) and (14); but this correlation is not also sub modeled within the *TOC* model.

Further, the transformer *LSF* (or *LF*) could be shown to be a partial function of the minimum load as in (15) - a relation that is often overlooked in many *TOC* sensitivity analyses.

Therefore, what significant errors in judgment, if any, are probable from ignoring these seeming collinearities during the sensitivity assessment of the *LF*/ΔTOC relation? In an attempt to answer this question, three cases were investigated:

The first case was to fix the minimum load at 0.3pu and vary the load factor from 0.55 to 1 in steps, while keeping all other variables and parameters of the *TOC* model constant, except the *LSF*. The resulting $\Delta TOC's$ were then plotted against their respective load factors and the gradient (representing the sensitivity of ΔTOC) of the trendline was derived and noted. Results are shown in table 1 and Fig. 1. This is the base case – a procedure the authors adjudge arbitrary and unrealistic. So, the following couple of cases were tailored to include a touch of the needed reality of the load pattern changes and the attendant load losses.

The second case (case A) was to assume that the variation in the *LF* was majorly due to the corresponding variation in the peak load, with the minimum load fixed at 0.2pu. The anticipated peak load during the first year of installation (*PL*) was then varied from 0.86pu to 0.95pu in steps; and of course, the *LF*, *LSF* and the PL^2 parameter will all vary according to (6), (13) to (15). The variation of load losses was obtained from the appropriate simulation of the transformers T_A and T_B under the corresponding *LF's*. All other variables were kept constant and again the $\Delta TOC's$ were then plotted against their respective load factors The gradient of the trendline was derived and noted. Results are shown in table 2 and Fig. 2.

Lastly, case B was based on the assumption that the variation in the *LF* was largely as a result of the corresponding variation in the minimum load; which was varied from 0.255pu to 0.345pu in steps, while pegging the peak load at 1.0pu. The *LF*, the load losses and *LSF* varied accordingly, similar to case A; while other variables were held constant. The $\Delta TOC's$ were again plotted against their respective load factors and the gradient of the trendline, derived and noted. The results are also shown in table 3 and Fig. 3.

For the same pair of transformer offers, the following results shall reveal that the foregoing cases gave three different levels of sensitivities depending on whether or not the computation of the *TOC* took account of the *LF*/load loss relation as well as the load profile dynamics that animates the *LF* variation. The minimum and/or maximum load changes of cases A and B which clearly affects the respective *LF* changes, serve as an approximation of the said dynamics; and cases A and B appear to be more realistic assumptions than the base case. Deviations of the respective cases from the base case was duly spotlighted.

III. Result

The unwitting procedure of arbitrarily varying the *LF* in a stepwise fashion to drive the *TOC* responses as in table 1, is not uncommon in many what-if analyses; as most authors are silent on the details. By keeping load related variables like the load loss (*LL*) and the peak load, amongst others, constant for instance, the *TOC* responses would most likely be inaccurately driven by the *LF* step changes. In the base case, as the *LF* was being varied, the *LL* and PL^2 variations for instance, were not captured accordingly in a real or virtual load profile scenario, for onward integration into the *TOC* model; so as to validly produce the *TOC* responses. Only the equivalent first cost of load losses (*B* value) was driven via just the *LSF*. So that the sensitivity of ΔTOC to *LF*, as typified by the trendline gradient (coefficient of *x*) of Fig. 1; would be grossly misleading if juxtaposed with those of other input variables like the interest rate, for instance.

Also, the trendline of Fig. 1 suggests that T_A remains the more cost-effective transformer option in terms of the *TOC*, as long as the load factor (*LF*) stays above 0.79; otherwise, T_B becomes preferred. This development tends to project T_B as the outrightly preferred choice for many load factor scenarios.

Table 2 and Fig. 2 typify the procedure recommended by this study, in which the load profile dynamics, though not precisely known, have been approximated by the maximum load variations. This reflects in the *LF* variations, which in turn influences vital inputs like the load losses and ultimately the *B* value. All of these tends to result in the proper driving of the ΔTOC responses, and a more realistic portrayal of the ΔTOC sensitivity to the *LF* variations; compared to the base case. From the trendline gradients of both case A and the base case, it may be observed that the sensitivity in case A seems to have risen to well over 5 times (got by dividing the gradient of case A by that of the base case).

TABLE 1: Base Case Data.

LF (pu)	DC (USD/kWh-year)	PLsq (pu)	EC (USD/kWh)	LSF (pu)	A ($/watt)	B ($/watt)	Load Loss for Transformer A (Watts)	Load Loss for Transformer B (Watts)	No Load Loss for Transformer A (Watts)	No Load Loss for Transformer B (Watts)	TOC for Transformer A (USD)	TOC for Transformer B (USD)
0.55	106.08	1.260095438	0.0583455	0.319563	4.176874	2.196117	61.0585888	99.3099318	138.592413	126.572401	1312.97477	1246.773107
0.6	106.08	1.260095438	0.0583455	0.38457	4.176874	2.483956	61.0585888	99.3099318	138.592413	126.572401	1330.549867	1275.358465
0.65	106.08	1.260095438	0.0583455	0.455943	4.176874	2.799979	61.0585888	99.3099318	138.592413	126.572401	1349.845772	1306.742667
0.7	106.08	1.260095438	0.0583455	0.53368	4.176874	3.144185	61.0585888	99.3099318	138.592413	126.572401	1370.862487	1340.925712
0.75	106.08	1.260095438	0.0583455	0.617783	4.176874	3.516574	61.0585888	99.3099318	138.592413	126.572401	1393.60001	1377.9076
0.8	106.08	1.260095438	0.0583455	0.70825	4.176874	3.917145	61.0585888	99.3099318	138.592413	126.572401	1418.058343	1417.688331
0.85	106.08	1.260095438	0.0583455	0.805083	4.176874	4.345899	61.0585888	99.3099318	138.592413	126.572401	1444.237484	1460.267906
0.9	106.08	1.260095438	0.0583455	0.90828	4.176874	4.802837	61.0585888	99.3099318	138.592413	126.572401	1472.137435	1505.646324
0.95	106.08	1.260095438	0.0583455	1.017843	4.176874	5.287957	61.0585888	99.3099318	138.592413	126.572401	1501.758194	1553.823586
1	106.08	1.260095438	0.0583455	1.13377	4.176874	5.80126	61.0585888	99.3099318	138.592413	126.572401	1533.099763	1604.799691

Further, the trendline of Fig. 2 tends to reveal that in terms of the *TOC*, the sweeping superiority of the cost-effectiveness of T_B appears overhyped by the base case results and perhaps misleading. That is, it may be observed from Fig. 2 that T_B will only remain the preferred choice if the LF exceeds about 0.612. This development tends to project T_A as the preferred choice for more load factor scenarios.

Also, in terms of the *LF* variable, making a choice between the transformer offers T_A and T_B in case A, has become a bit more difficult, compared to the base case; because the number of load factor instances favoring either offer has moved closer to the even up point (i.e., *LF* = 0.5).

As observed in table 3, the method of case B (also typifying the procedure recommended by this study) is similar to that of case A, except that the simulated load profile dynamics have been modeled with the minimum load variations, and this stimulus has again been communicated and integrated to the relevant *TOC* model input variables via the *LF* and the *LSF*. The corresponding losses have been duly capitalized and the resulting Δ*TOC* responses may be observed in Fig. 3. Again, this appears to be a more realistic procedure than that of the base case and the sensitivity is observed to have risen to well over twice of the base case.

Also, Fig. 3 tends to toe the line of Fig. 1 in terms of advancing the claims made about the cost-effectiveness of the transformer offers; except that case B presents a lower *LF* of about 0.63, below which T_B becomes the more lucrative choice.

It appears obvious that in a properly conducted *LF/TOC* study, the nature of the load pattern should be allowed to dictate the *LF*, which will in turn significantly play a role in determining the capitalization of the transformer load losses in particular, and eventually influence the preferred transformer choice in terms of the *TOC*. This organic connection among load related variables and parameters, ought to be allowed to manifest its obvious relevance during any transformer *TOC* sensitivity analysis.

TABLE 2: Case A Data.

Maximum load (pu)	LF (pu)	DC (USD/kWh-year)	PLsq (pu)	EC (USD/kWh)	LSF (pu)	A ($/watt)	B ($/watt)	Load Loss for Transformer A (Watts)	Load Loss for Transformer B (Watts)	No Load Loss for Transformer A (Watts)	No Load Loss for Transformer B (Watts)	TOC for Transformer A (USD)	TOC for Transformer B (USD)
0.86	0.616279	106.08	1.27487649	0.0583455	0.427108	4.176874	2.703651	83.3815874	130.494627	139.045006	130.842433	1406.208088	1399.324174
0.87	0.614943	106.08	1.304697154	0.0583455	0.425159	4.176874	2.757957	83.0130371	129.917451	139.038057	130.834804	1409.690784	1404.787187
0.88	0.613636	106.08	1.334862566	0.0583455	0.423259	4.176874	2.81281	82.6715438	129.382648	139.031606	130.82772	1413.256781	1410.379641
0.89	0.61236	106.08	1.365372726	0.0583455	0.421405	4.176874	2.868209	82.3569449	128.889964	139.025651	130.821181	1416.909507	1416.106901
0.9	0.611111	106.08	1.396227633	0.0583455	0.419597	4.176874	2.924155	82.0168072	128.357285	139.019199	130.814098	1420.495446	1421.730493
0.91	0.60989	106.08	1.427427287	0.0583455	0.417833	4.176874	2.980646	81.7034595	127.866562	139.013244	130.807559	1424.169874	1427.491649
0.92	0.608696	106.08	1.458971689	0.0583455	0.41611	4.176874	3.037685	81.3907125	127.376781	139.00729	130.801021	1427.85519	1433.269811
0.93	0.607527	106.08	1.490860839	0.0583455	0.414428	4.176874	3.095269	81.0785661	126.88794	139.001335	130.794483	1431.550985	1439.064336
0.94	0.606383	106.08	1.523094736	0.0583455	0.412785	4.176874	3.1534	80.7929596	126.440663	138.995877	130.78849	1435.340718	1445.00496
0.95	0.605263	106.08	1.555673381	0.0583455	0.411181	4.176874	3.212077	80.5078577	125.994177	138.990419	130.782497	1439.142852	1450.964958

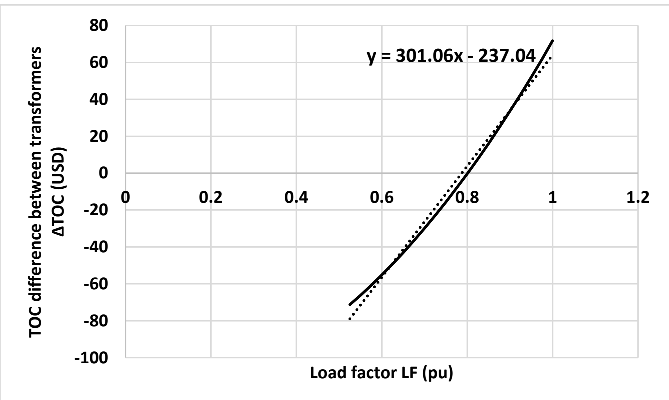

Fig. 1: LF/ΔTOC Relation (Base case).

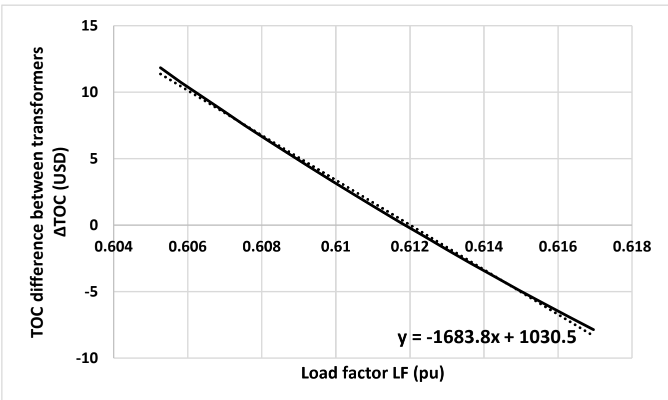

Fig. 2: LF/ΔTOC Relation (Case A).

TABLE 3: Case B Data.

Minimum load (pu)	LF (pu)	DC (USD/kWh-year)	PLsq (pu)	EC (USD/kWh)	LSF (pu)	A ($/watt)	B ($/watt)	Load Loss for Transformer A (Watts)	Load Loss for Transformer B (Watts)	No Load Loss for Transformer A (Watts)	No Load Loss for Transformer B (Watts)	TOC for Transformer A (USD)	TOC for Transformer B (USD)
0.255	0.6275	106.08	1.260095438	0.0583455	0.431637	4.176874	2.692358	86.3594204	135.158162	139.1006	130.903476	1413.516115	1410.661449
0.265	0.6325	106.08	1.260095438	0.0583455	0.436927	4.176874	2.715781	87.7057027	137.266569	139.125425	130.930732	1419.298772	1419.667022
0.275	0.6375	106.08	1.260095438	0.0583455	0.44228	4.176874	2.739485	89.0624124	139.391316	139.150252	130.957993	1425.198173	1428.855423
0.285	0.6425	106.08	1.260095438	0.0583455	0.447697	4.176874	2.763471	90.4295496	141.532404	139.175083	130.985256	1431.216206	1438.22961
0.295	0.6475	106.08	1.260095438	0.0583455	0.453178	4.176874	2.787739	91.8071142	143.689832	139.199917	131.012523	1437.354777	1447.792569
0.305	0.6525	106.08	1.260095438	0.0583455	0.458723	4.176874	2.812289	93.1951064	145.863601	139.224755	131.039794	1443.615811	1457.547313
0.315	0.6575	106.08	1.260095438	0.0583455	0.464331	4.176874	2.837121	94.593526	148.053711	139.249595	131.067068	1450.001249	1467.496885
0.325	0.6625	106.08	1.260095438	0.0583455	0.470003	4.176874	2.862235	96.0023731	150.26016	139.274439	131.094345	1456.51305	1477.644354
0.335	0.6675	106.08	1.260095438	0.0583455	0.475738	4.176874	2.88763	97.4216476	152.482951	139.299286	131.121626	1463.153191	1487.992815
0.345	0.6725	106.08	1.260095438	0.0583455	0.481537	4.176874	2.913307	98.8513497	154.722082	139.324136	131.14891	1469.923666	1498.545393

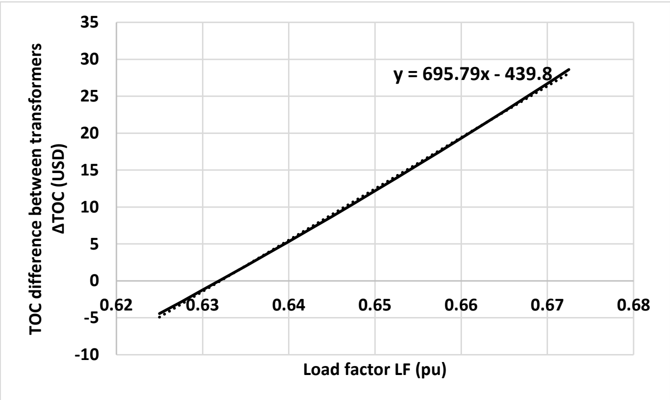

Fig. 3: LF/ΔTOC Relation (Case B).

IV. CONCLUSION

The analysis of the total owning cost of a transformer is quite quantitative in nature, and most of the time the quantities used in the evaluations are projected estimates. The fact that we do not have precise values for some quantities may be the harbinger of costly consequences for capital expenditure. One way to minimize this uncertainty is to ensure that the analytical procedures being employed are valid and as foolproof as possible. Usually, in the *TOC* sensitivity analysis, only one input variable at a time is changed so that the effect of each change on the Δ*TOC* could be assessed independent of the effect of other changes. However, this paper argues that while the *LF* is made to vary, some variables which may be inadvertently kept constant, are highly correlated with the LF; and that maintaining this status quo, will most likely paint a misleading portrait of the *LF/*Δ*TOC* relation. Results from this study suggest that the sensitivity of Δ*TOC* to *LF* variations may just have been long underrated – at least a doubling of the sensitivity level was observed in this study. Also, the load profile dynamics was observed to influence the inflection point for the preferred transformer offer. Issuers/evaluators of tenders as well as investors in transformers are by this study guided to be more circumspect in their sensitivity analyses towards a more reliable and cost-effective procurement decision.

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